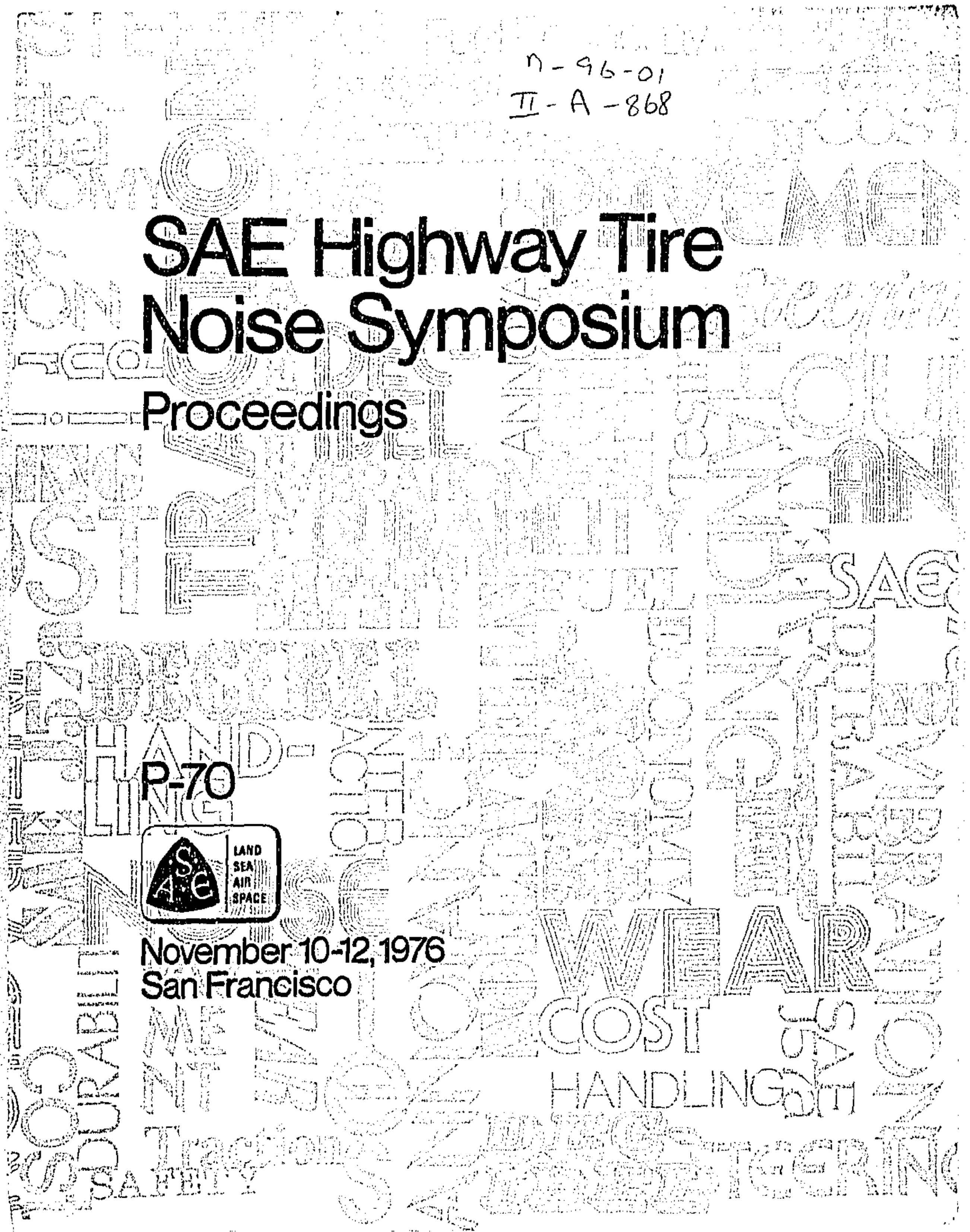

SAE Highway Tire Noise Symposium

Proceedings

P-70

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November 10-12, 1976
San Francisco

Proceedings from the SAE Highway Tire Noise Symposium

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INTRODUCTION

Although noise was the central theme, the objective of this three-day Symposium was to discuss all of the factors, and their interactions, that affect the performance of tires in doing their intended function. We were especially concerned with the relationship of these factors in regard to the potential for reducing highway tire noise, or that portion of community noise.

A second objective was to provide a written record, this Proceedings, to serve as a statement of knowledge as of November 1976. This Proceedings contains all of the presented papers, a transcript of the panel and individual discussions during the Symposium (edited for clarity and brevity, but not substantive content), and several pertinent statements submitted subsequent to the meeting.

The planning for this Symposium started with the basic premise that the existence of highway tire noise was recognized and that a redefinition of the problem was not needed. We frankly wanted a statement of today's facts, test data, and engineering observations. The papers and discussions presented at the Symposium represented many viewpoints; no one paper or presentation can be considered as a total response to the objective of this meeting. Indeed, we sought opposing viewpoints in order to provoke discussion and to get people involved in the dialogue.

There are many rather diverse topics wrapped around the central theme. These may well point out that tire noise measurement is in its adolesence, striving for maturity but not without some growing pains. The state-of-the-art seemingly still rests in individual, isolated studies as basic research or engineering investigations, in many instances concerned with very fundamental behavior.

Some of the papers spoke about impending regulatory action in one form or another. We, of course, recognize this eventuality. But first, we felt that, through this Symposium, we must define the issues and begin to elicit the information that is still needed. Then, hopefully, some conclusions can be drawn.

* * *

This Symposium was conducted by the Society of Automotive Engineers under a research contract from the U.S. Department of Transporation, Office of Noise Abatement. Responsibility for its definition and content was given to an ad hoc steering panel reporting to the SAE Vehicle Sound Level Committee. This panel had several tasks: planning the technical program, soliciting participants and papers, arranging for the final program, participating actively in the Symposium, editing the transcript of the discussions, and preparing an overview statement (which follows these remarks). The members of the ad hoc panel, or those who in part constitute the "we" in the remarks above, are:

William A. Leasure, Jr.
U.S. Department of Transportation

Seymour Lippmann
Uniroyal Tire Company

Asa Sharp
Goodyear Tire and Rubber Company

Larry Strawhorn
American Trucking Associations

William J. Toth
Society of Automotive Engineers

Ronald J. Wasko
Motor Vehicle Manufacturers Association

This Symposium has gone from concept to reality in about eight months. It is to the credit of the authors that they were able to meet the constraint of limited time in so able a manner.

Recognition is also due those who acted as moderators of the Symposium sessions: John D. Eagleburger, E. Clair Hill, Robert L. Mason, Nicholas A. Miller, Robert H. Snyder, and George R. Thurman.

The arrangement of the Proceedings roughly follows the program of the Symposium: prepared statements followed by discussion for both the heavy truck tire and light vehicle tire panel presentations, and groupings of contributed papers in general topical areas. Some re-ordering of papers has been done to improve the continuity of subjects being presented.

It is hoped that you will agree with the steering panel that the objectives of the Symposium have been met with the publication of these Proceedings.

Ralph K. Hillquist
Symposium Chairman

SYMPOSIUM OVERVIEW

The Symposium served as a unique opportunity for tire and vehicle manufacturers, truck fleet operators, and government to pool their current professional thought, data, and engineering recommendations on the many facets of highway tire noise and interrelated factors. A considerable body of new information was brought out by, and for, this meeting.

If anyone assumed prior to this Symposium that the design and application of a pneumatic tire is a simple, straightforward procedure or that the tire-road interaction process which generates tire noise is a well-understood phenomena, his presumptions should now be dispelled. But, although divergent positions were taken during the Symposium and seemingly contradictory data were presented, trends can be identified in certain areas.

Tire noise, primarily truck tire noise, can be a source of community annoyance, especially in residential areas near high-speed highways. Many operational and design variables - speed, load, pavement surface, tread design, wear, size, inflation pressure, etc. - and their effect on tire noise have been documented, although not necessarily quantified in all cases. Whether the existing measurement procedure, specifically SAE J57a, is adequate to ensure accurate measurement of these effects remains an open question.

A strong concern for safety (both driver and public) and an attendant economic concern (both real costs and liability) were voiced by the heavy truck panel. Specific items cited were: carcass life and resistance to road hazard damage; tread depth and wear rates, in regard to traction and handling; tread-carcass separation, for avoidance of highway litter and accompanying hazards; and ejection of snow, mud, and debris from tread voids as it influences traction.

Tread wear was identified as a key factor in tire noise, vehicle handling and traction, and fleet economics. For all of these, sufficient data do not exist to enable a valid quantitative relationship to be established. Clearly, further study and definitive results are needed in these areas.

Pavement composition and surface texture were identified as major factors affecting the tire/pavement interaction concerning both traction and noise generation. Some surface textures, such as those resulting from grooving or drag finishing, can have a significant effect on the absolute, and relative sound levels of rib and cross-bar tires.

One paper presented lateral and longitudinal traction data indicating that rib tires generate higher cornering stiffness and skid coefficients than cross-bar tires on both wet and dry test pavements. The tractive effort which can be sustained by tires operating on deformable surfaces such as mud or snow remains unquantified, although one paper cited better snow traction obtained using lug-type tires.

Tire use practice/cost generalitites are difficult, if not impossible, to make on the basis of data presented. For example, some fleets reported difficulty in obtaining a single retread per radial carcass while others reported an average of three to four retreads. Although each fleet's tire program will be different due to the variety of truck configurations, geographic routes, fleet maintenance practices, or fleet retreading policies, trends should develop. Additional data are needed to quantify the array of current tire use practices and to evaluate possible effects of changes from these practices.

Heavy truck tire selection is appparently based on the fleet operating and economic experience, with a view to the success of the past rather than to a forecast or promise for the future. However, emerging regulatory actions (for example, FMVSS 121) indicate that greater constraints in tire selection may be placed on the heavy truck manufacturer and user as adequate in-use performance and compliance to regulations must be considered. This suggests that an integral consideration of tire, vehicle, and pavement properties, including their respective contraints, is in order. In effect, a re-evaluation of priorities of the compromises or trade-offs in performance characteristics should be studied.

Many of these factors were also apparent in the selection process for passenger car tires. Additionally, the passenger car criteria included the interior noise contribution of tires, through the chassis and isolation systems as well as from exterior noise radiation.

The test requirements and procedure of SAE Recommended Practice J57a were cited in many of the papers as inadequate for reliable and reproducible test data. However, some papers reported test results obtained by variations of SAE J57a open to interpretation. The problem is not a fundamental failing of the test procedure, but rather the difficulty of determining reproducible absolute sound levels for all tire types within the test practices of users of SAE J57a. This is compounded by the effects of different test surfaces, climatic conditions, and other such variables on test results. Thus, SAE J57a may be better suited to rank ordering of tires or tire-development activities than to determination of absolute sound levels for all tire types.

Outdoor noise testing can be costly and time consuming and is weather dependent; therefore, the concept of indoor testing deserves special attention since the potential benefits are great. Initial data from one manufacturer's laboratory wheel look encouraging, and the concept is being explored further. It must be remembered, however, that such a test must also relate to the community noise exposure.

Present understanding of the mechanisms of tire noise generation is incomplete, but progress is being made. Many researchers, however, are simply looking at tread related problems and not at the carcass itself. It is apparent that both "vibration" and "air pumping" can be significant generating mechanisms. Still needed is the necessary understanding to allow for technological advancements that will lower the present apparent noise floor.

There is a need for research focused in the following areas: (a) physical characterization of tire/pavement interaction and/or development of "standard" test surfaces; (b) development of alternative test procedures to SAE J57a; and (c) determination of tire noise generation mechanisms, so that design of tires can incorporate this understanding. To these ends, the tire and vehicle manufacturers might participate in joint research projects, so that their individual expertise in the tire engineering process can be brought to bear on the problem. Also, highway design personnel need to be involved regarding road surfaces that provide good traction and water runoff properties, yet do not signigicantly increase noise levels. The work in the United Kingdom shows that this can be done.

Looking at the basic theme for the Symposium, highway tire noise, it becomes apparent that a logical and orderly process for its definition and abatement can not be drawn from the information contained within the Proceedings. Many areas were uncovered in which a lack of substantive data exists. Nonetheless, it is felt to be necessary to evaluate highway tires as an integral part of the total highway transportation system, using as a starting point the data (both hard and soft) presented at the Symposium. Further research and test activity should not be unmindful of current and future regulatory activity, and if well-conceived and firmly founded technically, can lead to a timely reduction of highway tire noise.

Keynote Address

W. H. Close
U. S. Dept. of Transportation

HIGHWAY TIRE NOISE is the concern of outstanding specialists from the fields of tire manufacturing, truck fleet operations, automotive manufacturing and government. The Department of Transportation obviously believes this is an important subject which needs the attention, thought and input from all of these sectors if the best information is to be made available to meet the needs of State and Federal establishments in addressing the paramount issues of environmental concern today. SAE and indeed this Conference are dedicated to pooling professional thought, data, and engineering recommendations - not regulations - not talking. Government actions are discussed, but only as they set the perspective. Professional work must be separated from the political efforts that may follow on the subject of tire noise.

Many people have been involved with tire noise from the 1950s when a ground swell of public concern was first beginning to focus on truck noise as an environmental problem. Others have added their efforts since that time. In the early 1950s, environment and ecology were not yet the "in" thing. There were, however, growing groups of concerned citizens who lived near toll roads and major arterial highways who began to band together to try to exert influence on the amorphous mass of transportation.

Virtually all states had innocuous kinds of motor vehicle codes which required motor vehicles to be equipped with adequate mufflers and prohibited the use of muffler cut outs and the like. The youngsters of the day enjoyed jacked down cars equipped with Hollywood mufflers which resulted in the "sound of power." Enforcement of noise regulations were sporadic and judgements as to what was, and what was not, an adequate muffler were quite subjective. The ability of law enforcement agencies to be effective in enforcement of these statutes or motor vehicle codes, was dependent upon their willingness to spend a great deal of time before judges to establish credibility of their judgement over that of the offender who would contest any citation.

THE EVOLUTION OF STANDARDS

The net result, of course, was that very little in the way of effective enforcement, except for the most obvious violators, was experienced. Nonetheless, the industry recognized that there was a problem and that the problem was growing. Therefore, in 1954, the Automobile Manufacturers Association (AMA), which is, of course, the predecessor to the current MVMA, adopted a voluntary truck noise standard of 125 sones, measured at 50 ft under maximum noise producing test conditions.

The AMA voluntary standard and the use of sones as the metric were fairly loosely defined and fairly loosely subscribed to by members of this association, but were, at least, recognized by the general field of truck manufacturing.

The credibility of an industry group to set forth a Recommended Practice or to address this as a voluntary standard left something to be desired in the view of many people. Hence, the AMA approached the Society of Automotive Engineers (SAE) and requested that this professional body take a look at the question and try to determine what could be done to develop a consensus standard in this area. In 1957 the SAE reviewed the matter and adopted the Standard J672, which also prescribed 125 sones, measured at 50 ft under test conditions loosely prescribed.

In the case of the AMA and the SAE, in the 1950 time frame, no health or annoyance criteria existed by which these groups could make a determination as to what would be a sufficiently quiet recommended limit of noise, but rather, the numbers established were arrived at through jury test and were completely subjective evaluations of quiet, noisy, moderately noisy, etc., and "good engineering practice." The 125 sone limit and instrumentation required to measure and determine compliance with this limit were somewhat cumbersome. However, those too represented the nominal practice of the day and most importantly, the AMA and SAE set in motion a force to hold the line on noise during a time in which truck horsepower was climbing rapidly.

In the early 1960s, state regulatory efforts were begun in the attempt to bring about control of traffic noise; and trucks, in particular, were identified as a major noise source within the traffic mix. The State of New York was the first to adopt a noise regulation that included roadside tests to ensure the maintenance of adequate muffling systems throughout the life of the vehicle. Controversy over the effects of tire noise had created enough uncertainty as to limit the ultimate legislation to tests of vehicles at speeds of 35 mph or less. Subsequently, the State of California entered the picture with similar roadside noise tests. However, their approach to the problem was to add on several decibels to account for the addition of tire noise at speeds in excess of 35 mph. Subsequent revisions of the California noise standards to reduce the low speed truck noise were effectively pursued. However, continuing uncertainty regarding the contribution of tire noise, left the high speed limit where it was initially placed, at 90dB, using an A-weighted sound level and measured 50 ft to the side of the vehicle path.

During the course of deliberations by state regulators, a series of tests were run by interested sectors of the industry. In 1963, the American Trucking Associations, Inc. (ATA), conducted a series of truck noise tests at Saugerties, New York. This study produced a number of conclusions on truck noise which had previously been subject to much speculation, but little demonstration. The ATA study was the first report in the open literature that identified contributions of engine related noise and tire noise to overall truck noise. The report concluded with four recommendations - three of which were directed to truck manufacturers and operators and the fourth to tire manufacturers. This final recommendation to tire manufacturers stated that:

"Tire manufacturers must devote a great deal more effort to control of truck tire noise by designing quietness into the truck tires in the same manner that has been done in passenger car tires. If methods of quieting present day truck tires are known to the tire industry they should be made available to their own dealers and to motor carriers without delay."

As a result of the above recommendation, in 1964, the tire industry took its first steps toward setting up internal guidelines for dealing with truck tire noise. Through the auspices of the Rubber Manufacturers Association (RMA), the tire industry conducted a program to identify the magnitude and extent of the truck tire noise problem. A study conducted on the New York thruway by RMA personnel combined a series of truck and tire surveys, noise measurements and jury judgements as to the dominance and annoyance of tire noise as a part of the sounds of trucks passing by a point beside the roadway.

The results of this study were never published. However, summaries of the study by personnel in the tire industry have indicated that tire noise was identified by them as a major source of annoyance in about 40% of the trucks which passed by the judgement point.

The next significant contribution in the truck tire noise area occurred in September 1968, when the General Motors Proving Ground issued a report entitled "Truck Tire Noise: An Initial Survey of Tire Noise Variables." This study was made available in a limited fashion within the industry, but it was the first to provide a consistent set of controlled parametric measurements regarding the noise levels generated by truck tires operating on a variety of road surfaces with the vehicle coasting past the microphone. The study clearly indicated the effects of speed, load, and wear on tire noise and the noise level differences among several tread types.

Next on the agenda of actions, we have almost simultaneous steps taken by the SAE Vehicle Sound Level Committee to establish a Truck Tire Noise Subcommittee and the initiation of tire noise studies by the Dept. of Transportation, with work being performed by the National Bureau of Standards.

The charge to the SAE Truck Tire Noise Subcommittee was to develop a test procedure and a recommended sound level for truck tires... "consistent with the SAE Recommended Practice for maximum exterior sound levels of heavy duty trucks and buses, J 366." The Dept. of Transportation, on the other hand, was interested in developing an extensive series of tire noise tests to ascertain the more fine grain elements of the matrix which had been initiated in the GM Proving Ground study and to broaden the information base within the open literature.

The DOT program was undertaken with the realization that other programs administered by the Department, specifically the interstate highway program, had been adding high speed roadways at a rapid rate with the result that during the 1960s, the average speed of trucks on intercity routes was increasing at about 1 mph per year. The DOT program was conducted with the close cooperation of the American Trucking Associations and several member firms who provided in-service tires for the testing and special high powered trucks, when needed for testing combination vehicle tire noise. The SAE Truck Tire Subcommittee was composed principally of personnel from the tire manufacturers, augmented by automobile and truck manufacturers and government personnel.

It is interesting to note that despite the limited charter prescribed for the Truck Tire Noise Subcommittee many hours were spent on initial deliberations of the subcommittee focusing on what is the best approach to testing and placing objective numerical values on tire noise. This is to ensure that the annoyance within communities adjacent to our nation's high speed highways would be minimized.

It is not enough to be able to say: "Here is a test procedure which generates a reliable, repeatable number." That number must be translatable into reduced annoyance for those residents adjacent to highways or the test procedure and the effort to comply with it are worthless. This point can not be over-stressed.

ADMINISTERING NOISE REGULATIONS

We are, of course, concerned with the problems that may result from administering regulations. However, the ultimate objective of all of this effort is to provide tools and understanding which will facilitate the reduction of community noise levels and the annoyance associated with tire noise.

In-service noise limits, in California for example, have put a partial lid on tire noise, but enforcement has been limited. In the beginning, at least, California highway patrolmen did not write citations on high speed noise violators if, in their judgement, tire noise was the cause of the violation. In 1971, however, the California legislature addressed the issue of new product regulations for tires, as recommended by the special noise study group they had commissioned. The legislature enacted Sections 27502 and 27503, which stipulated that regulations were to be developed by the California Highway Patrol and filed with the legislature eight months after the Federal study on tire noise is available and that such regulations were to become effective one year after such filing. It was the intent of the legislature that the Commissioner of the Highway Patrol would consider recommendations of the U.S. Dept. of Transportation before developing independent standards for tire noise that would stipulate that no dealer or person holding a retail seller's permit could sell or offer for sale, etc., a tire which was not in compliance with the regulations when they come into effect. The legislation wisely included economic and technological feasibility and public safety among the criteria to be considered by the Highway Patrol in developing the regulations.

Shortly after these deliberations, the Federal Congressional activity, through Title 4 Amendments to the Clean Air Act, empowered the U.S. Environmental Protection Agency to conduct a comprehensive study of noise and to make recommendations for Federal legislative action. It is interesting to note that during public hearings held by EPA, representations were made by the RMA which pointed out that while there are tires that are quieter than those found in nominal practice at the time, traction and economic considerations argue persuasively for the use of the noisier tires. Limited data regarding traction were summarized and the contention was made that the quieter tires provided significantly lower values of traction and thus would represent a conflict between safety and environmental concerns. The RMA provided an Appendix to their statement containing the limited data available on the subject which, if analyzed in a selective way, supported their contentions of reduced traction. But these data also supported contentions that traction could be improved by using quieter tires. The overall conclusion a balanced assessment of these data would foster is that the understanding of tire traction and its effect or relationships with noise was inadequate to really answer the question at hand. Similarly, it was evident that while there was a very clear preference of motor carriers for the use of noisy cross-bar type tires on drive axles of their trucks, the real economics of their use was not clear, but was very highly colored by apparent economics associated with such tires as a result of the high mileage, first tread performance of such tires. Also evident at the time was that certain, predominantly retread, tires were in fairly wide use which had unjustifiably high noise levels by any standard of assessment.

It is certainly safe to say that when the Noise Control Act was enacted in the fall of 1972, information was insufficient to justify the immediate development of regulations regarding tire noise despite the fact that it was well known that choices between the pocket retread, the cross-bar and the rib tire were being made which affected community noise. The development of regulations, however, would also have to address safety, that is, traction, and economic impacts which were less well known.

It would not be sufficient merely to find examples where a given quiet tire was offered for sale and applied by consumers and say - "that proves the feasibility of a regulation at the level of that particular product." Such examples would not prove the reasonableness of a statewide or nationwide regulation. Thus, it is reasonable to observe that the regulators turned their attention to areas where answers regarding safety and economics were better known. It was, however, evident that if answers could be found to support tire noise regulations, community noise benefits could be realized in a shorter period of time following enactment of regulations than any other major noise control tactic, simply because of the rapid turnover rate of tires.

Meanwhile, in the case of truck noise regulations, for example, the test procedure calls for a lightly loaded vehicle passing-by a microphone with a wide-open throttle and not exceeding 35 mph, expressly to minimize tire noise. It has been determined, however, that even applying the quietest tires to a large truck tractor, tire noise is virtually equal to the lowest demonstrated engine noise levels produced today in research programs and is lurking immediately below the range of influence of noise produced by the exhaust, fan, engine, and drive-line of trucks that could be demonstrated to be in compliance with the Federal noise standards applicable for trucks in the 1980s. The problem of realizing the benefits of truck engineering noise control are more critical when we look at a fully loaded multi-axled truck cruising at high speeds on a highway near impacted areas. Here we see that the noise control on trucks and automobiles is demonstrated to be very effective according to the test procedure, but in the highway situation, all the benefits of noise reduction - through muffling, through use of quiet or thermatic fans, engine wrapping and cocooning, modifications which add thousands of dollars of cost and hundreds of pounds of weight to the vehicle - are completely lost due to the dominance of tire noise at the high-speed cruise conditions.

One hopes that sufficient information is presently available to address the many faceted problems of tire noise control, that sufficient data have been gathered by the professional engineers working on the problem of tire noise in the intervening years to sufficiently answer the questions so that the public servants charged with protecting the environment can move forward with their deliberations to fulfill their legislative mandates and produce reasonable regulations - if that be their conclusion - so that the benefits of tire noise control may be realized by the many thousands, and, indeed, millions of citizens who reside near the high speed highways of California and of our nation.

PART I
HEAVY TRUCK TIRE SELECTION AND USE

762000

Quiet Tires–
An Overview

D. R. Bob Watson
Global Van Lines Maintenance Facility

THE TRANSPORTATION INDUSTRY has an important equity in the basic vehicle. It has advanced to using adhesives to hold the vehicle's sheet metal panels together, ambient air sensors now deliver messages as part of an electronic brake system and the automatic transmission is a production line item on trucks capable of hauling 80,000 lb. Then why not have quiet commercial vehicles as well?

Tire and vehicle manufacturers are working toward this end. However, I would like to explore briefly some concerns on this subject. On the positive side, overall vehicle noise levels drop as new products are developed to meet this challenge. Conversely, the move to quiet has also introduced complications and serious questions relating to the human benefit, and of course, commercially, the cost. Profit may not be the sole objective of business but it is primary. Government and industry researchers have been actively engaged in vehicle noise study for years. It is impractical for industry to assimilate the findings in an abbreviated period and then act to an imposed timetable to use the knowledge to meet restrictions without introducing cost penalties to the user. Manufacturers have research and development programs to provide some checks and balances to government on those technical issues, and have performed quite well in advancing the state-of-the-art of vehicle engineering. This includes tire noise control.

Over the years we have given the tire manufacturer our vehicle data. The manufacturers are the experts who provide us, the user, a production tire that will meet our needs. They have worked hard to meet industry requirements, a task that is not always easy. Manufacturers must be able to supply us with tires that will perform under many varying conditions and be compatible with the total vehicle.

Manufacturers can, I believe, build tires with new tread designs to meet reasonable noise requirements. But, what are reasonable requirements?

The greatest concern in any new tire requirements is the time table involved. We at Global Van Lines have some tire control problems that are unique to some other segments of the transportation industry. We maintain a fleet consisting almost entirely of independent owner operators. These over-the-road vehicles run loaded at from 40,000 - 80,000 lb with both single and tandem drive axles. Miles operated in a year will vary from as few as 40,000 to as many as 160,000. These varying duty cycles obviously dictate that we have more than one set of tire types to use. Using lug tires on drive axles give an extended life and lower cost per mile. It is conceivable that a tractor could run for 2 - 3 years on a new set of drive tires. With a new tire regulation requiring the change over from those tires to a quieter radial or straight rib tire, the cost to individuals and corporations, both in changeovers and obsolescence of inventories, I hope, would be a consideration of anyone involved in such a regulation.

INVESTMENT

Global Van Lines is currently using radial tires on the majority of newer equipment, but as tire costs rise the Company is extremely cognizant of its investment in tires and of course the return on the investment in them. They are functional

ABSTRACT

Vehicle and tire manufacturers are currently working to produce quiet commercial vehicles and tires. While much time has been spent by both government and industry to gather data to cut vehicle noise, it seems that industry and government now wish to interpret this data and make use of it in a short period of time. But this cannot be done without consideration of cost.

We must consider the initial investment of new tires, the labor involved and importantly the national availability of those products as replacements are needed. Only with the full cooperation of government, manufacturers, and the transportation industry can this be accomplished.

and effective but it should be stressed they are used selectively on newer equipment specified for the transportation of heavier loads longer distance. In the household industry each vehicle must stand on its own merits. Radials are too expensive to use on all units, especially those making few intercity trips. Switching to them just for such hauls is not feasible either, as a single tire replacement constitutes a $17.00 labor cost.

TIRE SOURCE AND AVAILABILITY

This is a very delicate and complicated issue. Global Van Lines has used most tire brands, foreign and domestic, both in bias ply and radial ply tires and have encountered considerable difficulty with most domestic radials. One of our concerns is, should we be forced to use all radial tires in the future, could domestic and foreign manufacturers supply the industries' total needs? Do they have the capacity to meet the demand and would the tires be acceptable for safe economic use? We have found in the last years that all sizes of radial tires in the United States are not readily available. As we inventory tires in only one location in the country, on the West Coast, and attempt to keep our inventory at a reasonable level, Global relies on local distributors to fill the majority of our new tire needs at our home terminal. At other locations in the country, when it becomes necessary to replace tires we must contact a distributor in that location and purchase the tire on a national account program set up with the various manufacturers. This is necessary in that we do not have a terminal to terminal operation. In the household business our service is door to door, and I am concerned about the availability across the nation of tires to meet new quiet tire regulations in the case of emergencies such as this.

I am confident with the total vehicle noise level regulations we already have, if manufacturers of both vehicles and tires continue to develop new products and tread designs, the trucking industry will voluntarily meet reasonable and functional government challenges in the effort to create quiet trucks.

762001

Economic and Mobility Considerations in Truck Tire and Retread Selection

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ABSTRACT

A fleet tire program is stated in terms of general objectives, specific application factors and concept factors related to economic and mobility considerations in tire and retread selection. These must directly contribute to minimum, present value long-term total transportation costs for directly and indirectly related tire costs, within the parameters of safe, dependable and legal operations. At the present time, there does not exist a viable alternative to high traction, aggressive, self-cleaning tread in many drive tire applications satisfying the long-term economic considerations. A vehicle that is immobilized cannot supply a transportation function and, therefore, the cost per mile is infinite.

THE PROPER TIRE APPLICATION obviously must start with the many varied safety and/or legalistic parameters that are affecting the truck transportation industry and progress through a series of economic criteria to insure a cohesive coordinated program to facilitate safe and economical transportation. There exists a widespread opportunity for improved tire and retread selection in American fleets based on objectivity and factual decision making. The format as follows can be used in a technical evaluation to determine a proper tire or retread program needed for various applications. The first thing that must be done in this technical evaluation is to determine the general objectives of the tire and retread selection program.

GENERAL PROGRAM OBJECTIVES

The general program objectives include using products and procedures which will result in satisfactory safety, legal compliance, customer and driver acceptance, and product and vendor service. These general objectives must contribute to minimum LONG TERM total transportation costs for direct tire and retreading costs and indirect associated costs of maintenance, fuel and weight. These objectives are general in nature. Each application problem should be defined in terms of the general objectives. This will insure that no general objective is ignored since each has either a direct or indirect effect on the overall economics of fleet operation.

TECHNICAL CHARACTERISTICS - Once we have defined the application in terms of satisfying the general objectives, we must investigate the various technical characteristics of the application in question. This detailed investigation will include expected static and dynamic loads to be carried on each tire and each axle. This criteria will normally determine minimum tire size and ply rating.

The ratio of the weight on the drive axle or axles over the total gross combined weight (GCW) will effect the drive tire traction requirements. Our experience indicates that several application requirements demand the use of a high traction, aggressive, self-cleaning tread. A few examples of this requirement are trucks and tractors which operate in an unloaded condition in snow or mud. We have experienced numerous occurrences of units stuck in terminal yards, hills, loading docks, and truck stops for lack of aggressive tread drive tires.

The alternatives to aggressive tread tires are uneconomical to say the least. These include sanders, tire chains, shovels and tow trucks or refusal of customer loads in poor weather or with off-road loading or unloading sites. We have had considerable experience with these alternatives over the years. Chains are heavy (reduce payload), dangerous (back injuries when installing and broken cross chains), expensive (original cost and high maintenance costs), and noisy (on ice or dry pavement). The vehicle is often setting in the middle of the roadway in bad, low visibility weather when an attempt is made to install chains. This is a severe safety hazard to the installer and to other vehicles on the road. Chains also cause damage to the road surface. The vehicle's downtime alone for lack of aggressive tread drive tires far surpasses the extra original cost of the high traction tire.

The application must be investigated as to the climatic conditions including ambient temperature. Heat can be a limiting factor on tire carcass life and directly affect tire cost. The speed and speed duration that the tires will operate at given ambient and roadbed temperatures are important technical considerations. The higher the ambient temperature and the higher the speed and speed duration, the shorter carcass life.

The terrain and roadbed characteristics including amount of grade, curves, type of roadbed surface must be defined in order to resolve the proper tire solution. Both hills and curves influence traction requirements and affect tire economics as does type of roadbed. For example, our experience in the copper mines of Arizona and iron mines of Minnesota resulted in the selection of steel cord tires for puncture resistance. We have established that two layers of retread on a radial tire carcass is a cost effective program to reduce impact and cut related tire failures in a northern Iowa quarry operation.

Each tire application technical definition must include any unusual or abnormal operation characteristics. If any criteria is slighted, it could invalidate the entire application definition. Examples include the percentage of time or miles a vehicle is loaded, how the vehicle weight is distributed, vehicles running in lime dust or running on a road littered with steel scrap. A partially loaded liquid bulk trailer ascending a steep grade has severe traction problems caused by the weight transfer from the drive wheels. We have encountered similar examples in recent years and these conditions did influence our tire selection.

TECHNICAL CONCEPT FACTORS

Once the application characteristics have been defined in both general objectives and technical factors, we compare the definitions to the decision criteria in the fleet general tire policies and procedures to determine where this specific application is in phase with or clashes with our current standards. The technical concept factor decisions are under continual review and collectively represent the current tire program. Our current position on these concept factors do influence our final decision on all specific tire application studies.

One concept factor we thoroughly investigated was the steel radial versus the bias ply tire and subsequently we adopted steel radial tires as our fleet standard. The associated fuel savings, tire damage reduction and extended carcass life were variables in our decision. Many years ago the tubeless tire was established as our fleet standard. The lighter weight, reduced number of component parts, reduced fire hazard, and reduced maintenance continue to fully justify this policy.

The dual tire versus single tire concept is being re-evaluated. Whereas we now use only dual tires on drive and trailer axles, our tests indicate that the radial single tire will save as much fuel compared to radial duals as the radial dual tire saves compared to bias tires. In addition, the single tire costs and weighs less than two dual tires.

Another concept factor is straight rib versus crossbar or aggressive tread tires for drive tire application. The need for aggressive tread tires has been previously discussed. Aggressive tread tires are purchased for a number of drive tire applications and most radial carcasses are retreaded with an aggressive tread. Of the available alternatives to aggressive tread drive tires, there is no viable option in our operation.

We have investigated high tread tires versus low tread tires and found that our most economical procedure was to purchase premium high tread tires except where tire heat was a controlling application factor. Our number one carcasses are retreaded with 20/32 tread depth weighing 2.7 pounds per foot. Carcasses which have had repairs are retreaded with an 11/32 weighing 1.7 pound per foot. The lighter tread allows superior carcass heat dissipation and reduced failures.

REVIEW OF POLICY

Re-evaluation of our retreading program is undertaken on an annual basis. New tires with the best carcasses available are purchased since we retread all carcasses possible. Currently cold retreading is used, predicated upon our failure experience on "hot retreading" which was double that of cold retreading. The mileage received with our cold retread on a radial carcass is nearly double that formerly experienced with hot retreads on bias ply tires.

Standardization is a policy of our fleet which is applied to tires wherever possible. While oftentimes a smaller size tire would satisfy the general objectives and the technical application factor, the needed size is increased to agree with our standard size. Currently, 95% of our revenue equipment is on one of two size tires. We also standardize tires by vendor so that three vendors supply 90% of our total tires. In choosing our normal vendors, several factors are considered. These include vendor reputation, financial stability, engineering capability, production quality control, availability of local service and technical assistance, and the availability of the product itself. Any vendor that has serious problems in any of these areas would create an undesirable risk.

The normal purchase terms offered to us by our potential vendors are studied in depth. These include the price discount structure and resulting original tire price, the payment terms, freight costs, warehousing costs, and handling costs. Original tire price has to be adjusted to compensate for the purchase terms. For instance, payment terms of 60 days after tire delivery could be considered a 2% reduction in tire price. By purchasing a 6 month supply of tires with deliveries throughout the 6 months, a quantity price discount is sometimes available. If the large purchase must be delivered at one time, warehouse and handling costs must be compared to the amount of the quantity discount. The use of the economic lot size formula will establish shipping quantity.

Economic lot size formula $Q = \sqrt{\frac{2RP}{CI}}$ can be used during this evaluation.

Where:

Q = Lot Size
R = Consumption Forecast (annual)
P = Order Costs
C = Unit Cost
I = Inventory Carrying Charges
2 = Conversion Factor for Average Inventory

EXAMPLE

R = 12,000 Tires
P = \$20
C = \$200
I = 12%

$$Q = \sqrt{\frac{2\,(12000)(20)}{(200)(.12)}} = 142 \text{ units}$$

This could be modified for shipping quantity requirements.

Vendor warranty is another important factor. No fleet intends to have the tire failures associated with warranty. A tire warranty usually does not compensate for accidents, downtime, equipment damage, service calls, and etc., that could be a result of a workmanship or material related tire failure.

Warranty is then a "deductible" insurance policy. However, a warranty policy can also be a measurement of a vendor's faith in his product. Warranty is sometimes a negotiable part of the purchase agreement and can partially protect a fleet from the financial effects of poor product quality.

We chose specific solutions to our particular application by investigating specific tires by brand, construction type and tread design. We again must rely upon the industry experience and our own empirical data for specific tires including tread wear rate, carcass recappability, tire failure problems, the tires susceptibility to irregular tread wear, and tire carcass market value. Carcass market value is important as a measure of carcass recappability if retreading is planned. If retreading is not planned, carcass disposal value must be used in calculating the present value tire cost per mile.

Tire weight can be an important factor in many applications where the total vehicle weight is legally regulated and the cargo characteristics allow loading the units to the maximum legal GCW. A 10 lb lighter tire will allow 180 lb more payload on an 18 tire combination unit each load. If each pound of payload is worth \$2.00/year revenue, then \$360/year increased revenue per unit could be possible with the lighter tires.

CONSTANT REAPPRAISAL IS NECESSARY

It is vitally important that our analysis program does not cease with the implementation of the desired solution. A constant reappraisal is necessary in order to determine whether or not our specific solutions are in fact providing satisfactory results and also whether or not our factor decisions continue to be valid. A vivid example of the need for reappraisal occurred in a fleet we purchased in 1974. The application of this fleet was in an area with which we had little knowledge, experience, or base data. The application solution has been changed four different times in this fleet and a satisfactory solution has yet to be achieved. We are continually experimenting to improve the tire problem results in this given fleet. Several vendors have been involved in the problem and they are also expanding their knowledge because of the problems encountered.

ECONOMIC CONSIDERATIONS

The various technical considerations and concept factors we have discussed can be reduced to quantifiable economic costs by the individual tire user. The key variables in a particular application from an economic point of view include:

1. Initial tire cost
2. Expected tread life and associated direct and indirect costs such as repairs, downtime, warranty recovery, and fuel or weight savings
3. Salvage value of the carcass and/or

TABLE 1 - ILLUSTRATION OF ECONOMIC COSTS OVER TIRE LIFE

End of Cycle Month From Initial	Cycle	No. of Tires Start of Cycle	Failure Rate %	Median Tread Life/Tire	Recappability Rate %	Running Costs/ Tire	Total Miles (000)	Running Costs		Recapping Costs	
								Total	Present Value	Total	Present Value
	Initial Tread	1000	10	95,000	90	20	95,000	20,000	18,942.61	44,550	40,330.53
10	1st Cap	810	20	112,500	75	20	91,125	16,200	13,721.77	21,870	17,483.08
22.5	2nd Cap	486	30	106,250	50	20	51,638	9,720	7,270.16	7,650	5,400.00
35.0	3rd Cap	170	40	100,000	25	20	17,000	3,400	2,245.64	1,170	729.32
47.5	4th Cap	20	60	87,500	0	20	2,275	520	303.28	--	--
TOTALS							257,038	49,840	42,483.46	75,240	63,942.93

Initial Investment 200 x 1000	$200,000
Running Costs & Recapping Costs	125,080
Present Value of Running Costs and Recapping Costs	106,426

expected recappability

The empirical data required to undertake a comparative analysis of various tire alternatives can be obtained from user historical data, user test data and/or industry test data. Since tire cost involve expenditures over time, the time value of money - the fact that a dollar cost in the future is less expensive than a dollar spent today - can play a roll in sophisticated cost analysis. The concept of discounting cash flow to a net present value is widely used in financial analysis of alternatives and can be applied to tire costs. The tire that results in the minimum present value per mile of tread life is preferred. The following illustration depicts an analysis of tire costs using the present value per mile methodology. The present value method is particularly appropriate to use when evaluating tire alternatives that extend beyond a one year time interval.

To illustrate this concept of net present value applied to the factors we discussed consider the following assumptions:

1. The initial cost of a steel radial tire is $200. The failures are random over the life of the tread.

2. The first recap costs an average of $55 per tire (1/2 drive tread and 1/2 trailer tread) and subsequent trailer caps cost $45 each.

3. The running costs including dismounting, mounting, repairing, wrecker calls, and downtime are $20 per original tire or retread spread uniformly over the tread life.

4. The expected failure rates and recappability rates are predicated as shown in the table.

5. The usage rate is 10,000 miles/month with four cycles of tread.

6. The present value discount rate is 12%/year (1%/month).

Table 1 represents a particular tire alternative from initial purchase to final capping four years later. The total cost, excluding initial purchase, for 1,000 tires is 125,080 for running and recapping over 257 million miles of tread life. Discounting these future costs to a present value basis results in 17.5% reduction overall to $106,426. The total present value, including initial investment of $200,000, is $306,426 or a 1.2 mil/mile present value.

A fleet tire program is stated in terms of general objectives, specific application factors and concept factors related to economic and mobility considerations in tire and retread selection. These must directly contribute to minimum present value long-term total transportation costs for directly and indirectly related tire costs within the parameters of safe, dependable and legal operations. At the present time there does not exist a viable alternative to high traction, aggressive, self-cleaning tread in many drive tire applications satisfying the long-term economic considerations. A vehicle that is immobilized can't supply a transportation function and, therefore, the cost per mile is infinite.

762002

Current Fleet Tire Economics

B. Bolstad and H. Ames
Transcon Lines

OUR PRIMARY OBJECTIVE in selecting tires for operation in the fleet has been the safety of both our drivers and the general public, and secondarily, protecting the property transported. Adoption of tubeless type tires in 1967 has enchanced achievement of the above objectives. Obviously, total cost of operation is of major concern, but has not taken precedence over the primary objective of furthering safety. In the future, safety will continue to be the primary objective regardless of additional factors that must now be considered, such as fuel economy and noise.

To achieve our primary selection objective, the tires purchased have been the highest quality tires manufactured by the major domestic producers. Hopefully, in purchasing the highest quality tires available, specifically a durable carcass with a high degree of integrity, failures would be minimized and total operating costs would be reduced. The above approach has until recently, satisfactorily achieved our objectives while controlling total tire operating cost at a reasonable level. During the last 24 months, an alarming degree in degradation of tire durability has been experienced, reaching unlivable proportions.

BIAS PLY TIRE EXPERIENCES

Transcon has annually purchased 15,000 - 20,000 new tires during the 1970 thru 1975 period. New tire purchases have constituted approximately 50% of the total number of tires in service. New tire selection is based upon continual testing and evaluation of the various products currently available. Unfortunately, tire quality and durability is by far, the most variable and unpredictable factor encountered in a fleet operation. The tire that is performing satisfactorily today may exhibit totally unacceptable performance when next purchased, hence the need for continual testing and evaluation. In our operation, safety has too frequently been jeopardized due to unpredictable variations in quality and durability.

In 1970, of the total new tires placed in service, 10% were removed and scrapped due to non-repairable carcass damage and failures. These tires could not be repaired and/or recapped to permit continued usage. Of the 10% scrapped, 20% were adjusted by the tire manufacturer on the basis that the carcass deficiency was their responsibility. Therefore, of the total new tires placed in service, 2% were scrapped due to manufacturing deficiencies and 8% were scrapped due to a combination of road hazard damage and abuse such as "running flat". By the end of 1975, 50% of the new tires placed in service during the year were scrapped due to carcass damage or failures, with the manufacturers assuming responsibility for 80% of the failures. Of the total new tires placed in service in 1975, 40% were scrapped due to manufacturing deficiencies, whereas the number scrapped due to fleet induced problems had nominally increased from 8% in 1970 to 10% in 1975.

From the standpoint of safety, the ramifications of our current experience is alarming. New tires are operated in the most safety sensitive equipment position, the tractor steering axle! It is our policy to remove steering axle tires at 50% tread wear which is approximately 50,000 miles or 3 1/2 months of operation. The carcass failure mileage is unpredictable, does occur at early mileages, and occurs much too frequently, particularly

ABSTRACT

Transcon has gained extensive operating experience with tubeless, 11.00 x 22.5, nylon cord, bias ply construction tires mounted on 7.5 x 22.5 aluminum wheels. The six year period of 1970 thru 1975 will be discussed, further supported by data derived thru September of 1976. During this period, the significant factors and operating parameters affecting tire durability have not changed. Engine horsepower, geared speeds, average loads, routes and type of operation have remained constant. Pertinent fleet facts are summarized in the Appendix for the period 1970 thru 1975.

in the steering axle position.

From an economic standpoint, the cost of bias ply tires had increased 20% during 1975, and 36% during 1976, as compared to 1970 levels. By the same token, the new tire original carcass failure rate attributable to manufacturing deficiencies increased by an astonomical 1900%, involving 40% of the new tires placed in service in 1975 as opposed to 2% in 1970.

Recapping is an important factor in minimizing total tire costs. Historically, it has been possible to recap a tire at least 1 1/2 times prior to scrapping the carcass due to failure or non-repairable damage. Currently our cost to recap a tire is less than 25% of the cost of a new tire. Therefore, the value of the carcass, if recappable, represents 75% of the total new tire cost. Assuming 1 1/2 recaps per new tire and the cost of installing two recaps per tire carcass, the operator obtained 250% total tread wear for 150% of the cost of the new tire.

Of the total tires in service, recaps have constituted approximately 50% of the fleet tire population during the period 1970 - 1974. In 1975, the percentage dropped to 30%. In September of 1976, the percentage dropped further to 20%.

In 1970, 50% of the total tires recapped were removed from service and scrapped due to carcass damage and failure. In 1975, 70% of the total tires recapped were removed from service and scrapped. Since May of 1976, virtually all the tires recapped have been removed from service due to carcass failures. The adjustment rate for recapped tires has varied from 25 - 30%. In other words, the preponderance of the recap failures are due to carcass failures of the same nature that have afflicted the new original carcass. Only 25 - 30% of the recap failures have been attributable to deficient repairs, workmanship and materials in the recapping process.

In summary, we are faced with a 50% failure rate of new bias ply tires representing a 400% increase since 1970. The failure rate attributable to the hazards of fleet operation has ranged from 8% in 1970 to 10% in 1975. The drastic increase in the failure rate of new tires has been reflected in our recap experience. Wherein, we could obtain at least 1 1/2 recaps per tire in the period 1970 - 1974, the failure rate has increased to virtually 100% in 1976.

We can no longer purchase a new bias ply tire with sufficient carcass durability and integrity to operate for the usable tread life of the tire, let alone a carcass that can be recapped.

It would seem that tubeless bias ply tires would be at a high state of development. Our fleet experience has been gained through 10 years of usage and until recently our experience has been favorable. Safety of operation has degenerated to an intolerable level, the economics preclude further purchases. We conjecture over the demise of the tubeless bias ply tire. After all, the tire industry has received increasingly greater amounts of assistance from the federal government in the form of increasingly complex and stringent regulations to promote and insure safety in the usage of commercial highway vehicle tires. Now that the desired theoretical level of safety has been achieved and insured through the regulatory process, we have mounted an all out attack on the undesirable environmental aspect of tires in operation - noise. Will this also be pursued with the same seeming disregard for safety and cost exhibited in the implementation of the FMVSS 121 brake regulation?

RADIAL TIRE EXPERIENCE

Presently, 25% of the total tires in our operation are of tubeless, radial ply, steel cord, steel belted construction. These tires were not selected on the basis of extensive testing and evaluation, rather, they were purchased in desperation due to our recent disappointing experience with the formerly reliable tubeless, bias ply tire. The majority of the radial tires have been placed in service on trailer axles. This is considered the least sensitive position from the standpoint of safety and the least demanding in terms of the factors that are reflected by rate of tread wear and carcass durability and integrity.

These tires represent a major investment in the face of unfavorable economics. The premium for a domestic radial tire for steering axle or trailing axle usage is 25% as compared to a bias ply tire of comparable tread depth. Radial tires of domestic manufacture are not presently available in tread depths and configuration comparable to current bias ply, cross bar, deep tread designs. The premium for a radial versus bias ply tire for drive axle use is 12% greater for 35% less usable tread wear depth.

In the fall of 1975, radial tires were installed on the drive axle position on 25 tractors. Five tractors each were equipped with three domestic brands, five tractors were equipped with a comparable depth tire of foreign manufacture, and five tractors were equipped with a deeper tread depth tire supplied by the same foreign manufacturer. Our purpose was to determine on an accelerated basis, original new tire carcass durability, and further, carcass recappability and durability. None of the new original carcasses failed while worn down to the point of recapping. It should be noted that the original carcass durability testing was conducted during the least demanding winter months. The test radial tires were recapped and operated during the summer of 1976. The carcass failure rate for tires of domestic manufacture ranged from

25 - 65% during the first recap phase of testing. The two types of foreign manufactured tires did not incur any first recap tire failures. The test tires were removed recently due to traction limitations in winter operation.

As a result of this test, it was concluded that the radial tire carcass exhibited a high degree of durability and integrity during the original tread life when operated on the drive axle. The first recap carcass durability varied between the brands tested, some were considered satisfactory, some were not. No appreciable difference was detected in tread wear mileage between radial and bias ply tires. The total tire mileage achieved was directly proportional to the initial tread depth. Cross bar bias ply tires provided 30% more mileage than the domestic radials. In conjunction with this test, bias ply, rib tread tires were operated on the drive axle. The tread depth was comparable to the domestic radials. These tires provided 55% of the mileage achieved by the radials and 40% of the mileage achieved with cross bar bias ply tires.

Based upon original tread wear mileage, the premium cost of radial tires cannot be economically justified. We cannot predict carcass life in terms of recappability at this time, and economic justification for the use of radial tires is dependent upon this factor. We prefer to base our tire selection on extensive testing and evaluation, however, from the standpoint of safety, we see no alternative to converting our operation to radial tires despite our limited experience.

In addition to lack of economic justification, radial tires present the following additional problems as opposed to bias ply construction:

1. Available tread configurations provide insufficient drive axle traction.
2. The tire chain configuration currently used on bias ply tires will damage the sidewalls of radial tires. Therefore, new tire chains must be designed and purchased prior to converting drive axle tires to radials. Our radial drive axle operation will be limited during the forthcoming winter to five tractors due to lack of traction and tire chain compatibility. These tractors will carry tire chains designed in an attempt to provide the required compatibility.
3. Erratic wear when operated on steering and trailing axles.
4. Difficulty in applying hot type recaps. Cold recaps require a good shoulder condition and this is the area where erratic and rapid wear is encountered.
5. Difficult to repair punctures in terms of precluding moisture ingress in the steel belt and carcass cord area. If not completely sealed, moisture ingress results in corrosion of the steel materials and eventual failure. Proper repairs require two to three times as long to accomplish as bias ply tire repairs.
6. When operating as duals, the tire diameters must be mated to much closer tolerances, the same is true for air pressures in dual assemblies.
7. In the event of a carcass failure, the steel tire elements cause a much higher degree of damage to the equipment. This is especially critical in terms of adjacent steering and brake system components.
8. Radial tires are not readily available in sufficient quantities.
9. Last but not least, the lack of operating experience in the face of a rapid conversion to radial tire usage.

APPENDIX

TRANSCON FLEET STATISTICS, 1970-1975

Type:	Transcon Lines is a common carrier of general commodites
Routes:	Operates coast to coast over 42,000 route miles, serving 100 terminals located in 29 states
Annual Revenue Miles:	90 - 130 million
Average GCW Weight:	60,000 - 65,000 dependent upon trailer type
Line Haul Equipment:	850 tractors, 3500 trailers
Tractors	
Type:	4 x 2, single drive, COE sleepers 6 x 2, single drive, COE sleepers
Engine Horsepower:	240 hp
Geared Speed:	58 mph
Trailers	
Type:	28 ft, single axle, doubles trailers 45 ft, tandem axle, semi-trailers

Tires

Population:	25,000 - 32,000
Annual Tire Miles:	1.7 - 2.3 billion
Type:	75% tubeless, bias ply, nylon cord
Size:	11.00 x 22.5

Wheels

Type:	Aluminum disc
Size:	7.5 x 22.5

762003

Tire Use in a Common Carrier Fleet

H. P. Vollmer
Ryder Truck Lines, Inc.

IT MIGHT BE HELPFUL to briefly go through the evolution of Ryder Truck Lines' tire program to acquaint you with the approaches that are being taken in this common carrier fleet.

Back in 1967, Ryder Truck Lines operated on 10.00-20 tube type tires. At the time, we had selected a standard steering axle tire and had a second choice as an alternate. The selection was made as a result of testing tires through the mileage obtained, the cappability and the number of caps, and the safety factor and adjustments. At the same time, we had selected 3 or 4 brands of drive tires on the same basis, with preference given to that showing the lowest cost per mile.

Tire costs in the common carrier industry are usually around 2% of revenue and, therefore, have an important impact on the operating ratio and profitability of the truck line.

In 1969, we started testing tubeless tires, since we felt that we no longer wanted to stay with the tube type as it had problems such as the possibility of total blow-outs, tire fires, excessive downtime, and delay of service. Our tire tests were conducted on a run between Charlotte, N. C. and New York City in a sleeper operation. One of the immediate benefits was a reduction in road failures by 60%. The reason for this reduction was obvious, although nails which get caught in tires will stay in the carcass and the tire may develop into a slow leaker, the tubeless tire can be aired up without repair. A punctured tube by comparison, needs to be patched (or possibly replaced since old tubes usually stretch) immediately, requiring on the spot tire reinstallation or replacement. In addition, we found that tubeless tires ran cooler than tube type tires. Based on our experience at that time, we decided to convert our entire tractor and trailer fleet to tubeless tires.

Depending on the number of vehicles which need to be converted in a large fleet, it takes several years to accomplish this goal. I would like to make the point here that whatever conclusion will be drawn from this Symposium, as far as noise levels and tire requirements are concerned, before a final decision is made, the time factor of conversion must be given very careful consideration, as any type of short range legislation and enforcement will shut down the trucking industry. I do not believe either the government or our industry can afford another cost and safety debacle similar to the one we are now going through because of some unwise provisions in the new air brake regulation, FMVSSR1, and I urge both caution in the approach that is being taken and sufficient testing of equipment in service prior to finalizing any type of rule making.

STEEL BELTED RADIAL TIRES

After converting our fleet to tubeless tires, we looked at steel belted radial tires and their usefulness in our tire program. Basically, we tested the fuel savings first and after we had favorable experiences in that area, we then looked at the tread life and cappability.

We found in our testing that back in 1973, we had some 3 - 10% fuel savings by using steel belted radial tires depending on the brand of tire. As far as cappability is concerned, we were obtaining 1 1/2 caps on the bias tubeless tire and very shortly

ABSTRACT

As a common carrier, Ryder Truck Lines is part of the transportation system of the United States in a free enterprise economy. I need to point out the free enterprise concept, since we only can exist and perform our transportation service to the American public if we are operating on a profitable basis. Over-regulation in the areas of equipment operation, emissions, noise, or performance requirements can have a detrimental effect on the entire transportation system and subsequently be detrimental to the American economy.

found out that with the steel belted radial tires, we could expect 3 - 4 caps. Obviously, the purchase price of a steel belted radial tire is quite high, however, the cost/mile definitely decreases as the same carcass is capped 3 or 4 times versus 1 1/2 times on the bias tire. At this time, I need to mention that we are operating with a tag axle configuration. Our tractors have three axles, one up front for steering and two in the back. Only one of those two rear axles is powered, therefore, is called the drive axle, and the other which helps carry the load but is not connected to the engine is called the tag axle. As this arrangement leaves only the drive axle to transmit the power to move the equipment, it experiences more rapid tread rubber wear than either the steering axle or the tag axle.

Initially, we found in our radial tire study that we could expect 7000 miles/32nd in of tread depth on steering axles. For the drive wheel position we could expect 4000 miles/32nd and 14,000 miles/32nd on the tag axle position. With these projections, we are looking at the following mileages:

Steering Axle Tires	112,000
Drive Tires	64,000
Tag Axle Tires	224,000

The faster tread wear on the drive axle tires is obviously offset by the longer tread life on the tag axle tire. The cost per mile on these tires, depends on the initial price of acquisition and I have not computed that because each carrier and each fleet will have a slightly different purchase price which would either increase or decrease the cost per mile.

The difference in price between a bias tire and a radial tire is from a low of $9.70 to a high of $58.69, depending on the tire brand used. We are now testing an additional three domestic brands and one foreign brand of radial tires. Our initial fuel tests show that progress has been made in increasing the fuel mileage as a result of redesign of the tire. Our tests are not concluded, and at this stage, it is too early to say if the tread wear and the capability will turn out to be competitive with the brand we are operating at this time.

The change from tube type to steel belted radial tires has virtually eliminated the need of tire banks enroute and we have approximately 4000 tires at our major linehaul shop locations and at the terminals throughout the system. In addition, we have had no report of any accidents as the result of tire failures.

Non-uniformity of state and federal laws and regulations relating to the use of tires makes it quite difficult for common carriers operating through various regions within the United States. I would like to mention one of the state requirements such as the use of snow tires or chains, depending on the weather condition and road condition. We have found that the steel belted radial tire does perform well without chains and even without any aggressive type lug will handle equipment on interstate highways and over four lane state roads, even in the northern part of the country.

TIRE MAINTENANCE

One of the most important factors of a tire program is not the purchase of the tire but maintenance of the tire and the program itself. Fifty percent of the tire program is the problem of inflation. Proper tire inflation will increase the tire life, it will increase the tread life, the tire will run cooler, and depending on the tire that is being operated, it will prevent blow-outs from heat buildup. We, at Ryder Truck Lines, gauge steering axle tires physically at each fuel stop and once a week in all other positions. This frequency is higher than the recommendation of the tire manufacturers, however, in order to have control, we find it necessary for us to do that. A recent check on our fleet showed that 93% of our tires have the proper pressure, and we are operating on 90 lb cold. Three percent were slightly over-inflated, 3% were running between 75 - 85 lb, which we consider low, and only 1% had less than 70 lb. We consider a tire with 60 lb flat.

After making sure that one can maintain the correct air pressure for one's operation, the next item in a good tire program is proper matching or making sure that tires run together as duals and used together on an axle, all have virtually the same diameter. Remember these are 18 tires on a tractor/semi-trailer with a different wear rate on each of the axles, which means tires are not replaced in new sets as may be more typical for passenger cars.

Not only will mismatching affect tire life as a large tire paired with a smaller one will tend to do most of the work, it will also affect differentials on drive axles. Here, larger tires on one side of an axle will turn aroundmore slowly than smaller ones on the other side and that action will have to be compensated for in the differential causing rapid wear. We match tires within 1/4 in. In a large fleet, this presents one of the greatest challenges to keeping an effective tire program. In addition to our contract employees, we are engaging our supervisors in our major shops heavily in our tire program. They double check units on the yards, which have already been serviced, for inflation, as well as for matching. For example, during the first five months of this year, our supervisors checked 101,706 tires a second time to assure we have the proper air pressure and the proper matching on the vehicles.

In addition to the safety and wear of steel belted radial tires, it is obvious to everyone here that there are benefits in the noise area. However, I personally believe that the proposals for noise regulation and enforcement which would force their use are premature. From the information I have, the tire industry is not equipped and the fleets are not ready or in a satisfactory financial position to absorb the conversion to steel belted radial tires within the time frame that is proposed.

As far as noise levels are concerned, a survey, using the SAE J57a, pass-by vehicle test and utilizing the slow response method, we found that the tires generally fall within the following ranges:

Rib Radial	69 dB(A)
Cross-bar Radial	72 dB(A)
O. E. Rib Bias	71-73 dB(A)
Cross-bar Bias	75-80 dB(A)

The investigation further showed that the following factors have an affect on the noise levels generated by the tires in use and by the tire maintenance practiced by the fleets.

1. Speed - 3 - 6 dB(A) increase for each 10 mph increase.
2. Inflation - Underinflated tires produce higher dB(A) levels than properly inflated tires with the same load.
3. Size of Tire - Sound level increases 1 - 6 dB(A) with decrease in axle height from 22 - 20 in.
4. Number of Tires on Vehicle - Doubling number of tires increases level 2 - 3 dB(A).
5. Stage of Wear - Sound level increases 2 - 5 dB(A) from new to worn out stage depending on design.
6. Type Tread Design - Lug tires are generally 4 - 9 dB(A) higher than circumferentially ribbed tires with same ply construction.
7. Ply Construction - Generally radial tire constructions are about 2 - 3 dB(A) lower in noise level compared to comparable tread design in bias tires.
8. Road Surface - Smooth concrete surface yields 2 - 4 dB(A) higher levels than coarse asphalt surface.
9. Measurement Distance - Doubling measurement distance decreases level 6 dB(A) and conversely halving distance increases the same amount.

These comments were surveyed by the RCCC Tire, Wheel & Rim Study Group which polled tire manufacturers during the early part of 1975.

While the approach that we have taken is a suitable one for us, that does not mean it will work for everyone's fleet or every equipment operator. The same holds true for tire selection, for tire capping where we use a cold capping process, as well as of monitoring a tire program. Tire tests should be conducted on an individual fleet basis or on an individual operator basis to come up with the best tire for a specific application. This holds true for over the road, in the city operations, as well as in off the road operations. One of the most encouraging things that has happened during the past two years is the effort that has been made by the domestic tire industry to put a product on the market which will be in a position to compete with imports. However, taking the domestic supplies and the imports, there will not be sufficient tires available for common carrier operations to meet proposed noise requirements, unless the date for implementation and enforcement are brought to the point to allow an economical conversion to less noisy tires and to allow for additional research and development by tire manufacturers to have a satisfactory product on line. As far as our tire program is concerned, we use recapped tires for drive, tag, and trailer axle positions. For safety, we pull steering axle tires at 6/32nd in of tread depth and move them to the trailer position for wear down to the 3/32nd which we consider necessary for proper capping. Drive axle tires are used to tread depths of 3/32nd and are then pulled for capping.

Accounting practices are different from one fleet to the next, and I don't believe they should play a part as far as the use of tires in a common carrier fleet is concerned. Obviously, equipment trade cycles play a part in the type of modifications you will have to make to your tire program to retain the better performing tire in your fleet and turn loose of those that are not performing as specified. Through making a continual analysis of such factors, Ryder Truck Lines is presently using Michelin steel belted radial tires with rib type tread on all axles. Our recaps are Bandag.

In conclusion, I hope that I have been able to give some insight to the type of problems that can be expected in a tire program in a common carrier fleet. I also hope that I have been able to stimulate some thought as to the rule making and implementation of desirable noise levels. I think I have pointed out the difficulty financially, as well as time-frame wise, in converting large common carrier fleets from one type of tire to another.

762004

Tire Design Considerations for Refuse Vehicles

A. H. Berger
Browning-Ferris Industries

THE REFUSE INDUSTRY more and more is developing procedures through which trucks are selected to achieve maximum performance and chassis longevity. Among the things to be accomplished through proper vehicle specifications is minimizing the amount of dumping time, measured from the moment a refuse truck first enters a landfill to the time it leaves that area. The cycle involves having the truck enter the landfill area, empty its load, and leave in a minimum period of time with a maximum of maneuverability ease.

Many variables contribute to the length of stay at such a site. These include flat tires, freeing a stuck load, waiting to be directed to the proper dump area, coffee breaks, weighing stations, bad terrain, poor maneuverability, and equipment breakdowns.

Tire related questions which must be taken into consideration when establishing equipment specifications for refuse vehicles include:

1. What affect do front floatation tires have in a landfill?
2. What affect do cross-lug tires, as opposed to semi-lug tires, have on traction in a landfill?
3. What affect does an extra-deep tread on a cross-lug tire have on traction in a landfill?
4. What affect does an extra-deep lug tread have on a tire's self-cleaning ability?
5. What affect do the differences in width and ground contact area between different tire models of equivalent sizes have on performance?

These questions and other related questions make selection of a heavy duty refuse truck a complex task. Considering such a purchase results in a $25,000 - $50,000 investment, it must be made wisely.

BFI has run tests to gather data needed to help make such decisions. What follows will be based upon the portion of that work involving tires, which was performed in 1973 and 1974. The findings should not be taken as absolute. However, it is felt that the condition of the landfill surface area should be considered as the only variable having a significant affect on them.

REAR TIRE TREAD EVALUATION

There were two primary purposes for tests shown in the following figures. They were:

1. What differences, if any, result in a landfill from the use of deep tread cross-lug rear tires in lieu of standard tread of semi-lug tread rear tires?
2. What affect does engine torque have on starting ability of a truck in a landfill?

For Tire Analysis, three sets having eight tires each were used.

Set 1 consisted of 10.00-20 - 12 ply tires taken from a BFI refuse truck. These tires were considered typical of rear tires used by many refuse companies. (See Fig. 1)

Set 2 consisted of eight 10.00-20 - 12 ply General ND Lugger tires. These tires are used by some refuse companies and are considered to have good gripping ability in a landfill. (See Fig. 7)

ABSTRACT

Browning-Ferris Industries (BFI) operates approximately 3500 trucks in 37 states and Canada. Those operations all involve moving trash from the customer to, in most cases, a landfill. This type of business is unique and certainly very different from general freight hauling. It generates special problems which should be considered by those writing noise regulations.

The basic area to be discussed is operation in the sanitary landfill. BFI estimates that on the average its trucks make six trips per day into such an arena. For that reason, tires satisfactory for conditions encountered there must be used. In choosing such a tire, however, the fact that many pickups and the trip to the landfill itself will be made on hard surfaced roads and highways cannot be overlooked. That important consideration is borne out by the fact that in spite of the slow conditions encountered at the dump site, BFI estimates its trucks average 18 mph overall and specifies that they be capable of 55 mph top speeds.

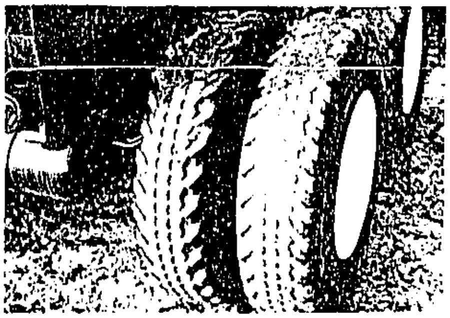

Fig. 1 - 10.00-20 - 12 ply semi-lug rear tires typical of those used on many refuse trucks

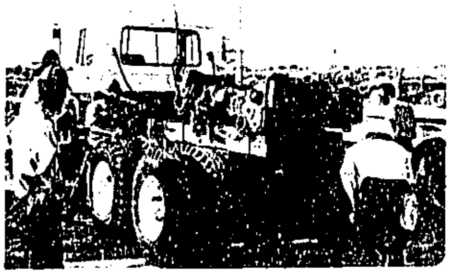

Fig. 2 - Minimum-traction condition

Set 3 consisted of eight 10.00-20 - 12 ply tires that had a BFI modified tread design. The modified tread was accomplished by hand-cutting eight premium quality extra-deep tires. It was anticipated that this tread pattern would provide excellent gripping ability in a landfill. (See Figs. 9 and 10)

A Mack R685ST truck powered by the 237HP-906 lb-ft standard ENDT675 Maxidyne engine was selected for the first test run (Fig. 1). It had 10.00-20 - 12 ply semi-lug rear tires typical of those used on many refuse trucks.

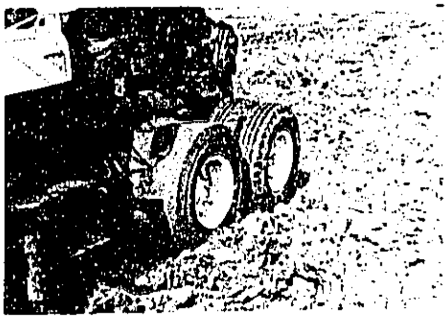

Fig. 3 - Simulated empty tandem axle weight of a front loader after dumping its load

Fig. 4 - Lack of an adequate lug tread was primary cause of the bogging down

In Fig. 2 with two engines chained to the frame, the rear axle weighed 10,500 lb, approximately the same as the tandem axle of a roll-off chassis would weigh after a box had been emptied. This is a minimum traction condition. When any resistance was encountered, the tires broke away, usually with the right front and left rear tires spinning at the same time.

To increase traction, four additional engines were added in Fig. 3, increasing the load on the tandem axle to 18,000 lb. This simulated the empty tandem axle weight of a front loader after dumping its load. Traction improved with the added weight, however, the inadequate tire tread still resulted in its frequent loss. Note the spinning of the forward axle of the tandem. The tread pattern of the non-spinning rear axle clearly shows the power-divider was of no help.

Two engines and the semi-lug rear tires were next mounted on a new Mack R686ST truck. It was powered by the 285 HP-1080 lb-ft intercooled Maxidyne ENDT676 engine. The transmission, rear axle ratio, governed engine rpm, and wheel base were identical to the just tested R685ST truck. The immediate driver reaction was one of greater pulling ease. This engine clearly was not working as hard

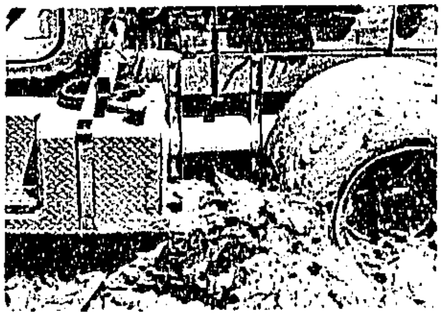

Fig. 5 - Poor traction of rear tires resulted in truck being badly bogged down

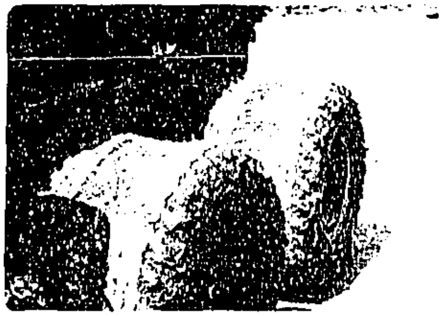

Fig. 6 – Poor condition of tires is obvious reason for loss of traction and frequent tire sidewall cuts common to the refuse industry

as the smaller Maxidyne. The drivers compared the rear wheel traction of this power-train carrying only two engines to the rear wheel traction of the R685ST power-train carrying six engines. Although there was some tire spinning, it did not occur as often as with two engines on the other truck. The lack of an adequate lug tread was the primary cause of the bogging down shown in Fig. 4.

The total payload was increased to six engines in Fig. 5. As a result of the poor traction of the rear tires, the truck bogged down badly at one point. The truck was rocked severely for several minutes in an unsuccessful attempt to free it.

Despite many attempts by the driver to free it, the truck in Fig. 6 had to be towed. As had happened with the R685ST truck, the automatic inter-axle power-divider was of no help when the truck was stuck because both tires were spinning on the same side.

Note the condition of the tires in Fig. 6 – an obvious reason for the loss of traction and frequent tire sidewall cuts common to the refuse industry.

The following opinions were voiced at this point in testing:

1. The truck probably would not have gotten stuck if it had been equipped with cross-lug tires.

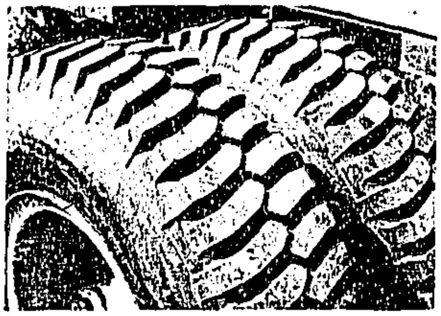

Fig. 7 – Cross-lug tires

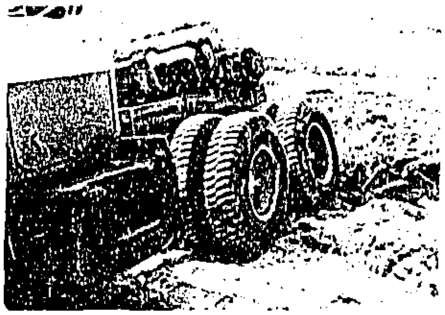

Fig. 8 – Rear tires did not spin, cross-lug tires had radically improved performance

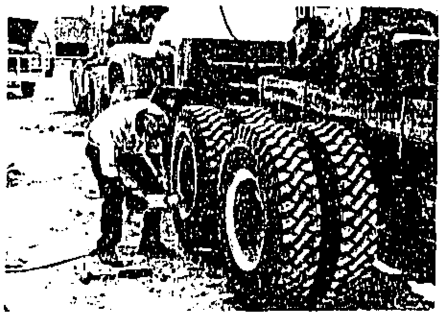

Fig. 9 – Rear tires replaced with BFI modified 10.00-20 – 12 ply super lug tires

2. With the semi-lug tires presently on the truck, the truck might not have gotten stuck with an automatic inter-wheel, inter-axle power divider combination as this would have allowed unbroken momentum without a loss of traction.

3. The truck definitely would not have gotten stuck if it had been equipped with both cross-lug tires and combination power dividers.

For the next test shown in Fig. 7, General 10.00-20 – 12 ply ND Lugger tires were mounted

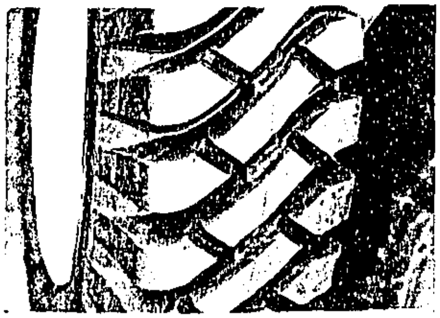

Fig. 10 – BFI modified tires hand cut to produce extra tread pattern and to give superior traction

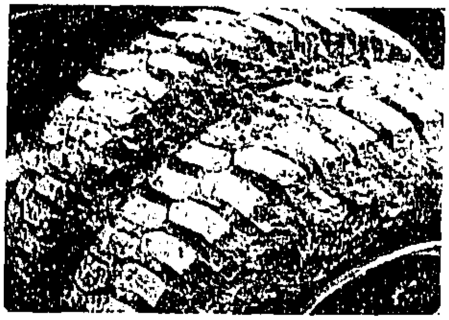

Fig. 11 - Lug flexing has begun to push out mud and clay

on the standard Maxidyne powered R685ST truck. Two engines were again chained to the frame to increase the tandem axle weight to 10,500 lb. Everything was identical in this test to that shown in Figs. 1 - 3 except for the cross-lug tires.

The engine held fairly constant at 800 rpm and seemed to pull easier with the extra traction tires (Fig. 8). At no time did the rear tires spin. They continually kept biting and pulling for maximum traction. There was no question that the cross-lug tread tires had radically improved performance.

It was decided that increasing the payload on the General ND Lugger tires would be of no additional value, since the effects of additional weight had already been determined. Without disturbing the two engine payload, the rear tires were removed and BFI modified 10.00-20 - 12 ply super lug tires were installed (Fig. 9).

The BFI modified tires were hand cut to produce a unique extra tread pattern, anticipated to give superior traction both in the landfill and on wet hard surfaces. Special note should be made of the depth of tread and gaps between lugs (Fig. 10).

The depth at the center of the tire and 2 in either side of it was 20/32 in. Premium tread tires usually have a maximum depth there of 13/32 in. The tread depth from 2 in of center to the outer width of the tire was 40/32 in. There, premium tires usually have a maximum depth of 20/32 in.

The extra wide gap between lugs provides extra cooling. It also allows additional room for lug flexing which helps keep mud and clay buildup to a minimum.

There was no noticeable performance difference between these tires and the standard ND Luggers when used on the R685ST truck having the two engine test load.

Note how the lug flexing has begun to push out the mud and clay in Fig. 11. A close examination shows that the mud is being pushed out at the outer bar ends where the rubber depth is 20/32 in. At the center tie bar, where the rubber depth is only 13/32 in, the mud and clay are receiving a minimum of push because of the limited amount of available flex. The flexing is noted by the gaps between the mud and rubber. This tire is considered a good cleaning tire.

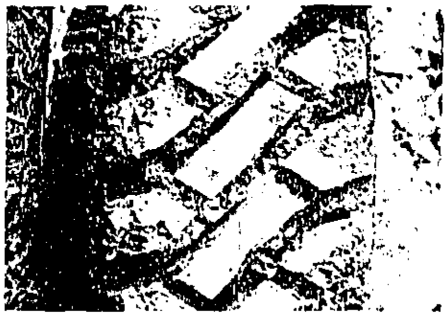

Fig. 12 - BFI modified super lugger had excellent cleaning characteristics

The BFI modified super lugger had excellent cleaning characteristics. Note how the mud and clay have been cleaned and pushed out as a result of superior lug flexing in Fig. 12.

Next, the General ND Lugger tires were installed on the higher powered R686ST truck (Fig. 13). Two engines were chained to the frame for a 10,500 lb tandem axle loading. The terrain was considered one of the worst in the test area. As had been experienced in going to the higher powered truck before, there was an immediate sensation of effortless pulling ability. The inter-axle power divider worked better in this test. When one tire began to spin, it immediately seemed to grab again. The power divider always seemed to be shifting the traction to the pulling axle. The truck seemed to maneuver quite easily.

In Fig. 14 without changing the two engine payload, the rear tires were changed to the BFI modified super luggers. As a result of all the criss-cross driving, the terrain was becoming very soft

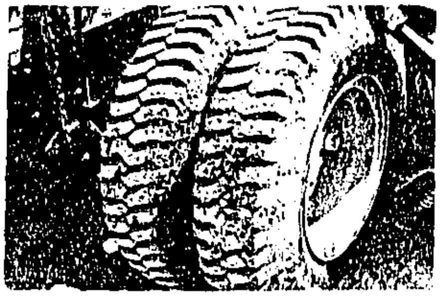

Fig. 13 - General ND lugger tires were installed on the higher powered R686ST truck

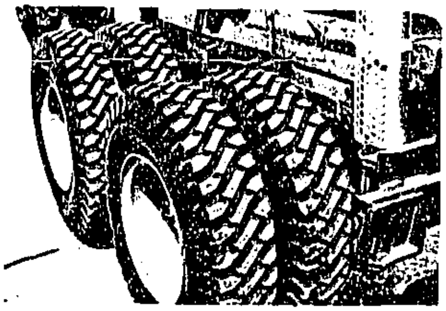

Fig. 14 - Rear tires are changed to BFI modified super luggers

with many ruts and crests. With these super lug tires there was no spinning of any kind.

Four additional engines were added to the payload in Fig. 15 to increase the tandem axle load to 18,000 lb. The BFI super lug tires remained on the rear. The truck would not bog down at all as long as the engine remained in the 800-1000 rpm range. At 1200-1400 rpm, and under adverse terrain conditions, the tires had a tendency to begin spinning. This was attributed more to a light tandem axle loading than to the tread design. The condition was easily corrected by letting up slightly on the accelerator. In previous tests with the same truck and the same load, but with semi-lug tires, tire spinning occurred at a far lower rpm. The maintenance of traction and excellent maneuverability was definitely a result of the super lug rear tires.

Although difficult to believe, the truck in Fig. 16 was stopped and started in the rut shown without any rear tire spin. This was attributed, in part, to the tread depth and design of the BFI modified rear lug tires.

Overall, it was determined that poor tread on the driving tires gave poor results in the landfill.

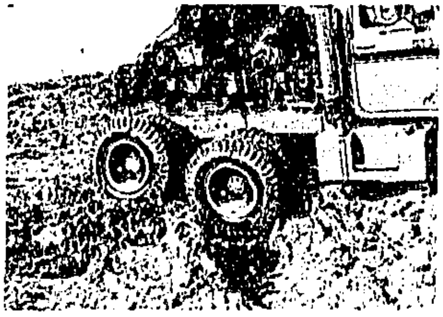

Fig. 15 - Four additional engines were added to the payload to increase the tandem axle load to 18,000 lb

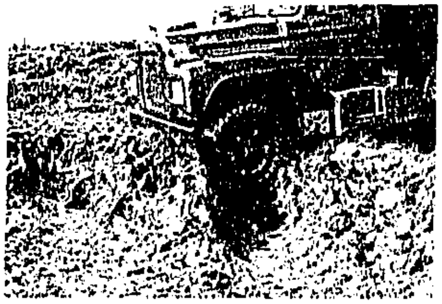

Fig. 16 - Truck was stopped and started in rut shown without any rear tire spin

The BFI designed rear traction tires offered an advantage over not only highway and semi-lug treads, but also over standard depth full cross-lug tires. That advantage was an ability to maintain maximum gripping power. The extreme depth of the lugs allowed above normal lug flexing which resulted in a rapid cleaning tire. It resisted mud and clay caking between the lugs and appeared to have maximum resistance to spinning.

FRONT TIRE SIZE EVALUATION

The primary purpose of the following group of tests was to evaluate what driving differences, if any, result from the use of front flotation tires in lieu of standard 10.00-20 or 11.00-20 tires in soft wet landfill terrain. The truck selected was a Mack MB685S Maxidyne with an E-Z Pack FL60-30 front loader. The body was weighted with skids containing six used diesel engine blocks.

Prior to any loading, the complete truck was weighed with the blade forward. The empty scale weights were:

Front Axle - 15,740 lb Tandem Axle - 17,630 lb
Total - 33,370 lb

In the first group of test runs, the packing blade was located in the forward position. The skids were in the forward end of the body and shored from the rear to prevent any load shifting. The scale weights were:

Front Axle - 19,390 lb Tandem Axle - 23,060 lb
Total - 42,450 lb

This loading simulated a heavy front loader or a roll-off with a container heavily loaded at the front of the box. Maximum weight was on the front axle.

In the second group of test runs, the skids (payload) were moved as far to the rear as possible and were shored by the packing blade at the rear of the body. The scale weights were:

Fig. 17 - With 19,390 lb on the front axle, the two 10.00 - 20 tires immediately sank into the soggy ground

Front Axle - 12,450 lb Tandem Axle - 30,000 lb
Total - 42,450 lb

This loading simulated a heavy rear loader (25-31 yd^3) or a roll-off with a container heavily loaded at the rear of the box. Minimum weight was on the front axle.

In Fig. 17 with 19,390 lb on the front axle, the two 10.00-20 tires immediately sank into the soggy ground. Note the slick track of the supposed lug tires (Fig. 18). These "lug" tires had no gripping ability whatsoever.

An attempt was made to back out the truck. Forward-reverse rocking proved unsuccessful. Finally, the truck had to be towed (Fig. 19).

To determine the effect of better rear lug tires, in Fig. 20 the rear tires were changed to the BFI designed 10.00-20 super lugs. The front tires were not changed. The truck seemed to pull considerably better. The initial reaction was that front flotation tires might not be necessary with the super lug tires on the rear. However, with the concentrated load of 135 lb/in^2 still on the front tires, the truck again bogged down.

An attempt was made to back the truck out, evaluating what additional traction the super lugs now provided. With the front tires settled into the ground, it quickly became evident that the extra gripping ability of the rear tires was of little value in this situation and again the truck had to be towed.

Next, flotation 15-22.5 - 16 ply tires were installed on the front axle (Fig. 21). Ground contact area per tire was increased from 72 in^2 to 100 in^2, reducing the tire load from 135 lb/in^2 to 97 lb/in^2.

The BFI designed super lug tires remained on the rear. Despite continual watering of the test area, the front tires now floated and rolled over the terrain. There was much less of a tendency to plow or bog down than with the 10.00-20 front tires.

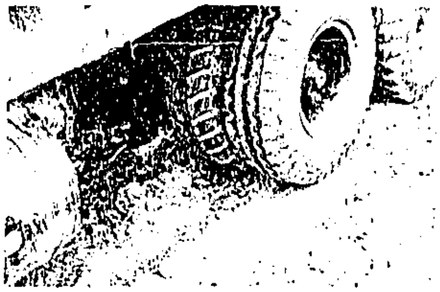

Fig. 18 - Note the slick track of the supposed lug tires. These "lug" tires had no gripping ability whatsoever

When the truck's forward motion was stopped, it was relatively easy to rock the truck between first gear and reverse. Note the floating characteristics of these front tires as compared to the sinking characteristics of the 10.00-20 front tires shown in Fig. 17.

OBSERVATIONS AND CONCLUDING REMARKS

In addition to the data developed in the material already shown, other testing was done with wider (16.5-22.5) front flotation tires, differing front axle loads, a variety of total overall gear reductions, and equipment built by engine and truck manufacturers other than Mack.

Many things were learned relative to operating trucks in the landfill. Some involved that area itself. Local regulations require that trash in such places be covered with dirt daily. This practically guarantees a slippery top surface which has many tire damaging hazards just under it.

Loaded equipment cuts through that top layer of dirt and gets traction from the material below. That results in much sidewall damage to tires and experience to date shows it to be worse with radials. Also, problems with achieving adequate traction are greater for the unloaded vehicle leaving

Fig. 19 - Forward-reverse rocking unsuccessful, the truck finally had to be towed

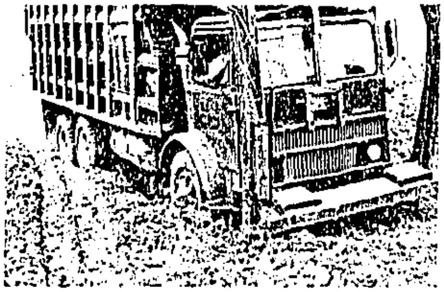

Fig. 20 - Rear tires changed to BFI designed 10.00 - 20 super-lugs

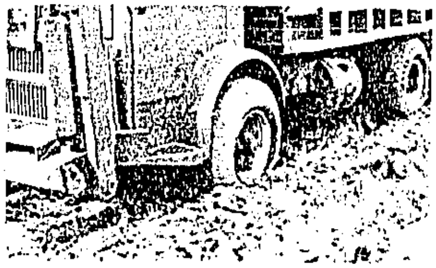

Fig. 21 - Floatation 15-22.5 16 ply tires were installed on the front axle

the dumping area than they are for it when it enters, loaded.

Maintaining vehicular momentum was the key to keeping axles from sinking and proper front tire floatation was necessary to achieve that. Equally important is a constant, adequate tractive effort output from the drive axles. Proper floatation of front tires combined with traction lugs on the rear enables the truck to roll over the terrain instead of plowing or sinking into it.

Superior floatation in landfill conditions is provided by 15-22.5 and 16.5 x 22.5 front tires. Using them reduces the tendency of the front end to sink and that results in less rear tire spin caused by the need to force the vehicle up out of deep front tire ruts. When the front tires sink to the extent their escape angles are no longer relatively low (the angle between a tangent drawn perpendicular to that tire radius bisecting the wedge of material in front of it, and a plane parallel to the roadway surface) even an aggressive rear tire tread may be inadequate to keep the truck moving.

A very low creeper gear was of no value in preventing or overcoming problems caused by either non-floating front tires or drive tires with non-aggressive tread. The nature of the terrain makes it more essential to be able to maintain traction when traveling through a landfill than having a creeper gear to assist in trying to get out of the hole once the truck has stopped. The momentum lost when the driver shifts to a very low gear cannot be regained. Further, starting initially in such a gear does not permit speeds high enough to keep the necessary momentum.

A final conclusion, for purposes of this Symposium, is that very aggressive lug type drive tires are absolutely necessary for successful operation of refuse trucks in landfills. Banning such tires in the name of noise reduction would result in extremely expensive alternate measures (such as towing all equipment in and out of dump site) being necessary.

762005

A Manufacturer Looks for Quiet Tires

W. C. Long
General Motors Corp.

TIRE SELECTION FOR HIGHWAY VEHICLES requires much consideration by the vehicle manufacturer. Some of the selection criteria are the following:

1. The load rating of the tire and the corresponding rim or wheel must match or be equal to, or greater than the rating of the axles on the vehicle,
2. One must consider tire carcass durability for the various operating conditions,
3. Tread wear,
4. Retreadability is important by reason of the fact that 75% of a truck tire's life is spent in the retreaded condition,
5. Ride and handling. Tire input to these phenomena is becoming more and more important, and may soon be taken out of the subjective evaluation into the measurable area,
6. Cost per mile,
7. Weight of the tire,
8. Rolling resistance. A fact that will become increasingly important as the cost of fuel increases,
9. Road hazard resistance,
10. FMVSS 119, the new tire regulations and corresponding requirements under FMVSS 120, the new wheel regulation,
11. FMVSS 121, the recent air brake regulation,
12. FMVSS 105, the hydraulic brake regulation, and
13. Noise level requirements.

Vehicle manufacturers must consider fans, engines, mufflers, tires and related wind noises. Primary consideration is the 35 mph pass-by test with noise levels measured while the vehicle is in its maximum acceleration. Considering an 83 dB(A) low speed standard, heavy service tire noise is not a major contributor at 35 mph under the present J366b conditions. The 50 mph coast-by test (SAE J57a) was devised in an effort to separate the various sources of noise emitted by truck tires. Since the 1972 "Truck Tire Noise Symposium" sponsored by SAE as part of the truck meeting at Fort Wayne, Indiana, much progress has been made by the tire manufacturers toward the development of a quieter drive axle tire.

Let us now consider what a truck tire has to do. It must support loads in a variety of environments, and at a variety of speeds. This accounts for the proliferation of tire constructions, tire materials and tread patterns used in truck tires. We require that the truck tire ride and handle as well as possible. It must have durability extending into hundreds of thousands of miles, and must be recappable. It must meet certain requirements because of the FMVSS - 121 air brake law, the FMVSS - 119 Tire law and now we must consider potential maximum noise level requirements. At the GMC Truck and Coach Division, we find that some lower pass-by noise level tires are now available. Lower noise level traction tire regulations will have obvious effects on customer demands for certain type tires. It has been common practice for many years in the trucking industry for the customer to specify all sorts of tires from a large variety of manufacturers.

Because of regulations such as FMVSS - 121 and the upcoming noise level regulations, we believe that it will be impossible for the vehicle manufacturer to honor such requests or specifications from our customers for certain type tires in

ABSTRACT

The selection of a heavy service tire for highway type vehicles requires careful consideration by the vehicle manufacturer. All the improvements that have been made in heavy service tires since 1923 are still with us, but it must also be noted that a few items that were not with us five years ago, such as FMVSS - 105 and FMVSS - 119 through FMVSS - 121 requirements have been added. In view of the impending noise level requirements for highway type vehicles, much work has been done by vehicle manufacturers to depress the various sounds emitted by their respective vehicles.

the future. This represents a major change in truck manufacturing policies and the purchaser's desires.

As you might suspect low noise requirements will eliminate some of the well known "cross bar" and "cross lug" type tires that have been familiar to our truck customers for a long time. This is obviously most important on tandem axled vehicles, but it is felt that control of engine related noise and control of tire noise will yield acceptable low noise level trucks. Another difficulty to be considered is the noise level produced by recapped tires, because the variety of retreads is great and this is of course, beyond the vehicle designer's control. This situation is most important to the truck owner because 75% of a truck tire's life is in the recap state.

Specialty vehicles, or highly vocationalized vehicles, such as those used in mining, logging, farming or off-highway operations, might present a special tire problem to the user of the vehicle. It is conceivable that special vehicle tires could spend 99% of their life in off-highway use and yet be penalized in traction requirements because of the noise level modifications required for the small amount of time spent on the highway to obtain fuel or repairs.

In the past, drive axle tires were developed with thicker, blocky treads (known as "lug" tires) at a small premium price. This type of tire has been the backbone of economically sound truck operations. The using vehicle yields more miles per tire dollar spent. A real tire bargain. Although the cross lug tire has been one of the major components which has helped the development of the trucking industry, the very nature of this tire and its retread cousins have caused some of our vehicular products to become noisy at highway speeds.

In an effort to determine what the minimum sound level obtainable on any truck is, early SAE J57a measurements were made on completely blank tires. The lowest level found was 68 dB(A). This is considerably quieter than the levels observed on some of today's production tires. Please note, however, that such a quiet tire is completely unsafe for highway use.

It is to the domestic tire manufacturer's credit that they have already developed and are preparing to ship new quiet drive axle tires. The new tires, we trust, will produce equal or better tread life, tractive effort, superior braking capabilities and lower sound levels.

It should also be obvious to the users that new tires require all new molds, and a probable increase in tire prices. Whether or not a further decrease in tire noise levels of drive axle tires is possible; the obvious question is "will it be cost effective?"

HEAVY TRUCK TIRE SELECTION AND USE
PANEL DISCUSSION

Mr. E. Clair Hill was moderator.

Papers were prepared and presented by the following panelists:

1. Mr. D. R. Watson presented "Quiet Tires - An Overview".
2. Mr. A.H. Berger presented "Tire Design Considerations for Refuse Vehicles".
3. Mr. W. C. Long presented "A Manufacturer Looks for Quiet Tires".
4. Mr. B. Bolstad (presenter) presented "Current Fleet Tire Economics".
5. Mr. K. D. Penaluna presented "Economic and Mobility Considerations in Tire and Retread Selection".
6. Mr. H. Vollmer presented "Tire Use in a Common Carrier Fleet".

Following the presentations, the floor was open for questions.

MR. HINDIN: Mr. Watson made a statement that radial tires were too expensive for those moving vans making few intercity trips. I assume you are saying that the radial tire is an intercity tire, but not a intracity tire. Can you comment a bit further on that?

MR. WATSON: On a high cube furniture van, usually 13 ft 6 in high, drop frame, a radial tire just does not perform sufficiently to warrant purchasing it. We are totally on air ride suspension, and with the combination of the high cube, that suspension, and a light load, the radial tire doesn't perform any better than a bias ply tire, in our experience.

It has a tendency to wear irregularly on a trailer axle, and cup out prematurely. Our tractors, are also loaded light, and a majority of them have air ride suspension.

Our basic radial problem is irregular wear and premature cupping on the light loads with the air ride suspension.

MR. HINDIN: That's with a 10.00-15?

MR. WATSON: That goes clear through the 10.00-20's. Our drop frames are all the 10.00-20's. Our 10.00-15's are on the electronic vans. They are basically for road use, and we have to go to radials on the majority of them. They are loaded more heavily. We still encounter the problem with the air ride suspension and the high cube. It seems the high trailer with the low floor and the small tires on that air ride suspension creates many different problems than on a regular spring suspension freight van.

MR. HERSHEY: We had some comments about the use of the tires for refuse vehicles. Do you have any estimate of how many trucks are involved in this kind of service where they actually have to go into landfills, into this mud?

MR. BERGER: I don't have an exact figure of how many refuse trucks there are in the United States. The number I have seen published is in excess of 80,000. Your question is how many of these have to go into the landfill, and I think you are talking about 99.44%. If they don't go into a landfill, the only other place they can go is to a transfer station. Because of their cost, there are very few of them. Ultimately material taken to a transfer station must be carried to a landfill. That is done with tractor-trailers, so you are replacing possibly four loads of a city-type refuse truck, but now you are carrying it with an 18-tire tractor-trailer.

In one sense you are only cutting down by roughly half the number of tires. We still have to dump the trash in the landfill; somehow it has to get off the road into the landfill.

MR. HILL: Of course, you all remember that trash trucks are not the only ones that travel both on and off the road. You have dump trucks, off-highway construction vehicles, and farm trucks. I wouldn't venture a guess as to how many of them there are.

MR. HINDIN: On your mobility work, Mr. Berger, instead of using dual tires on the drive axles, have you used large single tires?

MR. BERGER: Yes, we have tried that. The problem is that on a tandem axle, we know we are hauling 36,000 lb legally. We also know that because of the uncertainty of what we are carrying, that we have a tendency to run overloaded. It is possible we might go to 44,000 lb on a tandem.

We have learned, if you divide that by four rear tires, you find you need a single tire that can carry 11,000 lb. We know of none for the drive axles.

Even when we went to 18-22.5 flotations, and maintained the air pressure to get the maximum loading, we were running overloaded, and had premature tire failures. There really is not a flotation tire that will do this.

The second problem we ran into when we tried a larger tire was that there was no wheel equipment to handle it on the rear of the trucks. We have had to take such tires off the truck drive axles.

MR. COULTER: One of the things that we are considering is requiring the substitution of rib tires on some types of vehicles. One of the things coming out of this meeting is, that for some of the fleets, rib tires are perhaps a way of going that will cost a little bit more money, and another fleet is in a situation where doing that is impossible. Anybody that has to wander through the mud and the gluck of a construction site is going to have a lug.

Are the types of vehicles that are now running and which need to operate on lug tires, a large enough portion of the freeway traffic to worry about?

It might be that all that is required in the way of regulation is to exempt the fellow who spends a fair amount of time off-road and has to keep lugs. But regulate the fleets that operate from central city point to central city point and are able to run on quieter tires. Is it worth regulating them independently of everybody else to get the benefit, or are there enough of the off-highway vehicles on the highway to show very little benefit?

What I am trying to ask is if, in the long term, (from the figures I have seen there is not much point in doing anything for the next few years until the new vehicle regulations start to have an impact and start to bring the levels down) should we be talking about regulating only the fleets that are operating on the road and leave the others alone? Is that worth it, or will it just cause confusion?

MR. HILL: I don't really know how you would separate them because you have many vehicles that are operating both on and off-highway in the form of loggers, plywood haulers, chip haulers, bull haulers, etc. I also think that it is probably fair to say of those on the highway, whether they are common carriers or whatever, 75% of their drive position tires are cross rib design because of economics. Is that about right?

MR. LONG: I would say that, maybe higher.

MR. STRAWHORN: I think a response is that jackrabbits don't complain about noise. What you are saying is that the long-haul carrier is the one you would be looking at, and what I am saying is that most of his time is spent driving by the jackrabbits.

In the central city on the beltways where the complaints come from, this is where the garbage haulers are working and this is where the dump trucks are working. Although the overall percent of such vehicles may be low, and their total mileage may be low compared to the long-haulers, their work is right in the area where you get the complaints.

So I think that's where you get the problem, and I don't believe differentiating or separating just the long-haul carriers would help, because those vehicles left would still be making noise.

MR. CLOSE: Mr. Berger, I noticed in all of your tests and pictures your handcut tire was new, while the others weren't.

Do you have experience as to how long the new handcut tire stays new and gives you that new traction performance?

MR. BERGER: I knew that question was going to be asked, so I brought the information.

When we started this tire test program there were several areas that I had as objectives. The first thing was to get out of the landfill, which we accomplished.

The second thing was to reduce the flat tires.

We also looked for tread life, and recappability. We may be in the refuse business, but we are in the trucking business just like everybody else. We just haul a different commodity.

In working with the tire manufacturer in creating these deep lug tires, he was very hesitant as to the tread pattern that we wanted, but based on the pictures and subsequent discussion, two molds were made. The purpose of the mold (by the way, these were tubeless molds) was to get enough tires to to determine treadwear rates.

They were terrible. We are talking about anywhere from 200 - 400 miles per 32nd, which is very, very expensive.

Another thing we found out, however, was that because these were tubeless tires with an inflation sealer added, we had eliminated 90% of our flats, and for the first time in our lives, we were actually keeping the tires on the truck long enough to see what some of our other tire problems are.

The first reports of this type were that the tires on the rear axle of the tandem were wearing faster than the front axle of the tandem.

This report came out of an operation in Sandusky, Ohio. Now, the normal reaction to something like this is somebody put in a wrong rear axle ratio. One axle is running at one ratio and the other is running at another ratio.

So we went to Sandusky. We did everything in our power (they had the right ratios) but couldn't determine why one axle was wearing faster. The rear axle of the tandem was wearing twice as fast as the front axle, but everything was wearing evenly.

Then we started to get reports from San Jose, California very similar to that. A subsequent investigation proved to us that because of all the maneuvering that we were doing, the front axle of the tandem was acting like a single axle tractor, but the rear axle, because of the solid suspension, was being dragged around.

Now we had an opportunity to truly see tread life. The tire manufacturer built enough tires for us to put them on six tandem axle trucks. The noise level did not change, even though these tires were made from a mold. They were not handcut tires.

We had them made from three different compounds, which we termed A, B, and C. The tires were branded, and we did get different tread life with the different compounds.

We still weren't happy even though we actually got up to 600 miles per 32nd. Again, it depended on the type of operation. If we are talking about the front loader, that picks 100 to 150 containers a day, depending on several variables, it does a lot of twisting, going into apartment complexes and very tight areas. On the other hand, trucks that have less frequent pulls, which we call rolloffs, do a lot more driving during the day.

Anyway, we tried to analyze the tread wear per 32nd.

I have some figures with me that are astronomical, in my opinion. We are talking about 1505 miles per 32nd. Remember, we started at 200 and 300 miles per 32nd. Every month we check the mileage on the trucks for this test, also the air pressure, the tread depth, and the wear rate per 32nd.

We find that as the tread starts to wear down, the wear rates decrease, in other words, with the tires now we could be talking about 839 miles per 32nd, then up to 960 miles, 985 miles, 1120 miles, 1259 miles, 1223 miles. Again it is interesting that on the front axle of the tandem, the two right tires are at 1223 miles the two left tires at 1505 miles. This tells us the truck is making more right turns than left turns.

It also tells us that this is a city-type truck. It happens to be in Fairfax, Virginia servicing Washington, DC. That truck goes along a lot of divided highways or four-lane highways, takes a right, picks up the trash, comes out, takes a right; everything is a right turn. He is pivoting on the right.

Sandusky, Ohio involved a two-lane highway, a left into a plant, a right out, a right into a plant, a right out. We are able to tell by the wear rate of the tires what route the driver is on.

What we are interested in was why we jumped to 1500 miles per 32nd. The key is rotation, watching the air pressure and rotation.

We are still not happy, but we are making progress, so I would say in answer to the question, when we started out we recognized the fact that the lug tire wears very, very quickly, but we are at the point where we are getting better and better mileage.

MR. CLOSE: How long do those tires provide you enough traction to pull out of the dump?

MR. BERGER: What do you mean, how long?

MR. CLOSE: How much wear can you sustain before you are unable to get out? When do they stop wiggling and stop wearing so much that they stop digging out of the dump?

MR. BERGER: There is no question that the less tread we have the more we must be towed out. From a percentage point of view, it is difficult to say, because this is still a test program going on.

When the tires are brand new, traction is phenomenal. I don't know at what point of depth it changes. I do know this much: when we tried radial tires - which have half the depth - two interesting things happened: first, we didn't have the tractability in the landfill because a radial lug tire is not really a lug tire.

The second thing we have found out - which I cannot document because it has only been done at a couple of companies, and I am not really at the point where I want to stand up and wave a flag - but, we seem to get a faster wear factor out of a radial tire than a non-radial.

The only reason we can think of for that happening is that we do so much squirming (turning maneuvers that produce much tread scrubbing), and the radial tire likes to stick, so we are actually wiping out more rubber because of that.

We don't obtain as good mileage, even with rotation, with a radial tire, as we get with a bias ply tire, but it is not at the point where I can stand up and say that I am absolutely accurate.

I don't know how low of a tread depth you must have to noticeably lose traction. I do know this much: the difference between 20 and 40/32nds makes a difference, so I would have to say that when the 40 gets down to 20, we are in trouble. However, the other thing we are doing - and this is one of the requirements on the tread I mentioned - is that in the beginning we had 20/32nds of tread in in the inner four in, two in on either side of the center bar. When we get down to 20/32nds, which means there is no center bar really, the tire looks worn smooth in the center, so we effectively start with 20/32nds.

MR. NILSSON: Was your tire tread in any way a randomized pattern, or was it equally spaced? Was the space between blocks different around the tire?

MR. BERGER: The tire we used was an existing tire that we subsequently cut up, and we did open it up for a constant gap.

Now, from the shape of the tire, it opens up more toward the outside than in the middle, but it is a constant gap all the way around per in out. All the dimensions were the same.

I might add that with regard to the tire I mentioned, from which we are obtaining 1500 miles per 32nd, is not the tire we showed here. Regarding the tire we showed here, the best we have been able to obtain is about 900 miles per 32nd.

We went to a different tread design with a different tire manufacture, and very effectively have gotten a 60% increase in mileage.

MR. NILSSON: So you can make even quieter tires if you are randomizing the tread pattern, maybe?

MR. BERGER: That's entirely possible. It can be quieter, and it is entirely possible that we can get better tread wear.

I might state that when you talk about 1500 miles per 32nd on a 40/32nd tire, you are talking about 60,000 miles and for the refuse industry if you can get 25,000 - 30,000 miles before something damages the tire, you are doing well. We could, in working with the tire companies, possibly come up with a compromise in quieter tires and still achieve long mileage and good production. But I think it is very, very difficult and I think it requires a great deal of time.

MR. MASON: I have one more question on that quiet tire.
How did you document the noise of it?

MR. BERGER: We didn't measure it. We are quite clear as to what the sound of a wearing tire is. Riding by the side of the trucks in an automobile, we anticipated the normal sound and it did not occur.

Whether that means that a quieter tire can run at 88 dB(A) and not be heard, but another can run at 72, I doubt that is the case. I have to assume it is a quieter tire.

MR. BERGER: I want to ask a question of Mr. Close or anybody else from the government.

There was a presentation made this morning by Mr. Leasure that seems to counter a lot of the information given here, and based on what has been said this afternoon, I would like comment as to whether or not we are all off base, or is this a bit of an education to the point that we can feel there is some hope for what we are trying to accomplish here?

Is this really the good guys against the bad guys, or what do you think at this point with reference to the total economics, the traction and all that? Is there a trade-off between noise and economics?

MR. CLOSE: I guess I would preface the answer by saying I didn't hear one set of answers coming from this panel, but a whole variety that sort of expand the spectrum from totally successful, quieter tire operation on the East Coast and Midwest, to some feelings that, "noise be damned", which used to be the answer received from one carrier.

Safety was the predominant thing that was driving one operation to what happens to be quieter tires. Others say, "We need what looked like noisy tires, but we don't hear noise coming out of them."

I didn't hear one answer. I hope you didn't either. We have invited a cross-section of views to try to put these answers, or these opinions, or data, on the record, so that those who will make the decision about tire noise regulations - and I can tell you right now I am not the decision maker - will have a good record to look at, and that this record will be determined in a professional society meeting rather than in the adversary halls of a regulatory hearing in Washington.
Does that answer your question?

MR. BERGER: Let me phrase it very quickly. In your opinion, although you don't make the rules, is there an area for consideration for the specialized carrier, be it Ruan or Browning-Ferris or anyone like that?

MR. CLOSE: I think in terms of the considerations that will be given in California. In the past the Highway Patrol has indicated their concern with all the specialized interests of motor vehicle safety, noise, etc. I am sure it will happen again.

In terms of what will follow the identification of noise from tires as a major source of noise, again the consideration of all of the economics, and safety factors, will be given. How the answer will come out and how much weight will be given to a hauler of one commodity versus a hauler of another commodity, I certainly couldn't guess.

MR. CAMPBELL: The written record will show that Mr. Long displayed pictures of five or six of what he calls quiet cross-lug tires in contrast with pictures of real cross-lug tires, which are currently being used. The written record may not show that the so-called quiet cross-lug tires are not really cross-lug tires. Their lugs were cut down sufficiently to make them quieter, to approach the circumferential rib design configuration.

In doing that, you make more of a rib tire and less of a cross-lug, so you have an in between tire. The same goes for its performance characteristics. It is going to perform the way it looks, somewhere in between a cross-lug and a rib.

There is no free lunch on this tread design business. If you are going to give up some of the cross-lug, then you are going to give up some of the features that the cross-lug provide.

Without that understanding, Mr. Long's paper might be somewhat misleading.

MR. LONG: I would like to volunteer a challenge to the tire manufacturers at this stage of the game. I think tomorrow and the next day will see some fireworks regarding SAE J57a.

You all know that a standard surface is the one thing that we really need in the measurement of tire noise levels. I want to give you the germ of an idea; maybe you can make something out of it.

If you consider a single wheel trailer somewhat similar to or exactly like the one that Mr. Hickling, sitting back there, and Mr. Wilken have developed, upon a track made of some super material, the material of the future, you might be able to generate a completely standardized surface so that somebody testing the tire in Goteborg, or Yokohama, or wherever it might be, would obtain the same results that the domestic tire manufacturers or the regulatory agencies would measure.

A single wheel trailer dragged the tire down upon a track composed of an advanced composite material. Advanced composites are made of a variety of new materials. The one I have with me happens to be woven Teflar and high modulus gravity material. It will support fantastic loads, and you can control the surface.

It can be made in any thickness and in any length. You would, of course, have to tack it down to your track so it wouldn't move during the test cycle. You can mull that one over, gentlemen. I have a sample here, and if anyone wants to look at it he may.
It is made by General Dynamics in San Diego.

A second idea is for our friends in the governmental agencies. Why don't you keep your highways clean? I believe that if you had high-speed cleaners for the federal highways or state highways, as the case may be, that we would avoid a lot of the problems noticed on the front tires of trucks. Intrusion of metal, particularly in the right front tires, is a problem to fleet operators.

You may wish to design high-speed trucks, relatively high-speed cleaners, operating in the area of 50 mph, containing only magnets instead of the sweepers. I think a lot of our problems on the highways would be alleviated.

MR. STRAWHORN: I can't stand to see Mr. Ames not saying anything, so I will pick on him a little bit.

We have talked quite a bit about various wear rates because of different types of operations, but, Mr. Ames, you have the same operation, only you go in various parts of the country. Certainly your tractor and semitrailers, and to a lesser degree your doubles, are run in the mountainous parts of the West, the plains in the Midwest, and the rolling country in the East.

I would like to hear your comments on, given the same tires on the same equipment, what the territory itself has to do with tire wear.

If we came up with a wear rate or a cost per mile history of the tire in general, would that be something that would be true for each region, or does it vary markedly between regions?

MR. AMES: I will say regions will vary considerably; the more hills, the more turns you have, the more tread wear you will have. The Interstate Highway is the freest way to run. I really don't check closely by regions. I watch cost per mile and know what my tires are averaging per 32nd, and what the best buy is, because we are going to run all routes anyhow.

MR. HILL: I don't believe there is any question that terrain and operating conditions make a difference. In our own operations, as an example, we certainly don't expect to get the same tread mileage operating over the passes out of Denver at 11000 ft as we are going to get in Texas going across the prairie.

In a high density area where we have a lot of stores within a metropolitan area, we wipe off more tread maneuvering than we wear off going down the highway. You can pick it up immediately in tire cost per mile figures from division to division, depending on their location.

PART II
FUNCTIONAL REQUIREMENTS FOR LIGHT VEHICLE TIRES

762006

Functional Requirements for Light Vehicle Tires

J. H. Schutz
Chrysler Corp.

A VEHICLE MANUFACTURER must choose tires for a vehicle with a definition of that vehicle and all the physical and legal requirements firmly in mind. Tire selection criteria discussed in this paper are vehicle marketing, compliance to Federal Standards, ride quality, handling, tire-vehicle uniformity, tire durability, high speed capability, rolling resistance, skid and traction, tire weight, and various miscellaneous factors.

VEHICLE MARKETING

Vehicle marketing factors influence the basic choice of tires as to the desired performance level of ride, tread wear, handling and other qualities that make up perceived value in the eyes of the customer.

Styling and marketing dictate appearance factors including aspect ratio, sidewall treatment, and tread pattern. All qualities must, of course, be weighed against cost.

COMPLIANCE TO FEDERAL STANDARDS

Tire and Rim Association recommended practice, Federal Motor Vehicle Safety Standards 105A, 109, and 110 and individual state requirements determine the minimum size tire for a particular vehicle, the width and configuration of the wheel rim, and the level of dry traction performance in conjunction with the vehicle's braking capability. The tire's tolerance of overload and high speed operation, its resistance to impact damage, and the ability of the rim to retain the tire both under severe side load and upon air loss are also governed by these laws. The tire-vehicle system must comply with requirements for bumper heights, headlight aiming, rear visibility and noise level. In addition, tires are a significant factor in the vehicle's performance in emission and fuel economy testing. Future regulation that might further influence tire selection includes the increasing levels of fuel economy and reduced pass-by noise.

RIDE QUALITY

Ride quality selection is largely a subjective process done by a ride jury comparing control tires with experimental sets. Evaluations are generally made over a specific combination of public roads with a variety of surface textures and small impact bumps. Ratings of all tactile and audible sensations are made using a 1 - 10 rating system which relates to customer acceptance and competitive practice. The ride quality influenced most by tires is impact harshness, a combination of audible and tactile sensations produced inside a vehicle traversing a randomly rough surface. Particular segments of the sound spectrum stand out because of resonances in the tire carcass or the vehicle suspension, structure or body cavity.

"Boom," for example, is a relatively narrow band low frequency interior audible disturbance which certain radial ply tire-equipped vehicles are prone to exhibit because they have a floorpan resonance that is too close in frequency to a radial ply carcass resonance. "Road noise" likewise is an interior disturbance made up of a

ABSTRACT

Tire selection is an important task for a vehicle manufacturer. No other component has such a combined influence on a vehicle's ride, handling interior and exterior noise level, stopping ability, and appearance. Tires supplied on a new car affect the customer's perceived value and consequent acceptance of that vehicle and, later on, their replacement is likely to be the largest single maintenance expense for the first or second owner.

Consideration of many factors leads to the selection of tires for original equipment use. This paper reviews the major objectives of a new tire approval program at Chrysler. Tire selection from a vehicle manufacturer's point of view starts with a definition of the vehicle and a review of the physical and legal requirements that pertain.

series of vehicle resonances responding to the tire carcass which is being excited by a coarse road surface. Changing a tire's resonant response significantly is not usually possible other than by altering the basic construction of the tire, from radial to bias for example. Small shifts in frequency response, however, can often be made to enhance the ride quality of a particular tire-vehicle combination without adversely affecting other performance parameters.

Tread noise and slap are airborne disturbances that are particularly influenced by the tread pattern and tread radius. The tire manufacturer attempts to devise a tread element sequence that minimizes narrow band tread noise or whine, while producing desired performance for traction and tread wear. Evaluation for tread whine is made on closed surface asphalt which accentuates any whine tendency and is done subjectively and objectively with both interior and exterior pass-by recordings.

Tire slap over expansion joints is rated subjectively and is primarily dependent upon tread element damping and tread radius.

HANDLING

Vehicle handling is strongly influenced by tires. Tire-vehicle matching is done initially on an objective basis with computer models of the vehicle and tire force and moment characteristics of current or proposed tires. Final tuning of both the suspension and the tires is done largely by subjective jury evaluation with some use of instrumented vehicle dynamic comparisons. Elements of handling include:

1. Transient Stability,
2. Steady State Stability,
3. Directional Stability,
4. Nibble,
5. Steering Effort, and
6. Groove Wander.

Transient stability consisting of lane change and evasive maneuvers is important in terms of predictability in the hands of an average driver Quickness of steering response, steering gain, and the degree of damping in recovery all are influenced by the tires and all affect the driver's confidence level in the vehicle.

Steady state stability is influenced somewhat less by the tires except that the driver tends to sense the vehicle's performance level in a steady state turn such as an expressway entrance ramp by the noise level or protest emanating from the tires. Directional stability, or the tendency of the vehicle to maintain direction with a minimum of steering input, is a function in part of the tire's self-aligning torque and again is evaluated by ride jury. Nibble is a ride evaluator's term for the tire's ability to resist traversing a longitudinal ridge at a shallow angle such as a pavement shoulder or cable car track. Radial tires, because of their low camber sensitivity, are much superior to bias types in this respect. Groove wander, or the slight side-to-side shuffle that occurs on grooved pavement at first was thought related to nibble but investigations have shown it to be primarily related to the tread pattern and its groove and rib spacing. Tread pattern development aimed at eliminating that tendency is underway. Steering effort both in dry parking and in low speed maneuvers is a function of both tire construction and tread width, and is measured objectively.

The tire tread pattern is a significant influence in all aspects of handling, particularly transient stability where shoulder rib and tread element stiffness are factors, and groove wander in which rib width and spacing are critical.

TIRE-VEHICLE UNIFORMITY

Tire-vehicle uniformity refers to noise and/or vibration felt inside the vehicle which is generated on a smooth road surface as a result of irregularities in the tires. These qualities are significant in tire selection only in that the tire manufacturer must be able to produce a sufficient yield of tires having balance and uniformity levels that cause a minimum of ride distrubances.

Ride audits of selected tire sets are used to establish balance and uniformity specifications for each car line, specifications for which the tire manufacturer must screen on a 100% basis. Ride disturbances that are related primarily to tire uniformity include shake, a high speed vibration occurring at wheel revolution frequency (10-20 cps); roughness, a higher frequency (20-100 cps) tactile or audible disturbance in the middle speed ranges; waddle, a low speed low frequency lateral and/or vertical shuffling of the vehicle; and lead, a constant lateral force generated by the tires which the driver must overcome to maintain a straight heading.

TIRE DURABILITY

Tire durability performance is determined in a number of ways, both by the tire and vehicle manufacturer, and both on the road and in the lab. Road endurance is determined by tread wear, carcass and bead integrity, and belt and tread integrity. The load formulas which are used for establishing tire load-inflation tables are essentially empirically derived from the durability history of tires in typical service. Current durability testing is intended to reflect the limits or extremes of customer service and insure a margin of performance under reasonable operating conditions.

Customer expectations for tire performance center around tread wear, a direct measure of value received. Accordingly, tire manufacturers must be aware of factors affecting tread wear including climatic and road surface conditions wherever the tire is likely to be used, and any unusual influence from particular types of vehicles such as those with front wheel drive, independent rear suspension, or other suspension geometry factors.

Knowing all this, the tire engineer must devise tread wear tests which project realistic mileage values.

The vehicle manufacturer must first decide on a marketing basis what tires the customer will accept, and then after selecting suitable candidates, do whatever road testing is necessary to confirm their performance.

Accelerated endurance testing is done by both the tire and vehicle manufacturers to confirm a tire's integrity while being subjected to high cornering loads, driving and braking torques, severe impact loads, all on a variety of road surfaces at loads up to and including the tire's maxiumum rating. Durability testing of any new tread pattern must also include a thorough investigation of irregular wear tendencies such as shoulder or center wear, heel and toe wear, cupping or scalloping, and tearing of tread elements. Indoor wheel durability is used early in a tire development program to confirm the design before time consuming road testing is begun, and then is maintained as a quality audit test during production.

HIGH SPEED CAPABILITY

High speed capability may seem unimportant in this age of lowered speed limits and power-limiting emission controls, however the fact remains there are still many cars capable of approaching 100 mph and the tires must withstand speeds of that magnitude. Actual road tests of high speed durability must be run to confirm a design, and are done with three high speed tires and one test tire on a specially prepared vehicle on a test track. Laboratory tests again are used to maintain a check on a construction during production.

Two categories of vehicles require tires with specific high speed certification: police pursuit vehicles and those intended for export to certain European countries. Various police agencies require 125 mph capability, whereas the European requirements are usually that the vehicle manufacturer determine its top speed and then supply certification that the tires applied will run at that speed.

Tread pattern variations must be evaluated for their effect on high speed chunking, tearing, or cracking.

ROLLING RESISTANCE

Rolling resistance of tires is a substantial portion of overall vehicle drag and thus is an important quantity in the emissions-fuel economy development.

Currently, the most successful technique for rating tire effects on fuel economy is a direct vehicle road test measuring fuel consumption comparing control tires with test tires. Lab measurements of rolling resistance on large diameter wheels are not always good indicators of road performance mainly because of the slight reverse deflection in the contact patch.

A much greater disparity exists between road performance and the Clayton dynamometer used for vehicle emission tests because its two 8 in diameter rolls on 17 in centers cause severe localized stress. Radial tires, as a result, are generally worse for dynamometer fuel economy than bias types, the reverse of their typical road performance.

Selection of optimum constructions for rolling resistance is still done on the road, but investigations of dynamometer performance are currently active.

SKID AND TRACTION

Good dry traction performance is necessary for compliance with MVSS 105A and is generally attainable with current 78 series tires. Correlation between skid trailer values and vehicle performance has proved difficult so the bulk of our testing is run with vehicles selected at the maximum GVW for each tire size.

Superior wet traction and resistance to hydroplaning have been goals through all the development phases of the original equipment level radial ply tire. This development has been achieved through comparative testing of many experimental tread patterns both for wet skid using skid trailers or instrumented vehicles and for water flow patterns using glass road surfaces. This testing, done by tire and vehicle manufacturers, has produced tread patterns which yield exceptional traction performance at very little increase in noise level compared with typical bias belted tires. Pattern changes, such as for improved groove wander, must be compared with existing designs to insure acceptable performance, both for traction and noise level.

Snow and ice traction performance of new design highway tread tires is established usually at a winter test station on a frozen lake, or some similar expanse of flat undisturbed snow, by measuring pulling power and stopping distances compared with existing highway and snow treads.

TIRE WEIGHT

Tire weight has not really been a factor in tire selection prior to the past year when fuel economy targets were established that stimulated weight reduction activity. Weight reductions without significant changes in tire performance are being achieved in bias, bias-belted and radial types. Target weights based on vendor comparisons and estimates of weight saving potential are established by model year and may influence sourcing.

MISCELLANEOUS FACTORS

A variety of other miscellaneous tests are run on any new family of tires to insure their satisfactory performance including ozone effects on sidewall compounds, curb scuffing to compare different sidewall configurations for the degree of protection given the whitewall or raised letters, and a plant mounting trial to establish tire and rim compatibility through an automatic mounter.

A test that perhaps should be considered a durability test is one run with new families of tires to determine their run-soft capability, that is their tolerance of under-inflation, the degree of warning in the form of vibration, noise, or handling deterioration given the driver preceeding a failure, and the ultimate mode of failure resulting from under-inflation.

To summarize, any new tire design that is considered for original equipment use is subjected to a wide variety of tests to insure the expected ride and handling performance of the new vehicle and to provide the optimum combination of tread life, durability, fuel economy, skid and traction all in conjunction with an acceptable noise level. The interrelationships are complex and any significant shift in emphasis has the potential for deteriorating the balance in performance the customer has come to expect.

762007

Tire Parameters and Trade-Offs

J. D. Velte
Ford Motor Co.

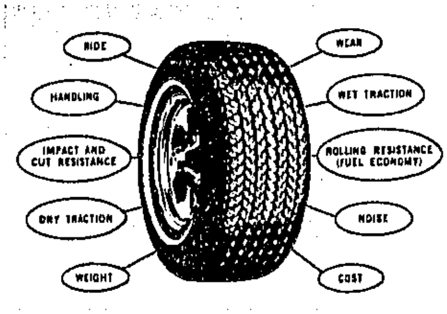

Fig. 1 - Items to be considered in tire - vehicle system

THE MODERN AUTOMOTIVE TIRE has progressed a long way with the motor vehicle from its initial inception. It is a vital factor affecting many aspects of the vehicle and therefore must be designed and considered as a part of the entire vehicle and not as an entity.

Fig. 1 depicts items that must be considered in the tire-vehicle system. Each of these is important, but equally important is the interrelationship among the items to achieve a balanced design. I would like to illustrate, very simply, what would happen to our tires if we optimized each of these items by itself. This will illustrate the interrelationships and the importance of having a balanced design that provides the best overall tire-vehicle combination for the customer.

WEAR

Let's optimize our tire for wear and see what we would have to trade-off. Our tire would look like Fig. 2. It would have hard, thick tread with a strong, steel belted radial ply carcass, a fairly low aspect ratio, and higher pressure.

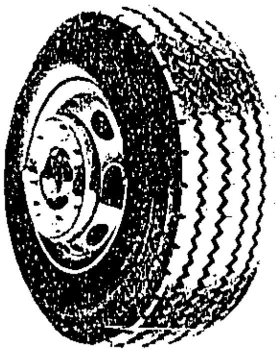

Fig. 2 - Optimize wear

The result of this design optimization would be to penalize ride, wet and dry traction, noise, cost and weight as outlined in Table 1.

RIDE

If we optimize ride, our tire could resemble Fig. 3, and would have a fine ribbed soft tread that was fairly smooth, a very flexible sidewall construction, and a low pressure-a fat balloon tire if you will.

As you can see in Table 2, optimizing for ride results in a degredation in wear, handling, impact and cut resistance, and rolling resistance.

ABSTRACT

A tire on a vehicle is not a separate entity to be considered only in itself. The tire is part of the entire vehicle and this entire vehicle must be considered in making tire selections.

Just as important are the components of a tire and the various parameters to be considered in tire design. Care must be taken that any attempt to optimize a single parameter does not jeopardize the overall quality.

Table 1 - Trade-Offs with Wear Optimized

Parameters	Trade-Offs
WEAR	- OPTIMIZED
RIDE	- WORSE DUE TO HEAVIER CONSTRUCTION
HANDLING	- EQUAL OR SLIGHTLY BETTER
WET TRACTION	- WORSE DUE TO HARD TREAD
DRY TRACTION	- WORSE DUE TO LESS FOOTPRINT
IMPACT/CUT RESISTANCE	- BETTER
ROLLING RESISTANCE	- BETTER
NOISE	- EQUAL OR SLIGHTLY WORSE
COST	- SLIGHTLY MORE
WEIGHT	- WORSE

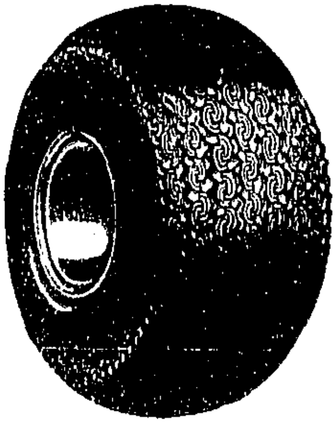

Fig. 3 - Optimize ride

HANDLING

If we "vote for handling", our tire will have an aggressive tread design, a low aspect ratio radial ply carcass, a softer slightly thinner tread compound, and higher tire pressure. (See Fig. 4)

As shown in Table 3, with handling optimized, the result will be a tire that's worse for wear, ride, noise, and cost.

WET TRACTION

Optimizing for wet traction, as in Fig. 5, will lead us to a tire that has low aspect ratios, lower pressure, and a tread design that has a good open cross pattern to let the water flow away from the footprint area. A softer tread compound would be used.

With wet traction optimized, we will lose out in wear, handling, rolling resistance, and noise as outlined in Table 4.

Table 2 - Trade-Offs with Ride Optimized

Parameters	Trade-Offs
WEAR	- WORSE DUE TO LOW PRESSURE AND THIN RIB ELEMENTS IN THE TREAD
RIDE	- OPTIMIZED
HANDLING	- WORSE DUE TO LOW PRESSURE AND FLEXIBLE SIDEWALL
WET TRACTION	- EQUAL OR BETTER
DRY TRACTION	- EQUAL OR BETTER
IMPACT/CUT RESISTANCE	- WORSE DUE TO FLEXIBLE CONSTRUCTION
ROLLING RESISTANCE	- WORSE
NOISE	- SLIGHTLY BETTER
COST	- EQUAL
WEIGHT	- EQUAL

Fig. 4 - Optimize handling

Table 3 - Trade-Offs with Handling Optimized

Parameters	Trade-Offs
WEAR	- WORSE DUE TO SOFTER, THINNER TREAD COMPOUND
RIDE	- WORSE DUE TO LOWER ASPECT RATIO, HIGHER PRESSURE
HANDLING	- OPTIMIZED
WET TRACTION	- BETTER DUE TO AGGRESSIVE TREAD, LOW ASPECT RATIO
DRY TRACTION	- BETTER DUE TO SOFTER COMPOUND
IMPACT/CUT RESISTANCE	- EQUAL
ROLLING RESISTANCE	- EQUAL OR BETTER
NOISE	- SLIGHTLY WORSE DUE TO AGGRESSIVE TREAD
COST	- SLIGHTLY WORSE
WEIGHT	- EQUAL OR BETTER .

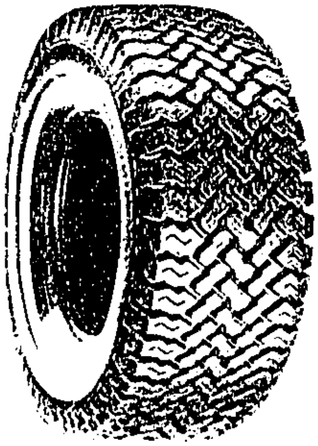

Fig. 5 - Optimize wet traction

Table 4 - Trade-Offs with Wet Traction Optimized

Parameters	Trade-Offs
WEAR	- WORSE DUE TO SOFTER TREAD COMPOUND
RIDE	- EQUAL
HANDLING	- WORSE DUE TO LOWER PRESSURE
WET TRACTION	- OPTIMIZED
DRY TRACTION	- EQUAL
IMPACT/CUT RESISTANCE	- BETTER DUE TO LOWER PRESSURE, SOFTER COMPOUND
ROLLING RESISTANCE	- WORSE DUE TO LOWER PRESSURE, SOFTER COMPOUND
NOISE	- WORSE DUE TO OPEN CROSS PATTERN TREAD DESIGN
COST	- EQUAL
WEIGHT	- EQUAL

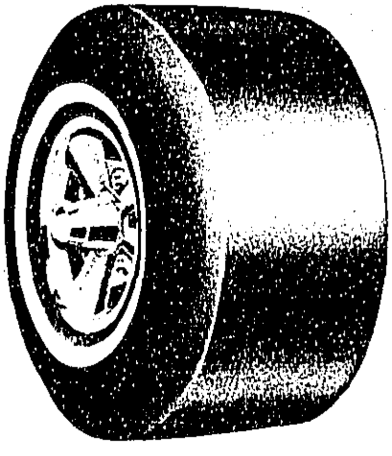

Fig. 6 - Optimize dry traction

Table 5 - Trade-Offs with Dry Traction Optimized

Parameters	Trade-Offs
WEAR	- WORSE DUE TO SOFTER, THINNER TREAD
RIDE	- WORSE DUE TO LOW ASPECT RATIO
HANDLING	- BETTER
WET TRACTION	- WORSE DUE TO SLICK TREAD
DRY TRACTION	- OPTIMIZED
IMPACT/CUT RESISTANCE	- WORSE DUE TO SOFTER, THINNER TREAD
ROLLING RESISTANCE	- WORSE DUE TO LARGER FOOTPRINT AREA
NOISE	- BETTER
COST	- WORSE
WEIGHT	- WORSE

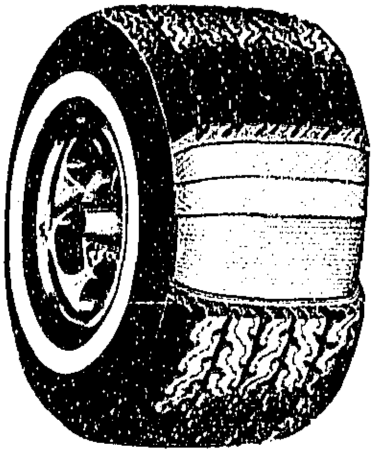

Fig. 7 - Optimize impact/cut resistance

DRY TRACTION

I'm sure you will recognize the California dragster slick if we optimize for best dry traction! The tire in Fig. 6 will have a very wide, soft, thinner tread with no tread pattern and a very low aspect ratio.

As you can see in Table 5 doing this will adversely affect wear, ride, wet traction, impact and cut resistance, rolling resistance, cost, and weight.

IMPACT AND CUT RESISTANCE

Optimizing for impact and cut resistance will require a thick tough tread with closed tread pattern, a belt wrapped down in the sidewall area, thick carcass, and lower inflation pressure. These features are shown in Fig. 7.

Table 6 - Trade-Offs with Impact/Cut Resistance Optimized

Parameters	Trade-Offs
WEAR	- BETTER
RIDE	- WORSE DUE TO THICK TREAD, THICK CARCASS
HANDLING	- EQUAL
WET TRACTION	- WORSE DUE TO HARD TREAD, CLOSED TREAD PATTERN
DRY TRACTION	- WORSE DUE TO HARD TREAD
IMPACT/CUT RESISTANCE	- OPTIMIZED
ROLLING RESISTANCE	- WORSE DUE TO INCREASED TIRE MASS
NOISE	- EQUAL OR SLIGHTLY WORSE DUE TO THICK, HARD TREAD
COST	- WORSE DUE TO HEAVIER CONSTRUCTION
WEIGHT	- WORSE DUE TO HEAVIER CONSTRUCTION

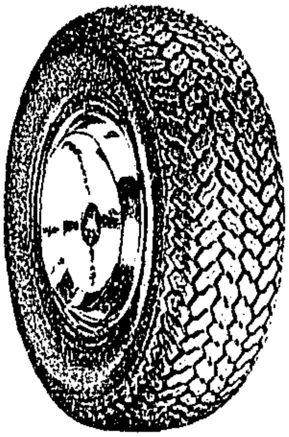

Fig. 8 - Optimize rolling resistance

See Table 6 for the complete list of trade-offs that are made when impact/cut resistance are optimized. Providing the best impact and cut resistance will degrade the tire for ride, wet and dry traction, noise, rolling resistance, cost, and weight.

ROLLING RESISTANCE

Providing the best rolling resistance (Fig. 8) will create a radial tire with a lighter constructed steel belt that has a higher aspect ratio, stiff sidewall, a higher pressure, and harder, thinner tread with open pattern.

As you can see in Table 7 optimizing rolling resistance provides a lot of negatives - wear, ride, dry traction, impact/cut resistance, and cost & weight.

Table 7 - Trade-offs with Rolling Resistance Optimized

Parameters	Trade-offs
WEAR	- WORSE DUE TO HARDER, THINNER TREAD
RIDE	- WORSE DUE TO HIGH ASPECT RATIO AND STIFF SIDEWALL
HANDLING	- BETTER DUE TO STIFF SIDEWALL
WET TRACTION	- EQUAL OR BETTER DUE TO OPEN PATTERN AND THIN TREAD
DRY TRACTION	- WORSE DUE TO REDUCED FOOTPRINT, HARDER TREAD
IMPACT/CUT RESISTANCE	- WORSE DUE TO THINNER TREAD AND HIGHER PRESSURE
ROLLING RESISTANCE	- OPTIMIZED
NOISE	- EQUAL
COST	- SLIGHTLY WORSE
WEIGHT	- SLIGHTLY WORSE

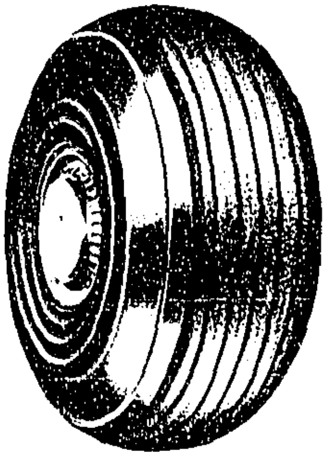

Fig. 9 - Optimize noise

NOISE

Optimizing for noise would probably give us a radial ply tire with a thin, straight, lightly ribbed tread, a medium stiffness - higher aspect ratio carcass, and slightly higher pressure. See Fig. 9.

As detailed in Table 8 optimizing for noise would cause us to lose in the area of wear, ride, handling, wet traction, and impact and cut resistance.

CHOICE INVOLVES TRADE-OFFS

As you have seen from the examples, a tire is a complex combination of items that must all be considered and properly balanced to provide the best result for the customer on his vehicle. We would not imply that any of these characteristics

Table 8 - Trade-Offs with Noise Optimized

Parameters	Trade-Offs
WEAR	- WORSE DUE TO THINNER TREAD
RIDE	- WORSE DUE TO HIGHER PRESSURE
HANDLING	- EQUAL OR WORSE DUE TO REDUCED FOOTPRINT
WET TRACTION	- WORSE DUE TO TREAD DESIGN
DRY TRACTION	- EQUAL
IMPACT/CUT RESISTANCE	- WORSE DUE TO THINNER TREAD
ROLLING RESISTANCE	- EQUAL OR SLIGHTLY BETTER
NOISE	- OPTIMIZED
COST	- EQUAL OR SLIGHTLY BETTER
WEIGHT	- EQUAL OR SLIGHTLY BETTER

is beyond improvement - surely the steady progress made by the tire manufacturers together with vehicle manufacturer's efforts during the history of the automotive industry offer sufficient proof to the contrary. I am sure that improvements will continue.

But we would like to stress the point that trade-offs are involved, and that care should be exercised lest we, in attempting to optimize any one parameter, wind up providing our customers with a poorer overall tire for his vehicle.

762008

General Motors Passenger Tire Performance Criteria

Kenneth G. Peterson, Fraser D. Smithson, and
Fredrick W. Hill, Jr.
General Motors Corp.

VEHICLE APPLICATION DETAILS must be analyzed first. These include items like the physical space available within the wheel wells, the tire static loaded radius requirements for ground clearance and bumper heights, individual wheel loads at various vehicle loading conditions and whether the vehicle is front or rear drive. Having defined these basic parameters, it is then possible to use a tire selection chart, shown in Fig. 1 which allows the possible tire sizes considered for use on the vehicle to be compared in terms of their overall diameter plotted against their section width. The chart shown illustrates some new ISO-T&RA metric tires that are designed with section width increments of 10 mm and aspect ratios in 5% increments of 70, 75 and 80. The GM original equipment tolerance boxes are indicated around the nominals. Various vehicle dimensional constraints are then plotted on the chart; for example, maximum allowable tire width constrains either the tire width itself for undriven wheels or tire width plus chain clearance dimensions for driven wheels. The overall diameter of the tire is limited by either the vehicle packaging clearances or static loaded radius requirements.

These considerations define the maximum width and O. D. of the tire. In addition, vehicle mass analyses define the required tire load capacity. A vehicle must be equipped with tires of a size that have sufficient load carrying capacity for both normal load and maximum vehicle load conditions as required by Federal Standard MVSS-109.

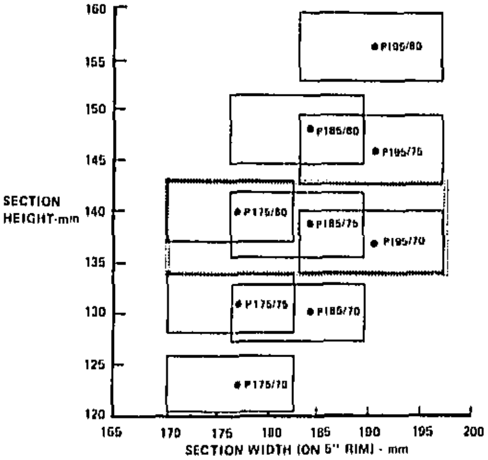

Fig. 1 - Section height versus section width

Given then a group of tires that meet the dimensional and load requirements, a selection can be made that is compatible with the overall intent of any given vehicle model. For example, a vehicle that is intended to have a sporty character might be equipped with a tire with a wide, sporty appearance. The particular combination of ride and handling characteristics desired for this model could include a firm, relatively hard subjective ride feel. For this situation, a 70 series tire could be selected and the appearance made more compatible with the

ABSTRACT

The purpose of this paper is to provide an overview of the process of selection, development and approval of General Motors original equipment TPC passenger car tires. We have attempted to minimize detail in each specific area, but intend to provide a general comprehension of the thought processes involved and the procedures used to select the proper tire size and type for a vehicle. We will then describe the tire performance criteria involved in the overall development and approval process and will subsequently consider tire noise requirements in somewhat greater detail. The paper will conclude by describing the General Motors Tire Performance Criteria (TPC) System, which is a documentation of the General Motors Tire Performance requirements and test procedures.

overall model intent by using raised white letters on the sidewall. Other vehicle models might use 75 or 80 aspect ratio tires with somewhat different combinations of overall performance characteristics that would be more compatible with that particular application.

TIRE DEVELOPMENT AND APPROVAL PROCESS

Once the tire size and type have been selected, it is then the responsibility of our Tire Development activity to provide the tire suppliers with a series of drawings describing the product required. These drawings cover the overall tire dimensions and tolerances for these dimensions, sidewall stamping information and configuration and a tread design guideline. The latter drawing describes several basic design constraints such as tread width, minimum void area, number of ribs and their percent of tread width, and/or which ribs may be cross vented, the number and size ratio of blocks in vented ribs and other items which are considered to be pertinent to a tire tread pattern's potential to provide adequate noise, traction and wear performance. The kerfing and off shoulder design is not specified or given guidelines and it is the vendor's prerogative to use these areas to provide an appearance consistent with his overall appearance goals. The vendor is also provided with any additional specific goals that may be required for original equipment application of the tire. These might include tire weight limits, some indication of the intended ride characteristics, etc.

At this point, each supplier prepares a tire mold drawing incorporating the basic tread and tire dimensions provided by General Motors and styles the design to fit the aesthetics of his particular tire line. Experimental molds are then ordered for each size and tire type. Upon receipt of these molds, initial tire samples are built and supplied to General Motors. These initial samples from the tire supplier are first checked to see that they meet the print requirements.

In the development of a new tread design, the tire is then subjectively evaluated for in car noise performance. Once the in car noise generated by the tire is considered by an experienced jury to be satisfactory relative to a known noise "control" tire, the passby noise level of the development tire construction is measured. After the complete development and approval process has been successfully completed, the passby noise level is again measured on actual production samples of each finally approved tire construction to verify that production built tires also meet the performance requirement. (A more complete discussion of tire noise considerations is given in the following section.) A development tire that has successfully met the dimensional and noise performance requirements is then evaluated for wet and dry traction performance.

Simultaneously, with the previously described evaluations which are very dependent on tread pattern, the tire submission is also tested to determine its force and moment or handling properties. These are quantitative measures of the lateral force (cornering) and steering moment capabilities of the tire and are fully described in Refs. 1, 2 and 3.

If the tire exhibits force and moment properties in the realm of those designated as initial goals derived from past tire history and initial vehicle computer simulation and is adequate for traction and noise, the tire construction would be provided to the particular vehicle development group that has the overall total vehicle design responsibility. Vehicle development people would then subjectively evaluate the tire to determine whether the tire has acceptable ride and handling when applied to their vehicle. If in the first attempt the ride or handling is not acceptable, the tire vendor would make resubmissions of slightly tuned constructions until acceptability is obtained. Once the tire has been approved for ride and handling, it is evaluated using additional tire qualification tests. These consist of a high speed evaluation and an accelerated tire endurance test, which evaluates structural integrity and relative wear potential.

Details of all GM TPC tests and requirements have previously been presented in Ref. 1. Once all required tests have been successfully completed, a particular tire submission has then verified that it has been designed to meet the General Motors tire performance requirements. The tire development group subsequently issues an engineering approval which tells our Purchasing and Quality Assurance groups that this particular construction submitted by the tire supplier has met the specified engineering requirements. The supplier is then required to provide the Quality Assurance Department with an initial production sample of the particular tire construction from each manufacturing plant that intends to manufacture that tire. The initial production sample is then evaluated for dimensions, force and moment, weight, uniformity, high speed capability and passby noise. If the tire again successfully completes all of these tests, the tire will receive quality approval which allows shipment to General Motors assembly plants.

TIRE NOISE CONSIDERATIONS

The preceeding discussion has been a brief overview of the process of selecting, obtaining engineering approval and releasing a tire for a General Motors production vehicle. We will now expand on the previous discussion of tire noise. The initial considerations of tire noise are embodied in the tread design guide drawing. This drawing has been developed over many years of testing and the guidelines set out for recommended range of total number of blocks, block size variation, percent void area, number of grooves, groove width, see through, etc., are intended to provide an optimal balance of wear, traction and noise while still allowing some freedom for individual tire suppliers to provide identity for their tire. It has been determined that a considerable amount of tread void area (approximately > 28%) and lateral groove content is required in a tread design if a tire is to provide adequate wet and snow traction performance. However, a tire that has this kind of void area and lateral content need not necessarily be a "noisy" tire. If due care is taken in the selection of the number, shape, size and sequencing of the blocks and the distribution of vertical pressure in the contact patch is properly controlled, then a high traction, long wearing tire with relatively low noise performance can be produced. However, if one were to design only to reduce the noise emitting properties of a tire, the quietest tire would be one with a very non-agressive tread design or no design at all. Unfortunately, this tire would have very poor wet and snow traction performance.

The proper footprint pressure distribution is very important, as a "quiet" tread pattern can be made noisy by improper shaping of the tire contour and subsequent redistribution of the tire vertical loading among the various tread ribs and blocks (*). The footprint leading edge shape is also instrumental in determining the effective phasing of the various tread rows. It is primarily for these reasons that actual production samples of tire constructions are again measured after a tire construction (and tread pattern) has been given engineering approval. Subsequent production build variation that could result in a modification of the contact pressure distribution can result in a "noisy" tire even though the development tires with the same tread pattern were sufficiently "quiet".

We have required that tires used as original equipment on GM vehicles will be as quiet as reasonably possible, relative to both our environmental passby noise criterion as well as a subjective in car noise criterion, while still providing desirable all weather traction capability, tread life, vehicle ride and handling and desirable performance in all other areas in which the tire is an important element in the overall vehicle system. While this session is stressing "environmental" noise, we must consider in car noise performance also, as the interior of the vehicle is the environment of the occupants.

We use two test procedures to allow us to evaluate a tire's overall noise performance. The passby noise test involves a set of four candidate tires installed on a vehicle that is coasted engine off, in neutral past a microphone located 25 ft from the vehicle lane of travel. The dbA weighted sound level measured must be no more than 4 dbA greater than the noise level generated by a set of four control tires. The control tires for this test are bias belted ASTM E501 Standard Skid tires. These tires are straight circumferential grooved tires with five solid ribs, no cross vents and no kerfing. Consequently, they represent a low passby noise level tire on a surface with smooth macro texture. Measurements have shown this control tire to have passby noise levels approximately 2 - 4 dbA below the range of the bias belted tires previously used on GM vehicles. The rationale behind the tire passby noise test procedure and a summary of the experience obtained using it are discussed in detail in Refs. 4 and 5.

A tire that exhibits adequate passby noise performance can still generate tonal noise that can be objectionable to the vehicle passengers. Consequently, the subjective in car evaluation uses a jury of four or five experienced raters. Two identical candidate tires are installed on the rear positions of the vehicle with blank treaded tires on the front positions. The vehicle is accelerated to approximately 60 - 70 mph on a smooth roadway with minimal macro texture (a newly surfaced asphalt road is representative) and allowed to coast down in neutral to approximately 30 mph. The most annoying noise level detected during the coastdown is rated by each of the jurors. The absolute level of the rating scale is initially determined relative to the noise level of a "noisy" control tire which is run before each test sequence and periodically throughout a series of evaluations. For a tire approval ride involving more than one candidate, the jurors are not told what tire they are evaluating other than the initial "calibration" run with the "control" tire.

These tire noise test procedures and requirements then allow the development of a radial tire with environmental passby noise levels no higher than those generated by the bias belted tires previously used on our vehicles and interior noise performance that is not objectionable to the vehicle occupants. This can be accomplished without sacrificing performance in all the other areas in which the tire must provide desirable overall vehicle performance.

GENERAL MOTORS TIRE PERFORMANCE CRITERIA (TPC) SYSTEM

As a means of providing documentation of our original equipment tire performance require-

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*Numbers in parentheses designate References at end of paper.

ments to provide guidance to our customers and aftermarket tire manufacturers, General Motors has adopted a formal Tire Performance Criteria (TPC) System. This system covers the following dimensional and performance areas.

- Dimensions
  - Maximum Size
  - Static Loaded Radius
  - Revolutions Per Mile
- Endurance
- High Speed
- Traction
  - Wet
  - Dry
  - Snow
  - Passby Noise
- Force & Moment Characteristics
  - Cornering Coefficient
  - Aligning Torque Coefficient
  - Load Sensitivity
  - Load Transfer Sensitivity
- Uniformity
  - Radial Force Variation
  - Lateral Force Variation
  - Conicity
  - Plysteer
- Balance

(For a detailed review of these criterion, consult Ref. 1)

The specific objectives of this system were to provide the General Motors Corporation with improved specifications for original equipment tires so that all the suppliers' tires are equal to or above specified minimum performance levels, and to provide the customer with a system by which he could identify and obtain replacement tires designed to provide performance characteristics comparable to those of the original equipment tires originally installed on his vehicle.

Car owners replacing their tires with tires marked with the same TPC specification number as those provided originally with the vehicle will get tires that were designed to have equivalent dimensions and performance characteristics. This is important as it offers the customer an opportunity to more nearly maintain the design characteristics of his vehicle and should eliminate much of the confusion that occurs during purchase of replacement tires.

GM also furnishes TPC specifications to all replacement tire manufacturers which quantify the tire characteristics considered necessary to best meet the needs of GM vehicles. In addition, a service has also been established to make available to replacement tire manufacturers information which will enable them to provide equivalent replacement tires for General Motors vehicles.

SUMMARY

The intent of this paper has been to provide some insight into the overall process used by General Motors to select, develop and approve original equipment tires used on GM vehicles. These tires must produce a vehicle/tire system with a proper combination of performance characteristics in all of those areas that are influenced by the tire. All of the Tire Performance Criteria (TPC) areas have been presented, including a tire passby noise requirement. An in car subjective tonal noise requirement is also put on original equipment tires. While both of these noise performance requirements are certainly considered important, it should be obvious that all the other tire performance areas are also important, and that a proper balance of all tire performance properties is necessary in any tires applied to GM vehicles.

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762009

Tire Selection and Performance Criteria for Original Equipment of Light Vehicles

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WHILE IT IS NO DOUBT EXTREMELY VALUABLE to get a group of scientists and engineers specializing in one particular subject together to exchange information at a symposium, there is a great and natural tendency for such an assemblage to suffer collectively from what is referred to these days as "tunnel vision".

I attended a symposium on tire traction three years ago where the attitude of most of the non-tire people seemed to be that we should forget all other aspects of tire performance in order to improve wet pavement traction capability.

In April, 1975, when the effects of the oil shortage were still on everyone's mind, a symposium was held under SAE auspices on the subject of fuel economy where the prevailing attitude of non-tire people seemed to be that we should forget all other aspects of tire performance and concentrate on reducing rolling resistance.

I have the great fear that many non-tire people at this time will be of the opinion that we should forget about all other aspects of tire performance and concentrate on reducing the noise created by the interaction of the tire and the road.

Fortunately we have in a symposium an opportunity to put all tire performance criteria into perspective and to relate noise to the many other considerations which are equally or more important to the consumer and the general public.

TIRE NOISE REDUCTION

Another participant in this program will discuss the history of tire noise reduction and it is pointed out that tread design noise treatments (scrambling of the size of the individual tread elements) was practiced in the tire industry in the case of passenger car tires starting as long ago as 1931.

Elimination of annoying frequency concentrations resulting from tire tread patterns have gone hand-in-hand with increases in traction elements within the tread design so that passenger car tire passby noise has not been a recognizable source of irritating noise to the public for many years.

In a 1972 SAE paper, Galloway and Jones (1)* reported the results of an extensive survey of the population relative to the source and annoyance factors of noises perceived in their normal environments. The only tire noise mentioned was squeal, and tires were not otherwise identified as a recognizable contributor to vehicle noise.

Vargovick (2) reported in 1972 that under cruise conditions tire/road noise was a partial factor in total noise below 500 Hz and a major contributor to the total vehicle noise above 500 Hz. An exception at the higher frequency was the high power

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*Numbers in parentheses designate References at end of paper.

ABSTRACT

The purpose of this paper is to review in general terms the process of tire selection and performance criteria for light vehicles - particularly passenger cars, as seen from the viewpoint of an original equipment tire supplier.

This paper proposes the role of passenger car tires in overall community noise is minor. There is almost nothing that can be done to reduce passenger car tire noise below its current level. The author states that the noise perceived inside the car is just as important to consider as passby noise. Lastly, the author stresses that noise is only one of many factors which must be considered in designing and selecting tires for passenger cars.

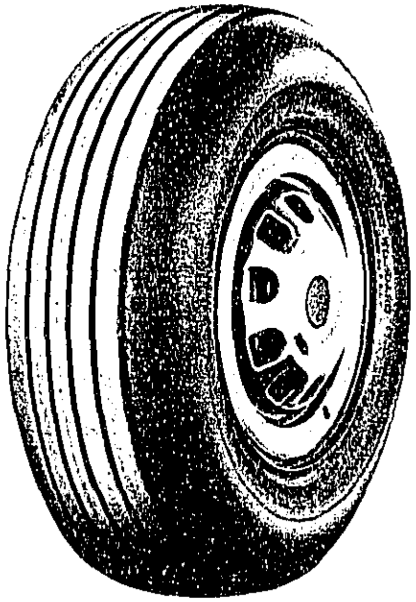

Fig. 1 - Simple tread design

sport compact cars where engine/exhaust noise was a major factor. Under accelerating (open throttle) conditions engine/exhaust noise was the dominant source.

Four years later, Veres (3) stated his conclusion that under cruise conditions tires had become the dominant source for all passenger cars - apparently due to the elimination of high powered sport compact cars from their line.

TIRE/ROAD NOISE VERSUS OTHER VEHICLE NOISE

To put tire/road noise in some perspective relative to the other vehicle noises, I would like to quote from the Report of a Panel of the Federal Government Interagency Task Force on Motor Vehicle Goals Beyond 1980, issued this year:

"In normal operation the noise output of most automobiles is fairly well balanced among sources. Thus, while tire noise may dominate in some situation, reducing the emissions of that source might effect only a small general improvement before wind, exhaust or engine noise became dominant. If major reductions in automobile noise are to be realized, it may be necessary to attack all sources simultaneously."

Something must be mentioned regarding the effect of the road on the tire/road noise. We can do no better than to quote Veres' to the effect that road surface textures can change the noise created by a given tire by as much as 6 dB. This is confirmed by Fuller (4). Fuller actually found a variation in noise of more than 10 dB on a group of eight concrete surfaces and of 4 dB on a group of six blacktop surfaces - all with the same tire.

Veres' work confirms tire company data which indicates that there is a range of something like 3 dB from the quietist, least aggressive tread pattern that could be made (either a completely bald tire or one having a simple design such as shown in Fig. 1) to the noisiest, most aggressive pattern utilized (such as the snow tire design illustrated in Fig. 2).

Veres also documented the effect of vehicle speed and environmental factors on the perceived noise level of a given tire.

Based on the work published by Veres and our own test results, it appears that the factors involving "tire" noise generation can be related quantitatively as follows:

Range of Quietest to Noisiest Tire Design at 40 mph 3 dB

Range of Quietest to Noisiest Surface at 40 mph 6 dB

Effect of 5 mph Speed Difference 2 dB

Effect of Possible Temperature Variation within 15 min 2 dB

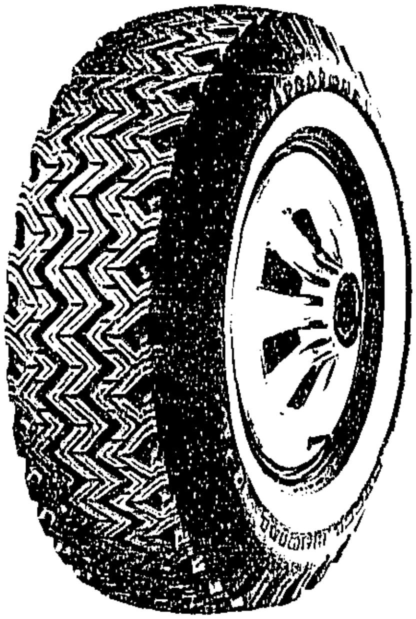

Fig. 2 - Snow-tire design tread is an example of aggressive tread

None of this takes into effect the additional noise of about 2 dB which would be added if the road surface were wet.

It is of interest to note that the snow tire illustrated in Fig. 2 is actually quieter than the tire illustrated in Fig. 1 on very smooth surfaces. Fuller's paper describes in some detail the effect of different surface textures on the noise generated by tires.

The sum of all this so far is that there is little hope of reducing passenger car noise levels by improvements in current tire tread patterns. Even if it were practical to eliminate the tread pattern of a tire altogether, neglecting the disastrous effect on wet pavement traction, we would have a reduction of less than 3 dB in noise on some surfaces and an actual increase in noise on other surfaces.

In discussing noise generated by tires in contact with the road, it should be recognized that there are other types of noises which are of importance to the occupants of the car. In this country, car occupants have as much right to be considered as bystanders along the road, since almost all of us are in a car for a substantial amount of time each week.

Other types of tire noise assessed during the process of tire selection for a new vehicle include expansion joint slap, cornering and braking squeal, and a variety of sounds which become annoying due to resonance of various components of the vehicle. Because each vehicle has different resonating members, the names for such noises cover a wide area - such words as boom, hiss, buzz, rumble, etc. crop up in tire evaluation work with each model change.

Practically none of these noises heard in the vehicle interior can be measured with a decibel meter since it is not the amplitude of the noise which creates the irritation; it is the particular combination of peak frequencies.

This matter of measuring tire noise with a sound level meter as compared with spectral analysis will no doubt receive further attention during this Symposium.

ORIGINAL TIRE SELECTION

The process of tire selection in the case of an original equipment application covers a multitude of factors, of which noise is only one. I would like to emphasize the large number of tire properties which must be suitable before a tire is accepted for application to a new vehicle.

Initial evaluations of a candidate tire generally include the aspects of performance listed below:

Appearance,
Sizing,
Ride,
Handling, and
Noise.

Each one of these items could be broken down even further. For example, handling could include force and moment measurement, straight-ahead stability, response to steering inputs, stability in a transient maneuver, etc.

Appearance may seem to be out of place in a listing of product evaluations but I don't think that engineers can be blind to the necessity of providing proper appearance irrespective of function. As an example, we might refer back to Fig. 1 which illustrates a tread pattern which has reasonably good straight-ahead braking ability on wet pavements but would obviously be completely unacceptable, due to its appearance, to the consumer.

Having satisfied the performance criteria established by the car manufacturer relative to these Initial Evaluations, tire samples are then tested for a number of other properties which list as Final Evaluations below:

High Load,
High Speed,
Treadwear,
Traction; wet, dry, snow,
Power Loss.

Nothing has been shown in these lists of performance evaluations relative to government safety standards. As I am sure all of you are aware, compliance with the Federal Motor Vehicle Tire Safety Standards, which include tests for high speed, endurance, breaking energy, bead push-off and physical dimensions is a necessity before the first tire can be sold.

Finally, tire characteristics which relate to vibrations below the audible level are measured for every tire applied to new vehicles. These measurements include balance, radial force variation (both overall and harmonics) of the loaded tire and lateral force variation. In addition tires for some vehicles require measurement of tread run-out, conicity (pseudo camber) and ply steer.

SUMMARY

Summing up, I have attempted to make the following points:

1. That the role of passenger car tires in the overall community noise situation is extremely minor. There is almost nothing we can do to reduce passenger car tire noise below its present level - and there doesn't appear to be any consumer objection to the present noise level, unless squeal is considered as a part of tire noise.

2. The noises generated by tires which are perceived inside the car are just as important as the passby noise but because of the complexity of in-the-car noise due to resonance of car compo-

nents, the attack on this type of noise relates more to frequency shifting than to sound level reduction.

3. Noise is only one of a multitude of factors which must be considered in designing and selecting tires for passenger cars. While noise and other aesthetic considerations cannot be forgotten, those tire performance qualities which relate to safety and economy must be given priority when a trade-off is made if the public is to be properly served by the tire selection process.

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Tire Selection for Replacement Use on Light Vehicles

J. W. Davis
Cooper Tire & Rubber Co.

REPLACEMENT TIRE SELECTION differs from initial tire selection enough to warrant a separate discussion of the criteria for this process. Reference 1* would supply informative background regarding tire characteristics before delving further into the subject of replacement tires.

In the United States today, there are about 133 million vehicles in use of which approximately 107 million are passenger cars and about 15 million are light trucks, making a total of 122 million out of the 133 million vehicles. Now these 122 million vehicles, the passenger cars and the light trucks which we consider light vehicles, have 488 million tires mounted on them. Of these, about 160 million need replacement each year. Most of these replacements are new tires; some are retreads. So, we're talking about 150 million passenger car tires and about 10 million light truck tires.

Of the passenger car tires, most buyers have the same expectations and thus the same performance requirements as those listed in Ref. 2. But large numbers have special needs. Some want special tires which meet their needs for higher traction in mud and snow, so they buy mud and snow tires. Some want tires which give higher levels of performance in relation to speed, cornering, acceleration; they buy 70, 60, 50 aspect ratio tires, many of which proudly display this performance image by raised white lettering. Others do not need these special characteristics, but like the image. They, too, buy these low aspect ratio tires especially with the big white letters.

Some buyers have had a problem with their previous tires. In their opinions, their expectations were not met in one or another of the phases of tire performance; either tread wear was too short; skid resistance was not good enough; handling deficiency was apparent; the ride was too hard or too rough; or some sort of tire failure was experienced.

These buyers are sensitized to that particular shortcoming, and will shop for replacements which are thought to be particularly good in that one performance aspect. These replacement tire buyers put different emphasis on some of the characteristics mentioned, but they all agree on the primary importance of another characteristic: PRICE.

My experience as a tire designer and tire engineer has been wholly in replacement tire manufacturing with Cooper Tire & Rubber Co. We make tires for a substantial organization of dealers and distributors of our own maker's brand.

In addition, we make tires for several nationwide distributors who own their own brand names and their own tire designs. We also make tires for regional distributors, some of whom own the design of their tires and some of whom do not. As a consequence, our factories produce about 160 lines of light vehicle tires with an average of 10 sizes in each line.

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*Numbers in parentheses designate References at end of paper.

ABSTRACT

Approximately 160 million light vehicle tires need replacement each year. Buyers have special needs and look for certain characteristics, often on the basis of what weakness existed in their previous tires.

The manufacturer must satisfy the consumer's demands for features and price. On the other side, they must comply with industry requirements, government standards, international requirements and the demands of the "marketplace." Through all of this, manufacturers must bear in mind not only the product's price, but the cost of research and testing in developing a "quiet tire" to please all.

Producing for so many distributors whose economic well-being is based upon our product, you will readily understand that we get a lot of advice - yes, even demands - regarding light vehicle tire characteristics. Cooper has been making tires for over 60 years, and our light vehicle tire customers have been giving this advice for an equal length of time.

To a manufacturer of replacement light vehicle tires, there are many product goals which must be reached within the limiting constraints of several external systems. These external systems are:

1. Industry standards of The Tire and Rim Association regarding nomenclature, dimensions, load capacity, operating pressure, and rim contours.

2. Government safety standards set out in the Federal Motor Vehicle Safety Standards 109, 110, 119 and 120, and other regulations of the Dept. of Transportation, Bureau of Motor Carrier Safety, etc., regarding marking, dimensions, durability in overload performance, durability in high speed performance, strength, and bead unseating of tubeless tires, etc. The Uniform Tire Quality Grading System of the DOT is also imminent, and will be a very severe constraint.

3. International requirements such as the International Standards Organization (ISO), European Economic Community, and the standards of countries to which we export.

4. The economic and social framework of the various markets in which we operate regarding safety and product liability, price and value, competition, and inadequate maintenance.

Within the complex framework of these constraints, we recognize the performance goals these light vehicle replacement tires must reach in order to be marketable. They include:

1. Durability of the tire body beyond the life of the tread. Recappability.
2. Long tread life, without irregular wear and cracking.
3. Good tread appearance when new, and during the life of the tread. (That word is tread, not thread.)
4. Good sidewall appearance both new and after use, without cracking, crazing, or yellowing of white sidewall.
5. High strength to resist impacts, both in tread and sidewall.
6. Good traction, both lateral and longitudinal, wet and dry, braking and accelerating on various pavements and unimproved surfaces, including winter conditions.
7. Soft ride without harshness, imbalance, non-uniformities, etc.
8. Good handling and cornering, straight tracking; without nibbling, side sway, bounce, etc.
9. Low pick-up and retention of stones.
10. Good high speed capability.
11. No objectionable noise.
12. Consistency in these performance levels from tire to tire.
13. Low rolling resistance.
14. Low cost.
15. Materials and manufacturing equipment availability.
16. Comparison with competing tires.

One must emphasize, the interdependence of these goals, often on an inverse basis. A few examples of inverse behavior:

6 vs. 2 Higher traction usually results in lower tread wear.

2 vs. 10 Increased tread wear usually results in decreased high speed performance.

7 vs. 8 Softer ride usually results in poorer handling.

The mutual effects are not simple, and many times they involve more than two performance goals. This results in very high development costs for improvements, increasing the economic risk involved.

Until recently complaints about a noisy tire have been handled by altering the tire tread design. Listening to a tire on the road and on a test wheel and analyzing its frequency spectra at two speeds usually reveals areas where better design will cure the problem. In my experience the complaints about tire noise have always been based upon annoying tonality; a whine or "singing" noise. I've never had a complaint based on total noise level. A very satisfactory "fix" of a design may give a higher A-weighted sound level than that of the original design.

While I appreciate the simplicity of the objective dB(A) number, the factor of annoyance is seldom measurable as a simple dB(A) number.

The cost of these changes has been considerable in development and testing, and in the cost of tire molds. A mold with good noise generation treatment is much more expensive than one without this feature. This cost is more pronounced for smaller tire manufacturers, who purchase fewer molds in each size and line.

In some cases the body fabric of the tire, while eminently successful for other features, has been changed because of the resulting vibrations and resonances.

Many times in the past, particular vehicle models, in the presence of certain tire/pavement interface vibration and noise spectra, have been found to amplify the tire noise to an objectionable point. The tires are often singled out improperly as the sole cause, and expensive investigations have been required to solve the real problem.

Manufacturers of light vehicle replacement tires are cognizant of the tire/road interaction noise, and have reduced its objectionable nature through tire design changes of many kinds. However, we are at a loss for solutions to some of the present noise complaints which result from sheer traffic volume and speed, coupled with light residential building construction, adverse locations of new multi-family dwellings, and now with specially-finished Portland Cement concrete pavements with deep transverse tining or scoring. We invite your help and suggestions.

We anticipate that the costs of the measures required to attain certain environmental benefits will be quite high, and we do not feel comfortable with the values assigned to some of the benefits. We have work to do to quantify the costs to us as a tire manufacturer, and the costs to our customers, the tire users.

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FUNCTIONAL REQUIREMENTS FOR LIGHT VEHICLE TIRES
PANEL DISCUSSION

Session 3 of the SAE Highway Tire Noise Symposium convened with the moderator being R. H. Snyder.

MR. SNYDER: All right, any questions? Mr. Hindin, did you have a question you wanted to ask?

MR. HINDIN: This is to Mr. Schutz. In your criteria for tires, under "others" you inserted something that was fairly new to me, and that is the "run soft" capability, degree of warning, and ultimate mode of failure. Is this something that the radial tire has introduced into the tire spectrum?

MR. SCHUTZ: No, not really. We have conducted a test of that sort dating back to bias belted tires. We consider it, I guess, a really good idea to establish this type of performance, and the tire's response to that type of condition; that is, a slow air loss running on an expressway. We have been looking at that type of situation, or that aspect of performance for a number of years, well before the radial tire came in.

MR. SNYDER: Would any of the rest of the panel like to comment on that question?

MR. SMITHSON: I would have to agree with Mr. Schutz. It is a very important factor. I think it might be an interesting comment in that radial tires, I think, have improved performance in terms of the length of time they will travel at lower pressures, in fact, they will run further.

Passenger car radial tires will run further totally deflated than a bias-type tire, but the one problem we do have is that a soft radial tire is less detectable to the driver. While the tire does perform better, the amount of warning time - at least if the deflation is in the initial phases - may take longer; but, you encounter things such as trying to subjectively evaluate at what level a customer will become sensitive to vibrations, and it leads to several thoughts on how you might handle it.

But in general, I don't think tires have undergone much change, other than the character of the way they perform, but inflation performance is in our minds - and I think in the minds of most manufacturers of tires and vehicles - which is an important aspect of tire performance.

MR. VELTE: I think that it is probably going to become a little more important due to a couple of factors: One, a radial tire always looks flat and people don't check it as often, at least that's our feeling. They look flat, so they don't bother putting air in them.

My wife's tolerance level is well below 16 psi inflation. She doesn't see anything in the vehicle. I think the other thing that we would really like to do is to have a tire that would be able to provide some "running flat" capability for a couple of miles, from the standpoint of providing some advantages in the vehicle itself, weight, and so forth, and also from the standpoint that it would provide some security for someone who was in perhaps a less desirable neighborhood, or by the side of the road where favorable facilities to make a tire change were not available. I think this will become more important.

MR. SNYDER: I ought to comment that this is not a tire noise question, and ask that we confine our questions to the subject relating to tire noises.

MR. COULTER: I will try to make my question more simple than the question I asked yesterday. I would like opinions from the panel.

My question is: In this panel's opinion, should we be using A-weighting if regulatory controls are necessary, or is everybody well enough equipped that we should use more complicated appraisal methods on tire noise?

MR. SNYDER: Who would like to answer that question?

MR. VELTE: I guess it doesn't make much difference, really, what yardstick you would use, as long as you understand the yardstick you are using, and you might apply it in any rational manner.

I think that if you go into a more complex analysis it would require more work to obtain the answer, so I would vote myself for the simplest yardstick that makes sense, and administer it with reason.

MR. CAMPBELL: Let me answer also. In the interests of waking up some people, let me disagree.

The message that I have been trying to communicate with respect to this question is that if you have a tire whose noise is objectionable, it is most likely due to a peak frequency, and not to the overall decibel level or the sound power generated.

Merely reducing the decibel level of a tire without handling the peak frequency problem doesn't solve the annoyance factor.

I think if the industry is interested in helping people, they should eliminate the "singers" in the tire population, if they exist, and the only way I know of accomplishing that is to look at the frequency spectrum.

I know that police enforcement officers don't have spectral analysis facilities at the side of the road, nor do we want them to have such facilities, and so the problem of enforcement is very difficult.

I think the constant reduction of decibel levels without concern for what is annoying people is a typical, if you wish, bureaucratic approach, with very little profit for the extreme costs that will be involved.

MR. SNYDER: Any other comments or questions?

MR. RAABE: Might I suggest, in this particular problem, that if you let the law enforcement people do it, the simplest possible way is for the people in the marketplace to take care of the tonal annoyance.

MR. SNYDER: Any more?

MR. CLOSE: I think I want to start off by disagreeing with Mr. Campbell's comment that tire noise was a very minor contributor to community noise or annoyance, and I think that in many studies this has not proven to be the case for the high speed beltways of our cities. The passenger car, while not a standout source of noise, is very much the floor that we are addressing; but, if we put that in the context of no answers really being available to greatly change that in the technological field today, I would agree.

That sets the stage for a point I would like anyone on the panel to address. Considering the range of noise levels of the nominal majority population of passenger car tires to be so small, and the problems of differences in levels that we will be talking about in the next session concerning test procedures, the benefits or lack of benefits in terms of production of tires and community annoyance that might result from some sort of passenger tire regulation hasn't really been addressed by this group, the same way that I think the particular car performance elements requirements have been.

Do you see that any regulations would really affect the tires within this narrow range of noise levels that they produce today, or they could conceivably result in lowering of passenger tire noise within the next three or four or five years?

MR. SNYDER: If there are no other volunteers, there are a couple of comments I would be happy to make about that.

It wasn't exactly stated, but it should be implicit in what was said, that the noise problem has been worked over pretty hard for a long period of time, and at the present level to accept Mr. Campbell's figure, a snow tire - which is discernibly different - is only three decibels noisier than the best rib tire.

Of course, it is possible to make very noisy tires. You can use sequences, it can go back a few years and you can put in reduced tire patterns that are unbelievably noisy, but, where we are at the highest level of technology and the matter has received a good deal of attention, and is in about the best possible expected condition.

I think the tire is designed with a great many constraints in mind, and conceivably there are improvements that could be made on noise, if attention is directed to it, but there have to be other tradeoffs, and in any case it is going to be a fairly tedious and a fairly lengthy kind of development.

If targets are set and sufficient lead times are arranged, no doubt constructive work can be done in that framework, but the potential floor to the tire noise problem is not too far away.

There is nothing that can be done that will make a huge improvement over the present commercial level. Now, does anybody seriously disagree with that?

MR. SMITHSON: No. I would like to add a comment. This is a comment to the past question.

I think the point is that there is a wide spectrum of replacement in original equipment tires. There are tires, I think, on the marketplace in small numbers which are at higher levels of noise than they need be, and don't necessarily generate any increased traction because of that noise; but, the majority of tires sold as replacements or as original equipment, are operating at a very efficient level and not far above the minimum shelf that we can obtain with a tire with essentially any tread on it at all.

If we try to take those tires down we will be taking sufficient losses.

I am not competent enough to say that the elimination of a few of those will make a dent in the community noise problem.

I think everyone will agree there are some tires that are noisier than they need be, but most of us are involved with tires that are already quiet, and if we have to go below where we are, we are in trouble technically.

MR. LIPPMAN: Mr. Close, the emphasis you placed on the experience of industry over a long period of time doesn't put it there. To a very large extent the problems have been solved. They have been worked on for years, and they have been solved by changing the quality of the noise, not the level primarily.

There have been cases where the level has been important, too.

If we are going to be talking about means for control of public reaction to noise, at this point unfortunately, we are in a position where we don't have this quantified so one could state a series of rules that relates to annoyance.

Mr. Campbell has simplified it a bit, and certainly tonal concentrations are an important matter. They aren't the total story, however, much more is involved than that.

I would suggest that the way to a definition of whether tonality is important to the public would be to pursue investigations that have only been touched upon. Tonality hasn't required any further in-depth investigations to solve the commercial problems which occur. There has been no need to obtain a definition, mathematical or mechanical, or some kind of definition of annoyance as perceived by the public. However, if we do define annoyance and then set our criteria for acceptance accordingly, this would result in some other definition of level than we are now using.

What I am saying is essentially that the technology doesn't presently exist to put levels on annoyance, and certainly the above A-weighted level is not a particularly good measurement for it at the present time.

Thank you.

MR. NILSSON: I think it should be possible to find a single number noise rating which better fits public annoyance than the dB(A) Leq does.

We have, at the present time, conducted a research projection at the Bureau of Acoustics where we have found a possibility for reducing the growth variance to public annoyance wherever preferred by taking into consideration the variation of the dB(A) level.

MR. CAMPBELL: I would like to comment, not on that, but on another question. I would like to comment on the first part of Mr. Close's question, the part which was a statement preceding the question.

He said that my paper pointed out the low interest in the public on entire noise, and I didn't dream that up. I quoted from Galloway and Jones' work, 1972, which to my knowledge is the only substantial investigation of what noise annoys the public with respect to motor vehicles.

The study was made over a reasonably wide number of people. I think it involved 2000 people in a variety of socioeconomic status levels, and I think the two locations used were Boston and Los Angeles, and results are published in a SAE paper in 1972.

I said in my paper that the intensity of noise created by tires was eleventh out of a list of twelve insofar as perception by the public of the various noises apparently generated by vehicles.

Tire noise was included in the term "traffic flow." It wasn't identified as tire noise itself.

Due to the accumulation of number of vehicles is a different table other than the intensity, the repetitiveness of cars going by in great numbers, passby noise, the travel flow noise is way up near the top.

They didn't ask the people what annoyed them the most, the occasional loud noise, or the continual flow of low noises, and Mr. Close in his introductory remarks said that he disputed the finding that people weren't annoyed by tire noises, and he said he knows of many beltway studies around urban areas which show that to be the case.

If they exist in the open literature, I am not aware of them. I think the point I am trying to make is that let's find out what is annoying people and do something about it. Let's not assume that the decibels are annoying.

I have been harping on the tune that peak frequencies annoy everybody, and some people don't agree with me, but let's find out.

Why don't we debate this? This is a matter on which you can survey 10,000 people and obtain the answers, and since we are going to spend millions of dollars on controlling this thing, I think a little bit of money spent on defining the problem before we start solving it would be helpful.

MR. SCHUTZ: One further brief comment on that: We seem to be in general agreement that there is a floor noise level for tires which it is going to be very difficult to go below.

If we do determine that the noise level of a flow of traffic is objectionable even with all of the tires at this noise level floor, obviously the next step then is to contain the noise, either with rebelts along the edge of the road containing the noise itself, or by restyling the vehicles to contain the noise level within the vehicle by putting shrouds around the tires and restricting the noise in that way.

MR. SNYDER: Mr. Hillquist?

MR. HILLQUIST: There is one group of vehicles that I think fits into the category of this morning's session.

They are light vehicles, yet they may have many of the same problems as yesterday's vehicles. These vehicles are the light truck, the recreation vehicle, and the four-wheel drive type of vehicle. There are probably some different compromises and some different factors that enter into tire selection and tire design for those. I wonder if any of the panel would make some comments in that regard?

MR. DAVIS: I would like to make a couple of observations on that, Mr. Hillquist.

I don't have much data, but a few months ago I did a little elementary surveying along the highway at highway speeds, and I found that while the loudest vehicles were the 18-wheelers that went by, the ones who were the most predominantly annoying were the four-wheel drive light trucks, the vehicles you are speaking of; and I think there are two or three factors here that bear some attention. I don't know just exactly how to get around them.

First, most of these vehicles use a very aggressive high traction tire. It is usually a deep tread, and the tread is widely spaced, and it is not modified, as are passenger car snow tires. It is a raw "dig in and go" type of tire, such as our friend, Mr. Berger, would feel happy with.

But these tires are noisy, and it isn't just the noise of the particular pair of tires on an axle; we encounter a large amount of axle fight on this vehicle, but which does things to the elements of the tire tread, and makes them perform in a way due to both driving and braking traction occurring at the same time between front-rear axle as a result of probably improper equalization of deflection on the two axles. I think this is a problem that needs some study.

Also, we encounter the different kinds of steering systems on these vehicles. They are always set up about eight or ten in higher than other vehicles, so we have a much wider loudspeaker from which the sound can emanate, and I agree, it is quite a problem.

At the same time, while this is a minority-type vehicle, I don't think we can ignore the fact that a minority of perhaps two or three million users can hardly be disregarded. I am sure there are a lot of things that have been done for minorities smaller than this in this country.

MR. CAMPBELL: Could I comment? I would like to make sure that Mr. Hillquist understands, and the record shows, that the tire industry has given equal attention to light truck tire noise generation and that the scrambling of the size of the elements of the tread design has been accomplished to the extent that it is possible to do so.

We have minimized the peak frequencies generated by this class of tires, just as we have with the passenger car tires. That is, our technology has been extended to this class of tire so that we are not unaware that they need to be quiet, too.

I think Mr. Davis mentioned earlier that by their very nature, these tires tend to be noisier to start with. They are approaching the truck tire, and what we can do with pitch scrambling around the tread design is not as successful as what we can do with passenger tires, insofar as getting down to the passenger tire noise level; but, it has been done to the extent that we know how to do it.

As far as I am concerned, they have been scrambled as well as anybody can scramble a pitch.

MR. CLENDENEN: I would like to direct this question to Mr. Campbell: During your presentation you mentioned the fact that road surfaces can contribute -

MR. SNYDER: Would you hold on? I think Mr. Hillquist wanted to respond.

MR. CLENDENEN: Did you want to respond?

MR. HILLQUIST: I guess frankly, Mr. Campbell, it was to get some of that light tire information into the record. I might make one other observation, that some years ago we did work on highway situations identifying those vehicles, and we determined the contribution to be to the upper 10% of sound levels observed at a roadside location, both for heavy and light vehicles.

We found that in two out of nine cities surveyed, that light trucks, and particularly four-wheel drive or recreation vehicle types, have significantly stood out.

In Detroit and Denver when we looked at it from a hobbyist point of view, we figured that these areas have types of people who enjoy off-road or get-out-of-the-city into the boonies type of recreational tastes, whereas that may not be the case in Manhattan or other places.

For a bit of comment, perhaps, because these types of cities and those locations attract people who seek recreation, there might be a greater tendency to accept that vehicle in your midst. I throw that out only as a suggestion, but in response to yesterday's comment of whether or not there were regional differences, my observation would be that there are in this recreational vehicle area, and we may be talking about different subsets of that minority that Mr. Davis has identified.

MR. CLENDENEN: To repeat the question that I had: In studies made here in the West with the Oregon Highway Department and the California Highway Department and the Washington Highway Department, we find there is a movement on the part of all of the western states to go to a highly tractionized pavement.

As an example, the cutting of the road surfaces in the State of California is set 3/8 in on center, and 1/16 in deep.

Now, we recognize the fact that we are also going to the brushed concrete surface on any new highways that are constructed in the State of California.

I am wondering, this is all from the standpoint of safety, greater coefficient of adhesion, as far as the road surface; however, we are going at cross points to making a more quiet tire, and are we at some point going to be working at cross points with the State Highway Departments due to the fact that they are trying to get a safer surface to operate on? Your thinking on that, please.

MR. CAMPBELL: It isn't the state; it is the Federal Highway Administration mandate that brushed concrete is the preferred concrete texture treatment.

They are paying the bill. The states may throw it out, but much of it comes from Uncle Sam, and he wants brushed concrete because it is better for traction, particularly when it is wet, of course. Sure, the Department of Transportation is wearing two hats. One says, "Let's make the environment quieter," and the other says, "Let's make the environment noisier with respect to the tire-road interface noise."

I think safety is going to win this argument. I believe people would rather have safe highways than two decibels less noise in their backyard. It should win. That isn't a technical question; that's a political question.

I think that this safety versus noise will be sorted out after a while, and priorities on a national level will get ranked in some reasonable order, irrespective of the volume of the proponents of one aspect or another.

I would like to also comment one more time on Mr. Hillquist's subject of these intermediate vehicles, some of which are, as Mr. Davis said, quite annoying, some of which are quite loud, or both.

I see no easy solution from a manufacturer's standpoint to solving that problem; but I do see an easy solution in setting up speed limits in regions where the annoyance exists, and the speed limit solves the problem, it seems to me, which the manufacturer's can solve, of providing the garbage dump mobility and the smooth pavement noise level.

I think the only way to control that is with local enforcement of speeds. I don't think you can do anything to the vehicle or tire manufacturer that is going to handle that problem.

MR. HILLQUIST: I find myself in a rather strange role of being the Devil's Advocate.

I am curious then if you are suggesting that along I-75 northbound from Detroit we should have 55 mph speed limits for passenger cars, and those hauling snowmobile trailers and the like and if it happens to be a four-wheel drive vehicle, perhaps 40 mph, so we can achieve the same relative sound level.

I would like some further explanation as to how you control it by speed limits in a traffic mix.

MR. CAMPBELL: You are the one who said Denver and Detroit have a high preponderance of this type of vehicle, for whatever reason.

If Denver and Detroit want to reduce the environmental noise level, they might have to impose a speed limit different from New York City's speed limit, because you have more of those funny vehicles, and the public - who wants all those snowmobile vehicles - is going to have to pay the price of slowing down their sedan when they go back and forth to work.

Perhaps the other way to do it is the way they do in Europe, which I think is very acceptable, and that is by putting a tag on the back of your vehicle saying that its maximum speed is such and such. The back of all trucks in Europe have a round, circular disk with a black number that says, "eighty kilometers," and the enforcement agencies can selectively enforce different speed limits for different classes of vehicles. I see nothing difficult about that, because they do it in Europe. It must be possible.

MR. SMITHSON: I have a comment. I think one problem that exists is that there is some concern in the traffic in terms of the relative velocities of vehicles that operate and how this conflicts with the safety problem.

The comment, if it is right, you can take things on with tunnel vision, but I think it needs to be documented that the work in improving texture, in putting macrotexture in pavements, is extremely well substantiated.

This is what must be done if one wishes to keep traction at a desirable level. The problem today with wet traction is with the worn tire. When the tread design that has been put on to be efficient in eliminating water is gone, then the only way we know to do it is to take it out through the pavement.

California is putting in thousands of miles of grooves on highways, which is creating problems for tire and vehicle manufacturers, because of the groove wander, and I might point out that it is fairly well standardized, or becoming so; but, they are taking that point of view because the data indicates they are having major reductions in wet road accidents.

MR. SNYDER: Mr. Coulter.

MR. COULTER: We are just in the midst of quite a bit of research. We have been grooving some of the areas around Toronto, and for the record it might be interesting.

We have only tried a very small number of tire mixes, but as long as the transverse grooving is there, we are now going from the plastic groove, to the diamond-cut groove, to the slot-cut groove, about 10 dB range on a rib tire, and going along the same chunk of highway grooved by the same contractor, we can see 5 dB variation from one end of it to the other.

There is a lot of optimization in grooving yet to be done, and there is a lot of grooving going on right now, miles and miles of it that we are going to be burdened with for several years.

In Ontario, the salt deteriorates the concrete surfaces, and I gather in about 10 - 20 years what will happen in Toronto is that the studs will cut up the original rough surface to take quite a bit of the life out of that concrete, as far as how the roughness lasting for the full life before the salt got to it.

Now, we are fortunate inasmuch as sound is concerned in that they are going to have to put asphalt on top of that surface eventually, or replace it with four in of concrete. Eventually that surface is going to get quiet again; but, the noisiest surface we have measured with an average rib tire has been the plastic groove, that is, as it is hardening the brushed surfaces, they seem to have solved the problem of loud noise levels with the cut grooving into the older surface by using a diamond grooving.

That's what we have a preliminary figure of about 5 dB less for the cut grooving than some of the new surfaces that have been plastic-grooved as they were laid.

MR. SNYDER: Thank you. I trust that somewhere there is another dialogue going on between people who are concerned about noise and the people that make highways, because in many things of this kind, the highway people seem to maintain a very low visibility.

The highways are more determining of what traction is than are the tires, judged by what we have heard today more determining of tire road noise than the tires themselves. Mr. Lippmann?

MR. LIPPMANN: I think it might be worthwhile pointing out that we have an interactive process going on in tire development and road development. We are in a position of confounding and this has happened to a degree in the controllability of the vehicle where the grooving has affected the steering properties of the vehicle, and where in the earlier grooving experiment there have been some rather disastrous results on motorcycles resulting in deaths.

I would suggest that we don't consider these as isolated phases. The tire cannot be developed for low noise level without consideration of the grooves, and the statement was made that some kinds of grooves are better for noise; but, that also reflects what kinds of tires went over them and what types of tires we will have in the future, and whether these tires are designed to mate with the kinds of grooving that you have experimented with.

I would be rather cautious about deciding at this point, or developing a long-range plan, both for tire design noise and grooves for the same purpose, and for the purposes of traction.

MR. SNYDER: Thank you. I don't see anybody else approaching the microphone, so I will turn it back to Mr. Hillquist.

PART III
TIRE SOUND MEASUREMENT

762011

Effect of Pavement Texture on Tire/Pavement Interaction Noise

D. B. Thrasher, R. F. Miller, and R. G. Bauman
B. F. Goodrich Co.

THE NOISE GENERATED from tire/pavement interaction can produce a significant contribution to overall vehicle noise. This means that the road surface also plays a major role in determining the noise which a tire generates. Differing road surfaces can reverse the relative noise levels generated by two different tires. As a result, if road surfaces are not carefully specified in regulatory or certification procedures the results of these procedures will be confusing at best, and capricious and discriminatory at worst. Unfortunately, a degree of confusion exists since in general many believe that the tire is responsible for noise generation, where in fact it is a tire/pavement interaction(1)* that is responsible for noise generation.

The importance of surfaces with varying degrees of pavement macrotexture, in this interaction noise generating problem is just beginning to be understood and accepted. Pavement macrotexture is a term used to describe the degree of surface roughness. Fig. 1 shows qualitative pavement macrotexture categories. A description of pavement microtexture is also shown in Fig. 1, but probably the effect of microtexture on tire/pavement interaction noise is relatively unimportant. In this paper the emphasis will be on pavement macrotexture (1 - 3). Surfaces with varying degrees of pavement macrotexture (low through high) will be described as surfaces having low, medium, and high texture.

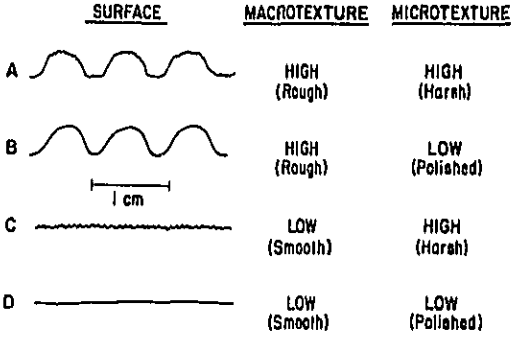

Fig. 1 - Qualitative pavement categories (after R. R. L.)

In 1973 the SAE Tire Noise Subcommittee ran tire/pavement noise tests on a number of different pavement textures. The results were reported by G. R. Thurman (4). This work showed that the interaction of a brushed concrete surface, (medium texture) with a straight rib heavy duty truck tire produced a noise level that was 5 dB(A) higher than that produced by the same straight rib tire running on a smooth concrete pavement, (low texture).

Hillquist and Carpenter (5) found that roadway surface texture is an important factor affecting passenger tire/pavement noise generation. Their

ABSTRACT

Pavement texture has a pronounced effect on what is commonly referred to as simply "tire noise". The disturbance in question should properly be called tire/pavement interaction noise. A noise ranking can be made among tires only when they are all measured on the identical pavement texture. The importance of pavement texture is most clearly apparent with smooth and rib tires. Highly textured surfaces cause the noise level of conventional rib truck tires to reach that of lug tires. Passenger tire noise rankings are reversed by pavement texture differences. The gradient of pavement texture, both lateral and longitudinal, is a definite problem affecting the reliability of passby noise measurements.

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*Numbers in parentheses designate References at end of paper.

experiments show that a change in sound level of 5 - 7 dB(A) can be attributed to variation in road surface texture, independent of tread pattern.

Leasure et al. (2) found that roadway surface texture affected automobile tire/pavement interaction noise more than it did truck tire/pavement interaction noise. They thought this might be due to the fact that the pavement texture within the tire/pavement interaction area is on the same scale as the tread element spacing typical of passenger car tires.

Veres (6) found that a change in road surface texture produced larger variations in noise level than did eleven different passenger tire tread patterns, which included one snow tire, tested on the same surface.

With this background in mind we decided that we needed noise passby data on both passenger and truck tires over a range of pavement textures. This is necessary for two reasons. First, the roadway surface texture rather than tread pattern may prove to be the factor which dominates noise level on a majority of roads, then it may be impossible to offset this effect with any modification in tread designs, and second, there are existing and pending automobile and truck noise regulations which require scientific information that will allow us to respond in a meaningful manner to government agencies, so that reasonable and useful vehicle noise regulations can be achieved.

Our effort in this paper will be to show how much effect pavement texture has on the tire/pavement interaction noise level, for both truck and passenger tires. We will discuss what effect pavement texture has on the noise generated by different tread designs, and on the best way to evaluate new tread designs.

EXPERIMENTAL

TEST SITES - Sites were selected to provide a range of pavement texture from fairly smooth black top (low texture), through a gradation of Portland cement concrete (PCC) surface finishes,(low through high texture). Figs. 2 - 5 show pictures of the road surface texture at the test sites. Surface 1 is smooth black top (low texture), Surface 2 is moderately smooth PCC (low texture), Surface 3 is a worn PCC with exposed aggregate (medium texture), Surface 4 is cross brushed PCC (high texture). Surfaces 2 and 3 are at the same test site. Surface 3 is the familiar worn track (exposed aggregate) that appears on PCC pavement after several years of use. This test site is on Ohio Route 21. Surface 2, low texture PCC was obtained by adjusting the vehicle path laterally about 3 ft (that is, out of the worn track). This placed the tires on the right of the vehicle on the unworn edge of the pavement and the tires on the left of the vehicle on the unworn strip of pavement between the worn tracks.

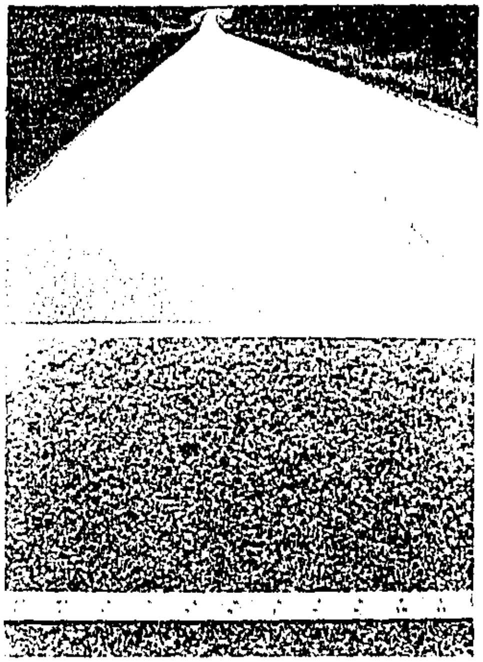

Fig. 2 - Smooth black top

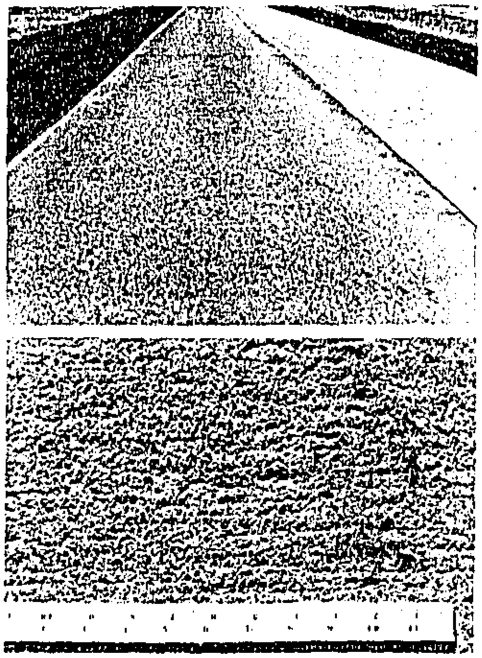

Fig. 3 - Moderately smooth PCC

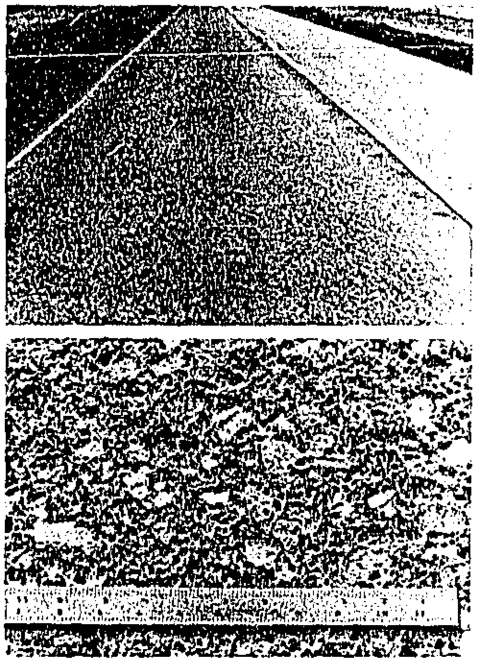

Fig. 4 - Worn PCC

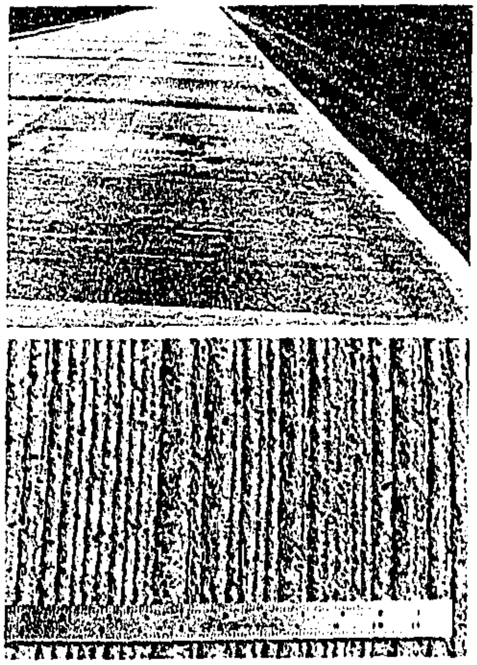

Fig. 5 - Cross brushed PCC

EQUIPMENT - Passby noise measurements were made with a General Radio (GR) 1561-A precision sound level meter operating in the dB(A) fast function mode. Periodic calibrations of the measurement system were by means of a GR 1562 calibrator. The A-weighted output of the sound level meter was tape recorded on a Nakamichi 550 stereo cassette system for spectral analysis in the laboratory. A Spectral Dynamics 330A analyzer was used for spectral analysis of the data.

Pavement temperature, air temperature, relative humidity and wind velocity were recorded for all passby noise measurements. No data were considered reliable at wind velocities above 5 mph, because vertical wind gradients, wind direction and wind velocity can influence the measured noise level.

Fig. 6 is a photograph of the test equipment at a measurement site. The microphone is located at a distance of 25 ft at a right angle to the automobile path and at a distance of 50 ft for the truck. The microphone was positioned 4 ft above ground level for both truck and automobile passby tests.

TIRES - The types of passenger test tires are patterned rib, discrete block, and snow. We also used the ASTM straight rib type tires and a blank tire of normal tread thickness for test purposes. The truck test tires are patterned rib, lug and straight rib HCR types. A photograph of the passenger tires is shown in Fig. 7 and a photograph of the truck tires is shown in Fig. 8. The passenger tires tested were H size except the ASTM tires which were G size. The truck tires are all 10.00-20 12 ply rating tires. The patterned rib type passenger tires are belted bias tires. The discrete block tires, the snow tires, and the blank tires are all radial tires.

VEHICLE DESCRIPTION - A 1973 GM Cutlass Salon automobile was used throughout our study on passenger tire/pavement interaction noise. A 173 in wheel base 1972 C60 Chevrolet truck, with two axles and fitted with four test tires (two front, two rear) was used throughout our study on truck tires.

Fig. 6 - Test equipment

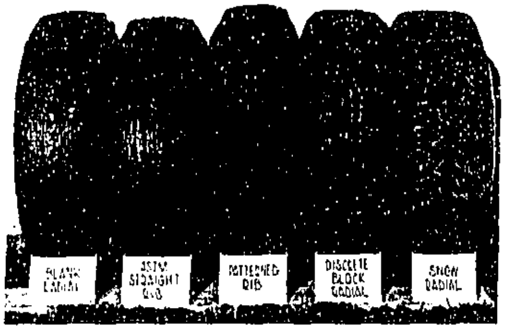

Fig. 7 - Passenger tires

Fig. 8 - Truck tires

TEST PROCEDURE - The vehicles were coasted by the microphone line at 50 mph for the truck data and 55 mph for the car data. The transmission was in neutral and the engine idling for 250 ft on each side of the microphone line. This provided up to 7 s of passby data on the occasion when there was no interfering vehicle. We also realized at least a 10 dB(A) rise and fall on either side of the peak passby noise level. Low speed coasting passby's and powered passby's showed that engine and exhaust noise were at least 10 dB(A) below the peak levels recorded for the tire/pavement interaction noise.

RESULTS AND DISCUSSION

PASSENGER TIRES - We shall discuss the results of the passenger tire/pavement interaction noise studies first. We will be drawing logical conclusions at each step and then moving on to the next point. It is important to keep in mind that passby noise measurements for all the automobile data, ours as well as the data taken from the literature, are made at 25 ft. Hence, the noise levels would be approximately 6 dB(A) lower at 50 ft.

PASSENGER TIRE/PAVEMENT INTERACTION NOISE INCREASES AS PAVEMENT TEXTURE INCREASES - Fig. 9 is a bar graph of peak passby noise levels for the four different pavement textures, for five different sets of passenger tires. Our vehicle was always equipped with test tires on the front and rear axle. The reason for this particular configuration will become apparent as the discussion proceeds.

Fig. 9 shows, in general, that the noise level increases as texture increases (Figs. 2 - 5) on the roadway for each and every test tire. The pavement surface feature of interest, which is believed to be important to tire/pavement interaction noise generation is "pavement macrotexture" (1 - 3). However, we believe that the orientation of the texture as well as its size is important on the tire/pavement interaction noise generation. For instance, we have found that for both discrete block and patterned rib tires, (see Fig. 7) there is a drop of 5 dB(A) when

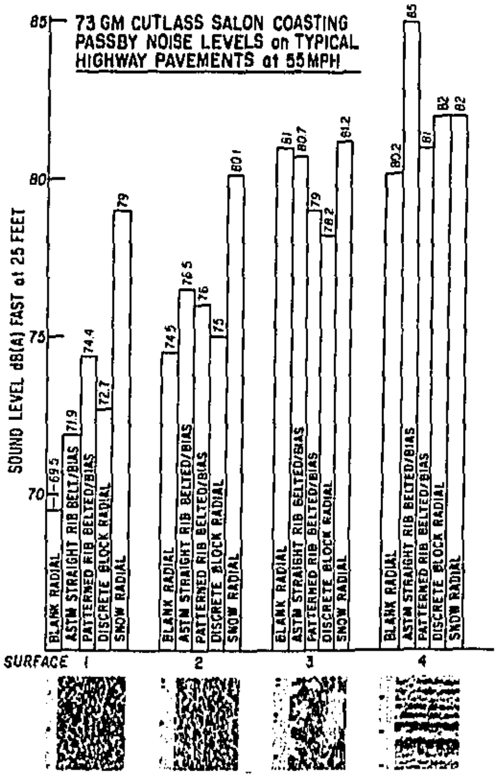

Fig. 9 - Peak passby noise levels for four different pavement textures, for five different sets of passenger tires

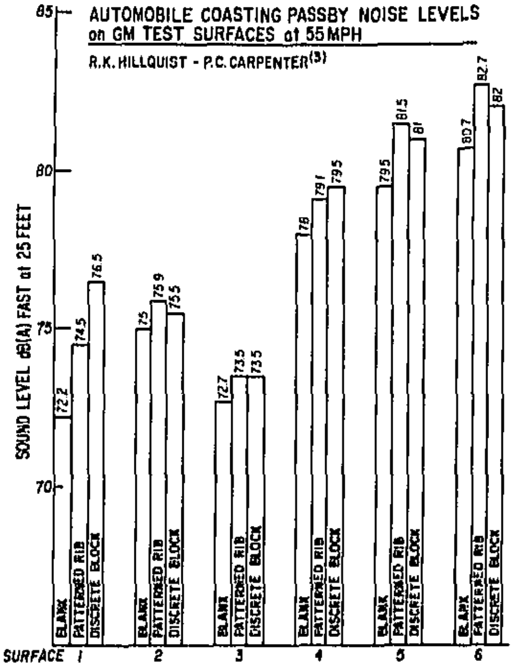

Fig. 10 - Tire/pavement interaction noise increases as texture on the roadway increases

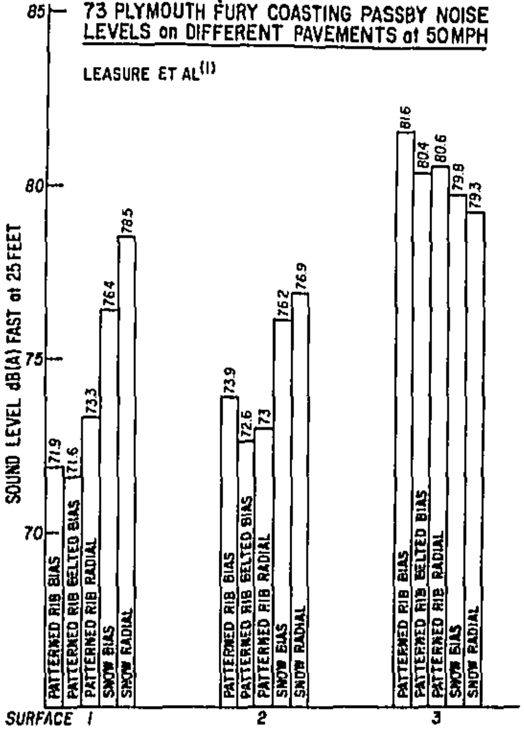

Fig. 11 - Tire/pavement interaction noise levels increases with the degree of texture on the roadway

going from a cross brushed to a longitudinal brushed surface of similar texture.

Fig. 10, Hillquist and Carpenter's data (5) also shows, in general, that the tire/pavement interaction noise increases as texture on the roadway increases. This is particularly true on their Surfaces 4, 5, and 6. A description of the surfaces used by Hillquist and Carpenter (5) is given in Appendix 1. It is difficult to meaningfully rank order their Surfaces 1, 2 and 3 with respect to, their degree of surface texture. Leasure's data (2), Fig. 11, again shows that tire/pavement interaction noise level increases with the degree of texture on the roadway. It would be useful to know whether their smooth concrete, (low texture) has more or less texture than their textured asphalt surface. A description of Leasure's surfaces is given in Appendix 1. Perhaps we can resolve the texture measurement problem as R. E. Veres suggests (7), "the tire noise signature under controlled conditions can provide a measure of pavement macrotexture."

It is clear from our results in this section that passenger tire/pavement interaction noise is strongly dependent on the degree of texture on the roadway. Consequently, rank ordering of passenger tire noise can only be achieved when pavement texture is defined at the same time that maximum permissible noise levels are defined.

PAVEMENT SURFACE TEXTURE - The effect of texture level on the roadway was tested by measuring the emitted noise when the vehicle was fitted with four blank or smooth tires. Fig. 9 shows that the noisiest surfaces are the cross brushed PCC surface which is Surface 4, and the worn track (exposed aggregate) on Route 21 which is Surface 3. The noisiest surfaces are 11 dB(A) higher than the quietest surface. Fuller (1) reported a variation of 10.7 dB(A) from the "quietest" to the "loudest" PCC surface finish for ASTM tires. Subjectively this represents at least a factor of two in loudness (8), quite a remarkable change in loudness between two road surface textures.

Fig. 10, Hillquist and Carpenter's data (5) shows that the pavement texture produces a change of 9 dB(A) between their noisiest and quietest surface. Once more there is a remarkable change in loudness between two road surface textures.

Perhaps the most important result of the work on blank tires is that the effect of pavement texture is extremely large on tire/pavement interaction noise.

TIRE PATTERN SENSITIVITY TO PAVEMENT TEXTURE - If we exclude the snow tire data, and the data on the ASTM tire for Surface 4, another interesting result can be obtained from Fig. 9. The tire/pavement interaction noise level on any one surface is relatively insensitive to the tread patterns tested here, including the blank tire. The maximum observed difference between tread patterns is 4.9 dB(A) which occurs on Surface 1, (low texture). In fact, if we consider only conventional patterned tires the maximum observed difference is 1.7 dB(A) and this occurs on Surface 1. Further, on all of the other surfaces the maximum observed difference in interaction noise level is 1 dB(A).

Fig. 10, Hillquist and Carpenter's data (5) shows that the tire/pavement interaction noise level on any one roadway surface is also relatively insensitive to the tread patterns tested here, including the blank tire. The maximum observed difference between tread patterns is 4.3 dB(A) on their surface one. Again if we only consider conventional patterned tires on this surface the maximum observed difference is 2 dB(A). On all of the other test surfaces the maximum difference is 1 dB(A).

If we once more excluded snow tire data, Leasure's data (2), Fig. 11 also shows that the tire/pavement interaction noise level on any one roadway surface is quite insensitive to tread pattern. Here the maximum observed difference between tread patterns is 1.7 dB(A) on their surface number one.

J. C. Walker and D. J. Major's data (9), also shows that the tire/pavement interaction noise level on any one roadway surface is to a considerable extent insensitive to tread pattern. Again, the validity of this statement is particularly true when snow tires are excluded.

The results of this section show that passenger tire/pavement interaction noise is relatively insensitive to tread pattern on any one roadway surface.

BLANK TIRE INTERACTION NOISE LEVEL - The data in Fig. 9 shows that the noise level of blank tires is within 3 dB(A) of the noise level of conventional tread pattern tires on Surfaces 2, 3, and 4. In fact on Surface 3, (medium texture) the blank tire is noisier than the conventional patterned rib tires and equal to the snow tire noise level. Further on Surface 4 all of the tires are equally noisy if we do not consider the ASTM straight rib tire.

Fig. 10, Hillquist and Carpenter's data (5) shows that the noise level of blank tires is within 2 dB(A) of the noise level of conventional tread pattern tires on Surfaces 2, 3, 4, 5, and 6.

The most important result of this analysis is that it clearly shows that the interaction noise levels of conventional patterned tires are almost at their lower limit. It is difficult to envision a tire which would be quieter than one which has no tread pattern when operating on a low texture surface.

EFFECT OF THE GRADIENT IN TEXTURE ACROSS THE ROADWAY - Fig. 9 shows that as we move from Surface 2 to 3 the blank tire interaction noise changes by 7 dB(A). More importantly the conventional patterned tires also change by at least 3 dB(A). Thus, by comparing Surface 2 with Surface 3 we can see one of the problems which arises in passby noise measurements. If the vehicle simply strays by a few feet from the normally worn track in the pavement to the less worn outside edge a dramatic shift in noise level occurs. Thus if a reliable noise measurement is to be made, the texture across the roadway must be uniform, and of course on a majority of highways it is not.

PAVEMENT TEXTURE AND SNOW TIRES - Fig. 9 clearly shows that the snow tire/pavement interaction noise level is significantly higher than the noise level emitted by conventional tread pattern tires on Surfaces 1 and 2, (low texture). However, as we move to medium and high textured Surfaces 3 and 4 the maximum observed difference between the snow tires and the conventional patterned tires is only 3 dB(A). As matter of fact, on Surface 4 the difference between snow tires and conventional tires is only 1 dB(A). It is interesting and informative that the blank tire is as noisy as the snow tire is on Surface 3, the worn track (exposed aggregate) on Route 21.

Fig. 11, Leasure's data (2) shows once more that the snow tire/pavement interaction noise level is significantly higher than the noise level emitted by conventional tread pattern tires on their Surfaces 1 and 2. However, on their Surface 3 the snow tires are the quietest tires.

J. C. Walker and D. J. Major's (9) data show that the snow tire/pavement interaction noise level is significantly higher than the noise level emitted by conventional tread pattern tires on the low texture surfaces. However, on medium and high texture surfaces there is only a difference of 2 dB(A) in level between snow tires and conventional tread pattern tires.

This section has shown that snow tires are significantly noisier than conventional rib patterned tires on low texture surfaces. But as pavement texture increases, the interaction noise increases more with rib tires than with snow tires. As a result, medium to high textured pavement causes the noise with rib tires to become equivalent to the noise with snow tires. In fact, on some high texture surfaces, conventional patterned tires are noisier than snow tires. This is a good example of rank order reversal with texture changes.

TEST TIRES ON BOTH AXLES - We noted in the beginning of the discussion and results section of this paper that the test vehicle was always fitted with the same tires on the front and rear axle. The reason for this can be seen in the analysis of the data on the ASTM straight rib tires. The ASTM tire/pavement interaction noise level on Surface 4,

Fig. 9 is high with respect to the other tread patterns. This result suggested that we measure the tire/pavement interaction noise level with the test vehicle fitted with ASTM tires on the front axle and snow tires on the rear axle. In this particular configuration the measured noise level was 1 dB(A) higher than when the test vehicle was equipped with four snow tires. Further analysis of the data in Fig. 9 reveals that with ASTM or blank tires on the front axle there will be an error in the measurement of the noise level associated with any pair of test tires on the rear axle, this is particularly true for medium and high textured road surfaces.

The results of this section show that tire/pavement interaction noise levels should be obtained only when the test vehicle is fitted with the same test tires on both the front and rear axle.

SPECTRAL ANALYSIS - Our discussion of the tire/pavement interaction noise problem clearly shows that the problem is complicated by the fact that both the tire and the pavement are responsible for the emitted noise. From a spectral analysis point of view we might speculate that the tire/pavement interaction noise signal is made up of at least three underlying component spectra. There is the spectra of the tire tread, the spectra of the pavement pattern, and the interaction spectra due to the tread being in contact with the road. These component spectra may combine in some unknown manner and the result will be the tire/pavement interaction noise signal spectrum. This presents a rather complex and experimentally difficult situation. However, it does present a conceptual starting point from which future studies of tire/pavement interaction noise can develop.

TRUCK TIRES - Now let us turn to the question of whether pavement texture is as important for truck tires as it is for passenger tires. After all, this is the area in which regulatory or certification concern is the greatest at the present time.

TRUCK TIRE/PAVEMENT INTERACTION NOISE VERSUS PAVEMENT MACROTEXTURE - Fig. 12 is a bar graph of peak passby noise levels for four different pavement textures for three different sets of 10.00-20 truck tires. The vehicle had four wheels and was fitted with the same test tires on the front and rear axle. Noise measurements were made at a distance of 50 ft.

Fig. 12 shows that there is little change in noise level for a given tire as we move from Surface 1 to 2. Of course as is well known, on these types of surfaces the interaction noise of lug tires is appreciably higher than that of patterned rib tires. However on Surface 4, high texture cross-brushed concrete, there is a large increase in the interaction noise of the patterned rib tire. In fact, the patterned rib tire is but one dB(A) less noisy than the lug tire is on Surface 4. The lug tire is appreciably noisier than the patterned rib tire on Surfaces 1, 2 and 3. There is little change in tire/pavement interaction noise for the straight rib HCR tire as we move from Surface 1 to Surface 2, (low texture). There are dramatic increases in the interaction noise as we take the HCR tire to Surface 3 and then to Surface 4, surfaces of increasing texture. It is very interesting that on Surface 4 the straight rib HCR tire is as noisy as the lug tire. Certainly, the straight rib HCR tire cannot be considered to be a quiet tire when it is operating on a surface of medium or high texture.

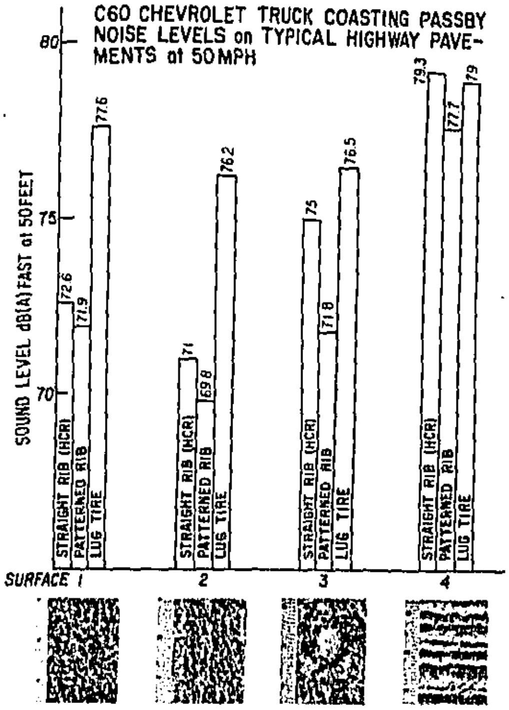

Fig. 12 - Peak passby noise levels for four different pavement textures for three different sets of 10:00 - 20 truck tires

M. C. P. Underwood's data (10) plotted as a bar graph of peak passby noise levels for three different pavement textures for four different sets of 10.00-20 truck tires is shown in Fig. 13. The vehicle was a two axle, six-wheeled lorry. The noise measuring microphone was located at 24.6 ft from the vehicle centerline. A description of the surfaces used by Underwood is given in Appendix 1.

The data in Fig. 13 shows that the lug tire is appreciably noisier than the patterned rib tires on his Surfaces 1 and 2. However, on his Surface 3 there is a large increase in the interaction noise of the patterned rib type tires. In fact, one of the patterned rib tires is just as noisy as the lug tire.

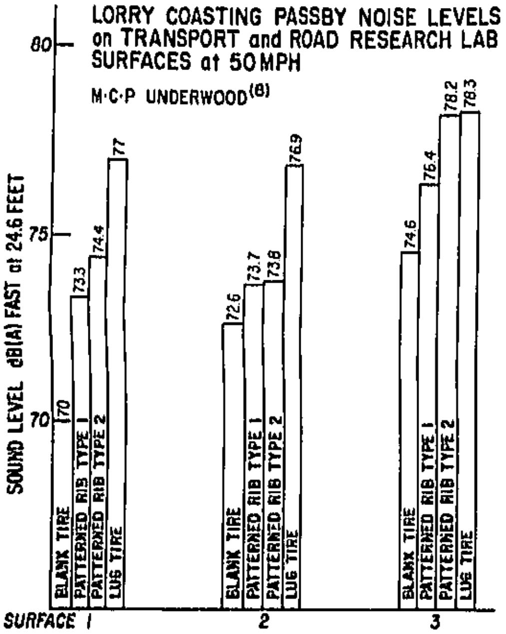

Fig. 13 - Peak passby noise levels for three different pavement textures for four different sets of 10:00 - 20 truck tires

Underwood's data on blank truck tires also allows us to examine the effect of texture level on noise. As we move from Surface 1 to 2 to 3 surfaces of increasing texture, the data in Fig. 13, clearly shows that the effect of pavement texture is large on tire/pavement interaction noise. It is interesting to note that the blank truck tire/pavement interaction noise level is appreciably lower than the lug tire interaction noise level on all three of his surfaces. However, on his Surface 2 the interaction noise level of the blank tire is but one dB(A) lower than the interaction noise level of the patterned tires.

A number of interesting informative deductions follow from the above discussion. Patterned rib truck tires are significantly quieter on low and medium texture surfaces than on high texture surfaces. Lug tires are significantly noisier than patterned rib tires on low and medium texture surfaces. But patterned rib truck tires are essentially equivalent to lug tires on high texture surfaces. The effect of pavement texture on interaction noise is large as is shown by the data on blank tires and by the data on patterned rib tires for surfaces of high texture. Again straight rib HCR tires are not quiet tires when they are running on surfaces with appreciable texture. Once again these results make clear the inadequacy of any regulatory or certification test, which does not specify the road surface exactly. Surfaces 3 and 4 are both surfaces which are not uncommon throughout the United States.

GENERAL CONSIDERATIONS - Some workers have reported that the interaction noise level decreases with increasing pavement texture. In fact, Fuller (1) showed a minimum for two passenger tire types (ASTM and a patterned rib) when their noise levels were plotted against parameters related to pavement texture. His other set of tires (mud and snow) did not show this effect. Nor does the addition to our Fig. 12 of another data point we have for the straight rib HCR tire on an extremely low textured (troweled) PCC skid test pavement. The level is 67 dB(A) which is 4 to 5 dB(A) lower than the values we show in Fig. 12 for this tire on low texture black top and PCC highways.

We have not yet found a quantitative procedure which we feel properly measures the factors of most importance to the tire/pavement interaction noise.

Veres (7) listed other researchers (11 - 14, 16) who claimed that tire/pavement interaction noise level decreases with increasing pavement texture rather than increasing with pavement texture as indicated in this paper. A foundation for this claim is that Haydon's work (11) on tire/pavement noise has the term $\frac{\partial Q}{\partial t}$ in the equation for acoustic intensity. Q is the volumetric flow rate from the source. One can argue that a smooth uniform road surface (low texture) permits better sealing of the tread elements and/or a better sealing of the voids in the pavement. The release of well-sealed voids will give rise to larger values of $\frac{\partial Q}{\partial t}$. Consequently, a low textured surface could increase the noise intensity according to this reasoning. However, Haydon points out that this would be true in particular for cup or pocket type treads. The use of cup type treads is not acceptable practice today.

Even our own investigators T. R. Wik and R. F. Miller (12) indicate that low textured surfaces will have the largest effect on cup type treads, which naturally seal well on smooth surfaces. Once more, the use of cup type treads is not acceptable practice today. Again Kilmer et al. (3) and another National Bureau of Standards report (13) show evidence for the inversely proportional relationship. However, in these reports it is only for pocket or cup type retreads. D. A. Corcoran's (14) Table 1 also shows that the interaction noise level decreases with increasing pavement texture. However, we believe that the data in Table 1 of Corcoran's paper may be mislabeled. The data Corcoran uses comes from the Rubber Manufacturers Association submission to the Environmental Protection Agency (15). What he calls a smooth surface was called by RMA a "smooth brushed concrete surface". We believe that this surface had a higher texture than the asphalt surface.

Finally, we find no evidence in F. M. Wiener's paper (16) that inverse relationship exists. The inverse relationship may hold for the now obsolete pocket or cup type tread patterns but there is little evidence for correctness of the inverse relationship for present day conventional rib or lug type tread designs.

CONCLUSIONS

Reasonable and enforceable vehicle noise regulations are possible only if pavement texture can be adequately defined at the same time that maximum permissible noise levels are defined.

We have shown that passenger tire/pavement interaction noise increases with pavement macrotexture.

Rank ordering of passenger tire noise can only be sensibly made when it is referenced to a specific identifiable surface.

Conventional rib patterned passenger tire/pavement interaction noise is close to the lower limit as far as the tire contribution is concerned.

Conventional patterned passenger tire/pavement interaction noise is relatively insensitive to tread pattern on any one surface.

Medium and high textured road surfaces cause conventional patterned passenger tires to be almost as noisy as snow tires.

Conventional patterned tire/pavement interaction noise can be higher than snow tire/pavement interaction noise on high textured surfaces.

Snow tires are significantly noisier than conventional tread patterns on low textured road surfaces.

Snow tire pavement interaction noise is relatively insensitive to pavement texture.

Differing road surfaces can reverse the noise level ranking for two different tires.

On low and medium textured surfaces, patterned rib tires are appreciably quieter than lug tires.

Highly textured road surfaces cause patterned rib truck tires to be as noisy as lug tires.

Straight rib truck tires are not quiet tires when they are running on medium and high textured road surfaces.

Tire/pavement interaction noise should only be evaluated when the vehicle is fitted with the same tires on both the front and rear axle.

An important area remaining for investigation is the spectral analysis of the road surface effect relative to the tire effect and of course their interactions.

The gradient in the pavement texture across the roadway as well as along the roadway will definitely be a problem with respect to the reliability of passby noise measurements for both trucks and automobiles.

It seems doubtful at this time, whether any practical significant reduction in noise generation for conventional rib type passenger and truck tires can be made by any tread pattern or construction change. The only hope for noise reduction in these cases would appear to be in pavement macrotexture reductions. Unfortunately, reduction in pavement texture would deteriorate the wet traction capability of the vehicle. In fact, current recommended highway design practice (18) is to increase rather than decrease pavement texture for safety purposes.

There are a host of problems which currently affect the measurement of passby noise. These problems are well documented in the literature (18 - 27). The results of this paper and our companion paper (17) augment the current dilemma. Perhaps, the best way to obtain a satisfactory solution as the problem is to avoid most, if not all, of the pitfalls associated with passby noise measurements. This could be done simply, by certifying or labeling tires as acceptable if they pass a noise measurement test. The noise measurement test could be made in an environment where the wind velocity and its gradient, the temperature and its gradient, site geometry, turbulence, surface texture, instrumentation,... etc. could all be rigidly controlled. This type of test procedure would provide the noise measurement reliability that both the government agencies and industry feel is necessary for reasonable and enforceable vehicle noise regulations.

ACKNOWLEDGMENTS

We would like to thank J. J. Scott and C. H. Cundiff for their efforts during the data collection and reduction parts of this experiment. Our thanks also go to K. D. Marshall and M. G. Pottinger for their lively discussions on the material presented in this paper.

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APPENDIX

Hillquist and Carpenter's test surfaces (5) were subjectively ranked in order of smoothest to roughest. Their description of the surfaces are as follows:

Surface 1 - smooth: Sheet asphalt covered with several layers of highway marking paint.

Surface 2 - smooth: Sheet asphalt with 3/8 in maximum size aggregate: random exposure on surface of aggregate.

Surface 3 - mild: Asphalt surface with a very homogenous coating of 3/8 in aggregate.

Surface 4 - rough: A triple-course surface treatment; the first course consisted of 1 in maximum aggregate followed by a course of 1/2 in aggregate followed by a course of 3/8 in aggregate.

Surface 5 - rough: A double-course surface treatment; the first course was 1 in maximum aggregate followed by a course of 1/2 in aggregate.

Surface 6 - rough: A single-course surface treatment of 3/4 in aggregate.

Leasure's test surfaces (2) are described as follows:

Surface 1 - smooth concrete.
Surface 2 - textured asphalt.
Surface 3 - continuous poured reinforced concrete on Interstate 81 near Carlisle, Pennsylvania.

M. C. P. Underwood's test surfaces (10) are described as follows:

Surface 1 - smooth concrete.
Surface 2 - coarse quartzite.
Surface 3 - motorway surface.

DISCUSSION

MR. COULTER: The comments I made this morning regarding grooving were about lateral grooving, not longitudinal grooving. It is most common, and is the same type of texturing as cross-brushed concrete. I have had discussions since this morning with people who say that such a surface does not exist in the United States. The cross-brush surface is getting to be a common surface, and it looks to me as if that surface is going to become common, especially in urban areas. There isn't much point in doing anything about crossbar noise.

MR. THURMAN: It is my understanding from a number of papers from highway designers, that they are strongly recommending surfaces such as this, and we were quite fortunate in our tests in that we did find a laterally textured surface, and were able to prove a point quite dramatically.

MR. COULTER: We have almost duplicated the results you have here. We did find that the cross-brushed surface varies quite a bit from place to place. There is about a 5 dB difference in radiated tire sound levels between the various surfaces.

MR. HERSHEY: I wonder if you have any idea how common each of the Surfaces, 1 through 4, are throughout the roads of the United States?

MR. THURMAN: Certainly. There is a large number of miles of Surface 1 around; also, the prevalence of Surface 2 is quite nominal. As you drive along and watch the surface carefully, you will see that you will get a worn track (surface 3) in almost any surface. It may not be quite as severe as the one described, and of course in other places it may be more severe. Surface 4 appears to be a surface of the future, if you can believe what the people in the highway design departments are saying.

MR. HERSHEY: So from your comment I would gather that road surfaces are predominantly 1 and 2?

MR. THURMAN: No, I would say they are predominantly 1, 2, and 3, and I think Surface 4 will be catching up very quickly.

MR. CAMPBELL: There seems to be a discrepancy between Mr. Thrasher's data and something I reported on from Fuller's paper. The record should be kept straight on the effect of pavement texture. Mr. Thrasher's experiments started with the middle range of pavement roughness and found that the rougher the pavement became, the louder it became. Fuller's paper and some other data we have, indicate that roads are also found to be much smoother than Surface 1. Your Surface 1 was a fairly new, unpolished surface as laid down, and after it is polished by years of service it can become slicker, become a much finer macrotexture, and then other things happen. I want to confirm what you said for your range of textures. You are not in conflict with Fuller even though I said that snow tires are quieter on very smooth surfaces. You didn't get that into that range.

MR. THURMAN: I think the surfaces I presented are rather typical surfaces. We are not talking about polished surfaces.

MR. WILLS: From everything that we have seen, it appears that most of your tests were evaluated on dry surface.

MR. THURMAN: That's correct.

MR. WILLS: What effect is there on a wet surface?

MR. THURMAN: We have not tested on wet surfaces. I think it is common knowledge that sound levels will increase. Mr. Leasure, do you have any measurements on wet surfaces?

MR. LEASURE: We saw a significant difference in the spectra due to wetness, but little or no difference in the A-weighted sound level. I think it depends on the amount of water that is on the roadway. Our surface was slightly damp, lightly wetted. If you have a bit more standing water, you obtain a little more sound and the A-weighted sound level, as well as the spectra, will change.

MR. THURMAN: I think in general that the level goes up as the surface becomes wetter.

MR. CLENDENEN: We took a real quick look at it, including ABG. The quieter tires became noisier with the water, and some of the noisier ones became quieter.

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Passby Tire/Pavement Interaction Noise Measurement Problems

R. F. Miller and D. B. Thrasher
B. F. Goodrich Co.

PASSBY MEASUREMENTS are extremely important because they are now used for the regulation (1-3)* of total vehicle noise and in separating out the components of the noise; engine-related and tire/pavement interaction noise. The regulation of tire/pavement noise alone is currently under consideration. Regulations for automobile noise now exist in many states and cities. Federal regulation of automobile noise is under discussion.

Unfortunately, passby noise measurements as presently defined are highly unsatisfactory for regulatory purposes because they do not adequately consider and control important variables. As a result they lead to confusion and potentially to unwarranted citations.

SAE Recommended Practice J57a (4) for the passby measurement of tire/pavement interaction noise was published in July, 1973. But many sources of uncertainty have appeared which are not adequately addressed by this procedure.

In addition, the uncertainty of passby noise measurements has been increased because current regulatory procedures have compromised even the basic known procedure requirements in order to increase the number of sites for enforcing the noise law.

Our purpose is to discuss the uncertainties in the present passby measurement procedure, since they can seriously affect the reliability of tire/pavement interaction noise measurements. These sources of uncertainty are listed below.

Factors Affecting Passby Noise Reading

1. Response time setting of the sound level meter.
2. Noise from other sources
   a. Multiple peaks
   b. Clear distance
   c. Ambient noise
3. Difference in noise level with direction of travel.
4. Other factors
   a. Pavement texture
   b. Curbs and guard rails
   c. Instrumentation Problems
   d. Other Procedure Problems

All of the data to be presented in this paper are for coastby test conditions, so that the tire/pavement noise is predominant. No measurements were made when the horizontal wind velocity was over 12 mph, including gusting. Our most recent measurements have been discontinued at wind velocities above 5 mph.

RESPONSE TIME SETTING OF THE SOUND LEVEL METER

Sound level meters provide a choice of response time: either "fast" or "slow" (SAE J57a Recommended Practice "Sound Level of Highway Truck Tires" (4) calls for the use of slow response. SAE J366 Recommended Practice "Exterior Sound Level for Heavy Trucks and Buses"(5) calls for the use of fast response. This is for a low speed acceleration test to measure engine noise. This appears to be unrelated to passby noise at highway speeds.) The usual passby maximum is broad and smooth enough that the fast response reading is usually about 1 dB higher than that for slow response. But for some passbys we find differences as large as 4 dB(A). In no case have we been able to attribute these differences to the tires. On the other hand, we have separated out site conditions which are responsible.

Pavement unevenness is a major cause of the

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*Numbers in parentheses designate References at end of paper.

ABSTRACT

This paper presents data for several tire/pavement interaction noise measurement problems present in passby tests. Two of these, the after peak and the difference of the passby maxima with direction of travel, have not been previously reported. The underlying causes of many of the problems are discussed. Probable interactions with current regulatory procedures on the overall vehicle passby levels are indicated. The need for much more precise site control is pointed out, especially with respect to atmospheric conditions which strongly affect the noise transmission path and with respect to the pavement texture.

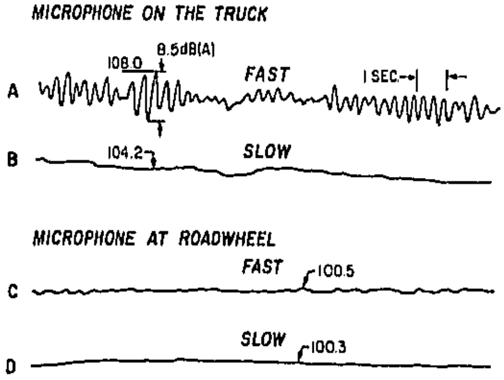

Fig. 1 - Effect of SLM response (dB(A))

increase in noise level of fast over slow response. This causes the truck to bounce and to vary the load on the tires. A 30% increase in load increases the noise level by 1.2 dB(A). Much greater changes in load often occur on uneven pavement.

The pavement unevenness effect was isolated by an experiment in which an on-board microphone was carried 18 in behind the contact of a tire on the rear axle of the test truck. The pavement had a relatively smooth texture but was slightly broken Portland cement concrete. The dB(A) versus time traces are shown in Fig. 1. Trace A is for fast response. The maximum sound level meter reading was 108 dB(A). Trace B is the same data read with slow response at 104.2 dB(A), a difference of 3.8 dB(A).

The lower traces C and D are the noise from the same tire on a roadwheel (laboratory test wheel). The microphone was again located 18 in behind the contact of the same tire used in the truck test. Both fast and slow response now give very nearly the same reading and both traces are free of the large variations shown for the truck test.

Apparently the only factors responsible for the difference between these data from the truck and the roadwheel are in the pavement. Atmospherics would not be expected to play a part in sound levels 18 in from the source.

The reason that fast response gives higher readings lies in the relationship of the time constants of the meter and the frequency of the noise level variation. Large noise level variations that occur in times of 0.3s are observable in the fast response trace for the truck. These correspond to the bouncing of the truck. The slow response averages out most of these fluctuations while the fast response does not. So the maximum of a passby will be read higher with fast response when the truck is caused to bounce. This is a factor over which the trucker, the vehicle manufacturer, and the tire manufacturer have no control whatsoever.

Thus, the use of fast response penalizes the user of the tires because of the site problem of pavement unevenness. Later we will discuss other site conditions that affect the difference between fast and slow response readings.

NOISE FROM OTHER SOURCES

MULTIPLE PEAKS - The passby dB(A) level versus distance or time for a given vehicle frequently consists of more than one major peak. An example of such a passby with multiple peaks is shown in Fig. Fig. 2.

The curve continuously shows the fast response dB(A) level as the isolated truck was coasted past the microphone line at 50 mph. There were two lug tires on the rear and two smooth tires on the front. The position of the rear axle is indicated for each 100 ft for 300 ft each side of the microphone line.

The peak nearest the microphone line will be called the main peak. Peaks to the right will be called after peaks. In this case the main peak is 77.5 dB(A) fast. There are two after peaks at 70.0 and 75.0 dB(A) fast. The valleys between the peaks are at 63.5 dB(A).

For ease of discussion we will now disregard the sharp 70 dB(A) after peak and discuss only the second after peak. This after peak has a level up to 75 dB(A), only 2.5 dB below the main peak. It extends from 275 to over 400 ft behind the truck.

Such after peaks are a serious problem in a real traffic situation. It would be impossible with a 6 dB(A) rise and fall rule (1 and 2) to recognize that such an after peak belongs to the wake of a truck that is over 275 ft away. Thus, such after peaks will add into the level attributed to other vehicles following the truck within the distance range of the after peak. If a passenger car at 70 dB(A) were in the region of the 75 dB(A) after peak of the truck, the car would be said to be 1 dB(A) above a 75 dB(A) limit (70 + 75 = 76 dB(A).

Another example of after peaking is shown in Fig. 3. The upper curve for fast response shows the after peak to be more than 5 dB(A) above the main peak. The 77.8 dB(A) after peak would put a 70 dB(A) passenger car 175 ft behind the truck at 78.5 dB(A). In fact the passenger car would be read

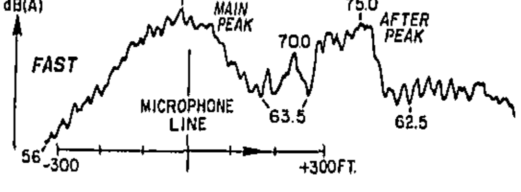

Fig. 2 - Multiple peaks

as if in violation of a 75 dB(A) limit with no contribution of noise from the car at all.

These examples are for very quiet trucks at 72.6 - 77.5 dB(A), well below the 90 dB(A) limit. With more tires and at the normally used highway speeds we might expect correspondingly larger after peaks. Such peaks could result in erroneously high readings for other trucks, as well as for passenger cars.

The response used for the sound level meter can alter the second example. With fast response, the rise and fall around the sharp after peak greatly exceeded the 6 dB(A) rule. Thus, it was considered an isolated event. However, when slow response was used, the rise was only 3.9 dB(A) so it would be disregarded or perhaps attributed to the original truck as it should have been. The use of slow response reduced the main peak by 1.4 dB(A). This difference has apparently also been increased by the conditions which give rise to the after peak. When after peaks are present there are usually sharp variations superimposed on the normally smoother main peak. These cause the fast response to read abnormally high.

It is evident that, in mixed traffic, it will be difficult to enforce fairly a level that is lower for passenger cars than for trucks.

We are convinced that the after peaks have their origin in local atmospheric conditions. This is based on the fact that a strong after peak was present in late afternoon tests but absent the next morning during tests using the same tires, same truck, same site, same direction of travel.

Strong after peaks were found in 17% of 614 passbys which were run in the absence of interfering traffic at three different sites.

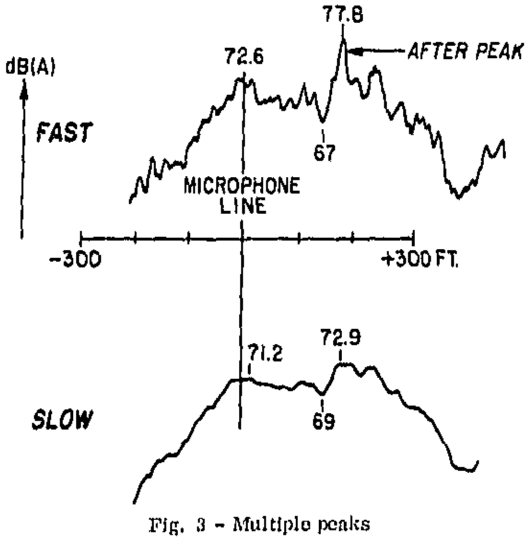

Fig. 3 - Multiple peaks

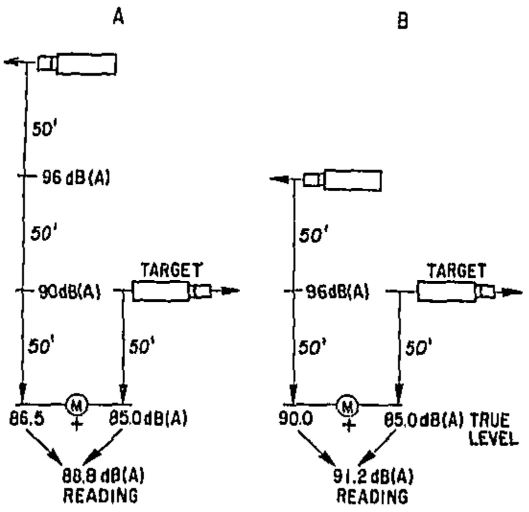

Fig. 4 - Clear distance

CLEAR DISTANCE - A specification for clear distance around the measured vehicle is required for other reasons than the presence of after peaks. A major problem is the main peak of a high noise level truck in opposing traffic on freeways where opposing traffic is separated by distances corresponding to clear distance specifications.

SAE J57a(4) specifies a clear distance around the measured vehicle of twice the microphone distance. The purpose of this is to reduce the likelihood of the main peak of other nearby vehicles from appreciably raising the noise level reading for the vehicle being measured.

Fig. 4 shows the importance of maintaining a large clear distance. In the example shown here, a 96 dB(A) truck is in opposing traffic. The true value of the truck presumably being measured is 85 dB(A). Example A shows that the actual combined reading for J57a clear distance is 88.8 dB(A).

On the other hand if the clear distance requirement is reduced, say, to equal the microphone distance(2), the example shown in B applies. Now the actual reading will be 91.2 dB(A). Therefore, the truck noise level which is 85 dB(A) will be read as 91.2 dB(A). It is evident that the use of a clear distance equal to the microphone distance will increase the number of erroneous citations over those resulting from the use of a clear distance equal to twice the microphone distance.

AMBIENT NOISE - The DOT Compliance Regulations(2) specify an ambient level of 10 dB(A) below the violation limit. However, it should be recognized that it is impossible to determine a true ambient level for any individual vehicle passby under

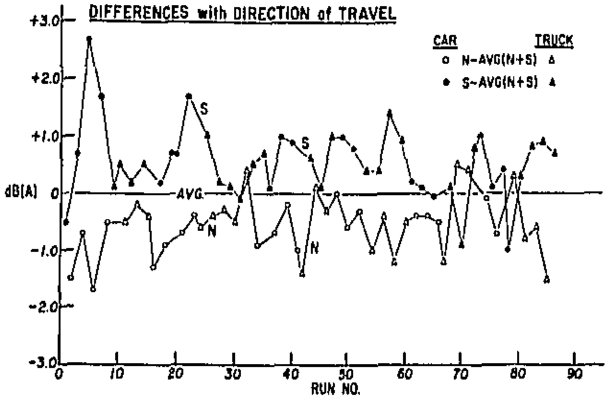

Fig. 5 - Differences with direction of travel

traffic conditions. If 10 dB(A) is really intended, then the closest approach to it could be made by requiring a 10 dB(A) rise and fall for a legitimate violation rather than only 6 dB(A) (1 and 2). A background level only 6dB(A) lower than the target vehicle would add 1 dB(A) to the reading made for its passby level.

EFFECT OF DIRECTION OF TRAVEL

Noise levels usually vary with direction of travel along a given lane of a test road. It is not a matter of lack of symmetry of tires or vehicle and it occurs coasting with the engine shut off. The observers along the highway cannot be aware that this effect is present since they never have the opportunity to measure the level of the same vehicle passing in both directions in the same lane. Thus, they may be reading 1 - 3 dB(A) too high or too low for many vehicles and be completely unaware of their error.

A typical example of the variation of noise level with direction of travel is shown in Fig. 5. The data sequence involved 5 - 8 coastbys of a set of passenger car tires, then 5 - 8 coastbys of a set of light truck tires, then back to another set of passenger car tires, etc. This provided uninterrupted measurements since the passenger car had its tires changed while the light truck was being coasted through the test area and vice versa. (One exception was a case where two truck sets were run back to back, runs 24 through 35.)

The coastbys for a given vehicle were alternated between north and south in the same lane. The microphone remained in a fixed position, 50 ft west of the center of the lane. The roadway was an idle race track. Thus, we can say with certainty that the highest ambient noise level was 16 dB(A) below the lowest tire/pavement noise level. The area around and including the pavement was flat and level without ditches, curbs, guard rails, or trees for 125 ft in all directions. The pavement was black top with very little texture.

The data points in Fig. 5 were determined as follows: a data point equals the noise level of a particular run, either north or south heading, minus the average of all of the noise level readings for that set of tires.

The interesting part of this data is that the south difference curve of Fig. 5 is not random but shows definite trends with run number (or time). The south direction differs from the average by as much as +2.7 dB(A). But the bias shifts, so that near the end of the testing, the south direction reaches -1.0 dB(A).

For example, the south deviation starts going positive with three points in line, then drops with three points in line, including a change of vehicle from the car to the truck. Then it remains below 0.5 dB(A) for several points. After this it climbs through a fairly regular series of points and goes through several more cycles with points lining up, passing fairly smoothly along regardless of vehicle change.

We are not certain of the source of these differences but such differences have existed at all test locations where passbys in both directions are possible. We strongly suspect atmospheric conditions like vertical wind gradients, vertical temperature gradients, turbulence, etc.; but far more elaborate test procedures are necessary to determine the source of the problem. Horizontal wind velocity was always below 12 mph.

Similar results were obtained in the recent RMA round robin tests of 10.00-20 truck tires. It was observed that two of the participants showed much larger run-to-run differences than did the other three. The two were reporting data in both directions. The other three ran in one direction only. If the data for adjacent opposite runs are averaged, the differences become similar to those run in one direction. Apparently those using one direction only were favored by more stable atmospheric conditions.

Veres(6) reported that the largest variability from coastby to coastby occurred on hot cloudless days. He suggested that thermal gradients near the road surface could alter the path from source to receiver to produce variations of 2 dB(A). His nighttime variations were within 1 dB(A).

Hemdal(7) made outdoor measurements of noise radiated by a loudspeaker. He found changes in level up to 2.7 dB(A) during a one minute reading interval. He attributed these to changes in the atmosphere. He accounted for these changes by suggesting the action of micro-meteorological inhomogeneities, that is, either temperature or vertical wind gradient cells of rather small dimension. We believe that the after peaks and the changes in level with direction of travel have a similar origin.

Errors of nearly 3 dB(A) have been observed with changing direction of travel. There seems to be no way to determine the amount or sign of the error when measurements are made for one direction only.

Differences with direction of travel and after peaks occur at horizontal wind velocities as low as 2 mph. Thus, a single measurement of horizontal wing velocity as in J57a is an entirely inadequate descriptor for atmospheric conditions which seriously affect passby noise measurement.

OTHER SOURCES OF UNCERTAINTY

PAVEMENT TEXTURE - The effects of pavement texture are discussed in another paper. (8) At this point we will summarize these effects and relate them more specifically to the measurement procedures.

Pavement texture differences cause passby noise levels to change by as much as 12 dB(A) from one pavement texture to another. Therefore, pavement texture must be specified in much greater detail than it is now done.

Lateral change in texture at the same site caused a change of 7 dB(A). This large change was produced by shifting the path of the vehicle 3 ft to the less worn pavement at the edge of the lane. Thus, the pavement texture must be uniform to give consistent results.

Evidently there is an effect of longitudinal gradients in texture, but we have been unable to separate this this from all of the other variables pertaining to a given site.

CURBS AND GUARD RAILS - A very modest experiment was performed to determine whether the reflection from curbs and guard rails would add to the measured noise level. We simulated a 12 in curb surmounted by a 12 in guard rail with a spacing of 6 in for a distance of 32 ft using wood planks. This system was at the edge of the lane on the side of the vehicle opposite the microphone.

An increase of 0.6 dB(A) was measured when the curb and guard rail system was added to the site. The results suggested that the effect would be greater for a continuous curb and guard rail system. Furthermore it is possible that the effect may change in combination with atmospheric variables.

We believe that further work is needed to establish some sort of correction factor to be used when curbs and/or guard rails are in the test site.

INSTRUMENTATION PROBLEMS - We have been concerned primarily with problems relating to the site and the procedure for measuring tire/pavement interaction noise. But instrumentation problems are also very real and often insidious.

A hand-held sound level meter with attached microphone has shown 3 dB(A) variations in reading. These occur with unintentional changes in the proximity of the operator's body. The lower values were obtained when the meter was held at arm's length. The operator had been aware initially of the recommendations of the manufacturer in the use of the hand-held meter.

The SAE J57a procedure is inadequate in regard to operator and observer proximity to the microphone. It is our practice never to allow anyone within 50 ft of the microphone. Our observer is always further from the roadway than is the microphone.

A Type I sound level meter of a major manufacturer deteriorated in response time characteristics in 1 1/2 years. It was found to be reading an average of 2 dB(A) low in slow response, yet its steady state calibration was correct.

Another "precision" Type I sound level meter responded to a taped passby quite differently as the range switch was changed. The meter read +10 dB(A) fast response on one range. When switched to 10dB greater attenuation, it read -2.2 dB(A). It had been expected to read 0.0 dB(A). When slow response was used the readings were +10 and -0.3 dB(A). Thus, the readings are far more self-consistent for slow response than for fast. (The system gain was increased slightly for the slow response readings so as to achieve the same +10 reading as was seen on fast response.)

OTHER PROCEDURE PROBLEMS - For the development of quieter tires, we are also concerned with a number of smaller problems. Since present noise levels approach that of a smooth tire on some pavements, we find it necessary to sort out tire-related noise differences smaller than 0.5 dB in order to evaluate the effect of a tread design change.

An example of these problems is lateral deviation of the vehicle which changes the microphone distance. A 1 ft deviation in 50 ft causes an 0.2 dB change, assuming no lateral gradient in pavement texture.

Another problem is determining the exact speed of the vehicle at the point at which the maximum value of the main peak occurs. This maximum has been found to occur anywhere within a region of 40 ft on either side of the microphone line. Therefore, a continuous recording of the speed is required, properly related to the A-weighted sound level. A 1 mph change at 50 mph causes about 0.3 dB change in the tire/pavement interaction noise level.

CONCLUSIONS

We have shown the presence of many uncertainties in present passby noise measurement techniques. Our attention has been primarily focused on the tire/pavement interaction contribution to the overall vehicle noise level. Many of the resulting errors are quite large. Present vehicle noise regulatory procedure increases the magnitude of many of these errors over that to be expected if the applicable provisions of the already inadequate SAE J57a were followed. Most of the sources of error can result in high readings and many are cumulative.

The response time selected on the sound level meter interacts with measurement variables. The use of fast response increases errors resulting from many site deficiencies as compared to the use of slow response.

The existence of after peaks of similar magnitude to the main peak can cause passby readings for other vehicles to be more than 8 dB too high. This places serious doubt upon the applicability of any noise level reading made beside the traveled highway.

The accurate measurement of passenger car noise at a considerably lower level than truck noise in a mixed traffic situation will be very difficult, if not impossible, primarily because of the after peaks of trucks.

Differences with direction of travel indicate another source of error which can produce readings at least 2.7 dB(A) too high.

After peaks and differences with direction are most probably caused by atmospheric gradients in the sound path. The simple criterion of a maximum horizontal wind velocity limit does not account for the important atmospheric effects.

There are many other site conditions for which adequate specifications are needed if responsible passby measurements are to be achieved. Of particular importance are pavement texture and texture gradient, clear distance and ambient noise. There is a wide range of interpretation as to the exact meaning of "relatively smooth concrete or asphalt" as specified in current regulations.

As the acceptable vehicle noise levels are reduced the errors in reading created by variable site conditions will become more and more serious.

Much more thorough work is required before reasonably accurate and repeatable passby measurements can be made.

ACKNOWLEDGMENTS

We appreciate the work of G. E. Gibson, J. D. Rankert, D. Szilagyi, C. H. Cundiff, and J. J. Scott in the data collection and reduction required for this paper. Our thanks also go to R. B. Bauman, K. D. Marshall, and M. G. Pottinger for discussions relating to the form of presentation.

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DISCUSSION

MR. HILLQUIST: Mr. Miller, you showed a slide that showed a rather random scattering, even though it tended to follow fast response data. You followed it with a slide that showed fast minus slow response relative data that had some unusual behavior. What did the slow data look like?

MR. MILLER: The variation of slow response data was about 1.5 dB(A); and I didn't draw the trend of it, but the total variation was quite a bit smaller than was indicated, fast minus slow.

MR. HERSHEY: On your right direction of travel versus left data, were all the "rights" in the same direction along the road, and all the "lefts" in the same direction?

MR. MILLER: Yes. We didn't move the microphone to the opposite side of the road and then run the vehicle in both directions, if that's what you mean.

MR. HERSHEY: Was there any other possible explanation of what causes a difference in sound level with direction of travel?

MR. MILLER: I don't think it had anything to do with the vehicle. It's atmospheric conditions, I feel certain. Actually, you see the effect changed eventually until the results were opposite with the passage of time. The vehicle wasn't changing.

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Round Robin Testing with SAE J 57a

D. G. Anderson
The Goodyear Tire and Rubber Co.
T. Benchea
The Firestone Tire and Rubber Co.
and F. E. Matyja
The General Tire and Rubber Co.

SAE RECOMMENDED PRACTICE J57a "Sound Level of Highway Truck Tires", is the only standard test method in use today for measuring the sound levels of truck tires. Work to develop this test method was started in 1968 by a subcommittee of the SAE Vehicle Sound Level Committee. This subcommittee was composed of representatives of the major truck and tire manufacturers, the U.S. Department of Transportation (DOT), the Tire Retreading Institute, and other interested parties. J57a was adopted by SAE in July 1973.

The J57a test procedure provides for measurement of the sound generated by a set of test tires mounted on the rear axle operated at 50 mph (80 kmh) and at maximum rated tire load. Slow meter response was chosen for J57a because it correlated better with subjective response and was more repeatable and accurate than fast meter response (1).*

Truck tire manufacturers have been using the J57a test method for years to study differences in sound levels of various tire designs. They have not made a practice of publishing the sound levels of their designs for at least one reason, that is, the authors of J57a state limits on the information obtainable from this method. J57a states: "The sound level of the tires being tested is valid only when the sound level of the vehicle equipped with quiet tires is at least 10 dB below that of the vehicle equipped with test tires. The sound levels obtained with this procedure may be used for a relative ranking of the test tires, if the sound level of the vehicle equipped with the quietest tires available is 3-10 dB lower than when equipped with the tires being tested." In other words, if the test vehicle equipped with quiet tires measures a typical 72 dB(A), then a sound level cannot be assigned to any tire found to be less than 82 dB(A) on J57a. In practice, most truck tire designs have sound levels which are less than 10 dB above that of the quietest tires available.

The tire industry recognizes that compliance testing of truck tires for sound level may be a possibility in the future. Since J57a is the only standard tire sound level test procedure in use today, it is conceivable that it may be considered by the federal government to certify the sound level of all highway truck tires.

In an effort to learn more about J57a, five tire manufacturers having permanent facilities meeting requirements for J57a coast-by noise testing, agreed in 1975 to supply truck tires and conduct a round robin test of their facilities. The participating companies were B. F. Goodrich, Firestone, Goodyear, General and UniRoyal.

It was hoped that answers to at least the following questions might be obtained from the results of this round robin:

1. What is the variation in sound levels for the same tires as measured by different test facilities?

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*Numbers in parentheses designate References at end of paper.

ABSTRACT

Eight sets of truck tires were coast-by tested for sound levels at five different testing facilities in a round robin sponsored by the RMA. SAE Recommended Practice J57a "Sound Level of Highway Truck Tires" was used to obtain the measurements. Variations in sound measurements for the individual tire sets at each test facility as well as variations from facility to facility are discussed. Also discussed are differences between fast meter response and slow meter response measurements.

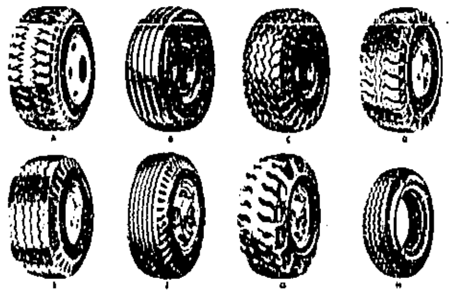


Fig. 1 - Tread patterns of test tires A through H

2. Can sound levels be assigned to tires using the J57a test procedure?
3. How consistently does J57a rank tires from quietest to loudest?
4. How do sound levels obtained using fast meter response compare with those using slow meter response?

TIRE SELECTION

Tires were selected for this test program to represent typical types of tire designs of both bias and radial constructions in rib and cross bar designs which are utilized in truck/bus service.

Eight sets of 10.00/10.00R20 tires (four tires/set) were selected and included three sets of bias rib tires, three sets of bias cross bar tires, one set of radial rib tires and one set of radial cross bar tires. Tread patterns of these tires designated A through H are shown in Fig. 1.

TEST CONDITIONS AND PROCEDURES

Participating tire manufacturers shipped the tires selected to the B. F. Goodrich Test Center in Pecos, Texas where the first coast-by sound level tests of the round robin program were conducted. Following completion of the tests at Pecos, the tires were shipped, mounted to the next test facility and tested in the following sequence: Firestone Test Center, Fort Stockton, Texas; Goodyear Proving Grounds, San Angelo, Texas; UniRoyal Proving Grounds, Laredo, Texas and General Tire & Rubber Company, TRC Track, East Liberty, Ohio.

Participants tested tires at facilities which are extensively used for passenger and heavy duty tire testing. Road surfaces, which were enclosed within the confines of the test facilities, permit not only sound level testing of tires but wear and tractive testing as well. Four of the five participants utilized their test facilities in Texas, where the terrain and climate conditions (generally good through the year) allow year round testing to take place.

Each tire was identified on the sidewall with alpha-numeric painted symbols and the individual tires were mounted in the same position at all test facilities.

The tires were furnished mounted on wheels and adjacent lug holes were marked so that when the tires were mounted on dual positions, they were indexed the same at each site. The tires were also marked with arrows to maintain the same direction of rotation during testing.

Participants agreed that both fast and slow, A-weighted peak response measurements would be taken and that, if possible, each run was to be tape recorded. A minimum of 12 measurements (six slow and six fast meter response) were to be made per set. Instrumentation used at the test sites is as shown in Table 1.

TEST PROCEDURE

The test procedure was that prescribed in SAE J57a. This procedure requires the test site to be located on a flat area free of reflecting surfaces with a vehicle path of smooth, semi-polished Portland cement. This rather loose definition of surface may be noted in the types of test surfaces utilized at the five sites to measure sound levels as described in Table 1. As will be shown elsewhere in this report, the degree of texture of the concrete surface contributed significantly to the sound levels measured from site to site. The microphone was located at a distance of 50 ft from the centerline of the vehicle path at a height of 4 ft above the ground plane. Sound generated by the test tires on the drive position was measured as the vehicle passed the test area in a coast-by condition at 50 mph. Vehicle types and models are shown in Table 1, and a test vehicle shown in Fig. 2.

The tires were run at tire loads and inflation pressures as shown in Table 1. Quiet tires were used on the front position of the trucks during testing as prescribed by SAE J57a.

Wind velocity, direction, ambient temperature and surface temperature were recorded. Due to the layout of test facilities, test direction varied amongst participants as shown in Table 1.

TEST RESULTS

The results of the RMA round robin test have been analyzed to determine the degree of variability in the sound levels of each of the eight sets of truck tires as measured at the five

Table 1 - Test Site Information

Site	Sound Level Meter	Vehicle	Load/Inflation	Test Direction	Surface
1	B & K Model 2204	GMC Straight Chassis - Open Cab	4760# - 75 PSI Bias & Radial	East to West	Medium brushed concrete with high coefficient and considerable microstructure and macrostructure
2	General Radio Model 1561A	GMC Astro - Flat Plane Bed	4760# - 75 PSI Bias & Radial	Odd Runs - SW to NE Even Runs - NE to SW	Portland Cement Concrete Terrazo
3	B & K Model 2203	White Freight - liner - Cab Over	4760# - 75 PSI 80 PSI - Radial	South to North	Burlap finished, brushed Portland cement.
4	B & K Model 2204	GMC Astro 12 foot box	4580# - 70 PSI Bias; 75 PSI Radial	Even Runs - North to South Odd Runs - South to North	Terrazo Ground Concrete with limited macrostructure.
5	General Radio Model 1981	GMC Diesel - V8 Short Cab	4760# - 75 PSI Bias; 95 PSI Radial	South to North	Brushed burlap concrete.

test locations. The results show that for the sample of tires tested, wide variations in measurements between test facilities did exist for four of the eight test sets.

Three relatively simple measures of variability were computed to show this spread in the sound level data. These are range of individual coast-by measurements for all facilities combined, maximum difference between mean dB(A) sound levels, and standard deviations about the mean sound levels. Those three measures of spread in the sound level data enable initial conclusions to be drawn without relying on highly sophisticated statistical analysis. A more complete statistical analysis of the data is presented in Appendix B to support conclusions drawn from the preliminary analysis.

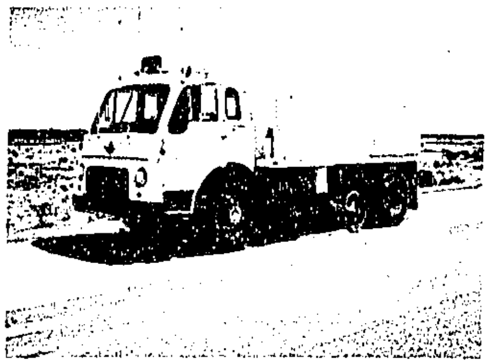
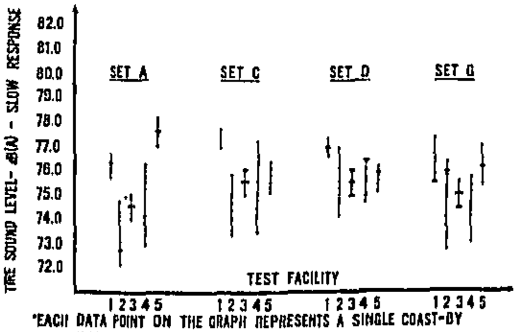


Fig. 2 - Representative test vehicle

PRESENTATION OF DATA

A graphical summary of individual tire sound level coast-by measurements of each test set at each test facility is shown in Figs. 3 and 4 for slow response readings. Each data point on the graphs represents one coast-by measurement. Fig. 3 shows sound level data for Sets A, C, D, and G. These sets represent the upper spectrum of tire sound levels for the selective group of



*EACH DATA POINT ON THE GRAPH REPRESENTS A SINGLE COAST-BY MEASUREMENT

Fig. 3 - Individual tire sound level coast-by measurements of Sets A, C, D and G for each test facility, slow response

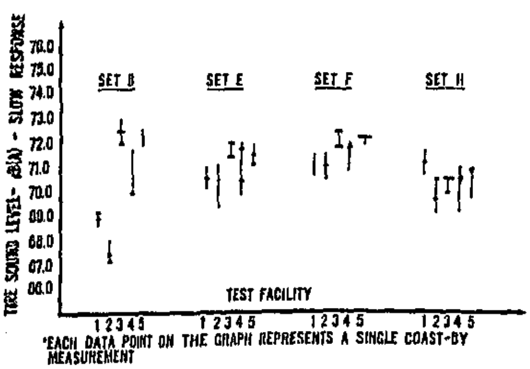
Table 2 - Range of Individual Tire Sound Level Measurements - dB(A)
All Test Facilities Combined

	Slow Response			Fast Response		
Set	Low Value	High Value	Difference	Low Value	High Value	Difference
A	72.2	78.1	5.9	74.2	80.9	6.7
B	67.2	72.5	5.3	67.9	75.2	7.3
C	73.4	77.6	4.2	75.2	80.2	5.0
D	74.2	77.3	3.1	75.1	80.0	4.9
E	69.4	72.0	2.6	69.8	73.4	3.6
F	70.6	72.5	1.9	71.3	73.8	2.5
G	72.8	77.3	4.5	74.2	80.2	6.0
H	69.2	71.6	2.4	69.9	72.3	2.4

tires used in this study. Fig. 4 shows the sound level data for Sets B, E, F, and H, representing the lower spectrum of tire sound levels in this study.

RANGE-The range in data points for each test set at each facility can be observed from Figs. 3 and 4, as well as the spread of dB(A) levels from site to site. The range is defined as the difference between the highest value and the lowest value in a data set, and is a simple measure of variability in data. Numerical values for the range of each test set are shown in Table 2. Individual coast-by measurements for all facilities were combined into one data set, with the highest value, the lowest value, and the difference between them listed in Table 2 for both fast and slow response.

For slow response, the ranges for all test sets are from 1.9 dB(A) (Set F) to 5.9 dB(A) (Set A), with five of the eight sets having a range greater than 3.0 dB(A). For fast response, the ranges for all test sets are from 2.4 dB(A) (Set H) to 7.3 dB(A) (Set B), with six of the eight sets having a range greater than 3.0 dB(A). These



*EACH DATA POINT ON THE GRAPH REPRESENTS A SINGLE COAST-BY MEASUREMENT

Fig. 4 - Individual tire sound level coast-by measurements of Sets B, E, F, and H for each test facility, slow response

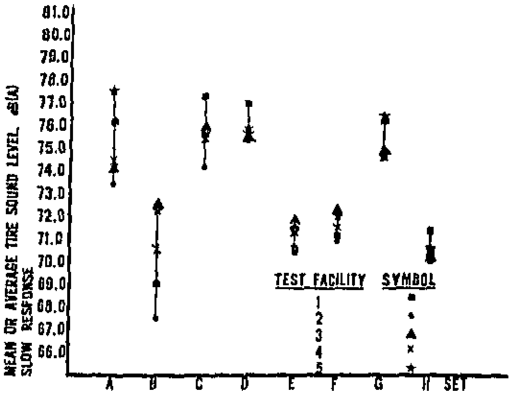


Fig. 5 - Mean or average tire sound level for each facility, slow response

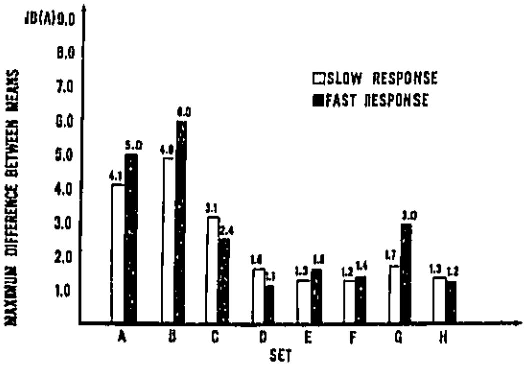


Fig. 6 - Maximum difference between mean tire sound levels at all test facilities

spreads in the individual coast-by measurements from site to site became especially significant since a 3 dB(A) difference represents an approximate doubling of the sound power level.

MAXIMUM DIFFERENCE BETWEEN MEANS-The mean sound level of a given test set is computed by averaging all individual coast-by measurements at each facility. The mean or average dB(A) sound levels of individual test sets for each facility are plotted in Fig. 5 for slow meter response. This graph provides a visual indication of the spread in the mean dB(A) levels between test facilities.

By comparing the mean sound level of each of the five facilities for each test set, the maximum difference between means is calculated by subtracting the lowest mean value from the highest. Results are shown graphically in Fig. 6. Note that for both fast and slow response, three of the eight sets exceeded a 3.0 dB(A) spread. This represents an approximate doubling of the sound power level. Variations as large as 5.0 dB(A) and 6.0 dB(A) were observed for Set A and Set B respectively on fast meter response.

The mean sound level for each test set, with all five test facilities' data combined is shown in Table 3. This Table shows that the fast response readings are on the average 1.4 dB(A) higher than the slow response readings.

STANDARD DEVIATIONS-The values of standard deviations of each test set for each facility are listed in Table 4. As would be expected, those sets which had the widest ranges also had the largest standard deviations. The standard deviation values are used in the statistical analysis, presented in Appendix B, to compute the range of the individual sound level measurements at a 90% confidence level and also a 90% confidence interval for σ, the

Table 3 - Mean or Average Tire Sound Levels, dB(A)
All Test Facilities Combined

Set	Slow response	Fast response	Difference between fast and slow
A	75.1	77.0	1.9
B	70.0	71.1	1.1
C	75.6	77.8	2.2
D	75.8	77.2	1.4
E	71.1	72.1	1.0
F	71.6	72.5	0.9
G	75.3	77.5	2.2
H	70.5	71.1	0.6
		Avg.	1.4

Table 4 - Summary of Standard Deviations, dB(A)

Test Facility

Set	1		2		3		4		5	
	Slow	Fast	Slow	Fast	Slow	Fast	Slow	Fast	Slow	Fast
A	0.29	0.45	0.89	0.84	0.38	0.41	1.15	1.65	0.37	0.70
B	0.16	0.23	0.28	0.39	0.18	0.00	0.60	0.93	0.22	0.79
C	0.23	0.40	0.83	1.23	0.38	0.15	1.25	1.25	0.11	0.73
D	0.21	0.21	0.95	1.98	0.16	0.41	0.67	0.88	0.35	0.10
E	0.26	0.25	0.55	0.83	0.27	0.26	0.71	0.68	0.28	0.27
F	0.28	0.28	0.32	0.53	0.27	0.27	0.35	0.15	0.01	0.37
G	0.68	0.62	1.42	2.24	0.38	0.20	0.84	1.12	0.50	0.71
H	0.28	0.37	0.44	0.63	0.26	0.27	0.58	0.75	0.45	0.27

population standard deviation.

The standard deviation for each data sample, when all individual sound level measurements for the five facilities are combined, are listed in Table 5 for both fast and slow response. The Table shows that the standard deviations for fast response readings are consistently higher. The difference in standard deviations between fast and slow response range from 0.01 - 0.46.

ANALYSIS OF DATA

SITE-TO-SITE VARIATIONS-Several of the tire sets in this study showed a wide spread in sound levels as measured by range of individual coast-by measurements, maximum difference between mean dB(A) levels, and standard deviation of the sample of coast-by measurements for each test set. These site-to-site variations are partly explained by differences in the texture of the test surfaces. Other factors may include test site layout, environmental conditions, vehicles, test personnel, instrumentation and general test method. Since a number of these variables are confounded, their relative individual significance cannot be measured in an investigation of this type.

Due to these differences in test surface, environmental conditions, general test method, etc, the assignment of a specific sound level to a tire is particularly suspect when the tire is measured at different test facilities. Data in this study demonstrate that a range of coast-by measurements for the same tire set can be as large as 7.3 dB(A) (Set B, fast response) and 5.9 dB(A) (Set A, slow response) when measured at different test facilities. Also, the standard deviations presented in Table 5, calculated from all facilities' data combined into one sample, can be used to determine the probability of the coast-by measurements falling within a certain range of values. An analysis in Appendix B shows that with 90% confidence (under statistical assumptions of normality and randomness of sample) the coast-by measurements of Set A, for example, fall within a range 72.4 - 77.8 dB(A) for slow response when measured at all five facilities. Thus, a single, universal dB(A) level should not be assigned to a tire unless allowances are made for these site-to-site variations in measurements.

Table 5 - Standard Deviations, dB(A)

All Test Facilities Combined

Set	Slow response	Fast response	Difference between fast and slow
A	1.62	1.94	0.32
B	2.00	2.32	0.32
C	1.23	1.24	0.01
D	0.81	1.07	0.26
E	0.68	0.76	0.08
F	0.55	0.64	0.09
G	1.14	1.60	0.46
H	0.59	0.66	0.07

Assignment of a range of values might be more realistic, by including an acceptable tolerance with the sound level measurement.

The possibility of ranking in-service truck tire sound levels is one particular area of interest where these large site-to-site differences must be considered. The same tire measured at different geographic locations may show variations in sound levels of several dB(A), thus diminishing the reproducibility of these measurements.

SINGLE SITE VARIAIONS-Although the J57a procedure attempts to minimize variables which affect the repeatability of coast-by measurements at a single facility, variations in measurements do occur. The graphs in Figs. 3 and 4 show the spread of measurements at each test facility for each tire set to be in a range of approximately 1-3 dB(A). The standard deviations for each facility are presented in Table 4. A comparison of these intra-site standard deviations with the standard deviations for all facilities combined (shown in Table 5), shows a smaller spread usually occurs at a single site. For example, Set A (slow response) shows a standard deviation of 0.29 dB(A) for facility #1 ranging to 1.15 dB(A) for facility #4. The standard deviation for the combined data is larger at 1.62 dB(A), indicating that the five facilities as a group measured Set A (slow response) with a greater spread in data than any of the individual facilities.

Variations in coast-by measurements at a single site also influence the assignment of specific sound levels to tires. Thus, if a test procedure is to be acceptable for measuring the specific sound levels of tires, it must not only generate repeatable results at a given test site, but also comparable sound levels at different test facilities, including an acceptable tolerance or range, for the population of commercially available tires.

Variations discussed above confirm the limitations of J57a test data as presently noted in this SAE published procedure. The J57a procedure now states that the data is not valid when the test tires measure less than 10 dB above the level of the vehicles equipped with quiet tires. Under this condition, relative ranking of tires may be used if the tires measure 3 - 10 dB above the quietest tires available.

RANKING-With respect to relative ranking of tires, the results of this study show that the test sets with the higher sound levels (Sets A, C, D, and G) consistently ranked higher than the tires with the lower sound levels (Sets B, E, F, and H) at all five facilities. However, the differences in sound levels among Sets A, C, D, and G were too small to consistently rank these test sets against one another. Similarly, the differences in sound levels among Sets B, E, F, and H were too small to consistently rank these sets against one another. The results suggest that a more substantial gross difference in sound levels between tires is necessary for consistent ranking.

SUMMARY

Five tire manufacturers conducted a round robin test, using the J57a procedure, in which eight sets of commercial truck tires were measured at each facility for peak, A-weighted sound levels.

This study found that wide variations existed for four of the eight test sets when the same tires were measured at different test facilities in accordance with J57a procedure. The extent of this variation was computed and presented by three simple measures of variability; the range, the maximum difference between means, and the standard deviation. These results are summarized as follows:

1. The range of individual measurements for all test facilities combined was as high as 7.3 dB(A) (Set B) for fast response and 5.9 dB(A) (Set A) for slow response.
2. The maximum difference between means was as high as 6.0 dB(A) (Set B) for fast response and 4.9 dB(A) (Set B) for slow response.
3. The standard deviation of the data sample for all test facilities combined was as high as 2.32 dB(A) (Set B) for fast response and 2.00 dB(A) (Set B) for slow response.

These site-to-site variations may be explained by differences in the texture of the test surfaces, as well as the other factors of test site layout, environmental conditions, vehicles, test personnel, instrumentation, and general test method.

Variations in single coast-by measurements at individual facilities, although usually smaller than site-to-site differences, fell in an approximate range of 1 - 3 dB(A) and must be considered when assigning a specific sound level to a tire.

The difference between fast and slow response readings were also noted. On the average, the fast response readings were 1.4 dB(A) higher in level and 0.4 dB(A) higher in maximum difference between means. The standard deviations for fast response readings were consistently higher (0.01 - 0.46). The sound level readings in this study were taken by trained technicians at industry sites, and greater differences between fast and slow response readings may occur if less experienced personnel are reading the fast response measurements.

Assignment of a specific sound level to a tire is impossible when measurements are taken at various test sites using the J57a procedure. The wide range of coast-by measurements, of up to several dB(A), clearly indicates the lack of reproducibility of an absolute tire sound level among test sites. There are simply too many variables, such as surface texture, environmental, and other procedural conditions, that are not sufficiently controlled.

This non-reproducibility of tire sound measurements has important significance when evaluating J57a for measuring in-service sound level requirements of truck tires. Such measurements must be based on a test method that is repeatable at a given site and reproducible among different sites if confusion is to be avoided. By nature, the J57a procedure is limited in satisfying these requirements.

REFERENCES

1. G. M. Dougherty, "Sound Levels of Highway Truck Tires", Proposed SAE Recommended Practice J57a. Published in SP 373 "Truck Tire Noise." Warrendale: Society of Automotive Engineers, Inc., 1972, Paper 720926.

APPENDIX A

Comparision of Mean Sound Levels Versus Reported Value Per J57a Procedure

The J57a coast-by noise testing procedure specifies a method for reporting the db(A) level of a tire set. The reported value is the average of the highest two measurements within 2 dB of each other. A comparison was made of J57a reported levels, as defined above, versus the mean sound levels computed in this study. Results are listed in Table A-1 for slow response. As would be expected, the J57a reported values are slightly higher than the mean values. The maximum difference between J57a reported values is also listed and is slightly less than the maximum difference between means. Three of the eight test sets show a maximum difference between J57a reported values greater than 2.0 dB (A).

This study has used the mean (or average) dB(A) sound level as the "typical" sound level for each test set for determining site-to-site variations. Other reporting methods are possible, such as, reporting the mean plus one standard deviation. This study has focused on variations in sound level measurements using the J57a procedure rather than analyzing alternative methods of reporting sound levels.

Table A-1 - Comparison of Mean Tire Sound Level and J-57a Reported* Tire Sound Level - dB(A), Slow Response

Test Facility

Set	1		2		3		4		5		Maximum Difference Between . . .	
	Mean Mean	Reported value	Mean	Reported value	Mean	Reported value	Mean	Reported value	Mean	Reported value	Means	Reported values
A	76.2	76.5	73.5	74.5	74.4	74.8	74.5	75.9	77.6	78.0	4.1	3.5
B	69.0	69.2	67.5	67.9	72.4	72.8	70.6	71.3	.3	72.5	4.9	4.9
C	77.3	77.6	74.2	75.4	75.6	76.0	75.5	77.0	75.7	76.2	3.1	2.2
D	77.0	77.2	75.4	76.0	75.5	76.0	75.5	76.5	75.8	76.1	1.6	1.2
E	70.6	70.9	70.5	71.1	71.8	72.0	71.2	72.0	71.5	71.8	1.3	1.1
F	71.2	71.5	71.1	71.5	72.3	72.5	61.6	72.0	72.2	72.2	1.2	1.0
G	76.2	77.0	74.6	76.1	74.9	75.3	74.6	75.6	76.3	76.8	1.7	1.7
H	71.3	71.6	70.0	70.5	70.3	70.5	70.4	71.0	70.5	70.9	1.3	1.1

* The reported value per J-57a is the average of the two highest measurements that are within 2 dB of each other

APPENDIX B
Statistical Analysis of RMA Round Robin Data

In order to support the conclusion that wide variations in tire sound levels between test facilities do exist for several test sets, a more thorough statistical analysis of the round robin data was performed. This more complete analysis, including statistical equations and terminology, is presented as an appendix, rather than in the text.

FREQUENCY DISTRIBUTIONS

Classical statistical analysis makes the assumption that the sample of data points generated in a given test or experiment often form a well defined frequency distribution, usually the well known normal or Gaussian distribution. In order to determine if the round robin data tended toward a normal distribution, the individual tire sound levels of each test set for all five test facilities were combined into one sample. A frequency histogram was plotted for each test set, both fast and slow response, using a class width of 1.0 dB(A) for all sets except Sets E, F, and H (ex. 69.0-69.9, 70.0-70.9, etc). A class width of .5 dB(A) was used for Sets E, F, and H because of their smaller data spread (ex. 70.0-70.4, 70.5-70.9, etc).

Two examples of frequency histograms for Set B and Set D, slow response, are shown in Fig. A-1. Set B was the only set which showed no central tendency toward a "typical" value. For a distribution of this type, the range of the individual measurements is a good measure of the variability, as presented in the preliminary analysis. The histograms of all other sets did show a tendency toward a normal distribution, as depicted by Set D in Fig. A-1. These results indicated some justification for using classical statistical analysis and assuming normal distributions for the samples of individual tire sound levels of each test set for all five facilities combined together.

RANGE OF INDIVIDUAL MEASUREMENTS AT 90% CONFIDENCE LEVEL

In order to show the spread in the coast-by data, a range was computed for the individual tire sound level measurements of each test set at a 90% confidence level. Based on the test samples obtained by the five test facilities and under the assumptions of a normal distribution, randomness of samples, etc, this computation indicates that 90 times out of 100, the individual measurements would fall within a certain range.

The results of these computations are listed in Table A-2 for Sets A through H, both fast and slow response. The ranges extend from 1.8 dB (A) (Set F) to 6.6 dB(A) (Set B) for slow response, and from 2.2 dB(A) (Sets F and H) to 7.6 dB(A) (Set B). These results are very similar to the values of the ranges of the actual individual measurements as determined in the preliminary analysis.

In calculating the range for the individual measurements, the following assumptions were made. Since the sample size, n, was greater than 30, let $\mu = \bar{x}$ and $\sigma = S_x$, and use the standard normal variate, z, instead of t-values in order to simplify the calculations. Hence,

$$P\left[\ \bar{x} - (1.645)\ (S_x) \leq x \leq \bar{x} + (1.645)(S_x)\right] = 0.9$$

Where: z = 1.645 is taken from the table for areas under the Standard Normal Curve

CONFIDENCE LEVEL CALCULATION FOR FIXED ± 1 dB(A) RANGE

A similar analysis was carried out to determine with what confidence level the individual sound level measurements would fall within a ± 1 dB(A) range about the mean or average value for all facilities combined. This is a reversal of the previous calculations that determined the range for a chosen confidence level of 90%.

The concept is shown graphically in Fig. A-2 and a list of results is presented in Table A-3. As would be expected, the sets with the widest spread in data have the lowest confidence level of falling within the selected acceptable range. The

Table A-2 - Calculated Range of Individual Measurements at 90% Confidence Level

All Test Facilities Combined

Set	Slow response - dB(A)	Fast response - dB(A)
A	$72.1 \le x \le 77.8$	$73.8 \le x \le 80.2$
B	$66.7 \le x \le 73.3$	$67.3 \le x \le 74.9$
C	$73.6 \le x \le 77.6$	$75.8 \le x \le 79.8$
D	$74.5 \le x \le 77.1$	$75.4 \le x \le 79.0$
E	$70.0 \le x \le 72.2$	$70.8 \le x \le 73.4$
F	$70.7 \le x \le 72.5$	$71.4 \le x \le 73.6$
G	$73.4 \le x \le 77.2$	$74.9\ \ x \le 80.1$
H	$69.5 \le x \le 71.5$	$70.0\ \ x \le 72.2$

Table A-3 - Percent Confidence That Individual Tire Sound Level Measurements Fall Within A ± 1 dB(A) Range

All Test Facilities Combined

Set	Slow response (%)	Fast response (%)
A	47	39
B	38	33
C	58	58
D	78	65
E	86	81
F	93	88
G	62	47
H	91	87

confidence levels range from 38% (Set B) to 93% (Set F) for slow response and from 33% (Set B) to 88% (Set F) for fast response.

For this calculation,

$$z = \frac{x-\bar{x}}{S_x} = \frac{1}{S_x}$$

Where:

$$(x-\bar{x}) = 1$$

Thus for a given z value, the confidence level can be obtained by referring to the Table for Areas under the Standard Normal Curve.

90% CONFIDENCE INTERVAL FOR THE STANDARD DEVIATION

In addition to calculating a range for the individual measurements at a 90% confidence level, a 90% confidence interval can be determined for both μ (the mean) and σ (the standard deviation). Since variability between test sites was the primary interest, only the σ calculations were made. The results are shown in Table A-4. An inference that the standard deviations for the population would fall within these stated intervals can be made with 90% confidence under the statistical assumptions of normality, randomness, etc.

For this calculation, the following relationship was used

$$X^2 = \frac{(\eta - 1)S^2}{\sigma^2}$$

Table A-4 - 90% Confidence Interval for σ (Standard Deviation)

All Test Facilities Combined

Set	Slow response - dB(A)	Fast response - dB(A)
A	$1.35 \leq \sigma \leq 2.03$	$1.60 \leq \sigma \leq 2.43$
B	$1.65 \leq \sigma \leq 2.56$	$1.92 \leq \sigma \leq 2.97$
C	$1.02 \leq \sigma \leq 1.51$	$1.03 \leq \sigma \leq 1.55$
D	$0.67 \leq \sigma \leq 1.01$	$0.90 \leq \sigma \leq 1.35$
E	$0.57 \leq \sigma \leq 0.85$	$0.61 \leq \sigma \leq 0.96$
F	$0.46 \leq \sigma \leq 0.69$	$0.53 \leq \sigma \leq 0.80$
G	$0.95 \leq \sigma \leq 1.43$	$1.31 \leq \sigma \leq 2.01$
H	$0.49 \leq \sigma \leq 0.74$	$0.55 \leq \sigma \leq 0.82$

Where:

η = sample size

S = standard deviation of sample

X^2 = tabular value, for chi-squared distribution

ν = $\eta - 1$

The 90% confidence interval is

$$P\left[X^2(1-\alpha/2);\ \nu \leq X^2 \leq X^2\alpha/2;\ \nu\right] 0.90$$

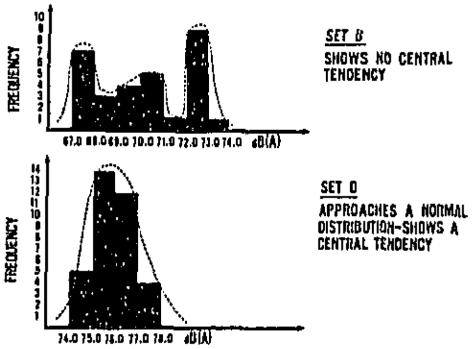
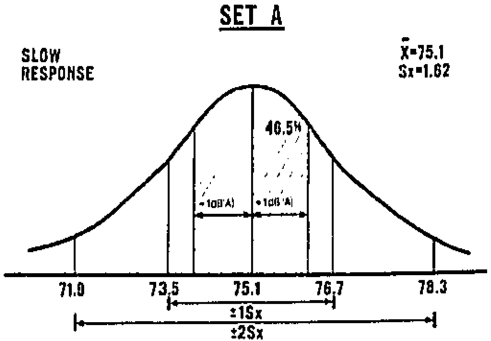


Fig. A-1 - Examples of frequency distributions-Sets B and D, slow response



CONCLUDE-WE CAN ONLY BE 46.5% CONFIDENT THAT INDIVIDUAL TIRE SOUND LEVEL MEASUREMENTS, FOR ALL TEST FACILITIES COMBINED, WILL FALL IN A ±1 dB(A) RANGE

Fig. A-2 - Example which graphically illustrates percent confidence that individual measurements for Set A, slow response, fall within a ± 1 dB(A) range

which equals

$$P\left[\frac{(n-1)S^2}{X^2\ (1-\alpha/2;\upsilon)} < \sigma^2 < \frac{(n-1)S^2}{X^2\ \alpha/2;\ \upsilon}\right] = 0.90$$

Where:

$$\sigma = \sqrt{\sigma^2}$$

ANALYSIS OF VARIANCE

An analysis of variance was performed on the round robin data to confirm the fact that the variations observed between the test facilities were significant and not due to random error alone. The analysis of variance was run at $\alpha = 0.05$ or 95% confidence level. The results are shown in Table A-5. All eight sets showed a statistically significant difference on slow response, and seven of eight sets showed a statistically significant difference on fast response.

The analysis of variance results only indicate whether or not at least two of the mean sound levels of each test set are significantly different from the others. It does not reveal which test facilities are significantly different or by how much. A conclusion can be made that, as a group, the variations between test facilities probably are statistically significantly different and are not caused by random error alone.

DISCUSSION

MR. THURMAN: The J57a procedure says that you shall run a minimum of three tests, and shall take the average of the two highest tests that differ by less than the number of tests that you run. How would the sites look, one to another, had you followed the procedure that J57a specifies for assigning a number?

MR. ANDERSON: We did make such a comparison. It is in the paper in an appendix. I don't have the table with me, but in the computed J57a values we still did see a wide variation between facilities. Mr. Lippman mentioned that in his paper, although our spread of values were slightly less; on the order of 1 dB(A) less than was shown there.

MR. BENCHEA: I might add also, in that particular appendix, the averages as computed through J57a are higher than those for the sound levels that we have computed.

MR. ANDERSON: Using the J57a procedure there is still a wide variation.

MR. WOOTTEN: Were the sound level meter outputs recorded on a strip chart recorder, or were they read from the meter face?

MR. BENCHEA: They were actually done both ways. We requested that each test facility make recordings, but, I know of one facility, for example, that did not have the recording instrumentation, so the readings were taken directly from the meter. Several of the sites did record their data. They had the proper instrumentation.

MR. WOOTTEN: This would probably account for many of the differences, because the meter

Table A-5 - Analysis of Variance Results

Is there a statistically significant difference between mean tire sound level measurements of each test facility?

Set	A	B	C	D	E	F	G	H
Slow Response	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fast Response	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes

dynamics is involved according to ANSI S1.4-1971. From ballistics tests we find that using the meter dynamic ballistics results in incorrect data.

MR. THURMAN: Another question?

MR. LIPPMANN: I would like to comment on the last question. We have examined the data in several ways. We did take the data dynamically on the spot with someone reading the meter. We have also processed the data through the recording equipment. We have used computers to determine the level, and we have used real time analyzers, and still we find variations.

MR. CLENDENEN: If you are using the slow response, there is an electrical time constant built into the meter, but when you are using a fast response, the time constant basically is the ballistics of the meter movement. Is that correct?

A PARTICIPANT: No, there is an electrical time constant for any type 1 meter.

MR. REITER: I heard Mr. Lippmann mention the use of spectral analyzers. I had a notion that the orientation of tires in a clamped dual pair would have something to do with the phasing of the tonal components related to the tread passage. I would expect it to show up in the tonality as deduced from the spectal analysis. Is there any evidence of that? Also the right and left hand dual pairs are connected to the differential, and there is a possibility of additional phase relationships arising for this reason.

MR. LIPPMANN: I think the point is well taken. I don't have specific information. We didn't look for phase additions of tones from various tires, but, from the things we did look for, that appears as though it would actually be the case. The phasing of the left side and right side would be an additional factor, but it isn't the only factor. Also, in my last answer, I misspoke slightly. We didn't obtain the tapes from the other testing companies, but we checked our own directly measured values with our tapes in a variety of ways, always using the same sound level meter to finally evaluate the signal or to calibrate the instrument. We obtained the same answer under those circumstances.

MR. MILLER: I brought in a slide in which we looked at the idea of phasing. We ran the truck with only four tires. We ran one lug tire on the rear with three smooth tires. Then we ran two lug tires, one on each side, again with two smooth tires on the front. If phasing was going on, we expected to find modulations of the fast response which would be greater with two tires at the rear than with one. Here are the two curves. Actually, as far as we can tell, there is really no difference in the level of modulation going on here, whether you have one tire or two tires, and we have run almost 1000 ft. We also took the average of the fast minus slow response for 12 runs. We would expect that if fast response is slowing up anything, we would get a bigger difference with two tires than with one. We carried the calculation out two decimal places. We can see there is essentially no difference between one tire or two tires in the difference between fast and slow responses. But look at the wave shape. It is hard to imagine that for any appreciable period that you would account for in and out-of-phase conditions with a wave shape like that. That's not a sine wave.

MR. THURMAN: You wouldn't expect to see a difference unless you looked at the spectrum in an extremely short period of time, because the tire is rotating at about 7 rps, and the typical tread pattern repeats itself about 4 times around the tire, or 3, depending on the manufacturer, or even 5. If you divide 1/7 by 3 or 4 or 5, you attain a short period of time, and a difference even in the spectra would have to occur in a very short instant of time. Certainly a sound level meter, even in the fast response time constant, is too slow to pick that up.

MR. ANDERSON: Mr. Ervin raised the question of phasing. At this point we are talking about the round-robin test. I would like the record to show that in this particular test the adjacent holes in the wheels were marked, and the tires were indexed the same at all test sites. Therefore, this particular dynamic condition was not present during these tests, and therefore was not a variable contributing to the variation as shown.

MR. MILLER: Part of the scatter that is attributed to the SAE J57a test is our fault. The measurements made at Pecos were made under abominable atmospheric conditions. We obtained an extremely large variation with direction of travel. We were one of the two participants who measured in both directions. If you average our pairs of data in opposite directions, you will find that our variation is as small as the others, but, the large scatter is attributed to the known variation in pavement texture between Pecos and the Firestone facility which accounts for about 5 dB(A) for a straight rib tire. Mr. Thurman reported this fact in the analysis that he made of the 1973 SAE tests. We had the same amount of variation at Pecos on brushed concrete and on smooth concrete.

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Measurement of Truck Tire Noise Using a Single-Wheel Trailer

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TIRE NOISE RESEARCH requires a test capability where the noise emanating from a tire can be examined in a realistic environment that has a minimum of interference from other noise sources and a minimum of reflections from surfaces other than the roadway. The single-wheel trailer 1* that is described here provides this capability. Although the trailer cannot be used in all weather, it has the advantage of testing on an actual roadway with realistic airflow conditions and allows the measurement of the far-field noise from a truck tire, a feature that many indoor facilities lack. In addition to the research on tire noise mechanisms for which it was designed, the trailer can be used for noise tests in truck tire development. It might also be considered for qualifying tires.

Since the trailer is a moving system with an associated airflow that includes wakes from both the towing vehicle and the test tire, special measurement procedures had to be developed to cope with these conditions. These special procedures were concerned with ways of combating wind noise on the microphones and correcting for Doppler shift and other effects. Nothing could be done to prevent the test tire from being immersed in the wake of the towing vehicle, but modifications were made to the towing vehicle to limit both the spread and the intensity of the turbulence. Limiting the spread of the towing vehicle's wake allowed microphones to be brought closer to the tire without being subjected to the high level of microphone wind noise induced by turbulent flow. This was important both for stationary arrays of microphones close to the roadway and for on-board microphones moving with the trailer. This latter feature allows the trailer to be used for simple comparative tests of one tire versus another using an on-board microphone with a regular nose cone.

Initially far-field measurements of the tire noise were made using a semi-circular array of microphones which obtained a "snap shot" of the noise as the tire moved through the center of the array. Simultaneous recordings of the noise at

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*Numbers in parentheses indicate References at end of paper.

ABSTRACT

Tire noise research at the GM Research Laboratories has centered around on-the-road testing with a variable-loading, single-wheel trailer consisting essentially of a truck wheel at the end of a forty foot beam. This approach has proved to be highly satisfactory since it can be used to make realistic tests of the noise from a single truck tire, in isolation from other noise sources and free from interference by echoes from the vehicle structure.

Measurement procedures have been developed both for semi-circular arrays of microphones on the ground and microphones and accelerometers traveling with the test tire. For the stationary semi-circular arrays, a digital analysis procedure has been developed to determine the narrow-band spectra and the radiation patterns of the sound emitted by the moving tire as it passes through the center of the semi-circular array. The associated computation includes corrections for the varying source-receiver distance during the time interval of the data, small run-to-run variations in the test conditions, and Doppler shift. In this way the power spectra and the radiation patterns are determined as if the semi-circular array were moving with the tire at a fixed radius. For microphones moving with the trailer, signal averaging methods are utilized to reduce background noise, especially wind noise. Also a new coherence-function method that eliminates wind noise in a system of three microphones has recently been developed and is currently being used for far-field measurements.

The tire noise trailer could be used for development work as well as for research. It might also be considered for qualifying tires.

each microphone were made using a multi-channel tape recorder. To reduce this data, computer programs were developed (2) to make corrections for:

A. The variation of the distance of the tire to each microphone during the brief interval of recording,

B. Doppler shift,

C. Run-to-run variations in the trailer velocity. The semicircular array was chosen to minimize the correction for distance that is generally involved with the use of stationary arrays and to ensure that the same piece of pavement was used in all the measurements.

In experiments with either a single lug or a single groove on an otherwise untreaded tire (3), a microphone traveling with the trailer was used to measure the sound of the tire. Signal averaging techniques were employed in this case to reduce the effect of the wind noise. Recently with the advent of modern Fourier analysis equipment, a new coherence-function method based on an array of three microphones was developed at the GM Research Labs (4) which essentially extracts from the wind noise background the power spectrum of the tire noise signal as received at each of the three microphones. This is currently being used to measure the far-field noise particularly when the microphones are in the wakes of the towing vehicle and of the tire.

In addition to the microphone measurements, measurements with accelerometers are being made of the vibrations of the tire. A slip ring system has been developed to convey this data to an on-board tape recorder simultaneously with the noise measurements.

An account of these various procedures and a description of the trailer together with information about its use from the subject matter of this paper. A brief discussion of the possible use of the trailer for development work and for tire qualification is also given.

GENERAL DESCRIPTION OF THE TRAILER AND ITS OPERATION

The various considerations involved in the design of the trailer and the towing truck system have been discussed in Ref. 1. Additional details are given in a GM Research publication (5). Only a brief description is given here.

The single-wheel trailer which is pictured in Figs. 1 and 2 separates the test tire a distance of 12.2 m (40 ft) from the nearest major noise source, namely the rear tires of the towing truck. A minimum of sound reflective surface is provided by the high, single-beam construction of the trailer. Suspension components and loading weights shown in Fig. 3 are located above the test tire, leaving an open field for sound radiation. A streamlined cover is placed over these components to reduce aerodynamic noise. The rear axle and wheels of the towing vehicle are enclosed to reduce interference noise from the rear tires and the differential. The towing truck and trailer can travel at speeds up to 113 km/h (70 mph).

The nominally sized test tire used on the trailer is the 10.00/20 load range F (12-ply) tire commonly mounted on tractor-semitrailer trucks. The tire is loaded by the trailer's weight and by removable weights mounted on the beam near the test tire. Tire loads from 11,700 to 22,000 N

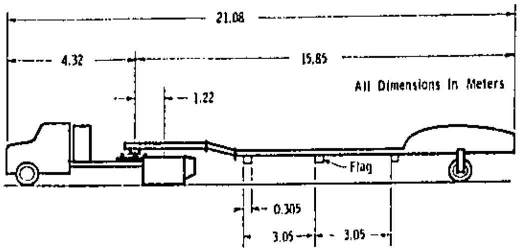

Fig. 1 - The single-wheel trailer and towing vehicle

Fig. 2 - The single-wheel trailer

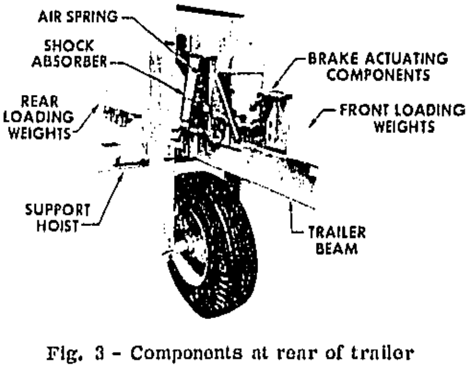

Fig. 3 - Components at rear of trailer

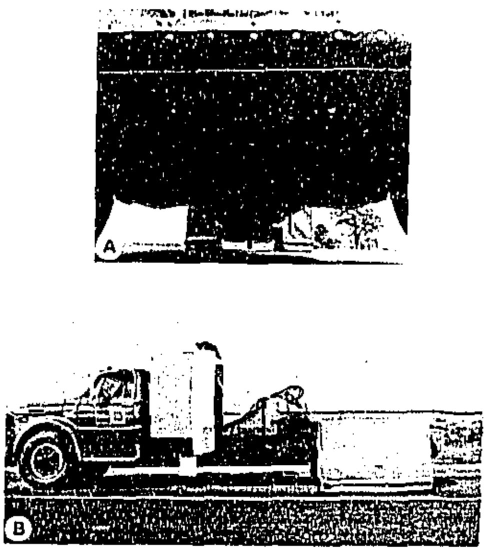

Fig. 4A and B - The underpan and air deflectors on the towing vehicle

(2620 to 5000 lb) or from 55 - 105% of the rated load of the nominal test tire are possible.

The trailer structure consists of a hollow square tube with joints for shortening the trailer and simplifying construction. Torsional forces from the beam are transmitted to the truck frame through a standard fifth wheel which in inverted from its usual position to keep the trunion pins perpendicular to the plane of the test tire at all times.

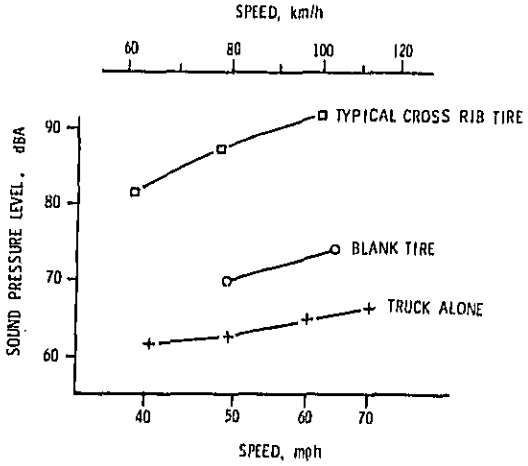

Fig. 5 - Measurements of the isolation of the test tire

The space under the streamlined cover on the trailer contains the loading weights, brake-actuating components and suspension components, as shown in Fig. 3. Also shown is part of a support hoist used for parking the trailer. A hydraulic disc brake is mounted in the trailer wheel and is actuated by an air-to-hydraulic unit on the trailer. The air for this unit is supplied by a conventional tractor-trailer air-brake system. The suspension system allows vertical motion of the wheel with respect to the trailer frame and employs an air spring and commercial shock absorbers.

The towing vehicle used is a GMC 6500 series truck with a 5.54 m (218 in) wheel base. Tires with straight circumferential ribs are used on the towing vehicle to minimize its tire noise. An under pan and air deflector, shown in Fig. 4, were added to the towing vehicle to reduce the vehicle's wake in the vicinity of the test tire. Model tests in a small towing tank showed that these had the effect of reducing the width of the vehicle's wake at the location of the test tire by almost a factor of 2. They also greatly diminished the size of the turbulent eddies in the wake.

The enclosure around the rear wheels of the towing vehicle, as shown in Fig. 4, was added to reduce the noise of the rear tires and the differential at measurement locations in the region of the test tire. The outside tire of each dual pair on the rear axle of the truck was removed to reduce the size of the enclosure. Also, a flow path was left between the wheels to diminish the wake of the enclosure, as recommended in the towing tank study. The enclosure consists of a layer of lead-filled vinyl sheet (4.94 kgm/m^2 or 1 lb/ft^2) lined with a blanket of fiberglass for sound absorption. After the enclosure was built, its effectiveness was tested in various ways as described in Ref. 1. An indication of the degree of isolation of the sound of the test tire above the background noise of the coasting towing truck is given in Fig. 5. This figure shows the noise of a typical cross-rib tire and a blank tire (with no tread pattern) compared to the background noise of the coasting towing vehicle alone. The measurement was made at a "worst case" location between the test tire and the towing vehicle along a radius 3.81 m (12.5 ft) from the test tire $\pi/6$ rad (30°) to the direction of travel. The microphone is 1.2 m (4 ft) above the ground. It is seen that the levels for the cross-rib tire are more than 20 dBA above those of the towing vehicle alone while the levels with a blank tire are 7 to 8 dBA above. For a microphone at the same radius and at $\pi/2$ rad (90°) or more to the direction of travel, the isolation is improved by more than 2 dBA. On a radius 3.8 m from the test tire, the

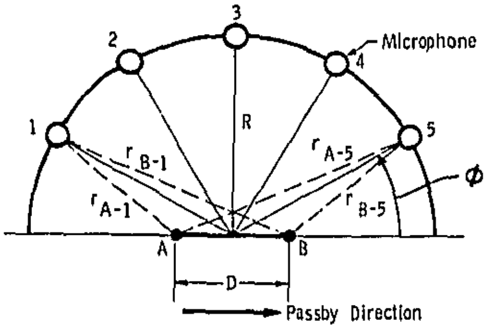

Fig. 6 - Configuration of semicircular microphone array

levels of blank tire noise are marginal but acceptable for the measurement of overall levels. Since the blank tire is as quiet as any tire presently built, it appears that the trailer and towing vehicle with sound enclosure system provide sufficient signal-to-noise to study noise from any tire type.

MEASUREMENTS WITH STATIONARY SEMICIRCULAR MICROPHONE ARRAYS

The semicircular array of microphones used in the tests is shown in Fig. 6. Essentially the sound of the tire is recorded as it passes through the center of the array over the segment of its path indicated in the Figure by the line AB of length D. Typically the radius of the semi-circle is 3.8 m (12.5 ft) and the length is 1.35 m (4.43 ft). The principal reasons for using the semicircular array were that corrections for variations of distance from the microphones during the period of recording were minimal, in contrast to the corrections required for other array configurations, and also that the same piece of pavement was used for each microphone in the array.

The microphones are considered to be in the far field of the tire while the tire is in the path segment AB. This assumption was verified by various tests. Of course it would be better to have as large a radius for the array as possible, but as indicated in Fig. 5 one cannot get further than 3.8 m from the tire and still have an acceptable signal-to-noise ratio for quiet tires. Another constraint is that the width of the towing vehicle and its wake prevents the stationary microphones from being placed close to the path of the test tire. Hence, the semicircular array cannot be used to explore the sound field directly fore and aft of a tire.

The precise location of the tire and its speed in relation to the semicircular array were determined with a photodiode signal recorded simultaneously with the signals from the five microphones on a multichannel FM tape recorder. The photodiode signal is generated when metal flags placed at suitable locations on the trailer ahead of the test tire as shown in Fig. 1 intersect a laser beam traversing the roadway.

The analysis of the data obtained with the semicircular array is being presented elsewhere (3) and will not be discussed in detail here. Essentially the data was digitized and the narrow-band spectra and the radiation patterns of the sound emanating from a tire were computed using fast Fourier transform (FFT) procedures. Various corrections had to be incorporated into the analysis. First the amplitude of the recorded signals had to be corrected according to the variation of the source-to-microphone distance during the time the tire traverses the distance D at the center of the array. This variation in source-to-microphone distance is illustrated in Fig. 6 for the micro-

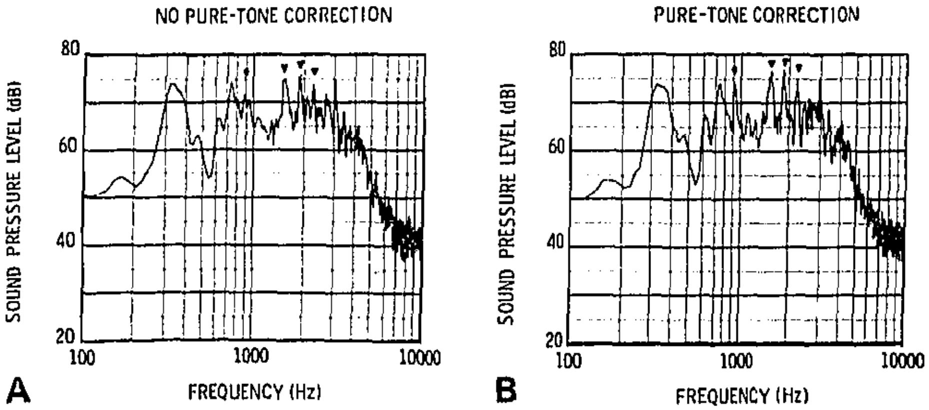

Fig. 7A and B - Effect of pure-tone correction for spectrum of a cross-bar tire averaged over ten runs

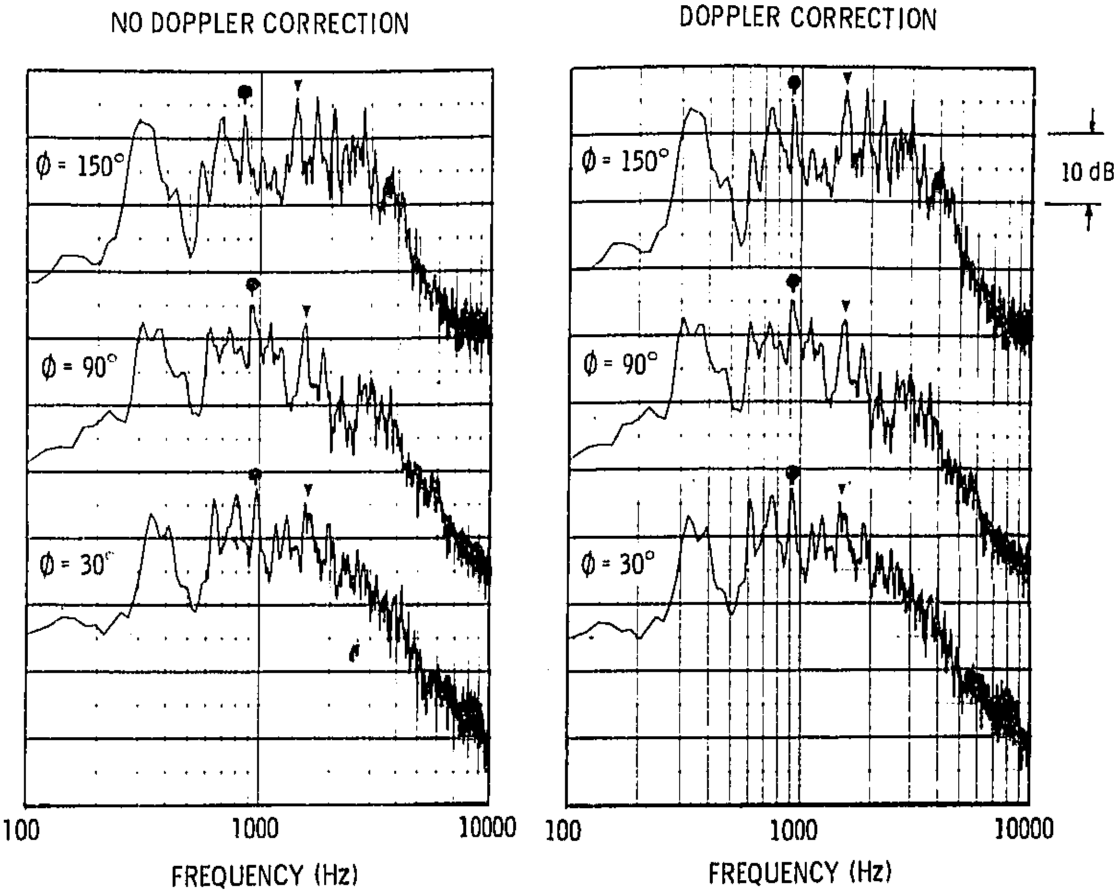

Fig. 8 - Effect of Doppler correction at different microphone locations

phones at locations at 1 and 5 where it was most extreme. Doppler frequency shifts in the narrow band spectra can be corrected using a relationship between the record length at each microphone and the corresponding Doppler shift. Finally a correction can be applied to offset the effect of run-to-run variations in the tire speed. Individual spectra are averaged over several runs to reduce the random error in the data. Since all runs could not be made at an identical speed, a blurring occurs during averaging for pure-tone peaks whose frequencies are proportional to tire speed. The correction reduces this blurring effect. It should be noted that the Doppler shift correction and the run-to-run pure-tone correction are not related in any way. The former is a correction for signals at different microphones for a particular passby run whereas the latter is a correction applied to several runs at a particular microphone.

Samples of the data, obtained with a cross-bar tire, are presented in Figs. 7 - 9. The forward speed of the tire was 97 km/h. Fig. 7 shows the sharper and, in some cases, higher peaks produced by using the pure-tone correction in spectra averaged over 10 runs. Fig. 8 shows a comparison between Doppler-corrected and non-Doppler-corrected spectra for microphones at locations 1, 3 and 5 in Fig. 6. The spectrum at location 3 is considered to be unaffected by Doppler shift and the peaks of the spectra at locations 1 and 5 when corrected line up with it. In the uncorrected spectra, the peaks shift to lower frequencies at location 1 behind the tire and to higher frequencies at location 5 ahead of the tire. The Doppler-corrected spectra correspond to what would be

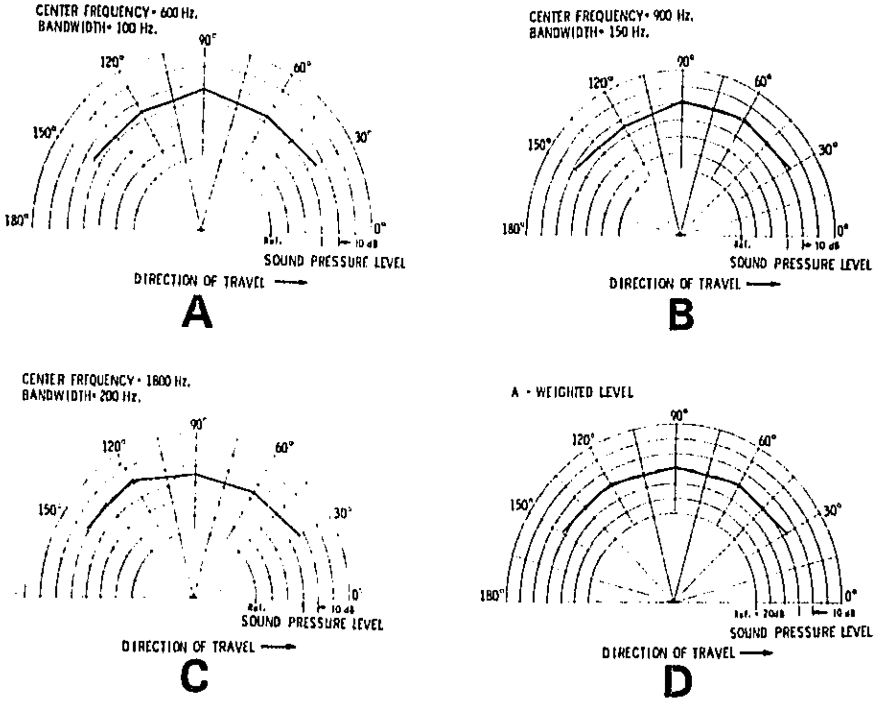

Fig. 9A, B, C, and D - Samples of radiation patterns for a cross-bar tire

measured by microphones moving with the tire. In Fig. 9, the radiation patterns of the cross-bar tire at 600, 900 and 1800 Hz together with an overall A-weighted level, are presented.

DATA ANALYSIS PROCEDURES FOR REDUCING WIND NOISE FOR MICROPHONES MOVING WITH THE TRAILER

For microphones moving with the trailer, problems are encountered with microphone wind noise particularly with the noise induced by the turbulence in the wake of the towing vehicle and of the tire. Because the spread of the wake of the towing truck is reduced by the airflow-control modifications on the truck as described above, it is possible to locate a microphone, with a nose cone, on a boom outside the wake and to make tire noise measurements that are relatively free of wind disturbance. Inside the wake measurements are possible only for microphones very close to a noisy tire. However, in general, for measurements contaminated with turbulence-induced noise, it is necessary to apply special data-analysis procedures to reduce or eliminate this noise. We are using two such procedures.

The first is the well-known technique of signal averaging. This has been applied, as discussed in Ref. 3, to the acoustical signals generated by a blank tire either with a single groove or a single lug. A tape recorder is used to make simultaneous recordings of the microphone signals and a once-per-revolution timing signal that occurs prior to the impact of the groove or lug on the pavement. The noise from consecutive impacts are then averaged with the triggering for each impact supplied by the once-per-revolution signal. The procedure was found to work satisfactorily only when the triggering occured not too far ahead of the impact of the single tread element indicating that it would not be possible to use the procedure easily for a complete row of tread elements. Data obtained using the signal-averaging procedure is presented in Ref. 3.

The signal-averaging method is valuable when it is necessary to know the time history of a signal, as is the case of the single groove and single lug experiments. When only the spectrum of the signal is desired, a powerful new method has been developed to achieve this. Essentially the method uses coherence-function relations between measurements at three microphones to "cancel out" the wind noise contribution and extract from the noise background the spectrum of the signal as received at each microphone. Simultaneous recordings are made of the measurements at the three microphones using a tape recorder. This information is then fed into a Fourier analyzer which has a four channel input system and which computes the auto-spectral density of the signal-plus-noise measured at each microphone together with the coherence functions between each pair of inputs from the microphones. These computed results are then combined to compute the auto-spectral density, or more simply the spectrum, of the signal alone as received at each microphone. This can be accomplished using a relatively simple keyboard operation on the Fourier analyzer. This method has been tested in laboratory experiments where it was demonstrated that a 10 - 15 dB reduction in wind noise could be achieved, the limitation on the amount of reduction being the dynamic range of the analyzer. The method is currently being applied to measurements made with an array of on-board microphones on the single-wheel trailer.

ACCELEROMETER MEASUREMENTS ON THE TIRE

A system has been developed to make accelerometer measurements on the test tire of the single wheel trailer. This utilizes the slip ring system shown in Fig. 10, which carried two channels of information. Simultaneous measurements from two accelerometers allow the measurement of vibration wave speeds and vibration attenuation in the tire when a single cross groove or a single cross lug test tire is studied. Techniques have been developed to adhere very small piezoelectric accelerometers (0.5 g) to the tire. A small impedence converting amplifier (FET) rides on the tire for each accelerometer. Tests conducted with accelerometers placed both on the shoulder and in the groove of a cross bar tire have demonstrated that accelerometers can be made to function successfully in this relatively severe impacting environment. Tests are proceeding using this system, recording noise and acceleration simultaneously.

POSSIBLE USE OF THE TRAILER FOR TIRE DEVELOPMENT AND TIRE QUALIFICATION

As has been stated, the single-wheel trailer described here was developed as a research tool. However, there are several factors that might allow it to be considered for tire development and as a means of qualifying tires. Clearly the trailer could not be used in a test involving a passby at 15 m (50 ft), because the background noise of the towing vehicle could create too great an interference. However, as indicated, a distance of 3.8 m (12.5 ft) appears to be in the far field of the tire noise and an acceptable signal to noise was obtained with a stationary microphone at this distance for a blank tire, which presumably represents the lowest attainable level of tire noise. It is also possible to attach a microphone 3.8 m from the tire outside the wake of the towing vehicle so that, with an ordinary microphone nose cone, an acceptable signal to noise can be obtained with present-day cross bar and rib tires.

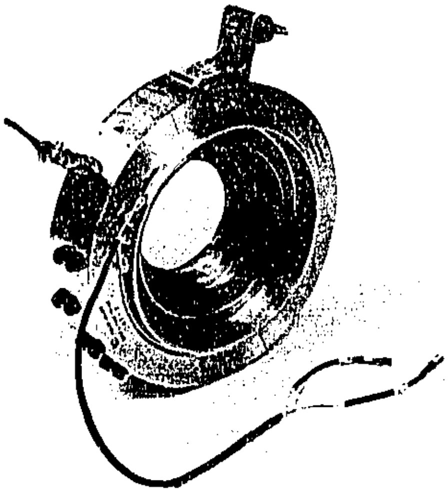

Fig. 10 - Slip ring assembly

The trailer would be attractive for development work because only one handcarved tire need be tested instead of the four or more that might usually be tested on a vehicle. For this type of study it would be preferable to use a microphone traveling with the trailer because a continuous recording makes it easier to perform spectral analyses of the tire noise.

For tire qualification, the principal advantage of the trailer is that the tire noise is divorced from other vehicle noise sources that exist in the coasting mode such as aerodynamic noise (6) and noise from the differential. This factor is important when considering the base level of noise used in making absolute measurements of tire noise and will become increasingly important as noise from tires is reduced. For this type of evaluation it would be preferable to use a stationary microphone. If a special standard surface is to be used for qualifying tires, another possible advantage of the trailer might be that it would require a narrower strap than would be required for a complete vehicle.

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DISCUSSION

MR. TREE: Concerning the rejection of the noise induced by turbulent flow, have you ever tried the new turbulence rejection screen manufactured by B & K?

MR. HICKLING: This is a porous sleeve attachment to the microphone?

MR. TREE: That's correct.

MR. HICKLING: We did talk about it, and we are aware of Mr. Baade's work and similar work by others. The problem with that device is that it makes the microphone system very directional, whereas this procedure that we use doesn't require any attachments to the microphone. It doesn't change the characteristics of the transducer in any way, so we don't impair the characteristics of the microphone in the way that the attachment that you mention would.

MR. NILSSON: I would like to ask you what lower limiting frequency you estimate you have on your on-board microphone system.

MR. HICKLING: Are you talking about wind noise interference?

MR. NILSSON: Yes.

MR. HICKLING: I have no information on that. I am reporting this information for Mr. Oswald and Mr. Wilkin, and I have no first-hand knowledge to answer your question specifically.

MR. NILSSON: Some others have experienced a lower limiting frequency of about 300 Hz.

MR. HICKLING: From what I have seen of wind noise characteristics, that is a very likely figure.

MR. NILSSON: Further, I would like to ask you another question. You told us that you used three microphones, and that you took the coherence function. Is that the kind of multiple input coherence function using all three signals constituting a matrix?

MR. HICKLING: No, we use the coherence function between pairs of inputs at a time.

MR. NILSSON: Just two at a time?

MR. HICKLING: Yes. We obtain the spectrum as received at each microphone. It wasn't an average obtained between the tires. You obtain data that would give you a radiation pattern, for example.

MR. NILSSON: Did you perform any tests to define the wind noise from the trailer itself, for instance, by driving the truck upwind and downwind?

MR. HICKLING: I am sorry to say we haven't done tests like that. We have conducted tests in a variety of conditions. We have, however, found quite good repeatability with the same tire on the same stretch of pavement. I think the figures that I have heard were within one or two dB for all the tests we made on any particular tire. The trailer has a very streamlined shape, and we have gone to a lot of trouble to streamline the struts on either side of the wheel. I think that any effect like that would be minimal, and I don't think it would be noticeable.

MR. THRASHER: Do you think other companies will be able to rent your facility in toto?

MR. HICKLING: There has already been approval from my management to allow anyone to use the design, or specifically we have one person who asked, and it was agreed upon in his case. I'm sure it would be true in any other case. With regard to using the facilities of the proving ground, I have no jurisdiction over that, and I can't say. I will say that I did ascertain how much it would cost to build a similar trailer. Unfortunately, it comes up to some figure like $50,000, and then the truck would be extra on top of that. I find that figure horrifying, but, other people say, "Well, other facilities cost a lot more than that." To me it is just a wheel on the end of a tube, and I don't see why it should cost so much.

762015

A Laboratory Procedure for Measuring the Sound Level of Truck Tires

S. A. Lippmann and K. A. Reid
Uniroyal Tire Co.

A RELATED PAPER (1)* given at this session evaluates the applicability of the SAE Recommended Practice, J57a - Sound Level of Highway Truck Tires to the regulation of tire sound levels and to the development of quieter tires. The evaluation finds the procedure inadequate, and finds the applications to national goals influenced by fundamental limitations of the procedure. The paper then arrives at a general outline of features required for a more suitable test method.

This paper investigates an alternate method of testing for tire noise. As a starting point for the presentation, it is well to consider a list of features for an improved procedure, which is derived from experience with J57a. These features are:

1. Statistical consistency of the new ratings with the SAE J57a ratings,
2. Reproducible to within ± 0.5 dB from one test facility to another, and with much less than ± 0.5 dB spread at any one facility,
3. Absence of noise inducing excitations due to the irregularities of the road surface,
4. Measurement of steady state sound so as to avoid the problems of peak transient capture or the dynamic responses of sound measuring equipment,
5. Elimination of tire load fluctuations which cause modulations in sound level or spectral content,
6. Accurate control of speed of travel (± 0.2 mph),
7. Speed adjustable to account for future changes in test conditions which might accompany alterations in national goals,
8. Rapid and economical to operate and requiring only a modest capital outlay in order to promote multiple test facilities,
9. Insensitive to weather conditions,
10. Relatively simple so as to preclude the need for highly trained specialists,
11. Compatible with normal spatial requirements for tire testing equipment,
12. Procedure and equipment of such a nature so that all pertinent factors can be specified in a written text, and therefore can be reduced to a standard,
13. Satisfactory signal to background noise ratio for evaluating quieter tire designs. (over 10 dB between signal and background),
14. Factors specified which control friction to avoid variable contributions of sounds emanating from slip-stick vibrations, (that is, safety walk, knurling, finish, etc.).
15. Short acoustical path (less than 10 ft) to avoid refraction and other effects due to the thermal and dynamic state of the air.
16. Major components and instrumentation to be commercially available, and not require special developments.

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*Numbers in parentheses designate References at end of Paper.

ABSTRACT

This presentation is a sequel to Paper 762035 in that an alternate method of testing for tire noise is investigated and the results of experimental studies are described. The alternate method is designed so as to preserve in the proposed measurements, the pertinence of J57a. Comparative testing of numerous tire designs in the two manners shows that this objective has indeed been accomplished.

Rather than presenting the experimental details behind each of the various foundations for the proposed method, this paper confines its discussion to the items significant to the description of the method and to a comparison with the J57a procedure.

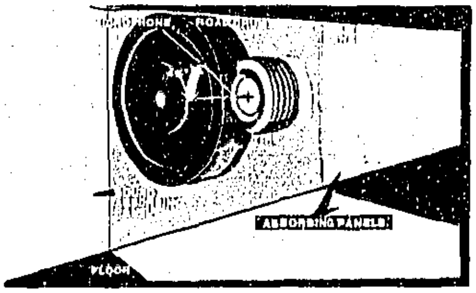

Fig. 1 - Schematic layout of drum test components for measuring truck tire sounds

GENERATING AND DETECTING THE TIRE SOUNDS

Many investigators have speculated about the possibility of measuring the sounds radiated by tires running against a steel drum in a laboratory. Since the steel drum can be finished so that the surface texture can be reproduced from machine to machine, constancy of tire-road friction among facilities can be attained and simultaneously road excited vibrations can be eliminated. Because of this capability and because of other commercially available features, drum machines are able to account for all of the above listed items except 1, 2 and 13. Consequently, machines of this nature are excellent candidates for further study.

The size of the drum which is suitable for the purpose is defined by the requirement that the processes of sound generation be substantially similar on the machine to the processes that occur when the tires are operated on trucks in service. This requirement follows indirectly from the first objective listed, consistency with J57a. From studies of the interfacial mechanics of sound generation, we have concluded that for usual sizes of truck tires, a drum 10 ft in diameter should serve the purpose quite well. In addition, 10 ft drums are already in existence in the tire industry and although expensive, are not prohibitive in cost.

The standard test drums (1/300 of a mile in circumference) usually employeed for fatigue testing of passenger tires appear to have too much curvature, but presumably might be found to be suitable. However, in order to avoid risking failure, we have used larger drums in our studies (that is 7 ft and 10 ft drums).

Another facet of the problem that most investigators are aware of is the role played by the road surface in the propagation of sound from the tire. In practice, tires run on relatively flat roads, and these roads provide an unyielding boundary to the air volume in which the sound propagates from the tire. The road surface consequently participates in the characteristics of propagation and of the radiated sound. On the test machines being considered, the equivalent road surface being a drum, is curved in the immediate vicinity of the tire. In addition, most drums are no more than 2 ft wide. Considering that the wave lengths which dominate the sounds radiated by truck tires at 50 mph are as long as 3 - 4 ft, it appears that there should be some acoustical implementation to the drum in order to better simulate the radiation of sound as it occurs in the presence of a flat road. This is accomplished in our procedure by providing a flat surface of 3/4 in plywood with a square hole in it which fulfills the acoustical functions of the road. The panel is installed so that the drum protrudes through it (and is tangent to its outer surface) in the region where the tire contacts the drum. This scheme is illustrated in Fig. 1. For convenience in our tests the plane of the plywood sheet is vertical and thus the acoustical environment is rotated 90° from the orientation it has on the road.

The dimensions of the plywood sheet required for the test procedure are determined by the choice of locations for the microphones. If the evaluation of sound is to be made in the near-field region, then the plywood sheet need only extend a fraction of a wave length or so beyond that location. Since the procedure envisioned at the outset of the project was to evaluate the near-field sound, the plywood sheet was required to extend only about 4 ft from the center of the contact patch between the tire and the wheel.

Microphone location is also a matter of prime importance. In theory, all of the acoustical information exists in the near-field region. From a series of appropriate near-field measurements, sound levels could be calculated for far-field locations. However, there are operational problems related to obtaining acoustical signals from many near-field locations and also related to the way these signals would have to be combined to yield measures of far-field sound levels. Multiple near-field measurements are likely to be incompatible with guidelines 8 and 10 which call for simplicity, rapidity and economy. The most favorable situation, of course, would be one in which only a single microphone location were needed.

Some further guidelines to microphone location can be discerned in the requirement that (for the present) the J57a road-side test and the new test are to be sensibly equivalent. It is generally appreciated that if the sound were to (which does not occur in fact) radiate from the tire with equal intensity in all directions, then the rating, (the peak reading of the J57a test) would approximately be that which corresponds to the closest approach of the tires to the microphone. Obviously, this is because the sound level from a relatively monopole source diminishes with the distance between the source and the point of measurement.

When the tires are closest to the microphone on the J57a test, the sound (for an equally directed radiation pattern) that impinges on the microphone is that which radiates primarily at right angles from the plane of the tires.

On the other hand, commercial tires do not radiate with equal intensity in all directions. The major portion of the sound energy is emitted from the exit of the contact patch. The peak level of sound detected on the roadside test therfore, radiates from the tire in a direction inclined rearward to the median plane of the tire. Such a rearward inclination is therefore expected to be ideal for obtaining a sound level reading on a laboratory test machine since the rating obtained is to correspond to the peak level obtained according to J57a. In fact, our experiments show that satisfactory correspondences occur when the microphone is in a plane which is at right angles to the plywood sheet, and is at 45° rearward to the plane of the tire.

Two other decisions need to be made concerning the location of the microphone - the distance from the tire, and the distance away from the plywood plane. At one extreme, the distance between the microphone and the tire is determined by the need to reduce noise by removing the microphone from the local wind currents that circulate close to the tire and the drum. On the other hand, if the microphone is close enough to the tire, then the sound level at that point is very much higher than that which can be returned to that location by error inducing reverberations or transmitted to that location from other interfering sources of noise. Still another factor is that the farther away the microphone is from the tire, the greater is the degree of desirable integration of sound radiated from various parts of the tire's surface. The compromise in our procedure is a microphone location 3 ft from the center of contact between the tire and the drum.

The distance of the microphone away from the plywood plane was initially chosen to be 3/50 of the 4 ft height (or 3 in) used in J57a. This choice preserves the same angular orientation of the line between the microphone location and the center of contact of the tire that occurs in the recommended practice. This location also appears to have worked out well.

The microphone location in the near-field where the ratio of reverberated sound levels to directly radiated levels are favorable, has a secondary consequence that reduces the cost and complexity of the test facility. Only a moderate degree of reverberant absorption is required in the room surrounding the test drum. The absorption can be accomplished with a scatter of reverberance repressing panels, and the room does not have to be equipped as an anechoic chamber.

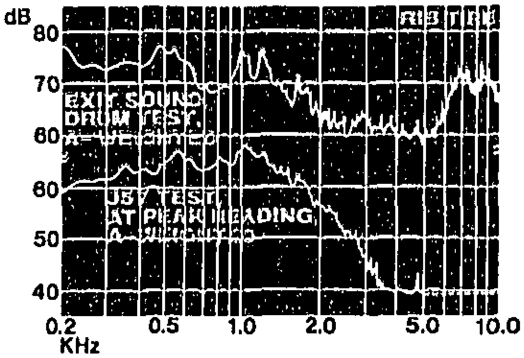

Fig. 2 - Spectral distributions of tire sounds - rib tires

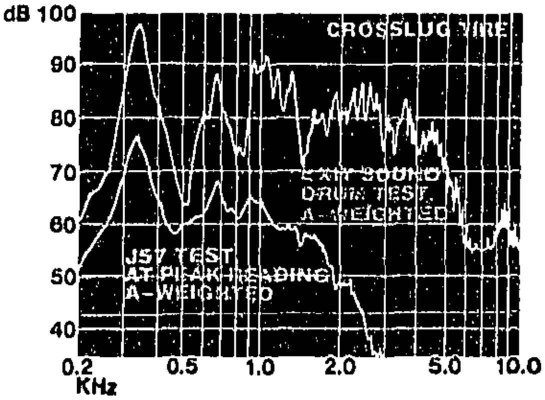

Fig. 3 - Spectral distributions of tire sounds - cross lug tires

SIGNAL CONDITIONING

One other physical effect that occurs in the J57a test needs to be considered before the new test procedure can be fully stated. This phenomena is the alteration in acoustical signal as it propagates from 3 ft away from the tire to the 50 ft location. Without some measure of these changes, it is not possible to specify a procedure that will lead to statistical consistency between the two kinds of tests. Furthermore, an examination of these changes in the acoustical signal, raises a more general issue for future consideration: "How is the detected acoustic signal to be weighted to account for annoyance in communities many times more distant from the truck than in J57a test?" No effort is made in this paper to treat the problem of community annoyance although the approach used for adjusting to the J57a test may be considered to be an example of one path to this kind of simulation.

Figs. 2 and 3 illustrate the differences in A-weighted sound spectrum for a typical rib and a typical lug tire measured both on the road drum and at the peak level for the J57a test. The sound detected at the drum is from the exit of the contact patch, but similar effects to those shown here are also found for other positions of the microphone.

One of the more striking observations from these two figures is the progressive attenuation with increased frequency of the sounds above 1500 Hz between the nearby and 50 ft locations on the two different tests. This has been attributed to the frequency selective attenuation of propagation across the road surface or to the multipolar nature of the sources on the tire for high frequency (that emphasize certain near-field intensities). In any event, there has been no confirmation of the reason, only the general observation of this phenomenon.

An examination of numerous pairs of curves for the drum tests and for J57a tests have led to an approximate rule for relating the two kinds of spectra above 1500 Hz. The spectrum of the J57a test is diminished from the drum test by 11 - 14 dB per octave for the major frequency content above 1500 Hz. From this rule, it then becomes possible to use a band-pass filter to adjust the spectrum of the drum test to match the high frequency content of the J57a test.

The choice of filter is dictated by commercial availability. The roll-off characteristics of most commercial filters approximate the multiple integration of the signal and as a result is offered in steps of 6 dB per octave (the frequency attenuation for integration). We have selected a 12 dB per octave filter for simulating the high frequency J57a spectra from drum spectra.

Figs. 2 and 3 also show the need for a low-pass roll off below 700 Hz for the drum test again to improve the simulation of the J57a test. This also is supported by observations for many tire designs. In the case of the low frequency content, the rate of attenuation is less severe than for high frequencies and we use 6 dB per octave for frequencies below 700 Hz.

One last observation from Figs. 2 and 3 and the nature of the signal treatment used is fully explored. For the drum tests, there is a greater range of sound level between the peaks and the adjacent valleys of the spectra than for the J57a tests. This phenomenon is typical of what would occur if broad-band extraneous noise were present during the J57a test such as if pavement induced noise were contributing. The J57a ratings appear to be larger than they would otherwise be because of additive noise sources. Consequently, in order to simulate the J57a test results, the levels measured on the drum are adjusted for an approximately constant amount of extraneous acoustical energy which adds to the tire signal. This additional acoustical energy will differ in magnitude with the pavement used, with the vehicle (turbulence, etc.), with wind levels, and so on. Therefore it is a property of the test facility employed and the wind conditions.

At the Laredo test grounds employed by Uni-Royal, tests are not run at wind speeds in excess of 8 mph and rarely below 3 mph and the wind component is considered to have a constant statistical value. The corresponding extraneous sources of noise are evaluated at about 71.8 dB(A).

The median value of extraneous sound estimated for the round robin tests of the five commercial test facilities referred to in the companion paper is 69.8 dB(A). These values will appear in the correlation studies which follow.

From both estimates, it is clear that tires whose sound levels are in the order of 70 - 75 dB cannot be measured precisely with SAE's Recommended Practice, J57a and the lower values could not be measured at all. Background noise sets a limit to how low the level of tire noise can be developed or regulated with the J57a procedures as the measuring tool.

CORRELATIONS BETWEEN THE DRUM TEST AND THE J57a TEST

A problem that arises in attempting to correlate any other test rating with the J57a rating follows from the variability of the J57a results. Fig. 4 which demonstrates the point is the same as Fig. 1 of the companion paper. The Figure

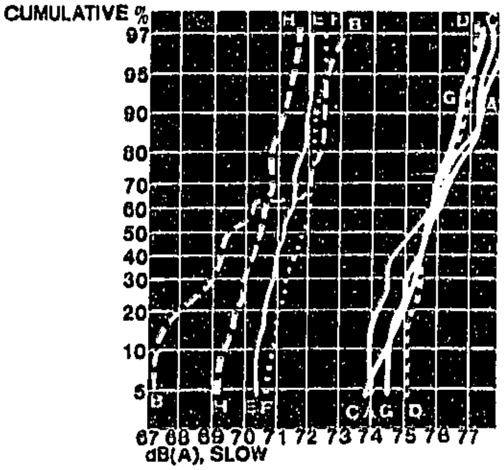

Fig. 4 - 1976 RMA round robin test - all individual runs

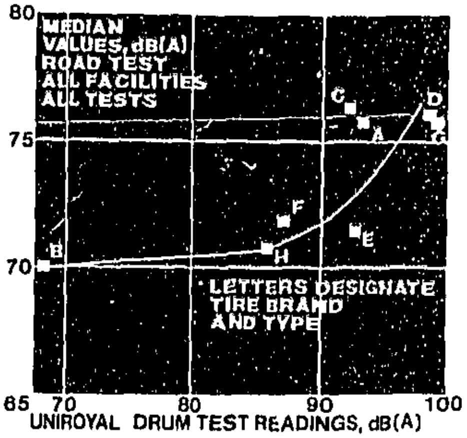

Fig. 5 - RMA round robin test data versus drum data

contains data taken from the RMA's round robin study of the repeatability of SAE's J57a procedure at five different test facilities. We see that there is a spread in measurements for all of the tests run on the same set of tires at the five facilities. Within the spread, overlapping values occur for different sets of tires. Consequently, if these values are to serve as a standard of performance for the drum test, some representative number must be derived from the distribution of readings for each of the sets of tires. The approach taken in our analysis is that the 50 percentile value for all tests on a set of tires represents its most probable J57a value. The 50 percentile (median) value is therfore used to test for correlation with the drum procedure.

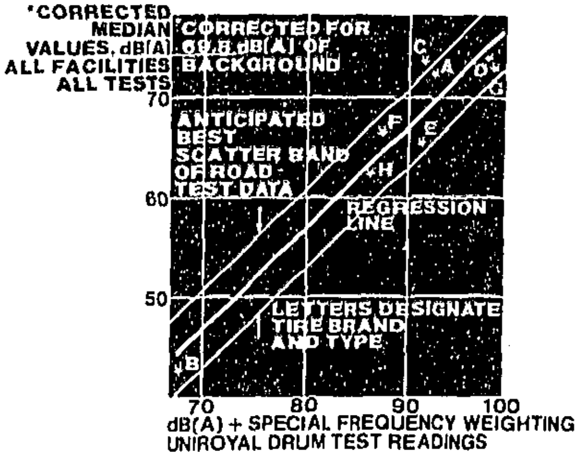

Fig. 6 - Adjusted RMA round robin test data versus weighted drum data

The correspondence between the raw data of the drum test and the median values of SAE's J57a is shown in Fig. 5. The data of this Figure do not contain adjustments for frequency or background noise. In contrast, Fig. 6 is a plot of the same data corrected as described in the foregoing. The data of Fig. 6 generate a linear relationship between the two test results within the bounds expected for the accuracy of the median values of the J57a test. Consequently, it appears that the drum test, including the adjustment of data for frequency content and extraneous noise, provides evaluations of the same significance as does the SAE J57a test procedure. Because of the tire types involved, this relation has been checked against a broad range of tread designs extending from smooth continuous circumferential ribs to some of the noisier commercial cross ribs. Radial ply tires are also included in the comparison.

Additional evidence can also be brought to bear on the quality of the correlation. Long before the round robin test was completed, measurements on UniRoyal's test pad (used for the J57a procedure) were being compared with the measurements conducted on the drum. There were fifteen different tire designs, some were intermediate development designs, some were advanced designs, some were commercial designs and all were different from those used in RMA's round robin test. Fig. 7 plots the comparative values using UniRoyal's extraneous noise level. Once again, there is an indicated linear relationship and the slope agrees with that obtained from the round robin test. In addition, the data once more are within the anticipated scatterband of SAE J57a.

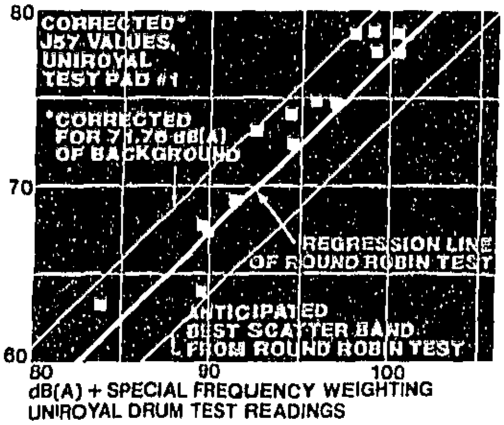

Fig. 7 - Truck tires of competitive manufacturers and experimental designs

STATUS OF NEW TEST METHOD

This paper has presented a description of a truck tire sound measuring procedure that operates in a laboratory, and whose evaluations correspond with the sense and purpose of SAE's J57a test procedure. The method is capable of considerable precision (repeatability is generally in the order of ± 0.1 dB) and is designed to avoid many of the problems associated with J57a.

In the absence of duplicates at other facilities it has not been possible to check the consistency of evaluations for differing test drums. However, from an examination of the factors recognized as affecting consistency, the writers do not anticipate unsolvable problems of this nature.

The drum test procedure has numerous advantages in flexibility. It offers the opportunity for modification in signal detection and processing in order to account for changing goals in curbing noise pollution. It is quite rapid, thereby accelerating new tire developments. It further assists in preliminary explorations of new designs since only one experimental tire is required instead of the four needed for SAE's J57a procedure.

We expect that as other groups explore this kind of measurement scheme, additional factors will be introduced and some of the approaches described here will be further modified and improved.

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DISCUSSION

MR. REITER: I should like to emphasize a point you made, Mr. Lippmann, and that is that I believe that even in the near future tire companies may build tires that radiate sounds that contain some pure tones in the spectrum. If they do build such tires, these pure tones can cause a variety of problems in any indoor facility, and some sort of treatment will certainly have to be employed to avoid annihilation of experimental data that you try to document when testing indoors with this type of tire.

MR. LIPPMANN: We tested tonal tires and there is no problem.

MR. REITER: What about the standing waves in the room?

MR. LIPPMANN: Yes, you do have to be concerned about standing waves. You might have to add absorption to the room.

MR. NILSSON: What you obviously have found is a kind of transfer function between the road test and drum test. Is that transfer function the same for all types of tires?

MR. LIPPMANN: We have tested the tires that appeared in the RMA round robin test and 15 other tires. We have had experience of an intermittent nature, in addition to these extensive test programs. We have not performed anything that doesn't agree so far. We are not claiming that this is the final answer. I would like to consider this a starting point, and that there will be a number of research outfits who will explore the limitations and extend the procedure beyond whatever limitations appear.

MR. THURMAN: I retired about a year ago, and at that time I proposed a procedure very much like the one that you have formulated, and the remarkable thing is that I had an attenuation rate of 12 to 14 dB above 1500 Hz based on much less data than you have, so I believe your figure has to be reasonably correct. I did not have the attenuation at the lower frequencies. I just took a casual glance at a few of the curves you had on the board and I couldn't see the need for it, but I suppose a more careful look would indicate such a need. I think this is an extremely encouraging result. Hopefully by the time the tire companies have to qualify their tires, a laboratory procedure can be standardized.

MR. CLOSE: I wonder if you could repeat what your definition is of the extraneous noise that you corrected for in your SAE J57a data?

MR. LIPPMANN: There are two definitions: one of them is philosophical and the other is exact. The exact definition is 71.6 dB for our particular facility. The philosophical definition is that there is that much noise coming in from the SAE J57a test that is going to be there, regardless of what tire is tested, and it will be the same providing we run the test in a relatively similar manner all the time. Now, for the interpretation of that number. We have several reasons from other discussions that have occurred today to which we may attribute the extraneous noise. We do know that the road surface influences the noise. There has been some suggestion that the road surface might change some mechanism of noise as it becomes rougher, or at least excites the tire differently. We also have some indications of turbulence. However, I don't think it is really necessary to attribute it to anything, providing the number can be sustained, that is that one has to correct a road test - an SAE J57a road test facility - by so many dB before a reproducible value is obtained.

MR. THURMAN: So in the kind of procedure that you are talking about today, in order to utilize a wheel data point to figure out what is meant in terms of the community, you would take this arbitrary number that you had for your particular facility, and add it to that value. Then would you expect to see these kinds of different levels in the community?

MR. LIPPMANN: I am not prepared to do that. You notice what I said was that I felt that a relationship could be made to community annoyance. I did not say that by this procedure we had arrived at a means for evaluating community annoyance.

MR. THURMAN: I was just talking about sound level.

MR. LIPPMANN: What we attempted to do was simulate the SAE J57a procedure. I think that you can do that.

MR. RICHARDS: How does a blank tire fit on your correlation curve? Have you tested a blank tire?

MR. LIPPMANN: Yes, it fits.

MR. RICHARDS: It seems like eventually you are going to run into a problem with directionality. In the DOT publication "Spectral and Directional Characteristic of Noise Generated by Truck Tires," different tires and different mechanisms seem to produce different directionality. It doesn't seem like your one measurement position will be able to handle that.

MR. LIPPMANN: Maybe so. I can't argue that it will. That will certainly be one of the things that needs to be looked at in future development; but, if we look at the paper given by General Motors Research, the radiation pattern seems to be fairly uniform in that region.

MR. RICHARDS: I offer a suggestion. It seems like what we are seeking is sound power. You can make your tests even simpler, if you use a reverberation room.

MR. LIPPMANN: I thought of that, but that wasn't the objective. I think sound power might be a better measure but it wasn't community purposes that we were addressing here, but rather simulation of the SAE J57a procedure.

762016

On-Board Passenger Tire Sound Generation Study Road Versus Lab Wheel

D. G. Anderson and S. P. Landers
The Goodyear Tire & Rubber Co.

TIRE RESEARCH STUDIES which investigate mechanisms of sound generation and the effects of speed on dB(A) levels can best be carried out in a controlled test environment. The measurement of tire sound levels in an indoor, semi-anechoic laboratory provides a more controlled environment than road tests and provides an attractive alternative method to the SAE J57a coast-by test (1)* and the On-Board coast-down test. (2)

Experience with the J57a test method has shown it to be slow, expensive, and subject to variations which affect repeatability of measurements at a single test site and reproducibility among various test sites. (3) A standard indoor lab wheel tire sound generation test may reduce or eliminate many of these problems by enabling tighter control over test conditions (that is, speed, surface texture, temperature, etc.) and having no dependency on weather conditions.

If laboratory measurements are to be used to predict tire sound levels on the road, the data must be meaningful and show correlation with road tests. They must correlate not only for one tire or one type of tire, but for all tires. Unless laboratory measurements are valid for the population of tire sizes, constructions, and tread designs, the value of the test is questionable.

With these considerations in mind, a study was conducted to gain an initial broad overview of the feasibility of testing tires on a lab wheel. The test program was kept simple in design so that general observations could be made only of basic tread design parameters. In this initial study, tire size and construction were not varied. Our objective was to learn of potential problems which must be overcome in establishing an indoor sound generation test.

TEST PROCEDURE

The testing method used for this study was the On-Board Testing technique. (2) This procedure uses a microphone mounted directly on the test vehicle and properly positioned to monitor sound emitted from the rear contact area of the single test tire. The On-Board technique enabled a direct comparison of near-field sound generated by a tire when tested on both a road and a lab wheel.

The outdoor test procedure was duplicated as closely as possible on the indoor lab wheel. The same test vehicle used for outdoor road tests was moved indoors for lab wheel tests, Figs. 1 and 2. This similar vehicle usage assured that microphone position, tire load, and vehicle reflecting surfaces were essentially the same. The only major differences might be ambient noise level, absence of wind noise indoors, and test surface curvature and texture.

The laboratory wheel used is part of an indoor semi-anechoic test chamber. The ceiling and walls are acoustically treated, but the floor is smooth

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* Numbers in parentheses designate References at end of paper.

ABSTRACT

A study of the differences between the tire noise generated on the road and on a lab wheel was made using the "On-Board" testing technique. An Anechoic Chassis Roll facility was used for the lab wheel, allowing the use of exactly the same vehicle and microphone position for both tests. The only significant differences were the surface curvature and texture, and the absence of wind noise on the indoor lab wheel. Thirteen different carved designs were tested. There were basically three design types - rib, block, and lug - with varying void volume. The results of the study indicate there is good correlation in the more aggressive block and lug designs, but the quieter smooth and rib designs exhibit significant differences.

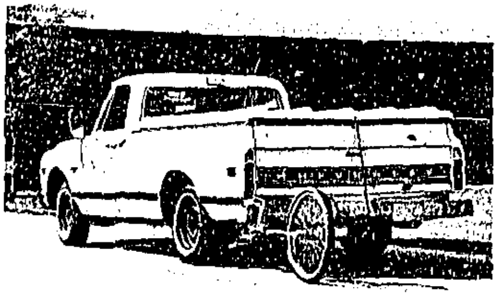

Fig. 1 - Test vehicle used for outdoor road tests

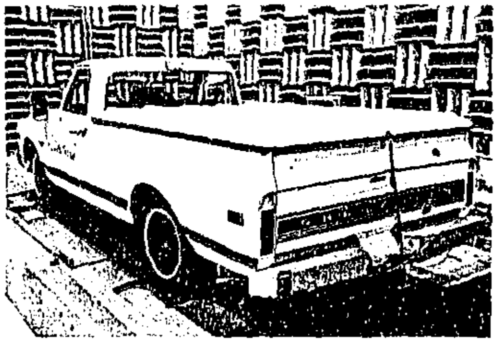

Fig. 2 - Test vehicle as viewed from inside semi-anechoic room

concrete. A vehicle can be positioned on chassis rolls located in the center of the room. Each tire can be driven by a lab wheel, but in this test program only the rear wheels were driven. A coast-down was performed with the vehicle in neutral and motor idling.

The laboratory wheel is two meters in diameter and has a smooth clean steel surface as shown in Fig. 3. No attempt was made in this study to simulate pavement texture or frictional characteristics of the asphalt road test surface, Fig. 4. It was suspected that texture, coefficient of friction and surface curvature are important parameters in the generation of tire sound. This study confirms their importance.

Both indoor and outdoor tests were conducted as coast-downs from 55 - 30 mph (88.6 - 48.3 km/h). Continuous recordings of tire sounds were made and steady-state, A-weighted sound level measurements were taken at 5 mph (8.1 km/h) intervals. No other filtering was performed on the data to adjust the frequency spectra of road or lab wheel tire sounds.

TEST TIRES

In this initial study, it was felt that the sophisticated tread designs of commercially popular tires were far too complex for use in the basic test evaluations. As an alternative, a series of H78-15 bias-belted tires with simple, very basic hand carved tread designs were used. All tires were carved from the same smooth or blank tread tire, ensuring that shape geometry and construction were similar.

Thirteen tires were tested. One tire was left uncarved and twelve were hand carved using three design types; rib, block, and lug, as shown in Figs. 5 - 7.

Tire treads can be designed with varying percent void or groove volume, depending on their intended use and other related design considerations. Within each of the basic carved design groups, four different void volumes are represented.

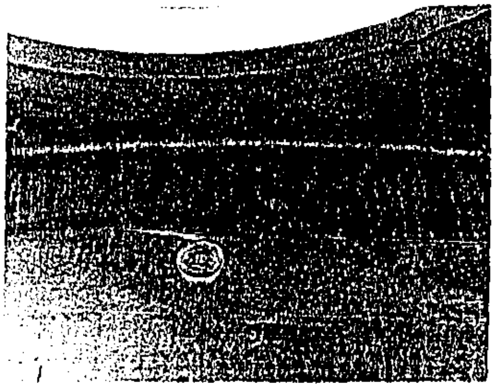

Fig. 3 - Smooth, steel test surface of lab wheel

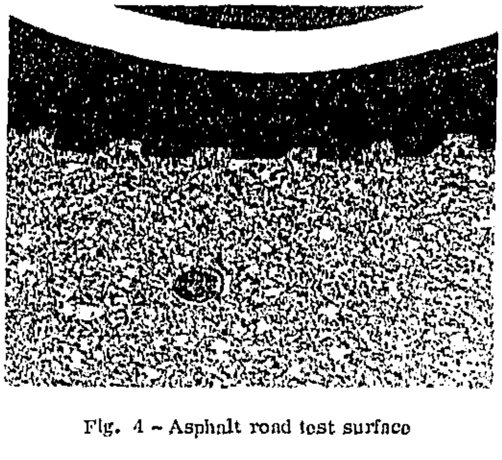

Fig. 4 - Asphalt road test surface

The test tires represent a spectrum of tread designs with void volumes that cover and extend beyond the ranges of currently available commercial tires. It was intended that these 13 tires give a broad overview of the differences that might arise from the many different possible tread designs.

TEST RESULTS

The results of this study were analyzed to determine the statistical correlation between the road tests and lab wheel measurements. A road versus lab wheel comparison of all data points generated in the test program is summarized graphically in Fig. 8. The data points represent near-field sound levels for all 13 test tires at each of the six coast-down speeds.

The calculated correlation coefficient for this data is 0.764, indicating that lab measurements did not linearly correlate well with the road measurements for the entire range of tire designs tested. An examination of the plotted data provides some explanation.

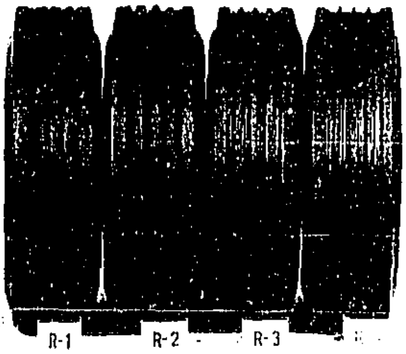

Fig. 5 - Test tires, rib designs

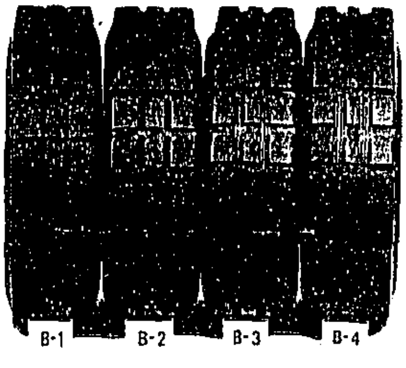

Fig. 6 - Test tires, block designs

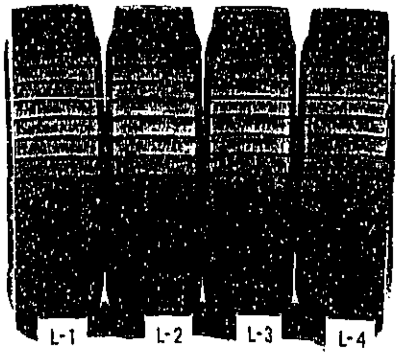

Fig. 7 - Test tires, lug designs

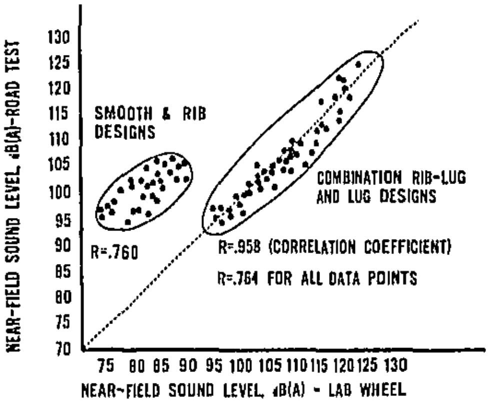

Fig. 8 - Road versus lab wheel comparison of near-field sound levels, dB(A), all tread designs

The data can be divided into two distinct groups, lug and combination rib-lug or block designs, and smooth and rib designs. The first group (lug and block designs) shows a very high correspondence between the road and lab wheel test results. The correlation coefficient for this group is 0.985. The lab wheel measurements are on the average one decibel higher than the road data, shifting the results slightly downward and to the right of the 45°, one-to-one correspondence line shown in Fig. 8. This shift is probably due to greater tire distortion caused by the surface curvature of the laboratory test wheel. The increased distortion may cause the block and lug designs to be slightly louder on the lab wheel. (4)

The smooth tire and rib designs measured quieter on the lab wheel than on the road. The levels were 18 dB(A) lower on the average. This group also had a wider scatter band than the more aggressive lug and block designs and a lower calculated correlation coefficient of 0.760. The reasons for this lower sound level and poorer correlation are uncertain, but are probably due to differences in test surfaces.

A further look into this larger discrepancy between road and wheel tests for rib tires indicates that the primary tire sound generation mechanism for rib designs must be different than for lug type designs. Referring to Fig. 9, which represents a sound level comparison at only one speed, 50 mph (80.5 km/h), the non-linearity in data points that exists throughout the total range of tread designs tested can be seen more clearly. A lower limit to the achievable sound level of this size tire appears to exist when measured on the road surface. Note that measured sound levels of several lug and block designs taken on the road were approximately the same as those of rib or smooth designs. If the tire sound generated by all test tires were of the same mechanism, it would be expected that at least those tires with essentially equivalent outdoor measurements would rate the same on the lab wheel. This was not the case. The sound generation mechanism for smooth and rib designs is apparently different than that for lug designs and is also more sensitive to changes in test surface.

The statistical correlation analysis for individual tread designs is presented in Table 1. The individual tire correlation coefficients range from 0.894 - 0.998. Thus the statistical correlation of individual tires is relatively high, even though the correlation for the total group is much lower as previously explained.

The strength of these individual linear relationships can be seen graphically in Fig. 10. The sound levels at each of the six coast-down speeds are plotted for representative tires of each design type. Note how the data for each design approach a straight line. However, the linear relationships change for different tread designs, probably due to the effects of surface texture and curvature on different sound generation mechanisms.

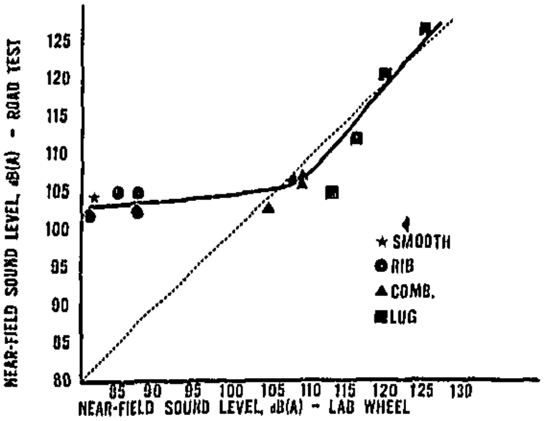

Fig. 9 - Road versus lab wheel comparison of near-field sound levels, dB(A), at 50 mph only

Table 1 - Correlation Coefficients - Road Versus Lab Wheel *

Test Tire		Group I Individual Test Tires	Group II Grouped by Tread Type	Group III	Group IV All Test Tires
	Smooth	0.991	0.991	0.760	0.761
Rib	R-1	0.967	0.785		
	R-2	0.967			
	R-3	0.994			
	R-4	0.992			
Block	B-1	0.998	0.960	0.858	
	B-2	0.991			
	B-3	0.978			
	B-4	0.944			
Lug	L-1	0.894	0.942		
	L-2	0.960			
	L-3	0.997			
	L-4	0.937			

* Measurements taken at six test speeds (30 - 65 mph).

A reasonable explanation of these trends might be the effects of the tread geometry itself on the linear relationship between road and lab wheel. Carving increasingly wider grooves into the test tires reduces the tread contact area and increases the tread pressure on each rib. This increased pressure could cause different aspects of surface characteristics to become influential. The tread rubber could be forced further into the pavement texture or less slippage could occur because of the increased normal force on each rib. Many possibilities exist, but most seem to be characteristic of rib tires only. The lug and block designs were affected less by changes in surface texture and curvature.

SUMMARY

The On-Board testing technique enables a direct comparison of near-field tire sound levels on the road and in the lab with surface texture and curvature the primary apparent differences in test conditions. Test results indicate that the interaction of these surface characteristics with different tire sound generation mechanisms is very important in evaluating the use of an indoor lab wheel to estimate the road sound level of the population to tire designs.

Smooth and rib designs showed a high sensitivity to the change from the flat, asphalt road surface to the curved, steel drum. These tires measured much quieter on the lab wheel. Individually, each rib design showed a relatively high statistical correlation between road and lab wheel. However, these linear relationships varied unpredictably, possibly due to the effects of the interaction between a changing tread geometry (wider groove widths) and different aspects of the surface characteristics. The result is a lower calculated correlation coefficient when the smooth and rib designs are analyzed as a group.

The mechanisms of sound generation of the lug and block designs were affected less by the different surface texture and curvature. These more aggressive tread designs showed a near one-to-one correspondence between road and lab wheel and had a calculated correlation coefficient of 0.958 for this limited group.

In this initial study, no attempt was made to simulate the road surface texture on the lab wheel. Certainly, this is an important area worthy of further investigation. A coarser, textured lab wheel surface may improve the linear correlation for the total range of tread designs by reducing differences between road and lab sound measurements of rib type designs. Other future efforts must be aimed at studying the effects of changing tire size, tire construction, microphone position, signal conditioning, and other test parameters. A similar correlation study must be conducted on truck tires.

The findings of this investigation into the use of an indoor laboratory test to measure tire sound level are encouraging. Although linear correlation between road and lab measurements for the entire range of tread designs tested did not exist when analyzed as a group, individual designs showed relatively high statistical correlation. Those problems associated with the inconsistencies in magnitude differences between road and lab wheel sound levels for varying tread designs do not appear to be insurmountable. However, much experimental work remains to be done to determine the laboratory test conditions that give the best correlation with actual road test sound levels for all tire designs. The advantages of the indoor test, such as controlled test environment, lower testing cost, and convenience, are good incentives to pursue the development of an indoor test.

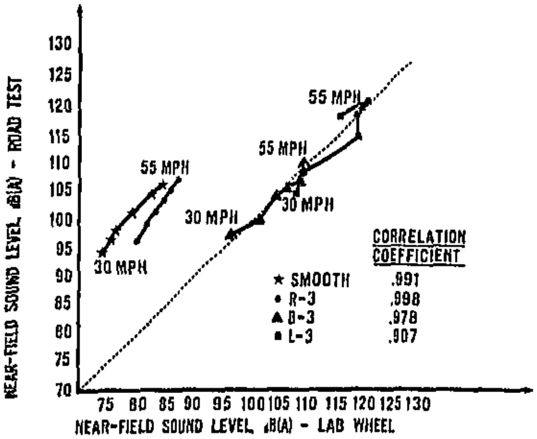

Fig. 10 - Road versus lab wheel comparison of near-field sound levels, dB(A) at six test speeds for smooth, R-3, B-3, and L-3 designs

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DISCUSSION

MR. HICKLING: Did you run all four wheels in the lab test, or just the one wheel?

MR. ANDERSON: The two rear wheels.

MR. MILLER: I want to comment. We hand cut tread patterns for two 10:00-20 tires. We cut one with 90 deg slots (transverse lugs) and another one with 60 deg slots. The outdoor data measured 18 in behind the tire showed similar results for both the 60 deg tire and the 90 deg tire but, the indoor results showed that the 90 deg tire was about 10 dB louder. The interesting thing is that what we expected to find occurred in the indoor test, but not in the outdoor test. I think we still have a long way to go before we have a satisfactory indoor test.

762017

On-Board Tire Sound Level Testing Technique

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THE ON-BOARD TESTING TECHNIQUE measures the near-field sound level of a single tire. The test was developed as a research tool primarily for use in studying the effects of speed on tire sound levels and the investigation of mechanisms which generate tire sounds. An important criterion of the measurement technique for these studies was to isolate the tire sound from other extraneous sounds such as wind and vehicle sounds. The near-field measurement approach, with the microphone mounted on-board the test vehicle and properly positioned behind the test tire, provides a measure of predominantly tire sound with sounds from other sources at a minimum.

The purpose of this paper is to describe the test conditions, procedures, and configuration of test equipment for the On-Board test. The test procedures and conditions differ from those specified in the standard SAE Recommended Practice J57a coast-by technique (1)*, and are applied primarily in investigative studies of tire sound generation, such as those reported in References 2 - 4.

TEST EQUIPMENT

The test equipment used in On-Board sound level testing is summarized and described in Table 1. Note that a light duty pick-up truck is used for the testing of both larger size passenger tires and light truck tires. This type of truck provides a stiffer suspension than a passenger car and, consequently, less movement of the mounted microphone. A special trailer is used for measuring the On-Board sound levels of heavy truck tires. The microphone and other electronic equipment are the same for testing of all tire sizes.

Table 1 - Summary of Test Equipment

1. Test Vehicle	Light pick-up truck (passenger and LT tires) Special trailer (heavy truck tires)
2. Test Tire	Passenger or LT tire is mounted to rear wheel position of test vehicle
3. Microphone	1" condenser type; mounted in fixed position behind the test tire
4. Windscreen	Foam or metal; protects microphone from debris and reduces wind noise
5. Sound Level Meter	B & K Model 2204/S; located in cab and connected to microphone by cable
6. Tape Recorder	Nagra Model IV-D; records tire sound for computer analysis
7. Signal Generator	Triggered, pure-tone generator; marks locations on data tape to be analyzed
8. Fifth Wheel	Mounted to rear of test vehicle; accurately determines test vehicle speed

The configuration of test vehicle, microphone, and fifth wheel is shown in Fig. 1. The instrumentation package (sound level meter, tape recorder, and triggered signal generator) is shown in Fig. 2 as viewed from inside the test vehicle.

An important feature of the On-Board test is the fixed microphone position behind the test tire. Directly behind a rolling tire exists a dead air space

ABSTRACT

The On-Board tire sound testing technique is a research tool characterized by a near field measurement and recording of tire sound generated at the rear of the tire footprint. The measuring microphone is located directly behind the tire within the envelope of the slip stream of air moving around the tire. The test allows the continuous coast-down through the complete operating speed range, excluding the Doppler effect characteristic of the coast-by test. By presenting the coast-down results in a three-dimensional (speed, frequency, sound level) graphical manner, the speed dependent trend sound and constant frequency resonant sound can be easily recognized.

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*Numbers in parentheses designate References at end of Paper.

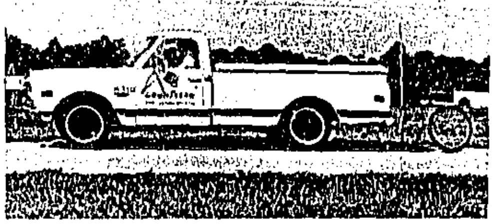

Fig. 1 - Test vehicle, microphone, and fifth wheel used for On-Board Testing Technique

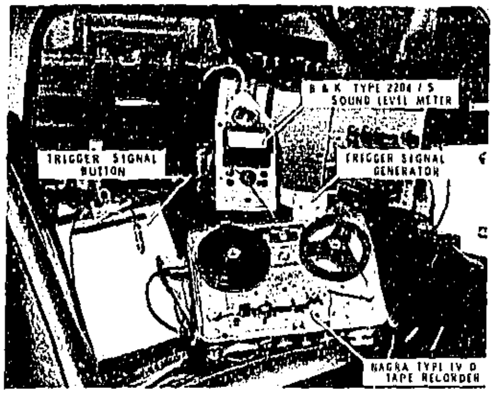

Fig. 2 - Instrumentation package as viewed from inside test vehicle

which is unaffected by the turbulent air flow. The size of the dead air pocket, although dependent upon the tire size and velocity, is usually just large enough to be suitable for placement of a microphone to monitor the tire sound emitted from the rear of the tire contact patch.

To insure placement within this dead air pocket, the microphone should be located as close to the rear of the contact patch of the test tire as practical, allowing clearance for a windscreen on the microphone head as shown in Fig. 3. The minimum distance for the microphone above the roadway must be governed by the test vehicle's suspension travel and load. The microphone should always be located high enough off of the roadway so that there is no danger of striking the pavement due to an unexpected bump or drop-off. The microphone should be centered with respect to the test tire and positioned at approximately equal distances from the tire and the roadway. The microphone axis should be aimed at the center of the rear of the contact patch.

TEST SITE

The test site should be straight and of sufficient length to allow for continuous coast-down of the test vehicle through the desired speed range. A one-half mile test site is normally required for the standard coast-down from 60 - 30 mph (96.6 - 48.3 km/h). A slight uphill grade is preferred to increase the deceleration rate and shorten the required distance.

The effects of different road surfaces can be studied, but all surfaces should be as uniform in texture as possible. A new asphalt surface is preferred because of uniformity and lack of expansion joints, cracks, holes or patches, all of which may cause abrupt fluctuations in the sound being monitored. The surface must be clean, dry and free of any debris that might be thrown up by the tires and hit the microphone.

TEST PROCEDURE

The initial test preparation includes adjusting tire load and inflation to T&RA recommended values, checking test surface for debris, and calibrating the sound level meter and tape recorder.

After the instrumentation is calibrated, the test proceeds as follows. The test vehicle is accelerated beyond the highest speed of the coast-down and put into neutral. The motor is left on, at an idle, so that the power steering and brakes are still operable. Application of the vehicle's brakes should be avoided during the test. As the test vehicle slows during the coast-down, a technician continually monitors the speed and sound level of the test tire. The coast-down is divided into several intervals at which data is taken. Test speeds at 5 mph (8.1 km/h) intervals have been found very acceptable. When vehicle speed corresponds to a desired test speed, the technician momentarily presses the trigger signal button and records the slow meter response reading on a test sheet. The coast-down should be slow enough

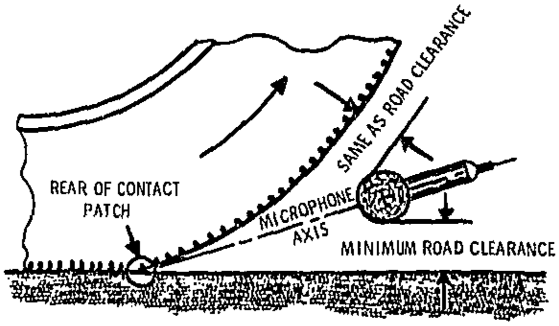

Fig. 3 - Microphone position

to insure that the technician has adequate time to perform these functions. This procedure is repeated at every test speed throughout the coast-down. Tire sound is recorded on magnetic tape throughout the coast-down. A triggered signal generator superimposes a pure high-frequency tone over the recorded tire sound to mark locations on the data tape for further computer analysis. This high frequency tone is filtered out before analyzing the recorded tire sound.

The lowest consistently practical speed for the On-Board tire noise procedure appears to be 30 mph (48.3 km/h). Below this speed, the protective envelope of dead air that protects the microphone often does not extend far enough back to shield the microphone from the air flowing around the tire. The maximum speed that can be tested is not presently limited by the air flow, but by length of the test site, which increases significantly with speed. Speeds higher than 60 mph (96.6 km/h), can be obtained, but usually at a sacrifice in the lower speed range. Normal coast-down is usually performed from 60 - 30 mph (96.6 km/h - 48.3 km/h).

DATA REDUCTION

The analog tire sound signal recorded during the test is played back into a Modcomp II/45 mini-computer and converted to digital values. Digital data are preferred over analog for added flexibility in computer analysis techniques. The analog data can be digitized at various sampling rates and periods, using different filters if desired. Data from each test speed are digitized and recorded on a magnetic tape that will then be read into an IBM 370/158 digital computer. The converted data are analyzed for frequency content, using successive fast fourier transforms. This analysis can be presented as separate plots for each speed or in composite three dimensional form.

The three stages of data recording, data conversion, and data analysis are shown diagramatically in Fig. 4.

PRESENTATION OF DATA

The tire sound coast-down can be presented graphically in a three-dimensional plot

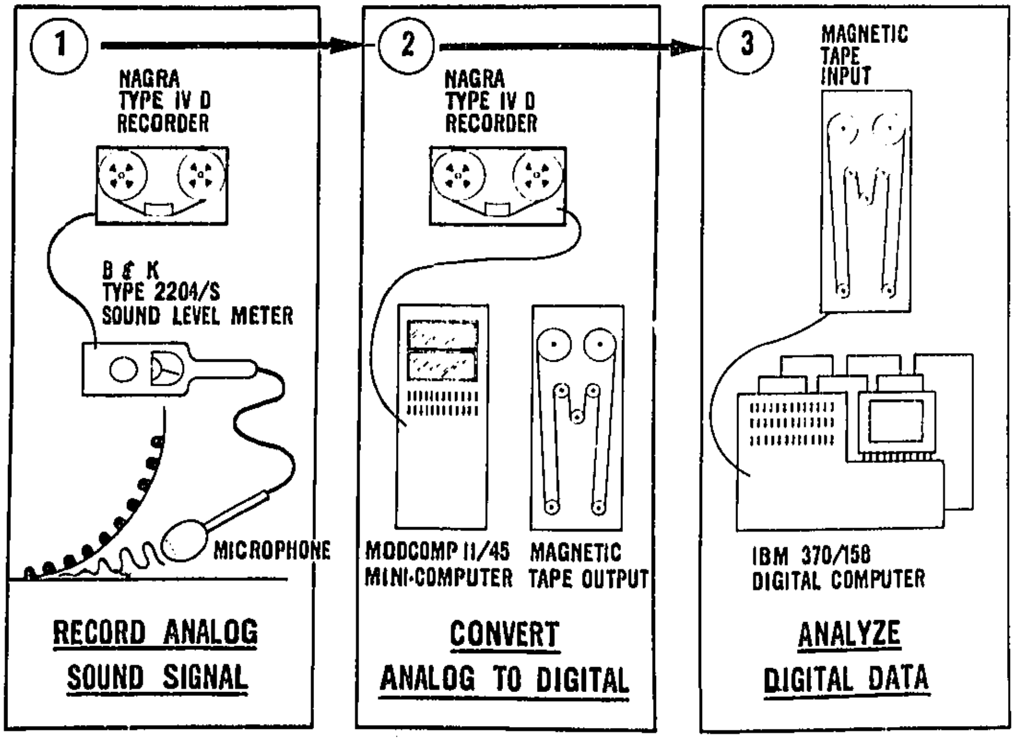

Fig. 4 - Three stages of 1) data recording, 2) data conversion, and 3) data analysis

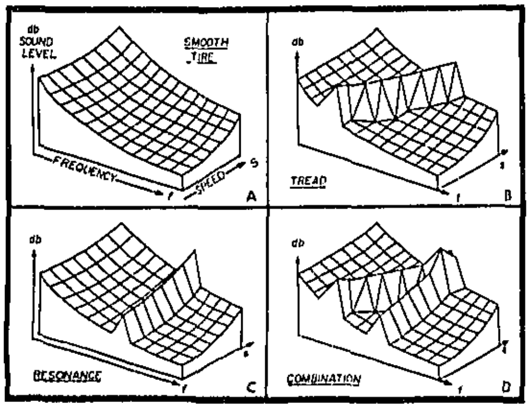

Fig. 5A-D - Three-dimensional plots showing speed, frequency, and sound level relationship of A) smooth tire sound, B) speed-dependent tread sound, C) resonant sound, independent of speed, D) combination of tread and resonant sounds

form. The three axes are speed, frequency, and sound level. This method of presentation makes it much easier to visualize how tire sound changes throughout the entire speed range of the test. This overall picture of the tire sound actually draws attention to problems or trends in the tire sound that might be easily overlooked if the data are presented as a series of separate two dimensional plots.

An ideal theoretical tire may have a plot such as the one shown in Fig. 5A. This plot is very smooth, with a general reduction of sound power as the frequency increases and the speed decreases. Most smooth or blank tread tires exhibit plots similar to this.

Generally, all commercial tires have tread designs that have a repeated pattern around the tire. The repetitive nature of these design elements tends to produce repetitive sound pulses. If the distances between these design elements are constant, the period of time between the sound pulses will be constant and a constant characteristic frequency or tone will be produced. In practice, commercial tires are usually pitched to reduce tonality by having a varying distance between repeating design elements to spread the sound energy into a wider range of frequencies. This frequency-dependent tread sound can be easily distinguished on the three dimensional plot, and appears as a diagonal ridge on the plot as shown in Fig. 5B. Harmonics of the characteristic frequency and pitch sequence modulation frequencies will also appear as diagonal ridges if they are of sufficient magnitude.

Another common characterisitc of tire sound that can be seen using the three dimensional plot is a tonal peak that has a constant frequency throughout the speed range. This sound appears as a ridge that is parallel to the speed axis as shown in Fig. 5C. The constant frequency tone must originate from mechanisms of tire sound that are frequency independent of speed, such as a structural or acoustic resonance.

A special tire sound problem occurs when both types of tonality ridges are present and intersect as shown in Fig. 5D. At the speed where the two cross, there will be a sudden increase in tonality and sometimes even in overall tire loudness as the two ridges reinforce each other. This additive effect can occur several times within the operating speed range of a tire as individual harmonics and the fundamental ridges cross one or more constant frequency ridges.

SUMMARY

The On-Board test is characterized by a near field measurement of the sound level from a single tire. The microphone is mounted directly behind the test tire within the wake of air flow around the tire. When the microphone is properly positioned, the sound that is measured is predominantly tire sound - with wind, vehicle and other extraneous sounds at a minimum. Microphone position is fixed relative to the test tire throughout the entire test, thus eliminating the Doppler effect (the frequency shifts in sound due to a relative velocity difference, and the changing distance and direction, between the sound source and the measurement position that are present in a coast-by test).

Sound level measurements and continuous sound recordings of the test tire are made as the vehicle coasts down through the desired speed range. This continuous measurement technique shortens the testing time and minimizes effects from other variables such as surface temperature, ambient sound level, tire temperature, and surface uniformity. Recordings of the tire sound can be analyzed and presented as a three dimensional "carpet" plot showing speed, frequency, and sound level. This graphical data presentation enhances understanding of the overall effects of speed on a given test tire.

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762018

Passby Sound Level Variability of Automobile Tires

Michael G. Richards
General Motors Proving Ground

TIRE NOISE HAS BEEN A CONCERN in the automotive industry for many years. General Motors has been studying tire noise since the early 1940s. Most of this early work was concerned only with the environment of the passengers.

The causes of both in-car and exterior tire noise are the same, but the rating techniques are very different. This paper deals only with exterior (passby) tire noise.

An exterior noise study concerned with cross lug truck tires was conducted at the GM Proving Ground in 1964. By the early 1970s a number of projects were being undertaken to study the parameters affecting tire noise and to determine the noise generation mechanisms.

The task of developing tire noise rating systems commenced in 1971. Soon after, the need for a standard test procedure arose.

In early 1973, GM management decided that the steel belted radial tires under development (TPC Program) should not generate higher passby levels that the bias belted OE tires then in use. This led to the TPC noise specification.

The rationale and development of the test procedure and specification will be discussed first, followed by data from testing at Milford, Michigan, using a bias belted OE tire as control, between May 1973 and November 1974. During 1974 the bias belted OE control tires went out of production and a decision was made to switch to the ASTM skid tire as control. To permit year round operation, testing since February 1975 has been done at GM's Mesa, Arizona facility.

TEST PROCEDURE

The purpose of developing this procedure was to provide a uniform means of measuring passby tire noise. This development closely paralleled the development of a truck tire noise procedure by SAE. The work of Hillquist and Carpenter (1)* pointed out the importance of road surfaces varia-

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*Numbers in parentheses designate References at end of paper.

ABSTRACT

A passby tire noise test procedure and specification were established as part of General Motor's Tire Performance Criteria (TPC) Program. This procedure was designed to permit testing on various road surfaces at different test sites. As surface texture is one of the most important parameters affecting tire noise a "correction" must be made to normalize the data. The "corrected" noise level of a tire is expressed as the difference (in decibels) between the level of the test tire and that of a control tire run on the same surface.

The data acquired in three years of testing are presented. During this period, two different control tires and three test surfaces were used to test nine sizes of Original Equipment (OE) radial tires from five vendors. The following conclusions and recommendations were reached.

Conclusions and Recommendations

1. The procedure has satisfied GM's objective of developing radial tires with noise levels as low as the bias belted tires they replace.
2. Use of a control tire to normalize the data is limited to the extent that its noise level varies with road surface in the same manner as does the noise of the test tires.
3. The ASTM skid tire (ASTM Standard Pavement Test Tire E501) is not an ideal noise control tire (with existing road surfaces).
4. Limitations of the control tire procedure can be resolved only by eliminating surface variability. A development program should be undertaken to study the feasibility of testing on a controlled (reproducible) surface. A control tire might still be required to normalize non-surface variables.

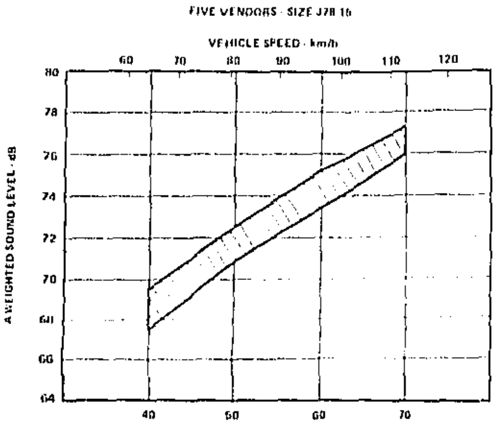

Fig. 1 - Passby noise levels - OE Bias tires at 7.6 m (25 ft)

bles, vehicle speed effects, road-to-microphone distance, etc. To minimize the contribution of the road surface our test work was done on a smooth (macro-texture), rolled, sand aggregate asphalt road. A speed of 80 km/h (50 mph) and a microphone distance of 7.6 m (25 ft) were selected to enable testing under higher ambient noise conditions. The equipment used and test site are the same as recommended in SAE J986a. For the test the vehicle approaches a point 38 m (125 ft) before the microphones, the transmission is placed in neutral and the ignition is shut off. The vehicle is coasted to a point 38 m (125 ft) past the microphones. Four measurements are made in each direction (eight total) and the average A-weighted sound level (dB(A)) reported (Fast Meter Response).

The vehicle is a standard production automobile loaded at 60 - 100% of recommended tire maximum load rating. The tires are balanced and inflated to the vehicle recommended pressure. When the test tires and control tires cannot be fitted to the same vehicle, each tire is run on a vehicle originally equipped with that size tire. This compromises the level of control, but still retains the original objectives that no tire, regardless of size and vehicle, exceed the control level.

The procedure established by Ford Motor Co. (2) is essentially the same except that the absolute noise level is reported rather than the level relative to a control tire.

SPECIFICATION ESTABLISHMENT - The passby noise levels of five (1971-1973) OE bias belted tire sets (J78-15) fell into a band approximately 2 dB(A) wide as shown in Fig. 1. The tread patterns of these tires are shown in Fig. 2. The tire set establishing the lower end of this band (Set 2, Fig. 2) was selected as a control. The specification then required, "The average levels measured from a four tire car set shall not exceed those of the control tires by more than 2 dB(A) at 80 km/h (50 mph)."

MILFORD DATA - OE CONTROL TIRES - Between May 1973 and November 1974, seventy-three sets of identical tread pattern, steel belted radial tires were tested at Milford, Michigan. Fig. 3 shows this 7 rib tread pattern. The bias belted control tires used in these tests is shown in Fig. 2, Set 2. The test tires ranged in size from BR78-13 to NR78-15. Six tire sets were rejected for noise. The average noise level of all tires tested was 0.76 dB(A) above the control tires. The only noise level trends noted in the data were with tire size (See Fig. 4) and with vendor. Both the average noise levels and the levels relative to the control tire ranked the vendors in the same order (See Table 1).

During this 18 month period the control tires were recorded 42 times, with an average level of 70.58 dB(A). Considering the fact that the test site was resurfaced twice during this period (with no before-after level changes) the spread in the data is small (one standard deviation = 1.03 dB(A)). This does not, however, indicate that specifying an absolute passby level is feasible. The exact same set of control tires, run on the same car at the same site, had a range of levels of 4.4 dB(A) during this 18 month period.

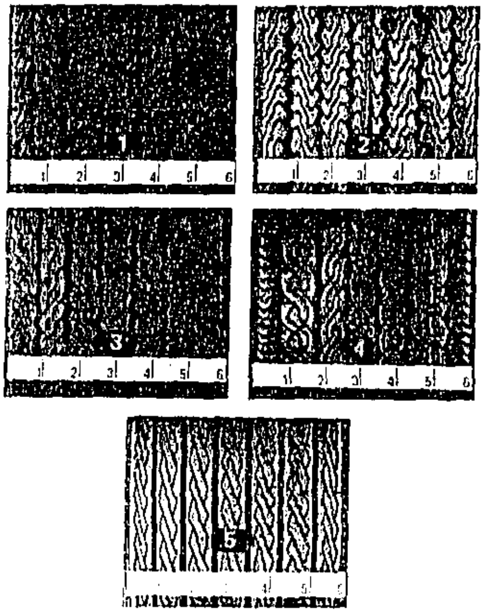

Fig. 2 - Tread patterns of OE Bias tires

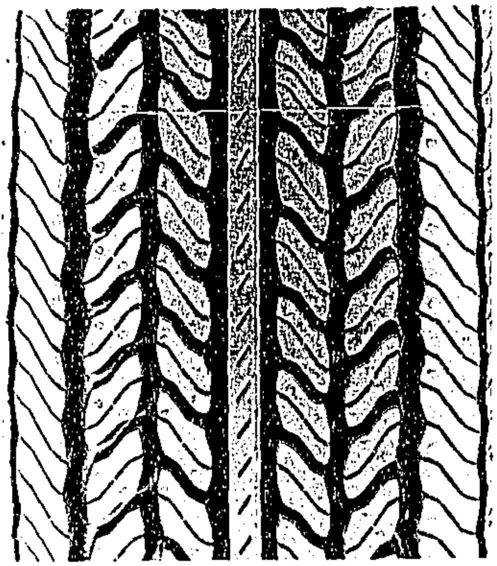

Fig. 3 - Seven rib tread pattern

Table 1 - Average Noise Levels Consistent to Control Tire Levels

Vendor	Samples	Average Level dB(A)	Level Relative to Control
A	12	70.3	+0.03
B	13	70.7	+0.17
C	13	70.9	+0.37
D	20	71.8	+1.28
E	13	71.9	+1.61

Table 2 - Vendor Ranking on Basis of Comparison

Vendor	Samples	Average Level dB(A)	Level Relative to Control
A	14	71.5	-1.91
B	13	71.3	-1.68
C	10	71.8	-1.24
D	16	72.4	+0.04
E	17	72.1	+0.26

TRANSITION TO ASTM CONTROL TIRE - GM decided in late 1974 to switch to the ASTM Standard Pavement Test Tire (G78-15 skid tire E501) as a control tire. This was prompted in part by the OE bias belted tire going out of production. At Milford, the ASTM tires had average passby levels 2 dB(A) lower than the OE bias control tires. The TPC specification was rewritten to read "--- shall not exceed the level of the control tires by more than 4 dB(A)."

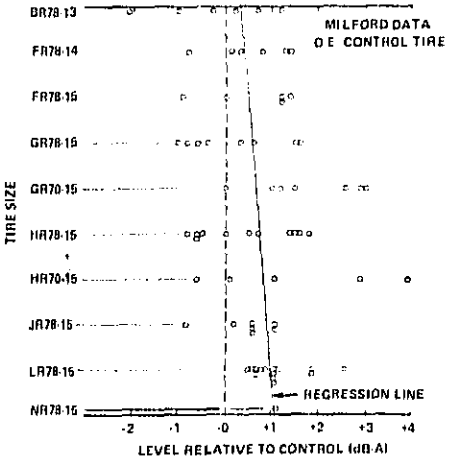

Fig. 4 - Passby tire noise level versus tire size

MESA DATA - ASTM CONTROL TIRE - All GM tire noise testing since February 1975 has been conducted at Mesa, Arizona. The test site meets the requirements of SAE J986a, but the sand aggregate in the asphalt is somewhat coarser than at Milford. Through September 28, 1976, seventy test tire sets have been run. The size range of these tires (from P155-13 to LR78-15), the range of vehicle sizes (from subcompact to full size) and range of construction materials were greater than experienced in the Milford tests. The P155-13 tires had a 5 rib tread pattern and a few samples (FR78-15) were glass belted radials.

Due primarily to the noise level of the ASTM skid tire being significantly higher at Mesa than at Milford (72.3 versus 68.6 dB(A)), the test tires averaged 0.41 dB(A) below the control tires. The trends with tire size were similar to those seen in the Milford data (see Fig. 5). The vendor ranking depends on the basis of comparison (that is, absolute level or level relative to control) as shown in Table 2. The levels relative to the control ranked the vendors in the same order they ranked at Milford.

In mid-May 1976 the Mesa site was given a surface treatment consisting of a solvent deposited low penetration asphalt. This should have had the effect of closing the open voids and thereby reducing the surface macrotexture. The coastby tire noise levels however, went up an average of 1.2 dB(A) in careful before-after tests. Spectral analysis showed most of the increase to be in the frequencies above 1 kHz. Similar results were

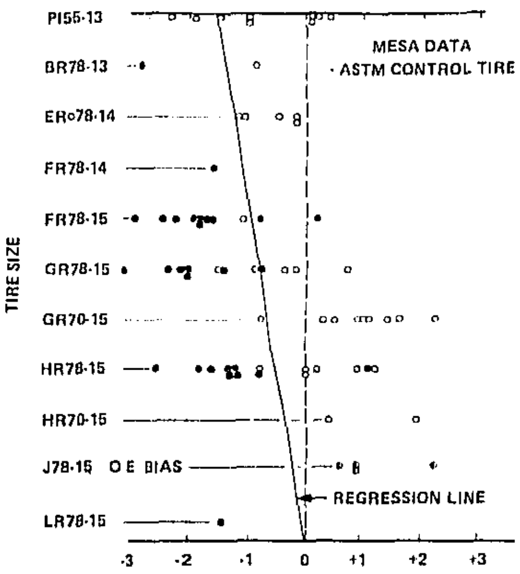

Fig. 5 - Passby tire noise level versus tire size

reported by Veres (2) where levels were higher on a painted surface than on the same concrete surface without paint. We suspect that the effect of painting (or seal coating) is to bring a different noise generation mechanism into play.

The spread in the noise levels of the ASTM control at Mesa has been even greater than with the OE control at Milford (one standard deviation = 1.25 versus 1.03 dB(A).

SUMMARY

From the data in Fig. 5, it is apparent that the original objectives for the tires under development have been met. The quietest of the five OE bias tires had test levels as high as any of the test tires.

In addition to screening the tires under development, the data acquired during these three years has given a better insight into the complexities of tire noise testing. With most of the test tires having noise levels lower than the control tires at Mesa, it is questionable whether the control tire concept is adequate for general purpose testing. This results from the fact the ASTM control tire noise does not vary with surface in a predictable manner. The Ford data (2) again supports this. In their work the level of the ASTM tire dropped with decreasing surface texture and then increased on the smoothest surfaces.

The idea of "calibrating" a test surface by monitoring the noise of a control tire will not work unless the noise mechanism of the control tire is the same as that of the test tire. As the predominant mechanism of experimental tires is seldom known, a different approach is required. We feel that the most promise lies in developing a control surface which can accurately be reproduced at any site.

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DISCUSSION

MR. THRASHER: I was interested in your not being able to obtain a correlation for the variability in the sound pressure level with temperature. Did you actually try to measure the temperature gradient from the road surface up a few in?

MR. RICHARDS: Our people only record the air ambient; I am not sure what the height is.

MR. HILLQUIST: 1.2 m.

MR. RICHARDS: They also record the actual surface temperature, but looking through the 70 runs I couldn't see much of anything relating to temperature, especially in the runs done on the same day. In this case, they would start before the sun would rise and the surface would be quite cool, on the order of 50 deg, and during the next 3 or 4 or 5 h, it would go up about 100 deg.

MR. ANDERSON: The critical thing is the gradient. If I recall correctly, Mr. Endon gave a paper at the Acoustical Society in Washington relying more on the gradient.

MR. RICHARDS: I think that makes sense.

MR. HILLQUIST: There are some tests which have been conducted at the test site at the Milford Proving Grounds and at the Desert Proving Grounds, particularly using passenger cars and trucks following the usual SAE J986 and J366 procedure. It was very carefully controlled using a single set of instrumentation. The test separated those factors which could be attributable to instrumentation, test operation, and surface and random variables. The conclusion was that all of these things boil down to tenths of decibels, as was reported earlier this year at the Noise Expo in New York by Mr. Rutledge. It appears that the instrumentation and physical differences are small, and that what Mr. Richards is finding out has really to do with tires and not measurement methodology.

MR. RICHARDS: I am not sure if it is so much the tires, but again in the tire-road interface area, there are deposits of dust on the road, and other such deposits.

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Possible Effect of Vehicle Aerodynamic Noise on SAE J57a Passby Noise Measurements

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DATA HAVE RECENTLY BEEN OBTAINED at the GM Research Laboratories that relate to the variation in measurement that have been observed with the SAE J57a test.

L. J. Oswald has been investigating the aerodynamic contributions to motor vehicle noise and has tested a number of different vehicles including a SAE J57a type stake-bed truck. In these tests, vehicles have been coasted into the wind and with the wind so that the velocity of the airflow over the vehicle could be varied while maintaining constant vehicle ground speed. In this way the effect of aerodynamic noise can be separated from tire noise.

The SAE J57a tests permit measurements to be made in winds up to 19 km/h (12 mph). Fig. 1 shows the effect of 12 mph winds on the passby noise of a loaded stake-bed truck fitted with four rib tires on the rear axle and coasting at a ground speed of 80 km/h (50 mph). The prevailing winds were running directly along the roadway so that, in one direction, the truck was heading into the wind and in the other direction, with the wind. The air speed on the truck (measured with a pitot tube attached to the truck) and the passby noise at 15 m were measured simultaneously. We see that when the truck is heading into a 12 mph wind, there is on the average an increase in noise of about 2.5 dB(A) and when the truck is moving with a 12 mph following wind, there is a decrease of 1.3 dB(A), giving a total range of 3.8 dB(A). If experimental scatter is included, the possible range in the measurement is about 6 dB(A).

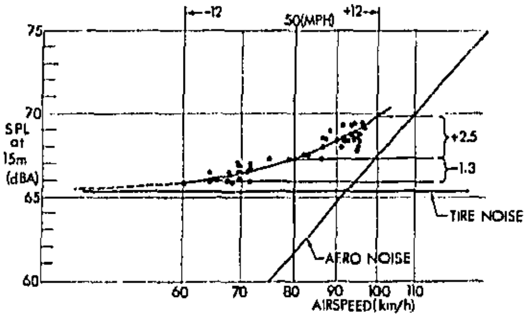


Fig. 1 - Stake bed truck - 80 km/h coastby with rib tires

As has been already stated, the data in Fig. 1 are used to separate the aerodynamic noise contribution from the contribution due to tire noise. For lower airspeeds, the aerodynamic contribution becomes negligible and the curve tends asymptotically to a constant value which is the tire noise of the vehicle at a 50 mph ground speed. The tire noise is seen to be about 65-1/2 dB(A). This value is then subtracted from the data to give the aerodynamic noise contribution which falls nearly along a straight-line as indicated in the Figure. This line has a sixth-power dependence on airspeed which is typical of dipole-type aerodynamic noise sources. When there is no prevailing wind (that is, when the airspeed is equal to the ground speed of the vehicle), the aerodynamic noise of the truck is seen to be about 61-1/2 dB(A). Added to the tire noise, this gives a total of about 67 dB(A) which is roughly an average of all the data points.

ABSTRACT

The aerodynamic contributions to motor vehicle noise have been investigated recently at the GM Research Labs. Vehicles have been coasted into the wind and with the wind while maintaining constant vehicle ground speed. The results of successive tests conclude that vehicle aerodynamic noise cannot be ignored in tire noise testing.

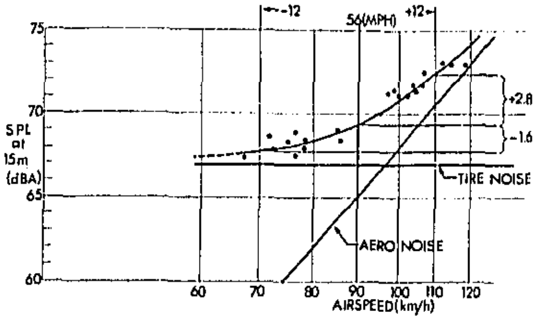


Fig. 2 - Stake bed truck - 90 km/h coastby with rib tires

The average value of 67 dB(A) for rib tires is somewhat lower than has been measured by others in the SAE J57a tests. This is probably due to the fact that, in conformity with the aerodynamic noise tests on other vehicles, the noise measurement was made at the point of closest proximity of the vehicle to the microphone, which was 15 m, rather than at the point of maximum noise in the test area as prescribed in the SAE J57a test procedure. The SAE J57a test also requires that the two highest readings be averaged rather than averaging all the data points. In addition, the test site had a relatively quiet, smooth asphalt pavement. Any or all of these factors may have contributed to the lower level for rib tires recorded in these tests.

Clearly as the tire noise increases, the relative effect of the aerodynamic noise of the vehicle will decrease so that for the noisier types of tires it will not be significant. However, if we are concerned with measuring the noise from quieter tires and in establishing a suitable base level from which to measure tire noise, vehicle aerodynamic noise cannot be ignored. For example, for a tire noise level of 71 dB(A), the aerodynamic noise of the truck will still give a 1-1/2 dB(A) spread in the data on the average if we test upwind and downwind in 12 mph winds. Adding experimental scatter gives a total spread of about 4 dB(A) for the same tires on the same pavement.

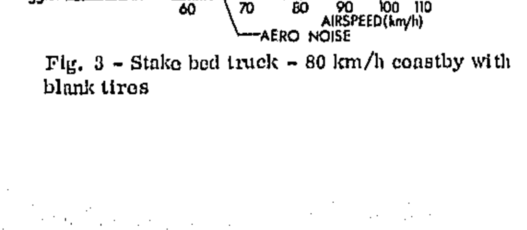


Fig. 3 - Stake bed truck - 80 km/h coastby with blank tires

If the ground speed is slightly higher at 90 km/h (56 mph), as shown in Fig. 2, the vehicle aerodynamic noise becomes more important. In still air it is 66 dB(A) while with a 12 mph head wind, it is about 71 dB(A) on the average.

Finally, it might be of interest to show the data for the same truck at a ground speed of 50 mph with two blank tires on the rear axle, as shown in Fig. 3. The vehicle aerodynamic noise is the same as that determined from the data in Fig. 1, but it is now significantly greater than the tire noise.

The results presented here clearly show that vehicle aerodynamic noise cannot be ignored in the methodology of tire noise testing.

DISCUSSION

MR. THRASHER: I think the graphs are very interesting. We were at the Ohio Transportation Center for four days about a year ago. We weren't quite as fortunate in that the wind was not directly down the path, but at a small angle with the path. We saw similar results to those reported. The change was greater for a low level tire noise than it was for a lug tire.

MR. HICKLING: I would like to make another point. When we made the airspeed measurement, we used a pitot tube on the vehicle, so we knew exactly what the instantaneous airspeed was at the time we were making the noise measurement. If you have a device that measures only the average wind speed, then you will obtain no information that will be helpful in determining the dependence of aerodynamic noise of vehicles on airspeed.

MR. CAMPBELL: I want to make sure that I understood what I saw, which was a graph which showed that at 62 mph aerodynamic noise is a greater contributor to the total vehicle noise than the rib tire noise. Is that correct?

MR. HICKLING: Essentially they are comparable.

MR. CAMPBELL: Comparable; so if we are talking about reducing the overall noise of vehicles, there is as much need to reduce the aerodynamic noise as there is to reduce the tire noise?

MR. HICKLING: If we are talking about the tire noise of a typical truck, then I don't think the effect of aerodynamic noise is so important. But, if we are talking about tire noise standards, and a base level for measuring tire noise, then I think aerodynamic noise cannot be eliminated from consideration.

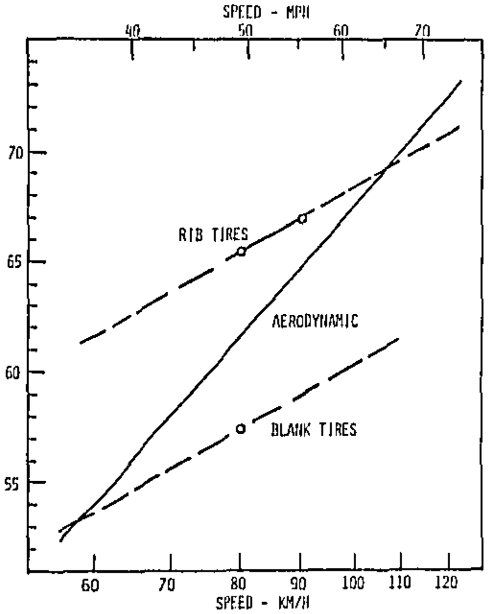
CONTRIBUTED COMMENT

Ralph K. Hillquist

The graphical technique used in this paper for the separation of tire and aerodynamic sounds, lacks some rigor as compared to a regression analysis. With the rather wide scatter bands, approximately 2 dB for rib tires and 4 dB for blank tires, it would seem that a statistical approach would give increased confidence in the results. However, the findings are quite interesting, particularly when viewed in summary form.

Reproduced on the Figure below, are the mean lines for aerodynamic noise, varying as the sixth power of speed, and three data points for tire noise (as determined in Figs 1, 2, and 3 of Oswald and Hickling). Fitted to the two data points for rib tires is a trend line varying as the third power of speed, representing the variation of tire sound (only) with speed. A line of similar slope is fitted through the single data point for blank tires, on the premise that both tire types have the same functional relationship with speed.

Oswald and Hickling observe correctly that the sound levels they have determined for rib tires are lower than those published by other testers. Beyond that, however, the differential of 8 dB between rib and blank tires is also much greater than previously reported. Consequently, the importance of tread pattern as a factor in abatement of tire noise is emphasized, but the premise that noise from rib tires is very near the (heretofore, apparently tire only) "noise floor" is cast into doubt.



It can be seen from the Figure that aerodynamic sound is equal in magnitude to blank tire sound at 36 mph and to rib tire sound at 67 mph. By projecting the trend lines downward to a point where aerodynamic sound does not significantly influence tire sound (10 dB difference in levels), it is found that valid measurement of rib tires can be made only below 31 mph, and of blank tires, below 17 mph, using the stake-bed truck of Oswald and Hickling. Obviously, testing at such low speeds is impractical because of the very quiet ambience needed.

The experimental procedure of measuring the sound level "at the point of closest proximity of the vehicle to the microphone" seems to ignore directionality of both tire and aerodynamic sounds, and as admitted, does not yield maximum sound levels. This procedure is "in conformity with the aerodynamic noise tests on other vehicles," which unfortunately are not cited. Greater confidence in these results would come from the use of standard test procedures or rationale for deviation from them.

The data presented by Oswald and Hickling seem to support their conclusion that "vehicle aerodynamic noise can not be ignored in . . . tire noise testing." However, because of the further implications of this data, continued study into the experimental methods used, and the quantification of truck aerodynamic and tire sounds is seen to be necessary so that abatement of community noise may continue.

AUTHOR'S CLOSURE TO CONTRIBUTED COMMENT

As indicated in our presentation, the data for the stake-bed truck is part of a study of the aerodynamic noise of vehicles which is intended to be published soon. We fully agree that an accurate statistical analysis of such data is necessary. With regard to the present data for the stake-bed truck, it is felt that the implications of the results are clear and would not be affected significantly by any additional refinements in analysis.

The question of directionality is an important one. It is a mistake, however, to suggest that the data that we have presented ignore this fact. In our tests we have measured the sound in different directions relative to the vehicle. To present meaningful data on the separation of aerodynamic noise from tire noise, we felt that it was necessary to standardize with respect to a particular direction, and in this instance, we chose a direction 90 deg to the fore-aft axis of the vehicle. We have found, in fact, that higher aerodynamic and tire noise levels occur in directions other than this 90 deg direction, which would explain to some extent the difference with the SAE J57a measurements. This will be discussed in the forthcoming publication on vehicle aerodynamic noise.

We are in agreement with Mr. Hillquist's observation that, divorced from vehicle aerodynamic noise, tire noise appears to demonstrate a third power dependence on velocity. We have found this consistently in a variety of cases. We feel that this result may be important in studying the mechanisms of tire-noise generation, but we are presently at a loss with regard to explaining it.

762020

An Industry Viewpoint of Tire Sound Reduction and Measurement Methodology

Frank E. Timmons
Rubber Manufacturers Association

FOR THE MOST PART, tire engineers have intuitively chosen to concentrate on the word "unwanted" in the usual definition of noise which is "unwanted sound". In a document entitled "About SOUND" published in May, 1976, by the U. S. Environmental Protection Agency, noise is characterized as follows:

> "Generally, any unwanted sound is referred to as noise. Thus, noise does not necessarily imply that the sound field is loud. It is the attributes making up a noise that determine whether it is annoying. Some of the main attributes are:
>
> 1. The frequency spectrum, broadband or narrowband
> 2. Intensity levels
> 3. Modulation characteristics
> 4. Time and place of the occurrence of the noise
> 5. Duration of the noise (short or continuous)
> 6. Individual background."

In order to reduce unwanted sound, tire design engineers have concentrated on two basic manifestations of noise from tires during the past 45 years. One is the noise created as the tire rolls along the highway in a straight line, and the other manifestation is the squeal which occurs during cornering or braking. By reducing the frequency peaks in the total sound spectrum, annoying concentrations in one limited frequency range have been diffused. Even though sound levels may not have been reduced to a great extent by following this approach, the "unwanted" aspect of tire/pavement interaction sounds has been substantially reduced in tires of current design. It should be noted that the sounds involved, in contrast to those controlled for example by OSHA, are primarily irritating, but not hazardous. We know of no study which would support a premise that tire noise is a hazard to the health and welfare of a community.

Recent reliance by regulatory bodies on decibel readings as the proper measure of noise levels tends to ignore the beneficial results the industry has achieved in changing the character of generated sounds.

NOISE OF THE ROLLING TIRE

Early investigators first tackled the problem of noise of the rolling tire. It soon became evident that the sound was generated at the interface between the tire tread and the road. As a consequence, the industry's earliest efforts to eliminate frequency peaks involved the selection of different tread pattern element lengths. These were scrambled around the circumference of the tire in a much less sophisticated manner than we are accustomed to today.

Fig. 1 is a photograph of a tread design used on tires developed for 1932 model cars. It had a simple three pitch tread design. By scrambling the pitches in an unsophisticated pattern, this simple noise treatment was adequate to eliminate what was then considered to be objectionable sound.

ABSTRACT

The objective of the study of sound created by tires has been to provide a public record assessing factors affecting tire/pavement noise reduction. The tire industry supports the objective of reducing noise, and has worked toward this goal for many years. Once highways in this country became smooth enough, and vehicles quiet enough for the noise created at the tire road interface to be identified, tire designers began including noise reduction as one of the design characteristics to be considered. It is recognized that these sounds are something separate from all other vehicle noise which is heard along side of the road. Substantial achievements in reducing tire/pavement noise has been accomplished over the years.

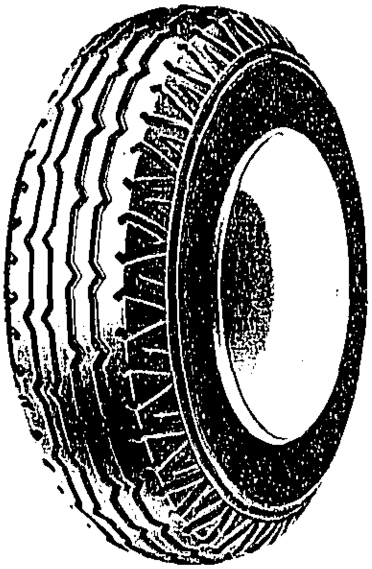


Fig. 1 - Tread design used on tires developed for 1932 model cars

During the 1930s not all tires were this quiet. One popular tread design consisted of a multiplicity of small vacuum cups which created a siren-like noise and was promoted by the manufacturer as "singing safety" - which is a tribute to their advertising department.

TREAD DESIGNS

Prior to World War II tire tread designs remained relatively simple with noise treatments not too much different from the early three pitch treatments illustrated by the 1932 tire shown in Fig. 1.

Following World War II improved roads permitted higher speeds, requiring modification of tread designs for improved traction. At the same time, demand grew for more complicated and sophisticated noise treatments.

A typical modern tread design is shown in Fig. 2. The same principle of varying pitch lengths of the tread elements around the circumference of the tire is still used to eliminate irritating characteristics.

The number of elements is so much greater than in the earlier tire, that the number of different pitch lengths has been increased in some cases to as many as twelve. The possibilities for sophisticated scrambling are many times greater than with a tread having only three pitches.

The tire you see in Fig. 2 is typical of modern passenger car tire tread designs. Each of the different pitch lengths has been painted with a separate color to emphasize the number of different pitch lengths which normally would not be noticed by the average observer.

If we rotated this tire you would observe that

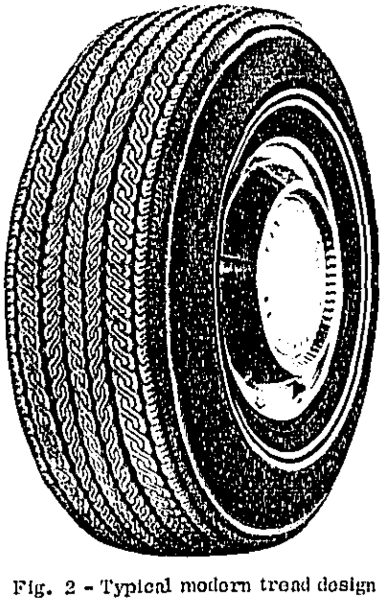


Fig. 2 - Typical modern tread design

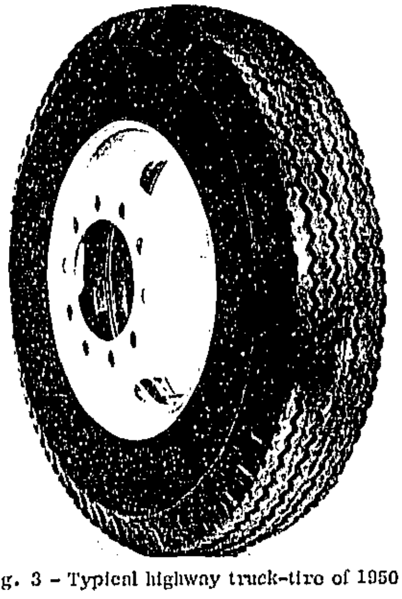


Fig. 3 - Typical highway truck-tire of 1950

the distinct brightly colored elements would blur into a uniform nondescript color.

Like the distinct color frequencies, the different pitch lengths result in distinct noise frequencies. When the tire is rotating at high speed, the blend of the various pitch lengths causes a blend of noise frequencies, which avoids objectionable tonal concentrations, so that the sound one hears is an unobjectionable blur similar to a blur of colors.

The same principles of tread design noise treatment that are used for passenger tires are now being applied to truck tires. Until the 1960s noise treatment of truck tires was of secondary importance. This is understandable since it is only in recent years that other noise sources on trucks have been substantially reduced.

Fig. 3 illustrates a typical highway truck tire introduced in 1950. At that time, noise treatment of truck tire tread designs were generally not used. However, a similar tire which had a simple noise treatment was introduced at about the same time for highway buses.

The mud and snow tire for light trucks illustrated in Fig. 4 was introduced in 1953. This tire had a rather uncomplicated three pitch treatment which eliminated any objectionable whine. Noise treatment of this design was used since tires with lugs or buttons generally create much more noise at the tire/road interface than continuous rib tires.

As with passenger cars, when truck speeds increased with increasing horsepower, the need for additional traction on wet pavements became apparent. New tread designs intended for improved performance on wet roads were introduced and have now become as common for trucks, as they did earlier for passenger cars. Fig. 5 illustrates a modern tread design that was introduced in 1961.

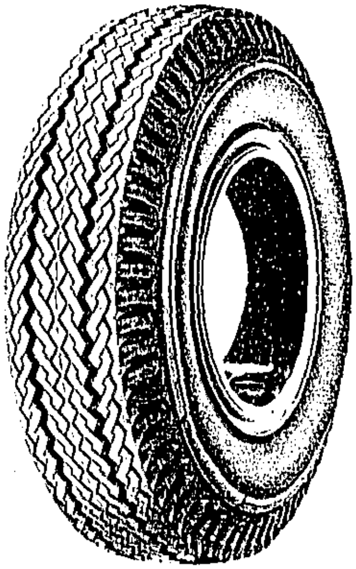


Fig. 5 - Modern tread design of 1961

Newer tread designs have a great number of small tread elements which in turn requires the use of a mixture of different pitch lengths.

Typical highway crossbar tread designs such as shown in Fig. 6 also have scrambled tread element

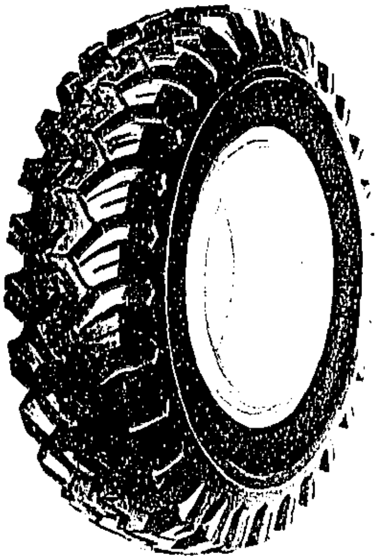


Fig. 4 - Mud and light snow tire for light-weight trucks of 1953

Fig. 6 - Typical highway crossbar tread design

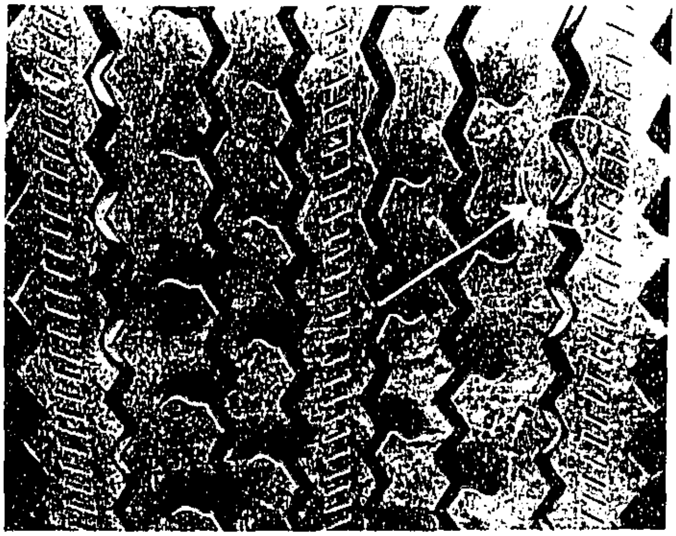


Fig. 7 - Squeal bumpers incorporated in many 1940 tread designs

pitch sequences. This design illustrates perhaps the maximum practical variation in dimensions of sound producing tread elements and lugs. The noise produced by this tire has not been considered objectionable.

CORNERING AND BRAKING SQUEAL

Now I would like to discuss a second source of noise which has concerned the tire industry for a number of years, cornering and braking squeal.

Many of us are old enough to remember 25 years ago or more when tire squeal was a part of normal driving. Those people who were unfortunate enough to live at a curve in the road had to accept the constant irritation of squealing tires.

Tire industry scientists and engineers determined through test and analysis that the source of squeal in passenger car tires is basically vibration of the outer rib of the tread design.

In earlier designs, the method selected for eliminating squeal was to provide dampening through the use of rubber bumpers in the outboard tire grooves which come in contact with the outer rib of the tire when the tread is distorted by cornering forces.

Fig. 7 illustrates the type of squeal bumpers incorporated in many tire tread designs in the late 1940s.

While these devices were effective in reducing or eliminating squeal, they tended to produce more noise in straight ahead rolling as the tire wore. To resolve this problem, at one time dampening characteristics were incorporated into the basic tread design. This is illustrated in Fig. 8 which is a picture of a standard original equipment tread design introduced in 1953. Note the proximity of the two ribs at regular intervals. This provided the necessary dampening when the outer rib is displaced during cornering.

The problem of squeal was eventually handled through the development of synthetic rubber compounds which have adequate dampening characteristics regardless of the tread design geometry. As a result, the mechanical dampening provided by tread design features is no longer required and tire squeal has become an almost forgotten phenomenon.

THE INDUSTRY AND RESEARCH

The tire industry has been successful in substantially reducing unwanted sound that has been historically identified by consumers as noise. Why then is government and industry faced with demands for vehicle noise reduction? We believe the answer is partly that the consumer is more sophisticated and is demanding a better quality of living conditions. More importantly, the trend toward urban living and increasing population gives us greater density of vehicles on the road, traveling at higher speeds, on new road surfaces many of which have been texturized for improved traction and water run off. These changing conditions result collectively in more total noise being generated.

Tire engineers and acousticians are addressing themselves to the problem. However, the industry

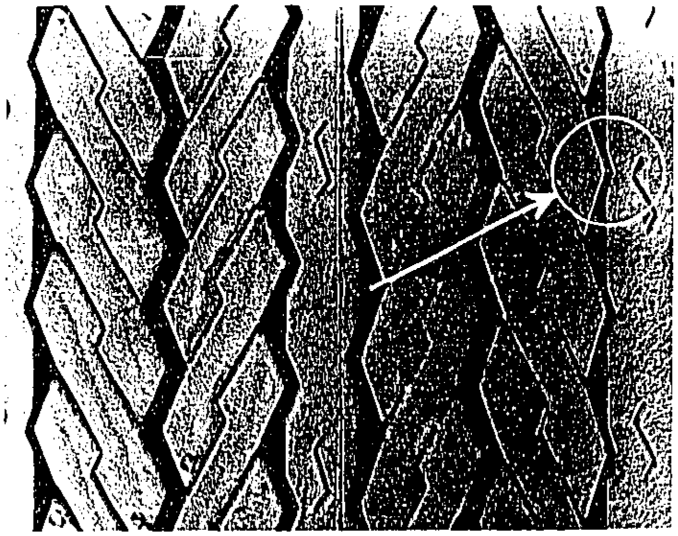


Fig. 8 - Standard original equipment tread design introduced in 1953

is working near the known bounds of technology. In order to expand these bounds, we must find better ways of identifying and measuring the undesirable properties of sounds and relating this to the process of sound generation in tires.

The tire industry has a number of research programs in progress. A tremendous amount of research and development manpower, dollars, and capital investments has been and will continue to be committed to this particular area of product performance.

Tire noise is, and for years has been, an important consideration in the design and development of new highway tire lines. Some people speculate that an easy way to reduce noise is simply to convert the trucking industry to radial ply tires. The tire industry is currently moving toward increased production of radial ply heavy truck tires as quickly as the ability to obtain necessary capitalization and increased technology permit. However, a hasty changeover forced by regulation could have a disastrous effect on the domestic tire industry. Further, there is insufficient knowledge to project whether the use of only radial ply tires in the myriad of tire applications would accomplish the objective of reducing tire/pavement interaction noise. For economic reasons, the trucking industry requires that tires be retreadable. The retreadability of radial ply heavy truck tires is at the present time somewhat of an unknown quantity. The retread industry is developing and must further develop technology to adequately handle the increased volumes and problems associated with recapping of these tires.

Some people also say the way to reduce tire/pavement interaction noise is to convert the trucking industry from cross bar or lug type tread designs to rib designs. The Federal Highway Administration is promoting increased use of aggressive pavement textures in recognition of the value of these surfaces in reducing accidents through improved traction. This type of surface can produce less noise with lug type tires than with rib type tires. Another significant consideration is service applications that dictate the need for aggressive traction tread tires, for example, in the construction industry, and other on-off road operations, particularly where mud, snow and other loosely packed surfaces are encountered. Experience has shown that the use of rib type tires in many of these applications do not provide satisfactory service, and in fact, would produce significant economic and logistical problems.

The SAE J57a coast-by test is the most prevalent method used throughout our industry to evaluate truck tires for sound generation. The procedure is not without fault, although it is reasonably useful to tire engineers. It is meaningful only when tests are conducted on the same test road surface, on the same test vehicle, using the same test equipment and personnel. In addition, constancy is required for the ambient conditions including weather, guardrails, buildings, adjacent vehicles, and other sound reflecting and absorbing objects in the test vicinity. The J57a recommended practice test results are most often used by individual manufacturers to compare certain tires in relative terms on a given surface or surfaces, but not to assign an absolute decibel level. The tire industry believes very strongly that the J57a test procedure is neither desirable nor adequate to assign an absolute and universal level to truck tire/pavement interaction noise. There are simply too many uncontrolled situational variables to allow a reasonable degree of confidence to be placed in the ratings as a means of communicating exact measures of tire noise. Similar vehicle pass-by tests for passenger cars suffer from the same shortcomings.

In an attempt to overcome the shortcomings of the SAE J57a pass-by test, substantial programs are underway in the tire industry to develop a practical, repeatable laboratory sound level test for tires which can be correlated with actual highway experience. Development of such a test has proven to be a somewhat complex task, but good progress is being made. A number of tire manufacturers have constructed highly sophisticated anechoic noise chambers with fixtures, chassis rolls, and other equipment for the purpose of developing laboratory test procedures. The objective is a relatively simple and practicable procedure that will provide a universal measurement of tire noise.

We would welcome and strongly encourage others in related industries or areas with expertise in the acoustical research field to come forward with information helpful in the advancement of this work. Above all, we encourage cooperation between industry and regulatory agencies so that only practical and meaningful standards will evolve, precluding unnecessary loss of time and money in costly litigation and eventual consumer disservice.

DISCUSSION

MR. HODGES: Obviously there is a tremendous interest in tire noise, and many efforts are being made to reduce it. Do you know if there is an equivalent program within the FHWA to noise-treat the roads with the same amount of effort and time that is being given here to tires?

MR. TIMMONS: Of course, I can't speak for the Federal Highway Administration, but I don't know of any programs they have with respect to noise. My understanding is that it mostly has to do with traction and safety.

MR. HODGES: The reason I ask the question is that we are privileged to have a 62 mile stretch of old U.S. Highway 50 which was built 34 years ago. There is one section left, which still has a 28 year old surface. We note with interest that a tandem axle truck and trailer has a significantly lower noise level on that road than it does on Interstate 80 from Reno to Salt Lake City and we were wondering why.

MR. TIMMONS: I don't know. Do you know, Mr. Close?

MR. CLOSE: FHWA does have a number of programs, many of which have already been reported in the literature in terms of relating tire noise to various original concrete brush finishes, as well as overlayment materials and aggregates, chip seals, etc. This has been done in large measure for passenger car noise, but some work has also been done in terms of truck tire noise. Variations obviously have been observed. Measurements have been made in terms of passby as well as interior automobile noise levels, so these data are available and are being factored into the FHWA design criteria. There are obvious tradeoffs, and there is not one set of directions in which you use this kind of material. However, this has to factor into the environmental impact statements, a meeting of the FHWA Highway Noise Standards that apply to new sections of road, or to major programs of reconditioning existing roads, so these factors are working in the system now. It will take time, because obviously the roads last longer than the tires.

MR. HODGES: We have noticed a difference in the noise level between dense-graded and open-graded asphalt. Since this is a Federal Highway specification, it seems to have a significant influence in terms of total dB level change.

MR. CLOSE: I think that is correct, and perhaps what we should do is to try to formulate a bibliography of the reports that have been completed and are in the literature, and try to include them in the proceedings of this conference.

MR. CLARK: I would like to take this opportunity to add something to the statements on pitching, because we may not come back to it again. Several times, tire designers have approached me with a tire design that is too noisy, and have, for one reason or another, said that they cannot change the design. Is there something that can be done in pitching to reduce the sound level of that particular tire? Pitching does not reduce the sound level of tires. It will, you know, make the sound better, but the overall sound level will be the same, if not increased.

MR. TIMMONS: I think that's really what we were trying to communicate with our paper. It is not the sound power generated, but it is the noise which is the annoyance factor of sound that pitching will help.

PART IV
TIRE SOUND GENERATION MECHANISMS

762021

The Relationship Between Truck Tire Vibration and Near and Far Field Sound Levels

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DURING THE LAST SEVERAL YEARS a large amount of tire noise data has been published. A significant portion of these data appear in the literature (1, 2, 3, 4).[*] However, these references do not nearly exhaust the tire noise data available. Most of the data presented are obtained from coast-by or pass-by tests where the peak A-weighted sound level is measured at 7.6 or 15.2 m (25 or 50 ft) from the centerline of vehicle travel along a line perpendicular to the vehicle path. These data have been quite valuable in characterizing the noise of tires. The intent of this paper is to show that measurements of the near field sound and sidewall vibration are comparable to the tire far field noise and thus may be used to reasonably evaluate tire noise characteristics. An additional objective of the paper is to show that the vibration and near field sound measurements are also of great value in the investigation and study of tire noise sources.

The near field sound was monitored through a 1 in condensor microphone attached to the test vehicle. The microphone was located approximately 15 cm (6 in) to the rear of the tire and 20 cm (8 in) above the road surface. The sound signal was measured on a precision sound level meter and recorded on a magnetic tape recorder located on the test vehicle. A miniature piezoelectric accelerometer was mounted on the tire sidewall with a quick-setting adhesive. The acceleration signal was telemetered to the cab of the test vehicle where it was recorded for later analyses simultaneously with the tire sound signal. Both the sound and acceleration data acquisition systems were calibrated so that absolute levels could be determined. Details of the telemetry system and its calibration are given in Ref. 5. The author's experience indicates that the experimental effort required in evaluating the tire noise characteristics through the near field sound and/or sidewall vibration measurement is considerably less than that required in the pass-by technique.

EXPERIMENTAL PROGRAM

Tire sidewall acceleration, near field sound, and far field sound levels were measured and are reported here for tests conducted on two tires at speeds of 64, 80, and 96 km/h (40, 50, 60 mph) operated at a single load on eight different test surfaces. The test surfaces and the rib and cross-bar tires designated tire TB and TD respectively are described completely in Ref 6. The test surfaces are those located at the Texas A & M Research Annex, College Station, Texas.

Fig. 1 shows the sound and vibration monitoring locations. Fig. 2 shows diagrammatically the instrumentation used in the data acquisition. Level analysis of the data was performed with a measuring amplifier operated in slow response with A-weighting.

A qualitative comparison or correlation of the sound and vibration signals was made by simply listening to the recorded signals through stereophonic headphones. The effect of test surface

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[*] Numbers in parentheses designate References at end of paper

ABSTRACT

The paper investigates and proves that measurement of the near field sound and sidewall vibration are comparable to the tire far field noise and thus may be used to reasonably evaluate tire noise characteristics. Other conclusions of the research include: Any two of the three quantities of A-weighted sidewall acceleration near field sound, and peak pass-by sound may be related by a constant for a given road surface and that vibration normal to the surface of the tire is coherent with the tire near field sound.

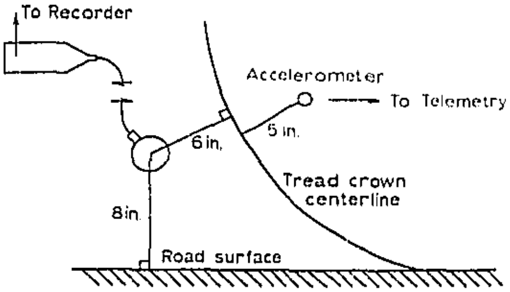

Fig. 1 - Measurement locations of the accelerometer and microphone relative to the tire and the road surface

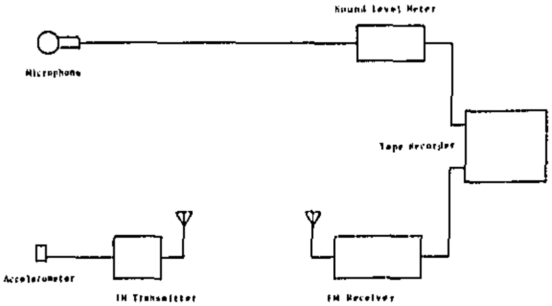

Fig. 2 - Elements of the vibration and sound data acquisition system

texture is readily detected by this method in both the sound and vibration signals. It is particularly convenient to perform these comparison tests since the test surfaces are rather short and produce signals that last for only a few seconds each. Thus, the qualitative comparison for four surfaces requires only about 20 s and provides an excellent indication that both vibration and sound are dependent on road surface texture.

The sound and vibration data for all the tests are given in Tables 1 and 2. In order to consolidate these results, the data were grouped according to the test surface texture classifications given in Ref. 6. That is, the data for the "smooth surfaces" (pads 1, 2, 3, 8) were averaged to give a single set of values. Similarly, the data for the "intermediate surfaces" (pads 4, 5, 6) were averaged, and the data for the "coarse surface" (pad 7) are unaltered. These consolidated data are presented in Table 3.

RESULTS

The consolidated data for the rib tire, TB, sidewall acceleration, near field and far field sound levels are shown in Figs. 3 - 5. The results for cross-bar tire, TD, are shown in Figs. 6 - 8. These results suggest that the difference between any two of the quantities is a constant for a given tire and test surface. For example,

$$C = L_{pff} - L_{acc} \qquad (1)$$

Where:

C is a constant difference between the far field A-weighted sound level, L_{pff}, and

L_{acc} the sidewall A-weighted acceleration level

The constant, C, may be determined in a least squares sense for each set of data. These constants obtained by the least squares procedure are given in Table 4 along with a standard deviation associated with each of the constants. These standard deviations suggest a reasonable correlation between the three quantities considered. Thus, tire sidewall acceleration or near field sound could be used to provide a reasonable prediction of the tire far field sound level.

PREDICTION OF SOUND LEVELS

Based on the results presented here and the tire noise data available in the literature an elementary relationship between the far field sound, vehicle speed, and distance from the source for a given pavement type can be postulated as:

$$L_{pff} = \alpha \log V/V_o + \beta \log r/r_o + \gamma \ . \qquad (2)$$

It is suggested that β be selected so that a doubling of distance results in a decrease of 5dB and that a reference speed of 1 km/h be used for V_o and a reference distance of 15.2 m be used for r_o. Thus, the constant β becomes -16.6 with r in meters and V in km/h. The constants α and γ can then be evaluated in a least squares sense for the test surfaces and data given in this report. These constants are tabulated for the two tires in Table 5, along with a standard deviation evaluated at the reference distance. The postulated relationship (2) could be expanded to include other parameters including test surface, tire tread type, wear, etc. Empirical curve fitting of this type is not a primary intent of this paper.

VIBRATION SOURCE SIZE

The data and results presented here and in

Table 1 - Rib Tire, TB Sidewall Acceleration (Re:10^{-5} m/s^2), Near Field and Far Field Sound Levels (Re:20μPa)

Test Pad 1

	Speed (km/h)		
	64	80	96
L_{PFF}(dBA)	74.4	77.1	78.3
L_{PNF}(dBA)	98.0	103, 0	103, 5
L_{PACCN}(dBA)	131.1	137.5	139.1

Test Pad 2

	Speed (km/h)		
	64	80	96
L_{PFF} (dBA)	72.0	77.1	76,6
L_{PNF} (dBA)	96.7	102.4	104.0
L_{PACCN}(dBA)	129.2	136.5	139.4

Test Pad 3

	Speed (km/h)		
	64	80	96
L_{PFF} (dBA)	71,2	77.4	76.5
L_{PNF} (dBA)	96.7	101.0	102,0
L_{PACCN}(dBA)	129.2	136.2	138.7

Test Pad 4

	Speed (km/h)		
	64	80	96
L_{PFF}(dBA)	72,2	77.4	77.0
L_{PNF} (dBA)	96.6	101.0	103.0
L_{PACCN} (dBA)	129,5	135.3	137,8

Test Pad 5

	Speed (km/h)		
	64	80	96
L_{PFF} (dBA)	70,7	75,3	76.4
L_{PNF} (dBA)	97.0	101,2	102,6
L_{PACCN}(dBA)	128.9	136,1	138,1

Test Pad 6

	Speed (km/h)		
	64	80	96
L_{PFF}(dBA)	72.5	75.6	78,6
L_{PNF} (dBA)	99.5	103.4	105,9
L_{PACCN}(dBA)	134,1	138.3	140,7

Test Pad 7

	Speed (km/h)		
	64	80	96
L_{PFF}(dBA)	74.1	78.1	81.2
L_{PNF}(dBA)	98.8	102.7	105.2
L_{PACCN}(dBA)	132.9	137.8	140.0

Test Pad 8

	Speed (km/h)		
	64	80	96
L_{PFF}(dBA)	68.5	73.3	75,8
L_{PNF}(dBA)	96.0	100.00	102.0
L_{PACCN}(dBA)	128.9	136.8	138,9

Table 2 – Cross-Bar Tire, TD Sidewall Acceleration (Re:10^{-5} m/s^2), Near Field and Far Field Sound Levels (Re:20μ Pa)

Test Pad 1

		Speed (km/h)	
	64	80	96
L_{PFF}(dBA)	77.3	81.3	82.5
L_{PNF}(dBA)	103.0	106.3	109.1
L_{PACCN}(dBA)	138.4	140.7	145.1

Test Pad 2

		Speed (km/h)	
	64	80	96
L_{PFF}(dBA)	78.5	80.2	81.9
L_{PNF}(dBA)	107.2	109.8	111.3
L_{PACCN}(dBA)	137.9	139.9	144.4

Test Pad 3

		Speed (km/h)	
	64	80	96
L_{PFF}(dBA)	75.9	77.7	79.5
L_{PNF}(dBA)	102.6	105.3	107.6
L_{PACCN}(dBA)	138.1	140.2	143.6

Test Pad 4

		Speed (km/h)	
	64	80	96
L_{PFF}(dBA)	73.9	76.7	79.3
L_{PNF}(dBA)	100.0	104.2	106.0
L_{PACCN} (dBA)	136.6	138.9	142.6

Test Pad 5

		Speed (km/h)	
	64	80	96
L_{PFF}(dBA)	73.2	75.3	78.8
L_{PNF}(dBA)	101.2	104.6	106.4
L_{PACCN}(dBA)	137.4	139.5	143.2

Test Pad 6

		Speed (km/h)	
	64	80	96
L_{PFF}(dBA)	75.8	79.1	81.7
L_{PNF}(dBA)	100.0	104.0	106.7
L_{PACCN}(dBA)	137.1	140.4	143.8

Test Pad 7

		Speed (km/h)	
	64	80	96
L_{PFF}(dBA)	74.4	78.4	81.6
L_{PNF}(dBA)	99.7	103.7	106.5
L_{PACCN}(dBA)	136.6	139.5	143.0

Test Pad 8

		Speed (km/h)	
	64	80	96
L_{PFF} (dBA)	76.0	78.1	80.9
L_{PNF}(dBA)	102.1	106.0	107.8
L_{PACCN}(dBA)	137.5	139.4	143.6

Table 3 - Consolidated Sidewall Acceleration (Re:10^{-5} m/s^2), Near Field and Far Field Sound Data (Re:20 μ Pa)

Tire TB

Smooth Surface (Test Pads 1, 2, 3, 8)

		Speed (km/h)	
	64	80	96
L_{PFF}(dBA)	71.5	76.3	76.8
L_{PNF}(dBA)	96.9	101.6	102.9
L_{PACCN}(dBA)	129.6	136.8	139.0

Intermediate Surface (Test Pads 4, 5, 6)

		Speed (km/h)	
	64	80	96
L_{PFF}(dBA)	71.8	76.1	77.3
L_{PNF}(dBA)	97.7	101.9	103.8
L_{PACCN}(dBA)	130.8	136.6	138.9

Coarse Surface (Test Pad 7)

		Speed (km/h)	
	64	80	96
L_{PFF}(dBA)	74.1	78.1	81.2
L_{PNF} (dBA)	98.8	102.7	105.2
L_{PACCN}(dBA)	132.9	137.8	140.0

Tire TD

Smooth Surface (Test Pads 1, 2, 3, 8)

		Speed (km/h)	
	64	80	96
L_{PFF}(dBA)	76.9	79.3	81.2
L_{PNF}(dBA)	103.7	106.9	109.0
L_{PACCN}(dBA)	138.0	140.1	144.2

Intermediate Surface (Test Pads 4, 5, 6)

		Speed (km/h)	
	64	80	96
L_{PFF}(dBA)	74.3	77.0	79.9
L_{PNF}(dBA)	100.4	104.3	106.4
L_{PACCN}(dBA)	137.0	139.6	143.2

Course Surface (Test Pad 7)

		Speed (km/h)	
	64	80	96
L_{PFF}(dBA)	74.4	78.4	81.6
L_{PNF}(dBA)	99.7	103.7	106.5
L_{PACCN}(dBA)	136.6	139.5	143.0

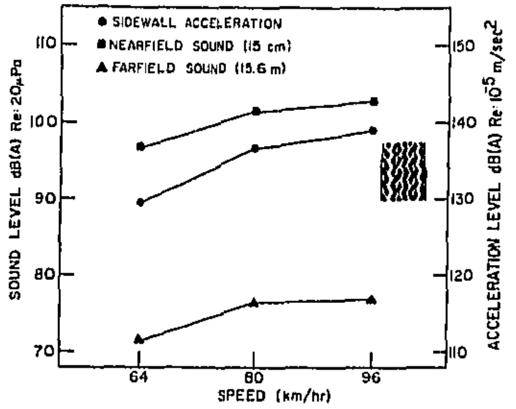

Fig. 3 - Truck tire sound and acceleration levels versus speed for rib type tire TB on smooth surfaces, tire load 2014 Kg (4432 lb)

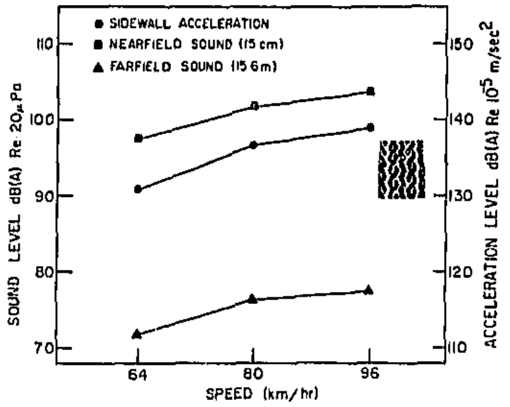

Fig. 4 - Sound pressure and acceleration level versus speed for rib tire TB on intermediate surfaces, tire load 2014 Kg (4432 lb)

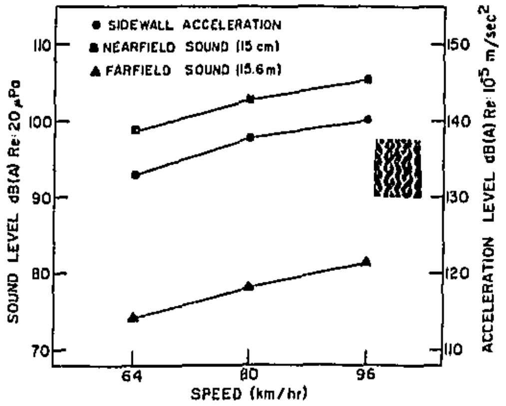

Fig. 5 - Sound pressure and acceleration level versus speed for rib tire TB on coarse surface, tire load 2014 Kg (4432 lb)

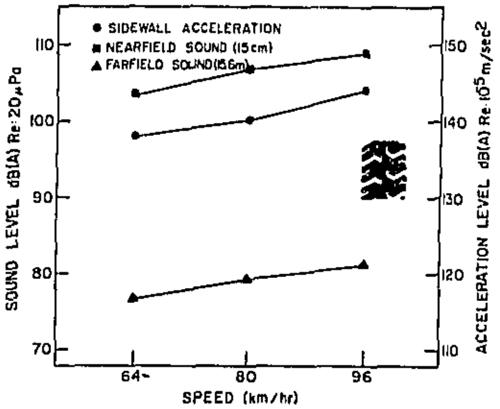

Fig. 6 - Sound pressure and acceleration levels versus speed for cross-bar tire TD on smooth surfaces, tire load 2014 Kg (4432 lb)

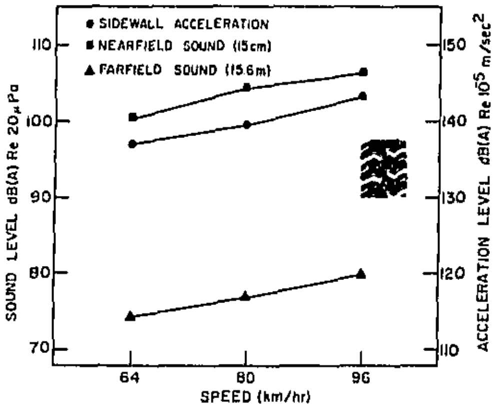

Fig. 7 - Sound pressure and acceleration level for cross-bar tire TD on intermediate surfaces, tire load 2014 Kg (4432 lb)

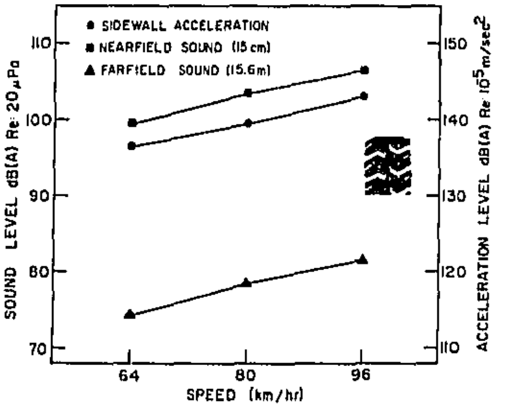

Fig. 8 - Sound pressure and acceleration level for cross-bar tire TD on coarse surface, tire load 2014 Kg (4432 lb)

Table 4 - Constants and Standard Deviations that Relate Sidewall Acceleration, Near Field and Far Field Sound Levels

Tire TB

Smooth Surface

$L_{PFF}-L_{PNF}$(dBA)	σ	$L_{PFF}-L_{PACCN}$(dBA)	σ	$L_{PNF}-L_{PACCN}$(dBA)	σ
−25.6	.44	−60.3	2.0	−34.7	1.8

Intermediate Surface

$L_{PFF}-L_{PNF}$(dBA)	σ	$L_{PFF}-L_{PACCN}$(dBA)	σ	$L_{PNF}-L_{PACCN}$(dBA)	σ
−26.1	.39	−59.1	1.3	−34.3	1.1

Coarse Surface

$L_{PFF}-L_{PNF}$(dBA)	σ	$L_{PFF}-L_{PACCN}$(dBA)	σ	$L_{PNF}-L_{PACCN}$(dBA)	σ
−24.4	.39	−59.1	.52	−34.7	.52

Tire TD

Smooth Surface

$L_{PFF}-L_{PNF}$(dBA)	σ	$L_{PFF}-L_{PACCN}$(dBA)	σ	$L_{PNF}-L_{PACCN}$(dBA)	σ
−27.4	.53	−61.6	1.2	−34.2	1.0

Intermediate Surface

$L_{PFF}-L_{PNF}$(dBA)	σ	$L_{PFF}-L_{PACCN}$(dBA)	σ	$L_{PNF}-L_{PACCN}$(dBA)	σ
−26.6	.62	−62.9	.39	−36.2	.82

Coarse Surface

$L_{PFF}-L_{PNF}$(dBA)	σ	$L_{PFF}-L_{PACCN}$(dBA)	σ	$L_{PNF}-L_{PACCN}$(dBA)	σ
−25.2	.25	−61.6	.57	−36.4	.56

Table 5 - Constants and Standard Deviations for the Prediction of Far Field Sound from the Expression

$$L_{pff} = \alpha \log V/V_o - 16.6 \log r + \gamma$$

Tire TB

	α	γ	σ
Smooth Surface	30.8	16.4	1.1
Intermediate Surface	31.7	14.9	0.73
Coarse Surface	40.3	1.28	0.06

Tire TD

	α	γ	σ
Smooth Surface	24.4	32.8	0.03
Intermediate Surface	31.6	17.0	0.22
Coarse Surface	40.9	0.56	0.03

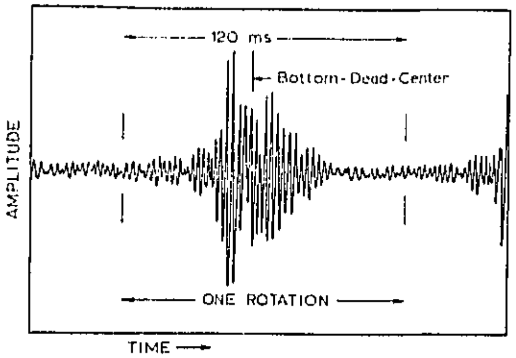

Fig. 9 - Acceleration time history for a single tire rotation

the literature indicate tire vibration to be a noise source. Two fundamental questions concerning this source are its size and the relative importance of the tread and sidewall vibrations of the tire in contributing to the noise generated. Examination and analysis of the sidewall and tread acceleration time histories provide insight in answering these questions. Fig. 9 shows a typical sidewall acceleration time history. It is apparent from this Figure that most of the vibrational energy occurs near the region of road contact. Analyses of the acceleration level during short time intervals corresponding to small portions of a single tire revolution clearly show the decay rate of tire vibration at a point on the tire sidewall. These acceleration levels determined for 6.4 ms intervals are shown in Fig. 10. The level of acceleration of a point on the tire is observed to decrease to 50% or 1/2 of its maximum value in a time interval of 8.8 ms at a test speed of 80 km/h. The maximum acceleration level is observed to occur just as a point on the tire leaves road contact. For 10:00 x 20 radial ply tires investigated it was found that the area of significant vibrational energy is restricted to the section of tire extending from the contact patch approximately 20 cm along the tread and sidewall. This region of significant tire vibration appears to be independent of vehicle speeds between 60 and 100 km/h. It has been shown that vibration measured normal to the surface is coherent with the sound produced by the tire (7,8); thus, it may be concluded that the tire vibration is a noise source related to the sound produced at the coherent frequencies. Analysis of this vibration source to determine relative contributions of tread and sidewall as a function of frequency is discussed in a subsequent paper (9).

TREAD/SIDEWALL TRANSFER FUNCTION

In addition to definition of the source size, the source location or radiating area must be established. The source location, tread/sidewall or both, can be investigated through the tread to sidewall frequency response or transfer function. The ordinary and complex frequency response functions are defined as

$$H_1 (f) = \left[\frac{S_y (f)}{S_x (f)} \right]^{1/2} \qquad (3)$$

and

$$H_2 (f) = \frac{S_{xy}(f)}{S_x (f)} \qquad (4)$$

Where:

S_x (f) is the spectral density of the tread acceleration,

S_y (f) is the spectral density of the sidewall vibration

S_{xy} (f) is the cross-spectral density between the tread and sidewall.

The results obtained from (3) and (4) may be considerably different since (4) provides an indication of events only common or phase locked between tread and sidewall. Expression (3) on the other hand may reflect inputs arriving at the sidewall position that are not related to the acceleration measured in the tread. Frequency response functions computed digitally according to the discrete forms of (3) and (4) are shown in

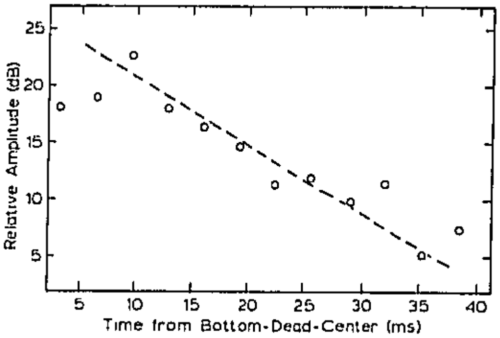

Fig. 10 - Tread vibration level versus time for a radial cross-bar truck tire. Vehicle speed 80 km/h, tire load 1155 Kg (2540 lb)

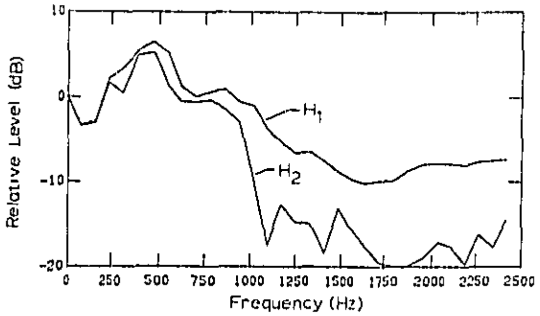

Fig. 11 - Tread to sidewall frequency response functions for a radial cross-bar truck tire. Vehicle speed 80 km/h, tire load 1155 Kg (2540 lb)

Fig. 11 for a cross-bar radial tire. Fig. 11 shows that the acceleration levels in both the tread and sidewall are of nearly the same magnitude below 1000 Hz. Thus, both the sidewall and tread can be noise sources or sound radiators. The identification of the noise contribution of the sidewall must be determined by additional analysis involving the coherence between the tread, sidewall, and near field sound. This analysis is beyond the current intent of the paper and is discussed in Ref. 9. Analysis of tire vibration has thus shown that the vibration source size has a characteristic dimension of approximately 20 cm and that the sidewall as well as the tread area may be contributing to the tire noise.

CONCLUSIONS

In this investigation it has been demonstrated that for loaded, new, cross-bar and rib type tires:

1. A-weighted sidewall acceleration, near field sound, and peak pass-by sound levels follow the same trends and any two of these quantities may be related by a constant for a given road surface.
2. Near field sound and/or sidewall acceleration can provide a meaningful estimate of the far field sound level.
3. The qualitative effect of road surface on both tire sound and vibration can be audibly detected through monitoring of recorded near field sound and sidewall acceleration signals.
4. The significant region of tire vibration has a characteristic dimension of approximately 20 cm.
5. The region of the tire in the vicinity of road contact dominates the tire vibration field.
6. Vibration normal to the surface of the tire is coherent with the tire near field sound.
7. Both tire sidewall and tread vibrations are potential producers of tire noise.

Continued investigation of these phenomena is required to further define the tire noise sources.

ACKNOWLEDGEMENT

The U. S. Department of Transportation Office of Noise Abatement is acknowledged for support of this work under D. O. T. Grant OS-20105.

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DISCUSSION

MR. THRASHER: You pleased me by making the statement that you used yourself as a detector; that lends much credibility to your data. Many of us forget that the best detector, as far as acoustics is concerned, is your ears. If it doesn't sound right, then there is a probability that the data are wrong.

MR. WILLS: I was wondering if these tires were balanced, and what effect would a balanced tire - opposed to an unbalanced tire - have on this particular test?

MR. EBERHARDT: The actual rotation frequency is about 7 Hz. We didn't balance the tires; however, we didn't detect any low frequency contribution due to imbalance at the rotation speed. We are more interested in higher frequency content. We do see a rotation rate frequency content complement (fundamental frequency equals the vehicle speed speed divided by the tread spacing); but, whether or not it is related to imbalance I can't say.

MR. POPE: If you were looking at acceleration in the sidewall, you would find that there was a large variation in acceleration due to centrifugal effects, even if no sound were radiated. Could you outline how you separated this effect?

MR. EBERHARDT: We are measuring normal to the surface. We are 90° to any centrifugal effects, and the accelerometer is not sensitive in that plane. In the tread region, this is not the case at all. Certainly what excitation is felt by the accelerometer is also felt by the tread as the motion changes from a circular arc to suddenly being in contact with the road, so there is a large spike which is easily seen in the data.

I think you also see this in the sidewall. Actually in the sidewall spectral history, you don't see the DC value, because the sidewall is not in contact with the road. You do see the spikes arising. The coherence between tread and sidewall is quite high. The energy moves from tread to sidewall quite readily.

MR. THRASHER: The accelerometer itself will not respond to a DC level. The response function does not go down to 0 Hz. As a result, you are not going to see the DC component. You will only see any AC portion.

MR. EBERHARDT: Correct, but when the accelerometer enters the contact patch there is AC value. There is a gradient, in a sense. We see the gradient, and the gradient is the very large spikes.

MR. REITER: I think the $R\omega^2$ (centrifugal acceleration) is very important, and is probably what is causing a lot of excitation of the tire. I agree that if you spin a tire with our system on it, you don't measure anything in terms of acceleration; there is no DC. Thus, I think what we are doing is correct, and I don't think there is a problem.

MR. THRASHER: I am interested in whether or not both of your tires were bias or radial ply, in order to obtain the relative decay rates of the acceleration signal on the sidewall or on the tread for the radial and bias tire.

MR. REITER: The data presented were for radial ply tires. We have data that you want; it is being organized for distribution. There are some significant differences, but we should probably wait before we talk about them.

762022

Research on Individual Noise Source Mechanisms of Truck Tires: Aeroacoustic Sources

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Fluid Dynamics Research Dept.

INVESTIGATIONS have been conducted into the mechanisms of tire noise generation using the single-wheel trailer discussed in Ref. (1)*. The various tire noise mechanisms that have been postulated in the literature can be divided roughly into three general areas associated with gross flow aerodynamics, air pumping between the treads of the tire and from small depressions in the roadway, and vibration of the tire and its treads. This paper presents results in the first two areas, which we have called collectively aeroacoustic sources. Work in the third area is proceeding and results from it will be reported at a later time.

GROSS-FLOW AERODYNAMIC NOISE

For a blank tire rolling on a smooth pavement into still air the possible aerodynamic sources are as depicted in Fig. 1. Because of the shape of the tire there are separated flow regions both ahead of it and behind it. Large-scale vortex shedding also occurs in the wake of the tire. Because the tire is spinning, noise can be generated by the incoming airflow impinging on the moving tread and sidewall surfaces. Finally, as proposed by Siddon (2), the spinning of the tire lowers the pressure in a small region near the ground directly behind the tire, and, as the airflow coming around the tire flows into this region, trailing vortices are formed which can inter-

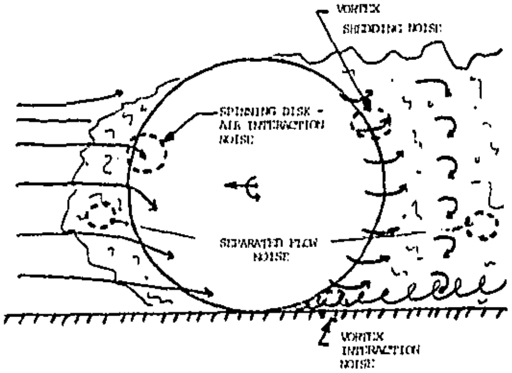

Fig. 1 - Possible gross flow aerodynamic noise sources

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*Numbers in parenthesis designate References at end of this paper.

ABSTRACT

The objectives of the tire-noise research being conducted at the GM Research Laboratories are to determine, in detail, the origins of tire noise and, if possible, to use this information to devise methods of quieting tires, particularly truck tires.

To date the noise mechanisms that have been investigated relate to the gross airflow around the tire, and the air-pumping between the treads. The first type of noise has been shown to be negligible, even for treadless tires. For the second type of noise, the investigations have centered principally around cross-bar tires where it was felt that the air-pumping mechanism might be most significant. In addition to on-the-road measurements, the study of the air-pumping mechanism has involved mathematical modeling and simulation tests in the laboratory. The measurements have clearly demonstrated the existence of the air-pumping mechanism and show that it is the major contributor to the noise from the type of cross-bar tire tested. Several means are suggested for reducing the noise of the air-pumping mechanism in cross-bar tires.

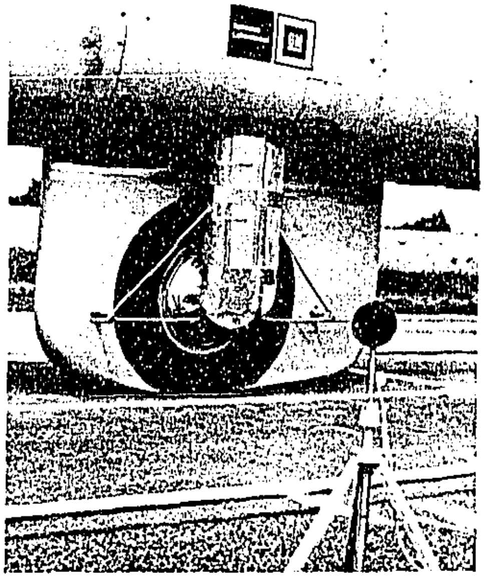


Fig. 2 - Fully streamlined tire mounted on single-wheel trailer

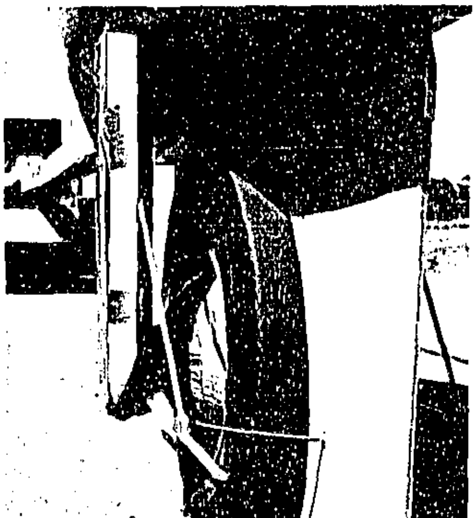


Fig. 3 - Splitter board to eliminate noise due to vortex shedding and interaction

act to form a pulsating monopole source.

Various flow-control devices were used to inhibit and interfere with these possible aerodynamic sources, both individually and collectively, to determine whether the presence of the sources could be detected in a passby measurement of the tire noise. Front and rear fairings, Fig. 2, were used to eliminate the noise from all the sources. A thin splitter board behind the tire, Fig. 3, was used to eliminate the noise both from vortex shedding and from vortex interaction and an airshield was used, Fig. 4, to eliminate the spinning disk-interaction noise. These tests were conducted with a blank tire rolling on a relatively smooth pavement in order to enhance the effect of the aerodynamic sources. The air shield and splitter plane were also used with a cross-bar tire because the spinning disk-interaction noise and the vortex interaction noise would be expected to be greatest in this case.

The passby noise was measured using a stationary, semicircular array of five microphones, Fig. 5, as described in the Ref. 1. Both 1/3 - octave

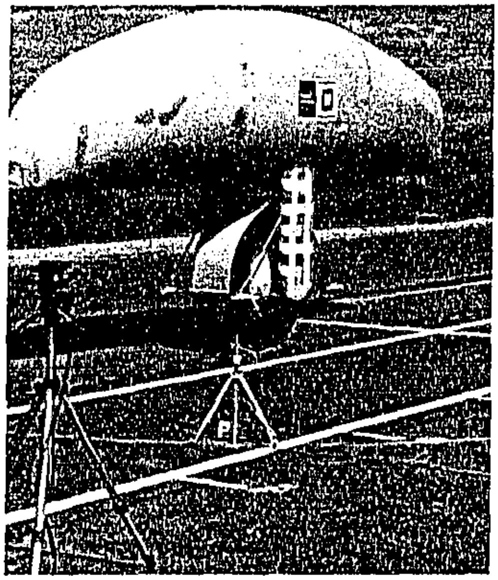


Fig. 4 - Airshield to eliminate spinning disk-interaction noise

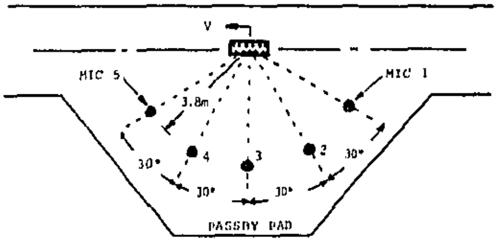


Fig. 5 - Stationary array of microphones to measure the noise radiation characteristics of a moving tire.

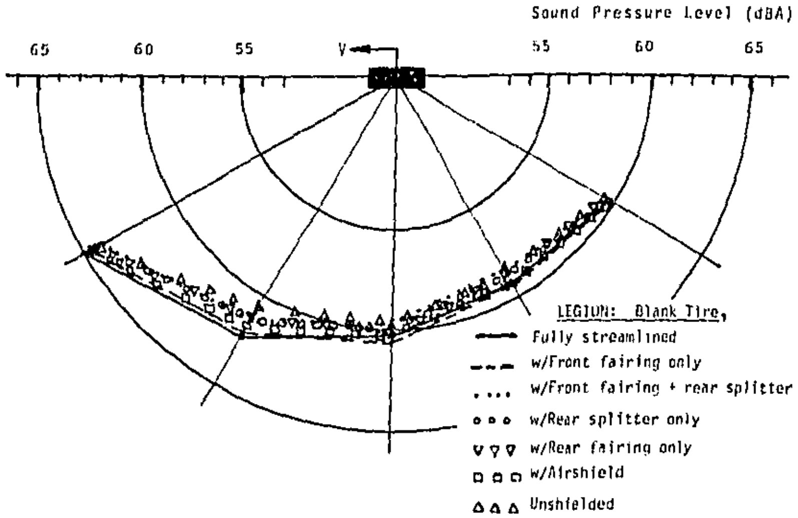


Fig. 6 - Sound radiation from configurations tested, V = 48 km/h

spectra and overall A-weighted radiation patterns were determined at 48, 72 and 96 km/h, the data being averaged over several runs. Results were compared with and without the flow-control devices.

The results at 48 km/h would not be expected to show the effects of aerodynamic noise as strongly as at higher speeds. However, with the possible aerodynamic sources reduced at this slow speed, it can be determined what effect, if any, the flow-control devices might have on the "scrubbing" noise radiated by the interaction occuring at the tire-roadway interface. All of these devices were configured to permit direct line-of-sight acoustic radiation from the tire contact patch to the microphones in the semi-circular array, while at the same time preventing acoustical reflections from traveling in the direction of the microphones. Fig. 6 shows that, within the limits of experimental accuracy (±1 dBA) with data obtained on different days under similar conditions of temperature, humidity and wind, no effect of the addition of these devices could be detected at 48 km/h.

At 96 km/h, the results were analyzed in greater detail, since the strongest effect of aerodynamic noise would be expected to occur at this highest speed. Results for all the various conditions tested are shown in Figs. 7 and 8. Fig. 7 gives the A-weighted radiation patterns obtained with the five-microphone array and shows that, within experimental error, no effect of gross flow aerodynamic noise from any of the possible sources could be detected for a blank tire. This conclusion is supported by the spectral data, an example of which is given in Fig. 8 for the microphone at position 3 in the array.

Additional tests were conducted with a cross-rib tire to see if the deep lugs in the tread could create an enhanced and detectable effect either in the spinning disc-interaction noise or in the vortex interaction noise. Use of the air shield and splitter board showed that no noticeable effect could be determined in the passby noise from this type of tire either.

Finally, a flow visualization test was conducted to determine whether there was any indication of a strong vortex interaction region near the ground in the near wake of the tire, as postulated by Siddon (2). A tufted grid was placed at various locations relative to the tire as shown in Fig. 9 and a movie camera was used to observe the tuft motion. The flow direction, as indicated by the tufts shown in Fig. 9, was all that was observed. It is seen that the tire does act somewhat in the manner of a centrifugal air pump. However, there is no evidence of vortices or of a vortex interaction region.

The results indicate that none of the postulated forms of gross flow aerodynamic noise depicted in Fig. 1 can be measured. However, given that our measurements are accurate only to within ±1 dBA and that some of the scatter shown in our results may be due to aerodynamic sources, then it can be estimated that, at most, aerodynamic noise levels at 3.8 m from a blank-tread tire are of the order of 52 to 55 dBA at 96 km/h. When this is considered relative to the fact that most tires are run on much rougher road surfaces, a blank tread tire generating normally 78-80 dBA at 3.8 m at 96 km/h (and higher for treaded tires), then gross flow aerodynamic noise of any type of truck tire at any highway speed

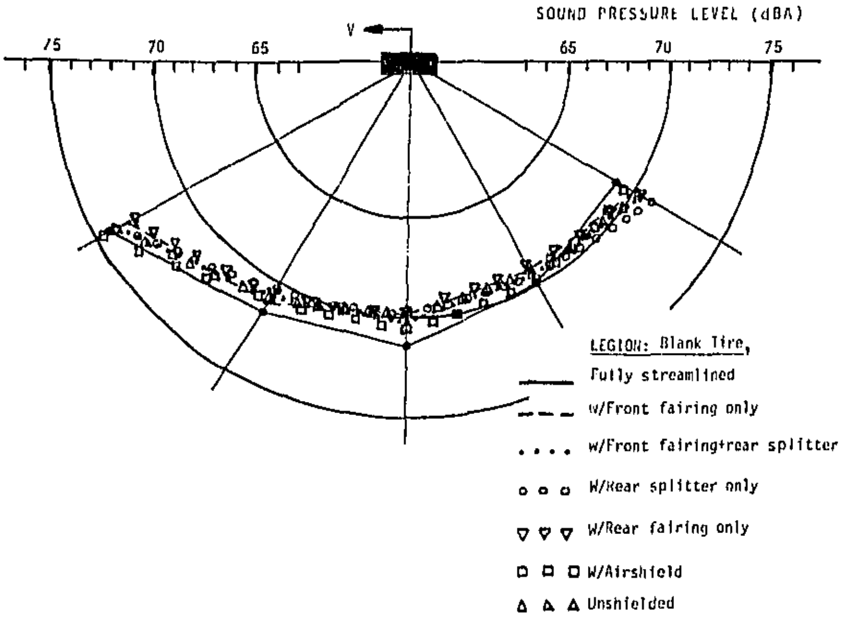


Fig. 7 - Sound radiation from configurations tested, V = 96 km/h

is insignificant. Presumably this conclusion would also hold for passenger car tires.

AIR PUMPING BETWEEN TIRE TREADS

The squeezing of air from the grooves of tires was first proposed as a tire noise mechanism by Hayden (3). The mechanism has subsequently been investigated by others (for example, Reference 4) but, as yet, neither a detailed description of the physical process nor a direct experimental verification of its existence has been provided. These are supplied in the work reported here. A related study by the GM Proving Ground on the noise from

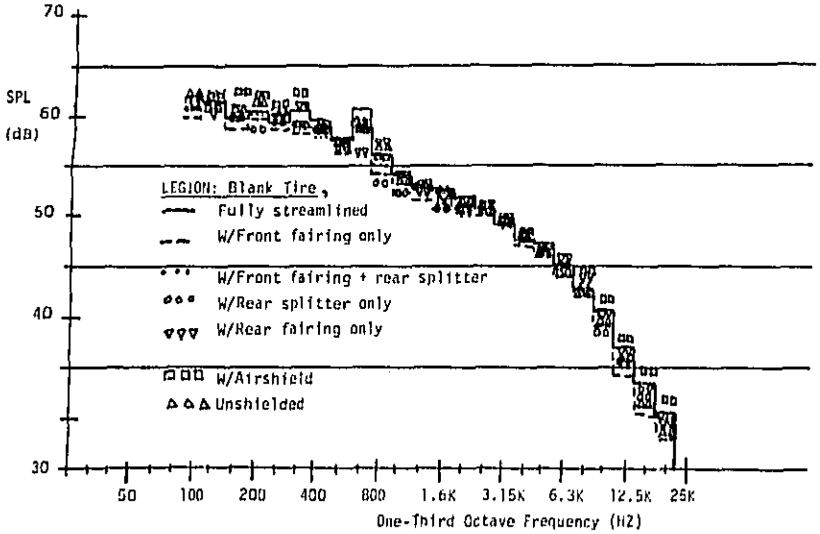


Fig. 8 - One-third octave noise spectrums of the configurations tested, V = 96 km/h, mic. 3 of array

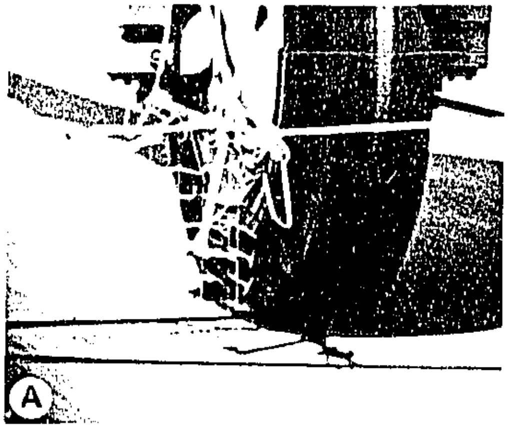
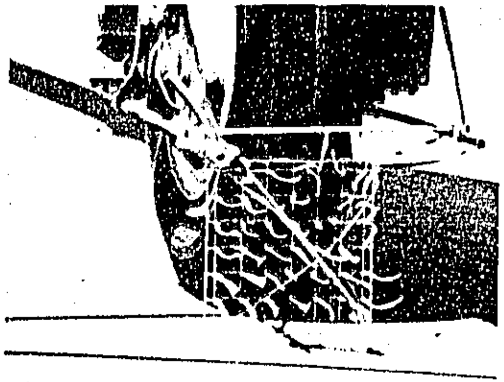


Fig. 9A - Side of tire

B

Fig. 9B - Rear of tire, 20 mm from treads



C

Fig. 9C - Rear of tire, 200 mm from treads

Fig. 9 - Photographs of tufted-grid flow visualization test to look for trailing vortices - 96 km/h

cross-bar tires is reported by Richards (5).

The approach adopted was to determine the characteristics of the air-pumping noise and at the same time develop a means of reducing the noise of the air pumping without affecting other likely noise mechanisms, in particular tire vibrations. With these tools the contribution of the air pumping mechanism in the overall noise from a tire could be evaluated. Mathematical modeling and laboratory simulation of the air pumping from a tire cross groove were used as a first step in this approach. It was found that the dominant feature of the sound generated by a single groove as it passes through the contact patch of the tire should be an initial pulse followed by a decaying sinusoid with frequency f_1 corresponding to the quarter wave resonance of the groove. The wave form was predicted to be almost triangular. The corresponding frequency spectrum showed a peak at f_1 and lower peaks at odd harmonics of f_1. The modeling and simulation methods also demonstrated that acoustical foam set in the groove reduces the peak sound pressure by factors of 4 or 5 as the groove is compressed. Acoustical foam also virtually eliminates the decaying sinusoid occuring after the initial pulse. The corresponding spectrum shows that the foam can reduce the peak at f_1 by about 30 dB and can reduce the sound in the range from $1/2\ f_1$ to $1 - 1/2\ f_1$ by more than 10 dB overall. In addition acoustical foam is flexible enough so that it should not affect the noise generated by tire vibrations which is the only other likely noise source.

The next step was to study the sound generated on the road either by a single cross groove (11 mm deep, 95 mm long and 22 mm wide) or a single lug (about 60 mm in circumferential width flanked by two cross grooves of the same dimensions as the single groove) cut in a blank tire. With these the time history of the sound shows how noise is generated as the single element (groove or lug) enters, passes through and exits from the contact patch.

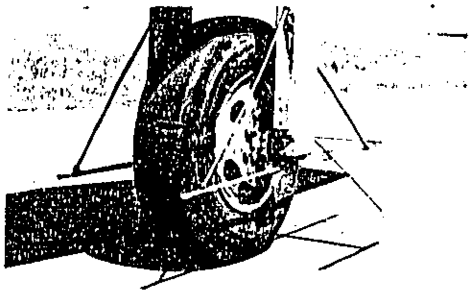


Fig. 10 - The single cross groove

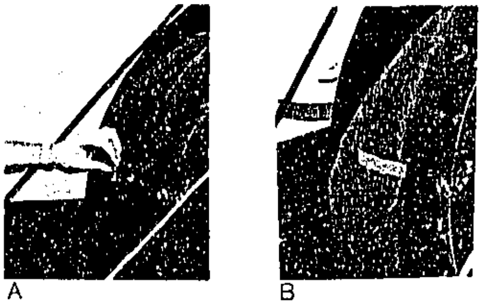

A
B

Fig. 11A & B - The single groove filled with acoustical foam

The test tire with the single groove is shown in Figs. 10 and 11 mounted on the single-wheel trailer (1). The sound was measured using microphones moving with the trailer. The microphone and its adjustable attachment is shown in Fig. 10. To reduce the interference caused by wind noise on the microphone, the sound of the tire with the single element is averaged over successive revolutions of the tire, a once-per-revolution pulse being recorded simultaneously with the sound. When averaged in this way, the sound produced by the single element tends to remain while the random part associated with the wind noise is greatly diminished.

The pressure-time histories* for different microphone positions around the tire with the single open groove is shown in Fig. 12, while Fig. 13 shows the corresponding plot for the groove filled with acoustical foam. The microphone positions are at 30° intervals on a semicircle of 0.61 m radius from the center of the contact patch and 0.15 m above the roadway. The measurements were made with a nose-cone-covered 1 in condenser microphone on the groove side of the tire at a vehicle speed of 72 km/h (45 mph). The trace at microphone position IV at the side of the tire, shown again in Fig. 14, clearly shows the passage of the open groove through the contact patch. High sound pressures at about 10 and 22 ms are generated as the groove enters and leaves the contact patch. The 12 ms interval between these events corresponds to the length of the contact patch at 72 km/h. The sound generated as the groove enters and leaves the contact patch is recorded strongly by the microphones to the front and side, but becomes less distinct for the microphones towards the rear. Similarly the sound generated as the groove exits the contact patch is not discernable from the microphone positions in front of the tire.

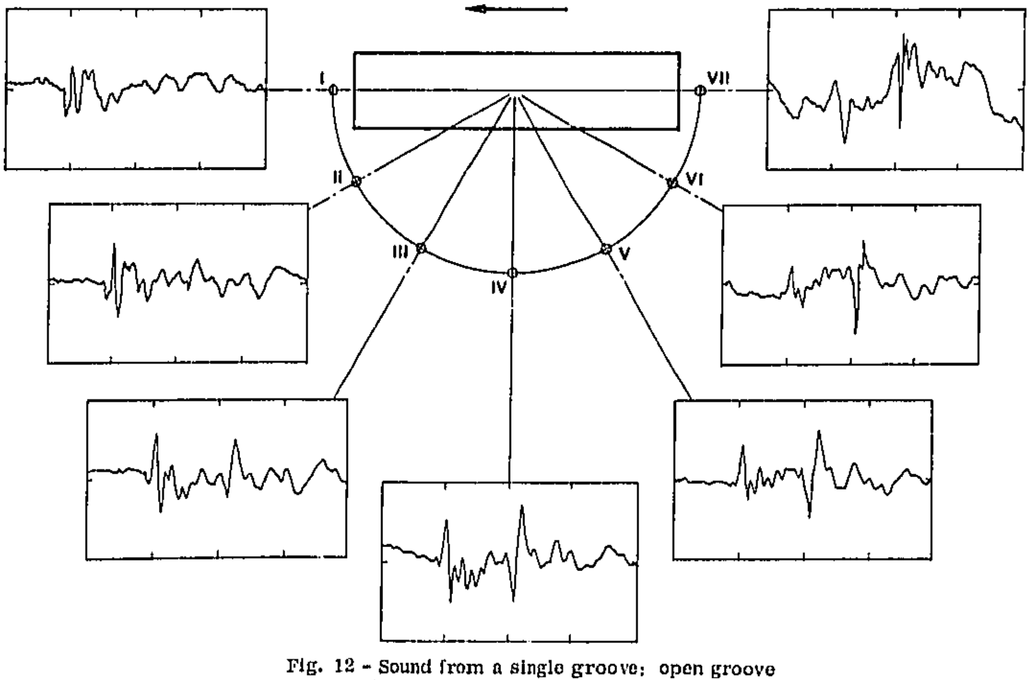


Fig. 12 - Sound from a single groove: open groove at 72 km/h (45 mph)

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*The value of P in all the figures is 4.16 N/m^2. The polarity of the instrumentation indicates that +P is negative sound pressure.

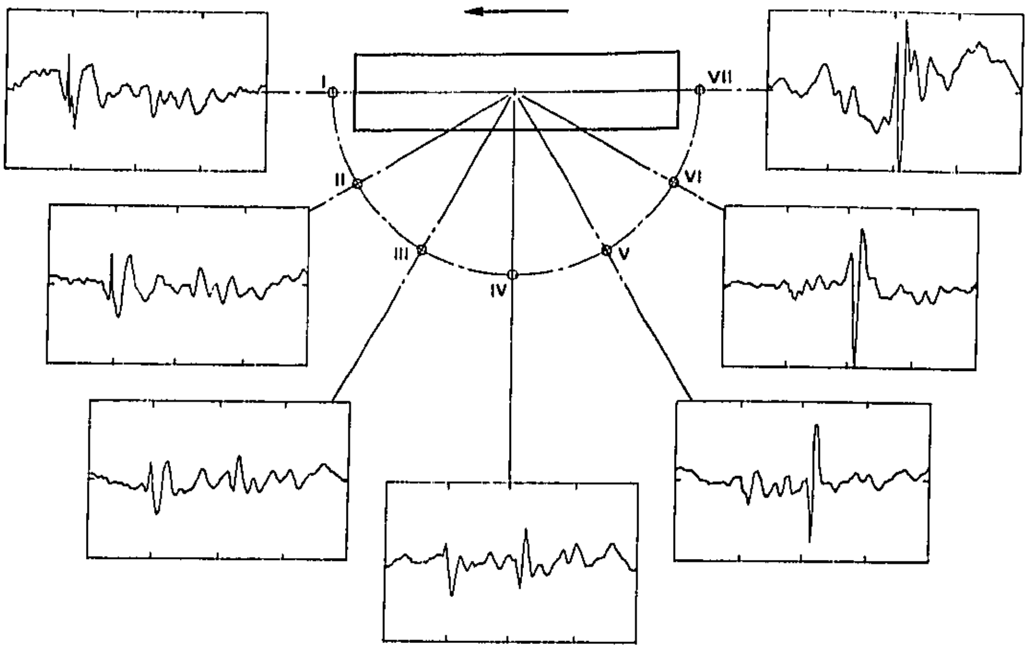
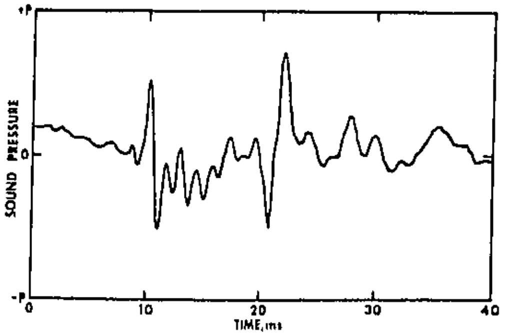


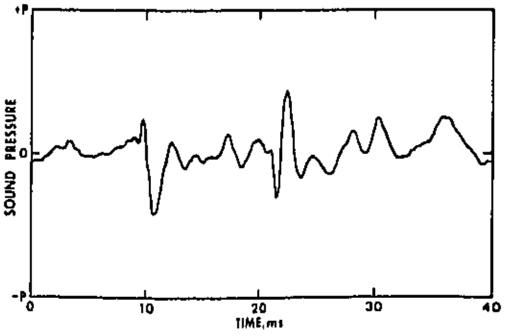
Fig. 13 - Sound from a single groove: foam filled groove at 72 km/h (45 mph)

Figs. 12 and 13 show that the generation of noise by a single cross groove is a complex process. Sound is generated at all phases of the groove's passage through the contact patch. The sound due to air pumping occurs as the groove enters and begins to pass throught the contact patch. The sound pressures for open and foam-filled single grooves at the side of the tire (microphone position IV) are plotted in Fig. 14 to allow a closer examination of the data. The decaying sinusoid predicted by the simulation and modeling studies is evident in Fig. 14 and begins as the groove enters the contact patch at about 10 ms and decays over the next 5 or 6 ms, or about one half of the contact patch length. The 800 Hz frequency is lower than the 900 Hz corresponding to the quarter-wave resonance of the groove, but is close to the 850 Hz predicted when a 5% correction is added to the length of the groove to account for the mass of air moving just outside the end of the groove as determined in the simulation studies. When acoustical foam is added to the groove, the 800 Hz sinusoid disappears.

Although each wiggle in the time histories of the noise of a single groove cannot be accounted for at this time, the data does yield an important conclusion. The presence of the decaying sinusoid at nearly the quarter-wave resonance frequency of the groove and the elimination of this component by the



A Open Groove



B Foam-Filled Groove

Fig. 14A & B - Sound from a single groove: microphone IV (90°), 72 km/h (45 mph)

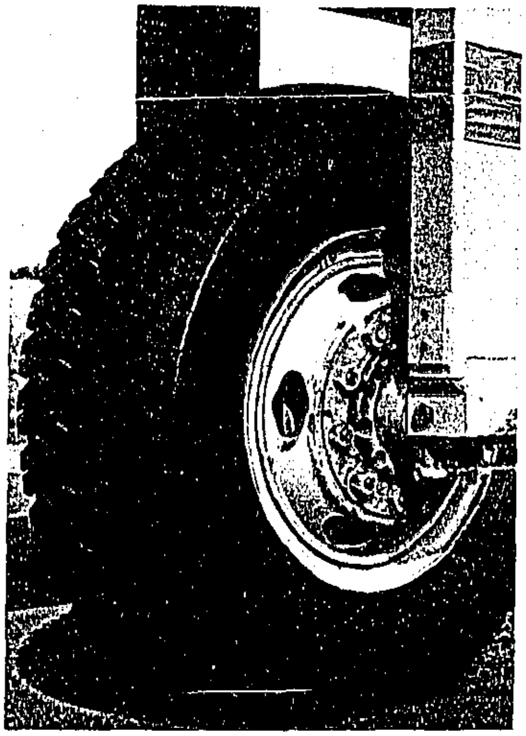


Fig. 15 - Test cross-bar tire

acoustical foam provide clear evidence that this component of the noise is generated by the compression of the groove and by the groove's response as an open-closed cavity.

The sound of the single cross lug was measured and analyzed in the same manner as the single cross groove. For the microphone position to the side, the sound generated by the single lug is similar to the superposition of the sound generated by two cross grooves. An oscillation of about 800 Hz follows the entry of each groove into the contact path which is eliminated by the presence of acoustical foam.

In the final part of this study, the noise of a commercial cross-bar tire, pictured in Fig. 15, was measured with and without acoustical foam in the cross grooves. The 42 lugs are unequally spaced, but the lengths of the grooves, as measured from the side-wall inward, are identical. This tire is typical of many commercial cross-bars and was chosed because it is a popular tire and because it has well-defined lugs and grooves. Also, noise levels measured under SAE J57a pass-by conditions are available for this tire (6, 7). A feature of this tread pattern and many others similar to it is that the grooves are not "vented" by circumferential grooves. If the air-pumping mechanism is a significant contribution to tire noise, it should be for this type of tire when all the air squeezed from the groove must pass out one end.

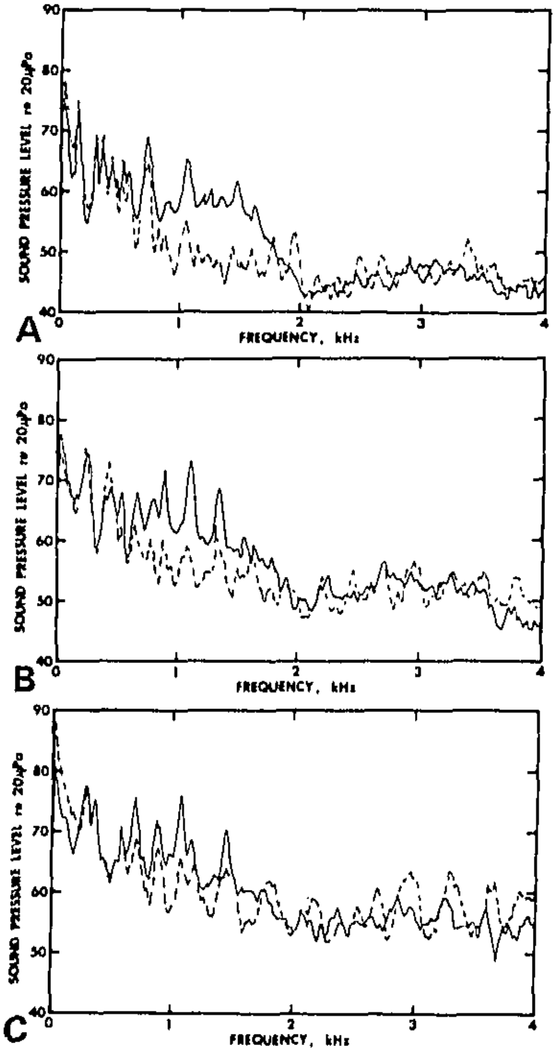


Fig. 16A, B, & C - Noise from cross-rib tire for microphone (A) 48 km/h, (B) 72 km/h (C) 96 km/h (Note: Solid lines denote open grooves, broken lines denote foam-filled grooves)

The noise was measured with and without foam for a microphone moving with the trailer. Pieces of acoustical foam were hand cut for the grooves on both sides of the tire and mounted with contact cement. Then it was loaded with 21.2 kN at an inflation pressure of 540 kPa (4760 lb at 75 psi) which are the maximum rated load conditions when the tire is used as one of a dual pair. Sound was measured at the side of the tire both close to the tire (position IV, 0.61 m out and 0.15 m above the roadway) and far from the tire (3.0 m out and 1.0 m above the roadway).

The narrow band spectra of the sound at the far microphone are shown in Fig. 16 for vehicle speeds of 48, 72 and 96 km/h (30, 45 and 60 mph). The presence of the foam has considerably reduced the noise in the range from about 600 Hz to about 1750 Hz. Reductions are 5 to 10 dB over much of the range with a maximum reduction of 13 dB at one peak. The frequency range of the reduction corresponds to the range where acoustical foam affects the air pumping mechanism for the quarter-wave resonance of the grooves of about 900 Hz. The air pumping mechanism is thus the largest contributor in the frequency range from 500 to 2000 Hz when measured to the side of the tire.

The air pumping mechanism is also the largest contributor to the A-weighted sound pressure level, but the contribution of all other sources is nearly as large. Differences between the A-weighted sound pressure levels measured with and without foam are 3.3, 4.5 and 4.3 dBA respectively at 48, 72 and 96 km/h. Assuming that the foam eliminated all of the noise generated by the air pumping and taking an average difference of 4 dBA, the other noise sources combined contribute about 2 dBA less noise than the air pumping mechanism.

The presence of other noise-generating mechanisms can also be seen in the differences of the spectra with and without acoustical foam in the grooves. If air pumping was the only mechanism of noise generation then the differences in the spectra, with and without foam, would be about 10 dB at 500 Hz and decrease to zero at very low frequencies. However, the noise measured below 600 Hz is almost unaffected by the presence of foam, indicating the dominance of other noise-generating mechanisms. Air-pumping must also not be the dominant mechanism for the range above about 2000 Hz, since the predictions would indicate large differences caused by the presence of foam at odd harmonics of the quarter-wave resonance frequency of the groove, that is, at about 2700 Hz and 3500 Hz. These differences, however, were not observed.

The understanding gained in this study suggests several means of reducing the noise generated by the air pumping. It should be recognized that the following are only suggestions at this time. Before they can be considered tread design guidelines, they should be tested to verify their effectiveness in reducing the air pumping noise without increasing the noise from other mechanisms and without reducing tire traction or increasing wear. The suggestions are:

1. Open the closed end of the cross grooves to circumferential grooves (Fig. 17A).

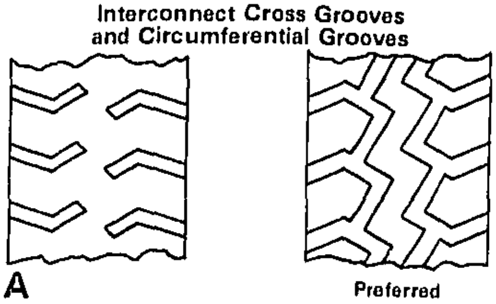

Interconnect Cross Grooves and Circumferential Grooves

Fig. 17A - Interconnect cross grooves and circumferential grooves

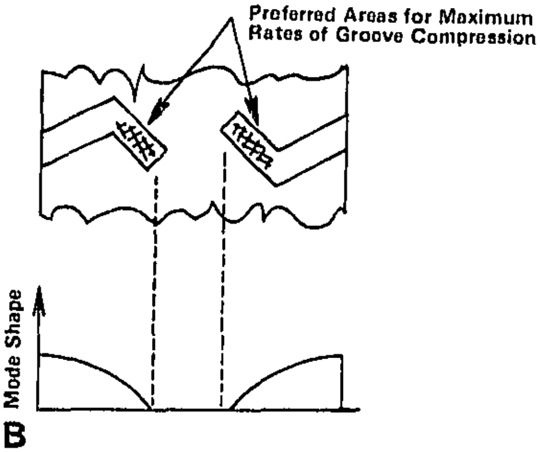


Fig. 17B - Move maximum rates of groove compression to the inside end of the groove

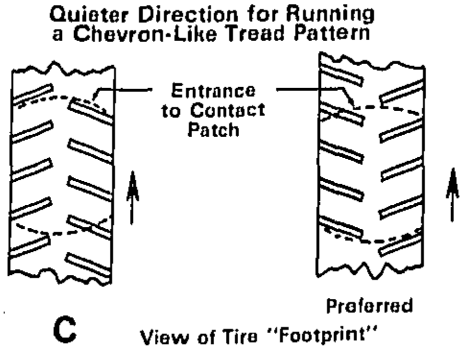

Quieter Direction for Running a Chevron-Like Tread Pattern

Fig. 17C - Quieter direction for running a Chevron-Like tread pattern

2. Change the tire to place the largest normal pressures (and, hence, the greatest compression rates of the tread rubber) near the closed end of the cross groove (Fig. 17B).

3. Vary the lengths of the cross grooves for different grooves of the same tire.

4. Place the grooves at the largest possible angle to the entrance of the contact patch. This would tend to reduce the rate of compression of the groove. Figure 17C illustrates this effect where a unidirectional Chevron tire is operated in both directions.

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DISCUSSION

MR. LIPPMANN: In one sense there can be no movement of air or establishment of pressure fluctuations in the air without some kind of pumping mechanism. There is a moving surface which is creating compression ahead of it. The distinction that people are trying to make when they talk about pumping and non-pumping mechanisms is between vibratory excitation and excitations that result from mere displacement not involving vibration.

What you have demonstrated by putting in foam is, first of all, that you can change the resonant properties of a cavity. That, I think, will be agreed upon by everyone, regardless of what the source of vibration was and what caused the excitation of air. As far as getting a net displacement of a boundary which causes air to be compressed, and therefore generate sound, that can also occur due to vibration in your models and in your experiments.

The tread blocks could come out, or one leading edge could come out from under the contact patch in a vibratory manner, displacing air ahead of it without the final edge coming out. It doesn't have to be due simply to radial compression of the tire.

What I am trying to communicate is that there are alternate explanations for the same phenomena. Certainly I would agree with you that you can change the resonant property of a groove by placing foam in it. However, I don't think it makes a distinction between the factors we are trying to make a distinction between, which is what the vibratory mechanisms involve.

MR. HICKLING: Putting the acoustical foam in the groove is not the only evidence that we have. The other is the characteristics of the pulse which was predicted by the model. The model is purely an air pumping mechanism model, so I think that we have to include it in the picture, too. The characteristics of the noise are the same as those found in the modeling studies, so I think this is additional evidence that aids in proving that the air pumping mechanism exists.

It should also be pointed out that the compression of the air in the groove, as the groove enters the contact patch, appears to be quite substantial. Using clay extruded from the groove, we have found that the change in volume is about 18%. A rapid compression of this magnitude would be expected to be quite a potent excitation for waves in the groove and the consequent radiated sound.

We have also done some tests, in which we have measured the vibrations in a single groove as the groove rotated in the tire. We have not completed those, but the evidence that we have indicates that there is no connection between these vibrations and the noise that we observe which we call air pumping.

MR. THRASHER: I did an experiment by cutting a single slot in the tire, just as you have shown, about 1 in long across the tread, about 1/4 in deep, and maybe 3/8 in wide. I ran the tire on the road and I tried to make my first measurement from 7 ft away on the ground plain.

To my surprise, I saw nothing. I went in and listened, and I heard nothing. Then I kept moving closer, and finally I put a probe tube on the microphone, and came within 1 in of the contact patch. Then I saw a pulse exactly the same as you have shown; but, in order to get a clear time picture of it, I had to move almost directly on top of it before I could see it at all. The frequency analysis of the noise at a distance did clearly show that the event was happening. Could you hear the single pulse?

MR. HICKLING: As I indicated, we made measurements with a microphone close to the tire, but not 2 in. Because the noise was relatively quiet, we had a great deal of signal averaging in order to observe this. The other measurement that we made with the cross-bar was made 10 ft away, and we didn't have any problem picking up the differences.

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Tire Noise Generation: The Roles of Tire and Road

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TIRE NOISE RESEARCH AT STANFORD was made possible by a novel facility for the study of automobile tire noise designed and constructed at the University. Initial experiments have aided our understanding of the sound generating mechanism. Previous work (1)* included the description of a tire sound field by the superposition of the sound fields of individual tread features.

BACKGROUND

Present work is a continuation of superposition research, including the fundamental basis for using such schemes. This paper will report on our experience in distinguishing between tire and road contributions to tire-road interaction noise. A complete report on all of our research will appear shortly (2).

FACILITY - Our specially quieted roadway simulation apparatus uses a 67 in diameter cast aluminum roadwheel with a 3-M Safety-Walk^R (medium grade) working surface. Small automobile tires can be studied under accurately controlled speeds and loads. The roadway wheel is in a pit in a hemi-anechoic room, with the tire rolling flush with the room's hard floor (Fig. 1). Finished inside dimensions of the room are 18 ft 6 in x 13 ft 6 in x 7 ft 9 in high; the anechoic walls and ceiling are lined with 6 in of high density mineral wool.

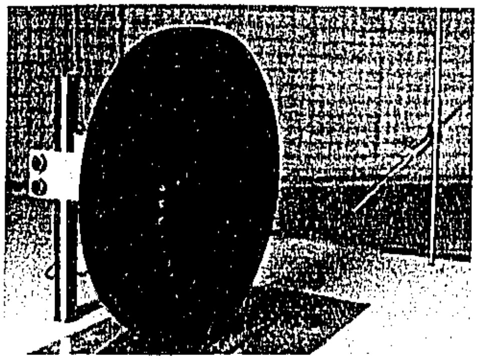

Fig. 1 - Tire in Hemi-Anechoic Test Laboratory

Instrumentation includes B&K microphones, preamplifiers, amplifiers, HP 2100A general purpose minicomputer with various peripherals including a high speed analog to digital converter, and other assorted high quality electronics. Electrical pulses are available for timing and synchronizing purposes at given locations in the tire rotation and the roadwheel rotation. All data acquisition and analysis was done using the computer after careful checking against direct analog techniques and by processing a variety of known signals, including sinusoids buried in white noise.

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*Numbers in Parentheses refer to References at end of Paper.

ABSTRACT

A hemi-anechoic room and roadwheel facility, for the study of noise from small automobile tires, has been constructed at Stanford University. Fundamental research on sound generation mechanisms and superposition of simple tread elements has been conducted.

Through use of the signal average, (roadwheel) tire noise may be separated into tire-rotation correlated and roadwheel-rotation correlated components which account for essentially all of the sound. Level and spectral characteristics of these components are examined for three tires with very simple tread patterns and one commercial type tire. Results suggest that several distinct excitation mechanisms are responsible for "tire vibration" noise. The "groove pipe resonance" is discussed.

Problems in coastby-roadwheel noise measurement correlation are examined. Published coastby data are contrasted with component separated roadwheel data. Legislative implications are also suggested.

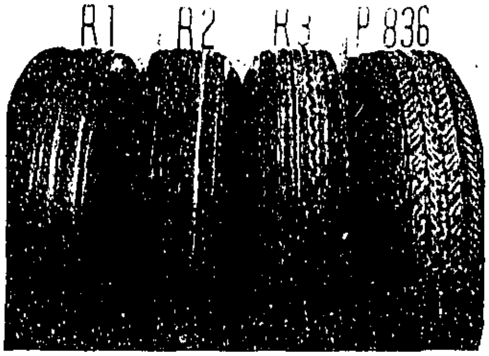

Fig. 2 - Test Tires. Tire R1 is blank, R2 and R3 hand cut treads in identical 175R-13 steel belted radial ply bodies. Tire P-836 is fully siped and pitch sequenced commercial design BR78-13 steel belted radial ply tire. Note near equivalence of 175R-13 and BR78-13 body sizes. Inflation pressure is 26 psi (cold) for all tests reported

TIRES - A number of special test tires have been supplied by Firestone. These have very simple tread patterns hand cut into identical bodies. Most of our work has been with size 175R-13 steel belted radial ply tires, though some preliminary work was done with size 6:00-13 bias ply tires. This report will be concerned with the three special tires and single commercial tire shown in Fig. 2.

THEORETICAL CONCEPTS

DECOMPOSITION OF ROADWHEEL TIRE NOISE - It is useful to describe tire noise in terms of three components. Letting p represent the acoustic pressure fluctuations at some point in the tire sound field, we write:

$$p = \hat{p}^T + \hat{p}^R + p'$$

Where:

$\hat{p}^T$ is a pressure fluctuation which is correlated with tire rotation ("tire periodic")

$\hat{p}^R$ is a pressure fluctuation which is correlated with roadwheel rotation ("road periodic")

p' is the remainder ("random")

Now p is measured directly by a microphone in the sound field. Physically, $\hat{p}^T$ is the sound which is the same each time a particular piece of tire is on the road, while $\hat{p}^R$ is the sound which is the same each time a particular piece of road is under the tire. The $\hat{p}^T$ and $\hat{p}^R$ components are educted from p using the appropriate rotation synchronization signal and the signal average technique described below*. The p' component is obtained by subtraction.

Further, it may be demonstrated that:

$$\overline{p^2} = \overline{(\hat{p}^T)^2} + \overline{(\hat{p}^R)^2} + \overline{(p')^2}$$

Where the ——— represents a time average.

Thus, we may speak of a total sound pressure level (SPL), defined in the usual sense:

$$\text{SPL} = 10 \log_{10} \frac{\overline{p^2}}{p_{ref}^2}$$

and three components defined in an analogous manner. No "cross terms" need be considered.

THE SIGNAL AVERAGE - The signal average is a well known conditional sampling measurement technique which can be used to extract a signal of known periodicity from "random" noise with which it is mixed (3).

Mathematically, we define the signal average:

$$\hat{f}^n(t) = \frac{1}{N} \sum_{n=1}^{N} f(t + n\tau_n)$$

Where:

$\hat{f}^n$ is the signal average of the time series f

t is time

τ_n is the known period of the signal to be extracted

N is the number of realizations in the ensemble

Typically N is chosen large enough so that independent ensembles, of N realizations each, yield sufficiently similar results. To obtain a meaningful result, we also require that the periodic component of the time series being signal averaged be stationary in the statistical sense.

Notice that f is any function of time, while, for sufficiently large N, $\hat{f}$ is a periodic function of time. Experimentally, timing pulses provided by a rotation synchronization signal are used to divide the time series f into N realizations, each of length τ_n. When these digitized realizations are segment-by-segment summed, the periodic component of the signal always reinforces the average while the random component is as likely to cancel as to reinforce. For a periodic signal mixed with Gaussian noise, it can be shown that the signal-to-noise ratio is improved by a factor of $\sqrt{N}$.

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*This assumes that the periods of tire and roadwheel rotation are sufficiently unrelated, which is the case for material presented in this report.

In the frequency domain the signal average corresponds to a "comb filter." Signals in a band around the basic frequency ($1/\tau_a$) and its harmonics are passed while remaining frequencies are rejected. The width of the pass band "teeth" is inversely proportional to N.

SPECTRA - The power spectrum for p is obtained using conventional digital techniques (4). The microphone signal is sampled and digitized under computer control. This signal is Fourier transformed after application of a Hamming data window to reduce spectral leakage. Several transformed realizations are averaged to yield a smoothed and statistically accurate result.

The same digitized microphone signal is then signal averaged, using the appropriate rotation synchronizations, to yield $\hat{p}^T$ and $\hat{p}^R$. Power spectra are obtained by Fourier transforming over a single complete period of each signal. Under these conditions there is no spectral leakage, and, thus, no data window need be applied. Additionally, since all data are utilized, no further smoothing of the transformed signal is required.

The power spectrum of the p' component is obtained by subtracting $\hat{p}^T$ and $\hat{p}^R$ from p. First the $\hat{p}$ spectra were converted to the equivalent bandwidth of the total spectrum using a linear interpolation scheme. Next, the "equivalent" Hamming windows were applied. Finally the subtraction was performed, and due notice taken of those frequencies which showed "negative energy" content.

EXPERIMENTAL RESULTS*

INTRODUCTION TO SPECTRA - THE BLANK TIRE - The procedure outlined above was performed and the total spectrum and its three components were obtained for the blank tire, R1 (Fig. 3). The most striking feature of these spectra is the clear difference in the frequency content of the roadwheel-rotation correlated and the tire-rotation correlated contributions to the total spectra. The tire periodic sound energy is primarily at frequencies below 700 Hz; the road periodic sound energy is mostly above 1000 Hz. Thus, the total sound spectrum has a "bimodal" appearance. Indeed, it was the desire to understand this bimodal structure, first detected by conventional spectral analysis, that prompted the signal averaging studies.

Note that the spectra are plotted in log-log coordinates and that decibels must be summed logarithmically. It is evident from Fig. 3 that spectrum corresponding to the sum of $\hat{p}^T$ and $\hat{p}^R$ is very close to the spectrum of the total source, indicating that practically all of the source energy

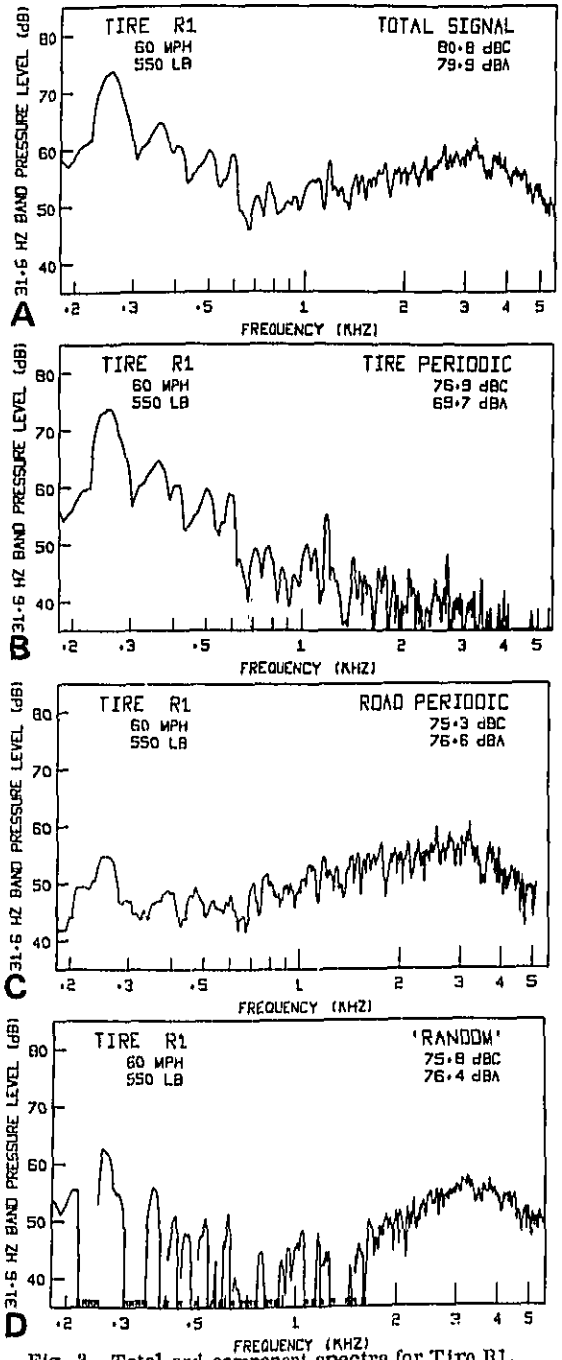

Fig. 3 - Total and component spectra for Tire R1, 60 mph, 550 lb load. The "x" in the random component spectrum indicates "negative energy" (see text). The microphone is in front of the tire, 3 ft from center of contact patch, 9 in above floor. Microphone location is same for all tests reported

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*All measurements reported here were made in front of the tire, 3 ft from the center of the contact patch and 9 in above the ground.

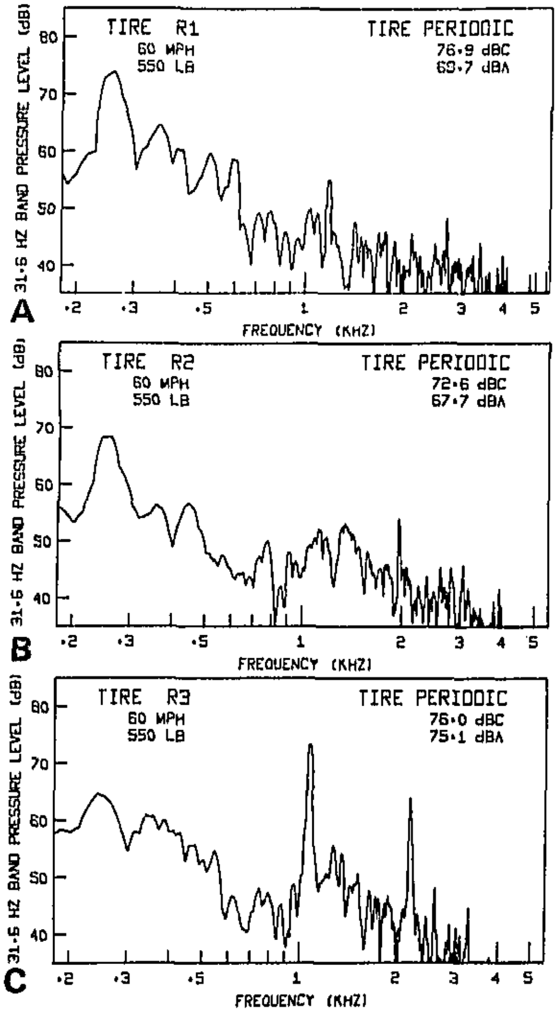


Fig. 4 - Tire-rotation correlated spectra. Tires R1, R2, and R3, 60 mph, 550 lb load

is deterministically related to tire and roadwheel rotation.

THE p' SPECTRUM - The p' spectrum (Fig. 3) requires some further explanation. Recall that it is obtained by subtraction of $\hat{p}^T$ and $\hat{p}^R$ from p. A preliminary uncertainty analysis indicates that the p' level observed may be attributed entirely to constituent uncertainties.

Notice how the spectral energy alternates "positive" and "negative" at the lower frequencies. Note, also, that the peaks appear narrower than the 31.6 Hz effective filter width. These effects are apparently due to the nature of the discrete spectral subtraction procedure and spectral leakage. While there is some residual portion of $\hat{p}^T$ remaining in $\hat{p}^R$, and vice versa, so that some energy is counted twice during the subtraction, since the residual levels are at least 18 dB down, they should not significantly affect the results.

The p' spectral energy at higher frequencies is believed to arise from "smearing" in the $\hat{p}$ components. Tire non-uniformities and a non-rigid suspension system cause the instantaneous location of the tire-road contact patch to deviate from its mean location. These deviations cause an apparent "jitter" in the rotation synchronization signals, which are defined relative to the mean contact patch location. Jitter in a rotation synchronization signal, however, will cause a portion of the periodic component to appear random in the signal average process; sharp, that is high frequency, features of the signal are smeared and lost. Smearing is more pronounced as more realizations are included in the signal average.

For the spectra of Fig. 3, a jitter analysis predicts the p' level within a few dB of that measured above 1 kHz. Essentially all of this may be attributed to $\hat{p}^R$ smearing since $\hat{p}^T$ contains little energy at these frequencies to begin with. Note that at 3 kHz fully one-half of the $\hat{p}^R$ signal is lost to smearing.

TIRE-ROTATION CORRELATED SPECTRA (R1, R2, R3) - All three tires show dominant $\hat{p}^T$ spectral peaks at similar lower frequencies (Fig. 4). Note that the overall level is slightly lower for R2 and for R1, though the basic spectra shapes are similar. The R3 spectra is also similar, but with additional spectral peaks (at 1.1 kHz and 2.2 kHz) which correspond to the rate of passage of the zigzag tread features through the contact patch (pitch length frequency and second harmonic).

A particularly interesting peak is the one which occurs at 260 Hz, the 18th rotational harmonic. Visual inspection of the tire shows 18 groups of curing mold vent stubs on the tire shoulders, approximately, though not exactly, equally spaced. These stubs in the shoulder area do not physically contact the road, and any stubs originally in the tread area have been worn away. It is clear that the stubs themselves do not produce the noise, but are symtomatic of the underlying source, circumferential non-uniformity in the tire.

Fig. 5 shows the variation of $\hat{p}^T$ with load for R1. Load trends for R2 and R3 are similar, excepting the R3 pitch length frequency and second harmonic peaks.

ROADWHEEL-ROTATION CORRELATED SPECTRA (R1, R2, R3) - The most striking feature of the roadwheel-rotation correlated spectra is the similarity of the R2 and R3 spectra (Fig. 6). Observe that with the addition of the broad spectral peak centered at 1500 Hz these are also similar to

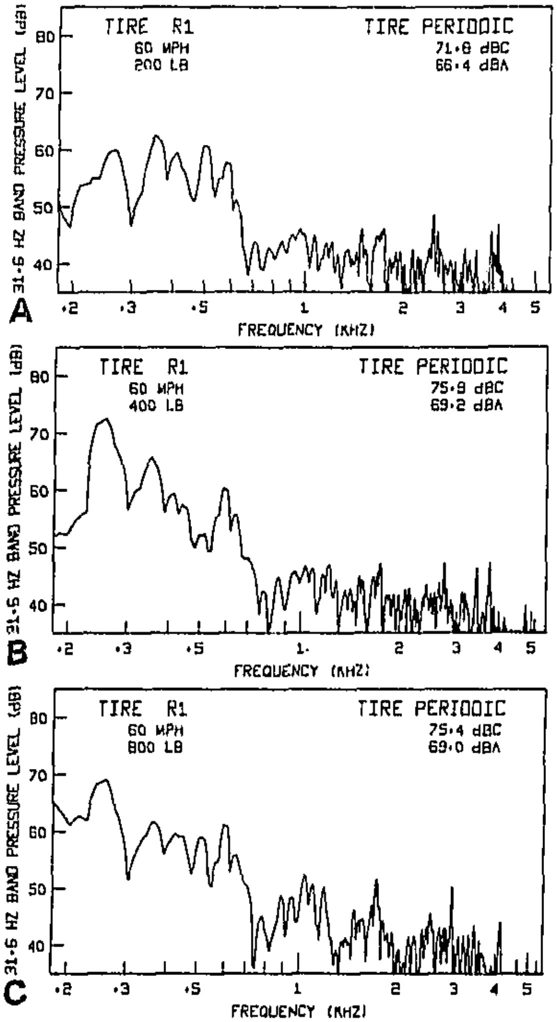


Fig. 5 - Effect of load on R1 tire periodic spectrum. Tire R2 and R3 (excepting pitch length frequencies) behaviors are similar

the R1 spectra. It was reported earlier (1) that this broad spectral peak is due to an acoustic resonance in the "groove pipe" formed when the tire seals against the roadwheel. Notice how the center frequency of the peak shifts lower as the load on the tire is increased (Fig. 7) and the contact patch lengthens.

The origin of the R1 "baseline" spectrum is still under investigation. The peak at 3 kHz is particularly interesting. Notice that it is nearly unaffected by load (Fig. 8). Moreover, the spectrum shape is little dependent on speed, though the overall level is. The spectrum shape is, however, a strong function of location around the tire.

A COMMERCIAL TIRE - Similar analyses were carried out for the commercial type tire, P-836 (Fig. 9). It is seen that essentially all of the measured noise is correlated with tire rotation. The frequency content of this noise may be attributed to the tread features passing through the contact patch.

There is still a roadwheel-rotation correlated component, although it is quite small compared to the total. This made $\hat{p}^R$ spectra impractical to obtain for the 550 lb loaded tire, but the $\hat{p}^R$ spectrum for the 200 lb loaded tire is shown in Fig. 9.

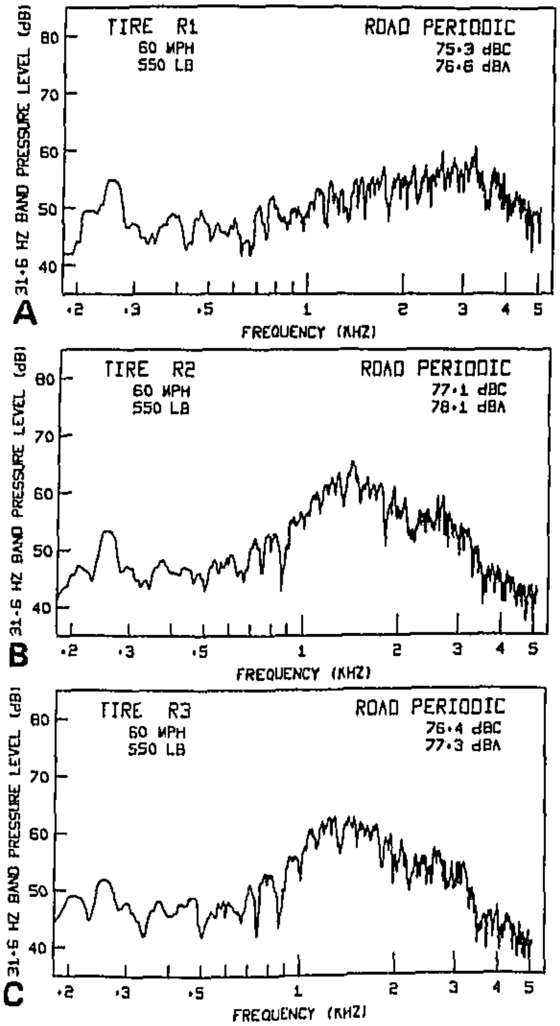


Fig. 6 - Roadwheel-rotation correlated spectra. Tires R1, R2, and R3, 60 mph, 550 lb load

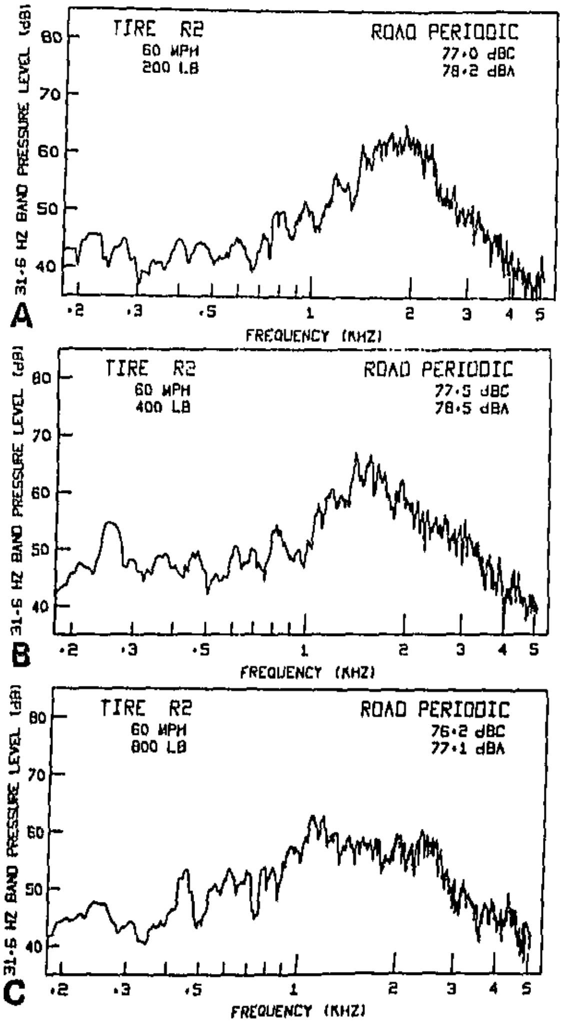


Fig. 7 - Effect of load on R2 road periodic spectrum. Note broad spectral peak attributable to "groove pipe" resonance. Tire R3 behavior is similar

It is fascinating to observe how similar this component is to that observed for R2 (Fig. 7), though one would expect direct comparison to be difficult because of experimental procedure differences. More realizations in the signal average were necessary to achieve sufficient noise rejection. This results, however, in more signal smearing, and consequential loss, due to contact patch jitter.

SPEED DEPENDENCE - Total spectra for the four tires, at 30 mph, are given in Fig. 10. The tire-rotation correlated and road-rotation correlated components for these can be inferred from the trends identified at 60 mph. Low frequencies dominate $\hat{p}^T$, high frequencies dominate $\hat{p}^R$ in the case of R1, R2, and R3. For P-836 essentially all of the total signal is tire-rotation correlated.

An extensive analysis of level versus speed was performed in an attempt to identify a systematic difference between $\hat{p}^T$ and $\hat{p}^R$ speed dependence. For the total sound pressure level (SPL), both 30 $\log_{10}V$ and 40 $\log_{10}V$ speed dependence have theoretical (5, 7, 8) and experimental (6, 7, 9, 10) bases. Our results (Fig. 11) show that $\hat{p}^R$ follows the 30 $\log_{10}V$ slope most closely, while $\hat{p}^T$ follows a

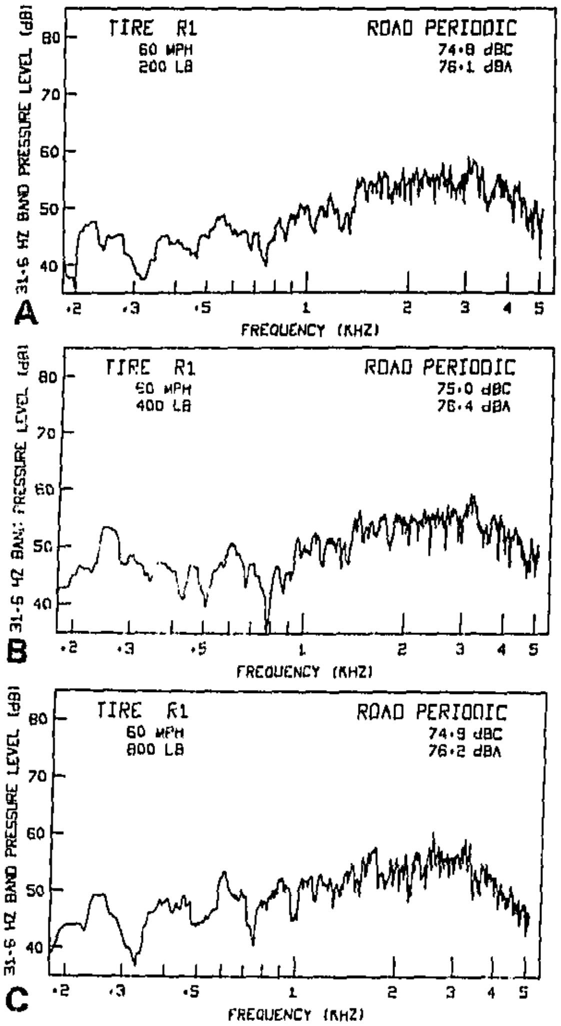


Fig. 8 - Effect of load on R1 road periodic spectrum. Note absence of groove pipe resonance

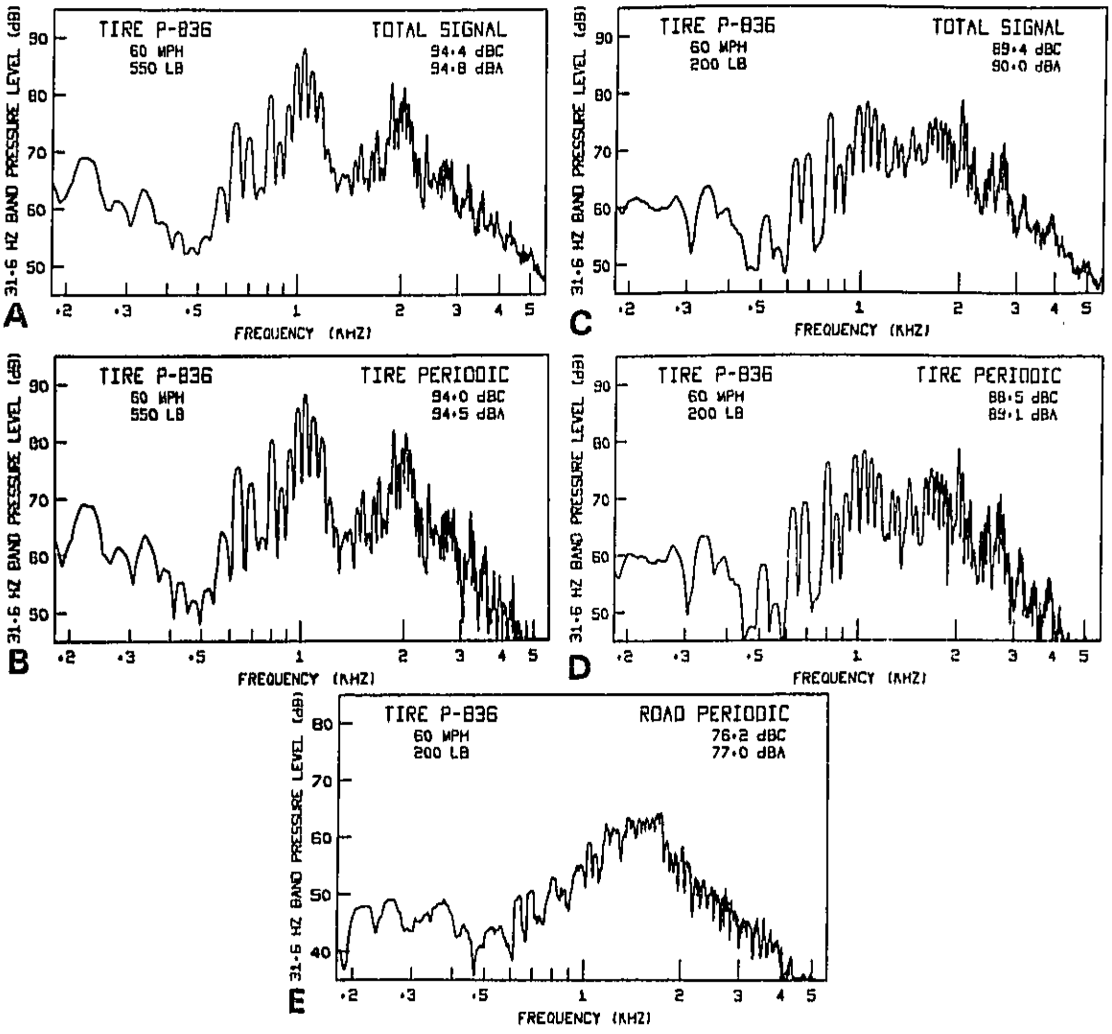


Fig. 9 - Total and component spectra for tire P-836

40 $\log_{10}V$ slope. Note that, although none have been applied, it is not expected that corrections for $\hat{p}$ smearing would alter these trends. The behavior of the total p SPL depends whether it is dominated by the $\hat{p}^T$ or the $\hat{p}^R$ component.

SUSPENSION SYSTEM AND ALIGNMENT - The basic suspension system consists of a tire holding device which is loaded through a low pressure pneumatic cylinder attached to the roadwheel frame. The pressurized loader acts as an air spring, while damping is provided by an adjustable automotive shock absorber. The effective unsprung mass of the system, with tire mounted, is 200 lb.

Two experiments were performed to evaluate the sensitivity of tire noise generation to the particular suspension system:

1. Unsprung mass. When the unsprung mass of the system was increased by 100 lb (50%), no change was seen in the $\hat{p}^T$ or $\hat{p}^R$ spectra for R1.
2. Damping. Similarly, when the shock absorber damping was increased, there was no change in either $\hat{p}^T$ or $\hat{p}^R$ for R1.

Earlier experiments (1,2) showed that tire-roadwheel alignment has a strong influence on the directional pattern of tire noise radiation. Total sound power radiated appeared only weakly influenced, however. The effect of alignment on $\hat{p}^T$ and $\hat{p}^R$ has not been systematically investigated.

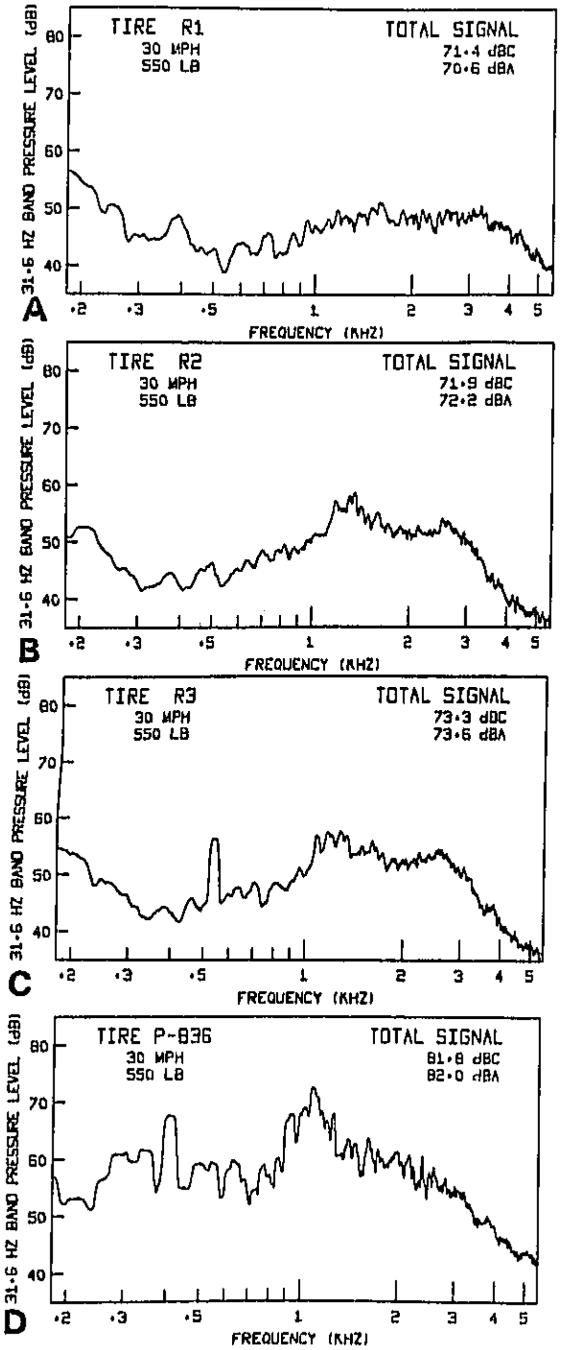
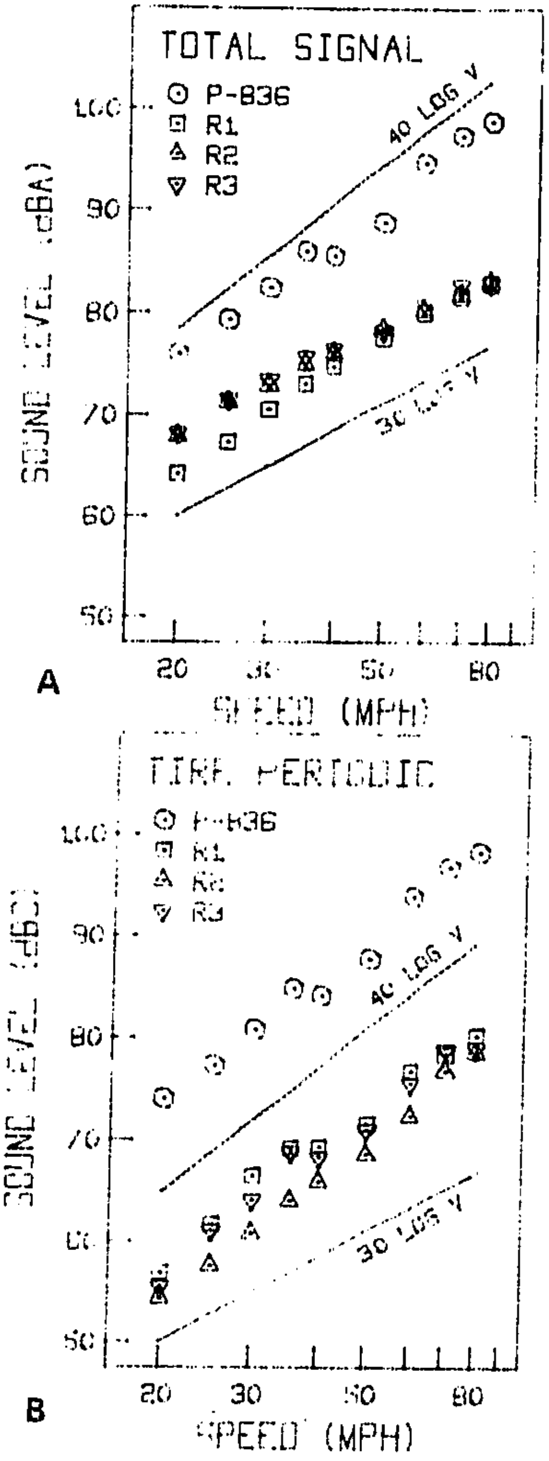


Fig. 10 - Total spectra for R1, R2, R3 and P-836 at 30 mph, 550 lb load



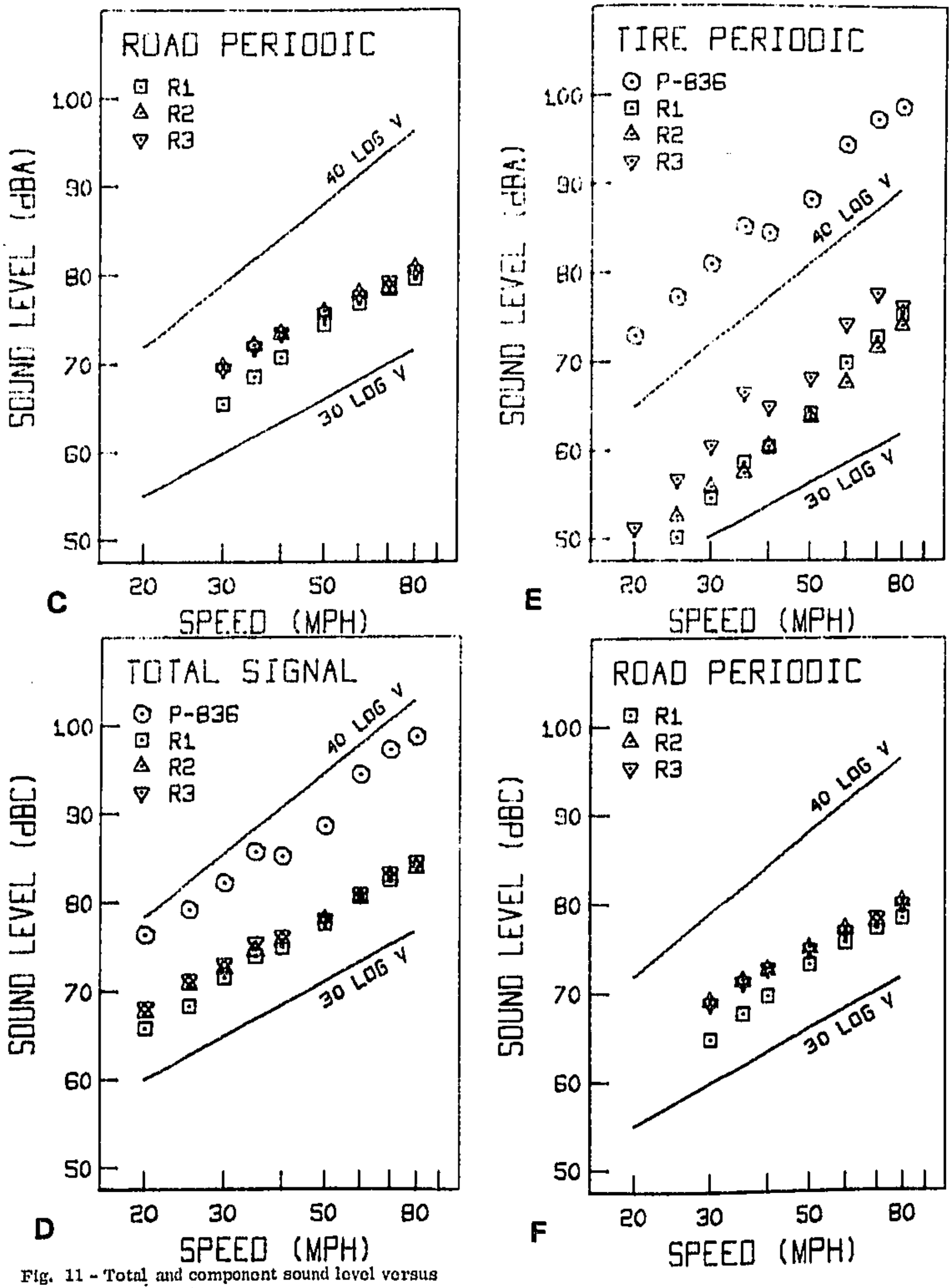


Fig. 11 - Total and component sound level versus speed, at 550 lb load

MECHANISM

INTERPRETATION OF ROTATION CORRELATED SIGNALS - Recall that physically, the tire-rotation correlated signal, $\hat{p}^T$, is that sound which is exactly the same on each complete tire rotation. The $\hat{p}^R$ signal is that sound which is exactly the same on each complete roadwheel rotation. It should be emphasized that the signal average process does not necessarily distinguish between the various possible sound generating mechanisms. However, by examining differences between $\hat{p}^T$ and $\hat{p}^R$ as tread pattern, road surface, speed, load, measuring location, etc. are varied, it may be possible to gain insight into mechanisms.

It has been observed that the p' component is, at best, of equal magnitude with the $\hat{p}$ components, and, probably, is much smaller. This presents a view of tire noise as a completely deterministic process. There are no "random fluctuations" needed to explain its origins. (This suggests that, for an in-service tire on a realistic road surface it may be possible to define a non-periodic road-correlated component analogous to $\hat{p}^R$. One simply subtracts the computed $\hat{p}^T$ component from the total p.)

It is not claimed that the tire-road interaction is the same for all combinations of tires and roads. Indeed, as will be discussed below, it is most plausable that both $\hat{p}^T$ and $\hat{p}^R$ will depend on both road and tire characteristics. One must remain aware that the signal average technique is a tool, and that the rotation correlated signals, products of work with this tool, require careful interpretation.

TIRE VIBRATION*- Our experimental results indicate the dominance of tire vibration as the source of (roadwheel) tire noise. No one experiment is conclusive; many single observations could support several source theories equally well. Taken together, however, the evidence strongly suggests that several forms of input excitation are responsible for subsequent vibrations and sound radiation. Three particularly interesting observations are discussed below.

Pitch Length Amplitudes are Frequency Dependent - We have observed that the amplitude of the R3 pitch length peak is quite dependent on frequency. The pitch length frequency is also dependent on speed, of course, but work with a different pitch length on a tire similar to R3 indicates that frequency is a more important sound generation parameter than speed (2). Results from the P-836 tire, which contains a mix of pitch lengths, also confirm this (Fig. 9,10). Notice that at 60 mph, the highest spectral peak occurs at 1.1 kHz. At 30 mph, for which the pitch length contributions should be at one-half the 60 mph frequencies, the highest peak is again at 1.1 kHz, not 550 Hz.

These observations may be partially attributed to frequency dependent superposition effects (1,2). However, the overall picture, as Richards (9) points out, is reminiscent of the response of a resonant system. Furthermore, the pitch length amplitude load dependence we have observed indicates that this hypothesized resonance is predominantly mechanical in nature and excited by fluctuating force inputs from tread elements, rather than a groove pipe or cavity resonance excited by air pumping, though this may also contribute.

Low Frequency Peaks in $\hat{p}^T$ Spectra - For R1, R2, R3, and P-836 these peaks occur at similar frequencies, but with different amplitudes. Earlier it was suggested that these peaks are associated with tire body non-uniformities introduced during the manufacturing process. These non-uniformities could cause fluctuating force inputs to the tire body when they move through the "standing deflections" as the tire rolls. For a given non-uniformity then, the level of input and resulting vibrational response should be governed by load, through the standing deflection imposed; and by tire body stiffness, through the tread pattern.

The R1, R2, and R3 tire bodies are from the same special production run so one might expect reasonably similar non-uniformities. Note the individual amplitude variations from tire to tire and with load. The 260 Hz peak, for example, tends to increase for a modest increase in load (Fig. 5). At higher loads, however, the standing deflection is apparently such that the driving non-uniformity is a less effective excitation. Note also that the 260 Hz peak tends to be lower for the grooved and thus flexible R2 than for the stiff R1 (Fig. 4).

The R1 $\hat{p}^R$ Spectrum - Previously it was stated that the origin of the R1 $\hat{p}^R$ spectra is poorly understood. Some important observations on mechanism, though, have been made.

In order to produce any $\hat{p}^R$ signal, there must be some "feature" of the roadwheel which "indexes" the sound, such that the same sound is produced whenever the tire is over that particular section of roadwheel. This indexing, then, should cause "index frequencies," dependent upon speed, and analogous to the pitch length frequencies of $\hat{p}^T$ spectra. In fact, these frequencies do exist, and can be identified in spectra taken at slightly different speeds.

The general insensitivity of the R1 $\hat{p}^R$ spectrum shape to speed changes (Figs. 3,10) is again reminiscent of the response of a resonant system - in this case, response to broadband excitation. The

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*See the discussion of tire-noise source mechanisms in (7).

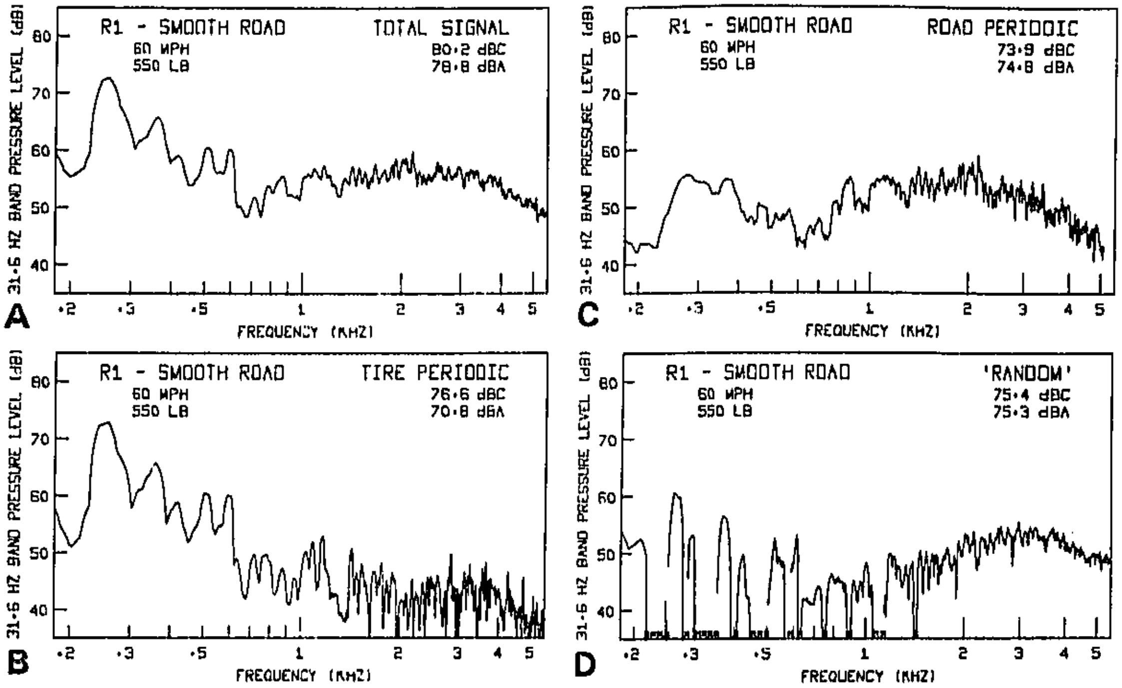

Fig. 12 - Total and component spectra for Tire R1 on "smooth" Con-Tact^R paper roadwheel surface, 60 mph, 550 lb load. Compare with corresponding spectra for "rough" Safety-Walk^R roadwheel surface (Fig. 3)

slight speed dependence which is observed as a flattening of the spectrum at lower speeds can be interpreted in two ways:

1. Frequency indexing by roadwheel features may be only approximately broadband; a high frequency roll-off may occur.

2. Apparent properties of the resonant system may be speed dependent. Centrifugal force, for example, tends to add stiffness to the tire body.

The relatively high frequency of the sound radiated, plus microphone probing which localizes the source to the contact patch region indicate that the hypothesized resonance must be local, not a body modal resonance. It should be emphasized that both the possible resonance and its excitation require further investigation.

One very plausible source of input excitation is stick-slip in the contact patch. It is well known that as a consequence of tire-road geometry, and independent of parameters such as alignment and braking torque, there is slip between the road and portions of the contact patch (11). One would expect this process to be discontinuous (stick-slip), and, to some extent, modulated by road surface texture (the "indexing").

To evaluate this excitation hypothesis, the Safety-Walk^R surface was removed from the roadwheel and replaced with smooth Con-Tact^R paper. For R1, at 60 mph, 550 lb load, the overall $\hat{p}^R$ level was reduced by 1.4 dBC (1.8 dBA) and the peak frequency was reduced from 3 kHz to 2 kHz (Figs. 3, 12). The lower overall level would be expected because tread slippage should occur more often on the smooth surface; relatively less elastic strain energy is stored and released in stick-slip. The peak frequency reduction can be explained in terms of index roll-off; the spacing between index features on the smoother road is longer so the input excitation tends to roll off at a lower frequency. For completeness, it should be noted that no change was seen in the $\hat{p}^T$ spectrum; $\underline{p}'$ was lower, and again entirely attributable to $\hat{p}^R$ smearing.

OTHER SOURCES - The only other source indicated by our research is the groove pipe resonance described earlier. After the load behavior was noted, positive identification was made through two experiments:

1. Ordinary knitting yarn was wrapped in the circumferential grooves, to act as a sound absorber without otherwise altering the tire or roadwheel properties. The resonance peak disappeared.
2. Helium gas was blown into the contact patch, to raise the local sound speed and shorten the apparent length of the pipe resonator. The resonance peak was observed to shift upward in frequency as expected.

Notice that the groove pipe resonance is observed in both $\hat{p}^R$ and $\hat{p}^T$ spectra. Apparently, however the road is a better pump to excite energy at the acoustic resonance frequency.

The existence is this groove pipe resonance for tires with circumferential grooves (R2, R3, P-836) suggests that other cavity resonances may be present for a tire with more complex grooves and slots (for example, P-836), but no systematic search has been conducted.

IMPLICATIONS FOR TIRE NOISE EVALUATION

It is well known that at moderate to high speeds the tires, typically, are the dominant source of noise from motor vehicles (7). Historically, the emphasis of tire noise evaluation has been gauging community impact and vehicular passenger comfort. Thus, realistic coastby measurement procedures were developed. These have been supplemented with all manner of special on- and off-vehicle measurements made by investigators more interested in the fundamental origins of tire noise (12).

At present, the only generally accepted technique for tire noise evaluation is the coastby measurement described by SAE J57a (13). It should be obvious, especially to those experienced with the J57 procedure, that an indoor measurement in a laboratory roadwheel facility could offer significant advantages. Truly standardized and well controlled test conditions, cost, and convenience are but three areas in which great improvements are possible. Unfortunately, however, no systematic correlation of results from indoor measurements and J57a measurements has ever been demonstrated.

It has been suggested that several differences between the boundary conditions imposed upon the tire in roadwheel versus coastby measurements are responsible for observed discrepancies. These differences may be categorized as:

1. Aerodynamic flow around the tire,
2. Road surface texture, and
3. Reverse curvature imparted to the tire by the roadwheel.

Insights provided by our research suggest several areas for further research on quantifying the effects of boundary condition differences, and achieving a coastby-roadwheel correlation.

AERODYNAMIC FLOW – Richards (9) has reported several coastby tests which indicate that the noise due to aerodynamic flow around a tire is negligible when compared with other sources. In our laboratory, we saw no appreciable change in level or spectral shape when the flow conditions around a tire were altered by partially removing the roadwheel boundary layer. These observations, plus the absence of any evidence for an aerodynamic flow source indicate that air flow boundary conditions need not be considered in a roadwheel-coastby correlation.

SURFACE TEXTURE – Passby tests indicate that as much as a 10 dBA difference in coastby sound level is observed when the same tire is run over different road surfaces. This overall range is nearly independent of tread design (blank, rib, block), although, if several different tires are tested, the tire quietest on one surface may not be quietest on another surface. Furthermore, it is observed that the surface to surface noise range for a single tire far exceeds the 3 dBA maximum range for different tread designs run on the same surface (10, 14). It should be obvious that any coastby-roadwheel correlation must consider surface texture effects.

It is interesting to examine Veres (10) near field-noise spectra for a blank tire on various road surfaces in the context of the periodic component spectra for our blank tire (Fig. 3). Over the eight surfaces reported, the Veres spectra show a 3 dB range at 200 Hz and at 10 dB range at 2000 Hz. Mindful of differences in microphone placement, the clear implication is that $\hat{p}^T$ is nearly independent of surface and all texture effects occur in the continuous analog to $\hat{p}^R$. Further research is required to verify this hypothesis and to determine whether it can be extended to patterned tread tires.

Unfortunately, present indications are that the effects of road surface texture are more complicated than this simple hypothesis suggests. Recall that for our patterned tires (R2, R3, P-836) $\hat{p}^R$ shows both vibration mechanism sound (that is, the R1 $\hat{p}^R$ spectra) and groove pipe resonance mechanism sound. Also, recall the coastby inconsistency mentioned above, that is, when a group of patterned tires is tested, the tire quietest on one surface may not be quietest on another. We might expect the mechanism by which vibration energy is input into the tire to be modified by different road and tire textures. Furthermore, road surface texture will affect both the pump for the groove pipe resonance, and the effective cavity shape.

There is no reason to believe that road texture will affect all mechanisms in the same manner. There is reason to believe that both $\hat{p}^T$ and $\hat{p}^R$ will be involved. Further research is required to quantify road texture effects.

ROADWHEEL CURVATURE – The effect of roadwheel curvature is to alter the standing deflection from that experienced by the tire on a flat road. To develop a coastby-roadwheel correlation, it is necessary to understand how the resulting differences in tire-road interaction affect sound production.

Recall that for the blank tire $\hat{p}^T$ varies with load while $\hat{p}^R$ does not (Figs. 6, 8). Since load changes affect the shape of the contact patch and the force distribution within it as much, or more than, curvature, the $\hat{p}^R$ insensitivity to load implies that curvature distortion of the contact patch itself is not important in sound generation. (For tires with phased tread patterns, this conclusion will need to be re-examined (2)). Rather, it appears that the nature of the tire standing deflection outside the contact patch and the transition into the contact patch are the essence of roadwheel curvature effects.

A blank tire, having a continuous tread band, will tend to show a smooth entry into, and exit from the contact area. A patterned tire, however, has tread areas of high flexibility (grooves and slots) and low flexibility (tread blocks). Thus the tread will tend to bulge and slap as tread elements hinge at the contact interface, accentuating vibrational input into the tire body and increasing sound radiation.

This accentuation of tread pattern noise (the $\tilde{p}^T$ component) may help to explain why roadwheel noise from the P-836 tire is as much as 20 dBA higher than R1 noise measured, at 60 mph, to the side of the tires (15 dBA measured in front) while typical coastby measurements (7, 10, 14) show only 3 dBA difference between blank and patterned tires run over the same road surface. Further research, with an attempt to quantify the bulging phenomena, is needed.

CONCLUSIONS

Non-uniformities in the tire (tread pattern, mass distribution, etc.) and non-uniformities in the road (surface texture) excite tire vibration in a deterministic manner. This process accounts for essentially all of roadwheel tire noise. There is no evidence that the suspension system significantly affects tire noise generation; alignment, however, may be important.

Legislative regulation of tire noise is, appropriately, based on the concept of coastby measurements. Though "correct," coastby measurements are cumbersome and subject to much uncertainty. Laboratory roadwheel measurements offer significant advantages, but, at present, show inconsistent correlation with coastby measurements. Application of the signal average, described here, should help refine roadwheel measurements and assist in achieving correlation.

Research on automobile tire noise and legislative regulation may be misdirected at present. For a commercial tire on a roadwheel, the tread pattern is responsible for the majority of tire noise. Reported observations indicate, however, that the road may be responsible for a large portion of the tire noise observed in coastby measurements on a realistic pavement surface. Further research is needed to clarify this situation so that proper action may be taken; the signal average techniques described here should be useful in this work also.

ACKNOWLEDGEMENTS

Tires were generously provided by the Firestone Tire and Rubber Company. This work was initiated under a grant from the Engineering Division of the National Science Foundation (NSF). However, NSF funding for this work is no longer available; the Stanford Program in this area will terminate this year with completion of Mr. Pope's Ph.D. dissertation. The roadwheel facility could be made available for use by others by special arrangements with Stanford.

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DISCUSSION

MR. THRASHER: You mentioned your signal processing technique might help us understand the curvature effect. Did you say that, and if so, how would you do this?

MR. POPE: I think we see a difference in curvature effect for the tire components. I don't think the curvature will have much effect on the road component. In other words, if we reproduce these tests on a larger diameter wheel, we would see a difference in the tire periodic component.

CONTRIBUTED COMMENT

W. F. Reiter and A. C. Eberhardt

Clear distinction should be made in discussion of the "air pumping" mechanism of sound generation as proposed by Hayden and the cavity resonance mechanism identified by Pope and Reynolds. At this conference, cavity resonance was repeatedly referred to as "air pumping." The cavity resonance mechanism arises from elastic waves within the cavity and their radiation to the far field. These elastic waves are produced at a frequency governed by the cavity size, boundary conditions, and properties of the acoustic medium. The disturbance that excites the elastic waves is not well identified at this time; it may be tire vibration or it may be some other phenomena. The "air pumping" mechanism proposed by Hayden is associated with a time rate of change of air flow into or out of voids of the tire or road surface. This phenomenon is not related to the elastic waves of the cavity resonance phenomena. Except for the "suction cup" type tires this mechanism does not appear to be a significant sound source.

It is hoped that in future discussion the cavity resonance or the air pumping mechanism will be clearly identified as the situation dictates.

762024

Cross Lug Tire Noise Mechanisms

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THE PURPOSE OF THIS PAPER is to outline the techniques used to identify and study the noise generation of cross lug tires. These techniques and/or the postulated tread pattern design guidelines can be used to evaluate the performance of an existing tire or aid in the design of future drive axle tires. This should allow retaining the desirable attributes of cross lug patterns (effective tread cooling, long tread life and good off road traction) and simultaneously minimize the undesirable noise characteristics.

Based on information in the literature and our previous tire noise work (3) this effort concentrated on the two most probable noise mechanisms:

1. Tread Vibration - generated by the tread lugs impacting the road.
2. Air Pumping - caused by the tire tread contacting the road and squeezing air out from between the lugs.

These mechanisms will be discussed separately, followed by a description of the test methods used to differentiate between the mechanisms, and lastly the tread pattern guidelines will be listed.

For clarification, a typical cross lug (cross bar) and a block pattern tire are shown in Fig. 1. Many present heavy truck tires exhibit a combination of these patterns. The tires used in this study were similar to the cross lug shown in Fig. 1 of 10.00 x 20 size, bias construction.

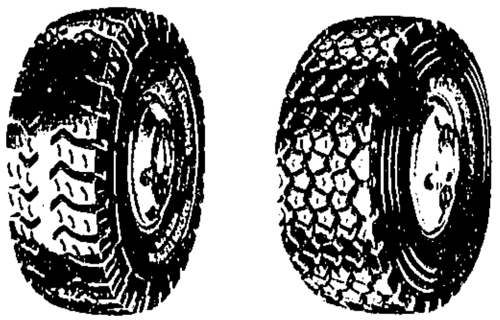
CROSS LUG
BLOCK PATTERN

Fig. 1 - Typical truck tires

TREAD VIBRATION

INPUT EXCITATION - Vibration pickups mounted in the tread rubber were used to record the tread vibration. This was done by bonding small accelerometers into holes in the tread rubber as near to the surface as possible. Measurements were made in the radial direction, in the center of the tread area, and near the edge of the tread. Fig. 2 is a sample of the total signal from the center accelerometer for two revolutions. Most of this acceleration is non-vibrational, resulting from the

ABSTRACT

This study was conducted to identify and better understand the predominant noise generation mechanisms of cross lug truck tires. These tires are often used on the drive axles of heavy trucks and have been found to be the principal contributor to exterior truck noise at highway speeds (1 and 2).* The end product of this study was to establish tread pattern design guidelines.

Two primary noise mechanisms of cross lug tires, tread vibration and air pumping, were identified and analyzed experimentally. The system inputs were determined, laboratory simulations run and experimental tests devised to differentiate between the mechanisms.

The conclusions reached are that both air pumping and vibration-caused noise are present in most truck tires. The predominating mechanism depends on the tread pattern, state of tread wear, road surface macrotexture, tire loading and vehicle speed.

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*Numbers in parentheses designate References at end of paper.

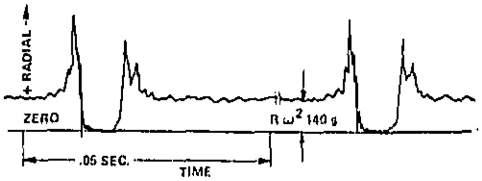

Fig. 2 - Tread accelerations - 96 km/h (60 mph), half load, 552 kPa (80 psi), center of tread

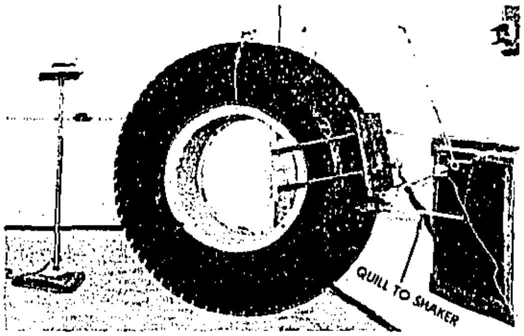

Fig. 3 - Tread vibration test

tread being pulled radially by centrifugal force approximately 90% of the time and resting on the ground the remainder of the time. The vibrational portion of the signal is shown as small ripples as the tread enters and exits the contact patch. These vibrations have amplitudes on the order of 40 g peak-to-peak (p-p) at 60 mph (96 km/h). These tread vibrations are assumed to be caused by the tread pattern (or road surface texture) modulating the tread acceleration (that is, the vibration amplitude is proportional to the overall tread acceleration). The basic tread acceleration level increases with the fourth power of vehicle speed ($x = R\omega^2$ and by definition, acceleration level $= 20 \log x/x_{ref}$

$$= 20 \log R\omega^2/x_{ref}$$

$$= 40 \log KV + \text{const.})$$

where:

R = tire radius
ω = angular frequency
K = constant
V = vehicle speed

Spectral analysis of the tread acceleration shows high amplitudes at the harmonics of once per revolution, all the way into the 3 - 4 kHz range. The A-weighted vibration amplitude tended to increase at 30 - 40 log V.

LABORATORY SIMULATION OF VIBRATION NOISE

- The laboratory simulations were run in a large reverberation room. A 2670 N (600 lb) force electrodynamic shaker located outside the room was used to excite the tire.

A clamping arrangement was used to apply full-scale static load. Fig. 3 shows the tread vibration set-up. A swept sine input was applied to the shaker for these tests. Ambient noise levels were measured with the shaker and quill operational but disconnected from the tire tread. Ambient noise levels were at least 10 dB below test levels.

Fig. 4 is a typical noise spectrum obtained in the reverberation room test. The signal from the microphone was C-weighted and filtered by a 5 Hz tracking filter. The characteristics for the reverberation room are such that the sound pressure level (SPL) is approximately numerically equal to the sound power level (PWL) re 10^{-12} watts. Comparing these data to data previously obtained in a similar manner on car tires (3) shows the truck tire to be a more efficient radiator. Pronounced peaks in the truck tire spectra were 6 - 12 dB higher than the car tire at similar input levels. The principal peak in the truck tire spectra is between 600 - 700 Hz, whereas, the car tire spectra peaked around 1 kHz. At full rated load, increasing the inflation pressure from 345 to 690 kPa (50 to 100 psi) did not shift the peak frequencies but did change the peak amplitude (down 4 dB @ 655 Hz and up 7 dB @ 200 Hz). At an inflation pressure of 552 kPa (80 psi), increasing the loading from one-half to full rated load consistently reduced the peak amplitude (2 - 6 dB) but increased the peak frequencies (20 - 35 Hz).

At the lower frequency spectrum peak (210 Hz) the tread vibration mode shape is simply a ring mode with nodal points ~ 0.3 m (12 in) apart around the tread circumference. The mode shapes at higher frequencies are more complex and difficult to display. At ~ 600 Hz the tread flexes at the transverse grooves causing every other lug to move radially out-of-phase relative to the adjacent lugs (see Fig. 5).

Transfer function analysis using the impulsive excitation procedure was also employed to study the vibration modes of individual tread lugs.

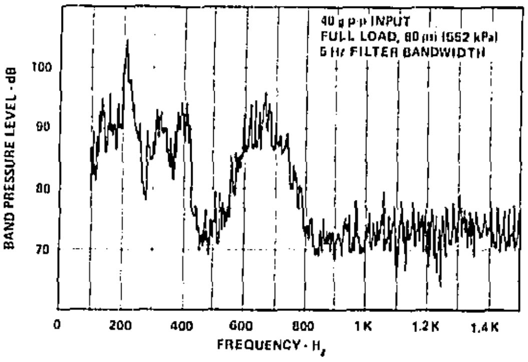

Fig. 4 - Vibration-caused noise spectrum

Monitoring tangential motion of the lugs and exciting the adjacent lugs either tangentially or radially produced predominant peaks in the 500 Hz range.

AIR PUMPING

SYSTEM INPUT - Direct measure of the change in volume or pressure buildup in the area between the tread lugs is difficult because a passive pressure or volume velocity transducer would act as a microphone and not differentiate air pumping from vibration generated noise.

The static change in volume was measured in two tests:

1. A new tire was held in a fixture and loaded from half to full rated load. Water displaced from the tread void volume was ~ 5% of the original volume.
2. Similarly, a partly worn tire on a loaded truck was measured as the tire rolled. This was done by sealing one transverse groove and connecting the volume to a graduated pipette filled with water. As the tire slowly rolled through the contact area, the volume changed 4%.

At highway speed these volume changes would be about half (2 - 3%) because the dynamic modulus of typical tire rubber is approximately twice the static modulus (4).

This volume change is assumed to be nearly constant with vehicle speed, the rate of change, however, increases such that the acoustic power increases as the fourth power of vehicle speed

$$(\bar{p} = \frac{v_o \omega \rho A}{4 \pi r}$$

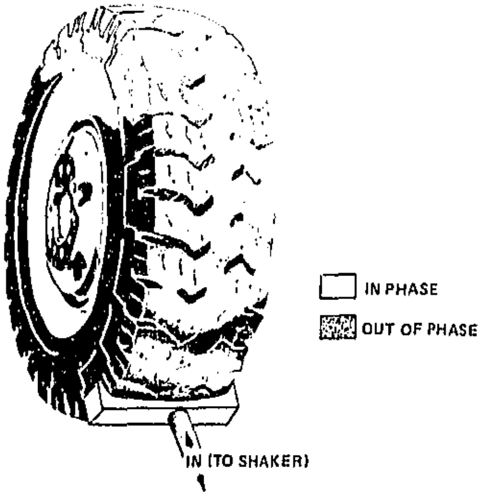

Fig. 5 - Vibration mode shape @ 600 Hz

Fig. 6 - Piston used for air pumping simulation

where:

p = sound pressure
v_o = source velocity
ρ = density
A = source area
r = distance from source.

Sound Pressure Level by definition:

$$SPL = 20 \log p/p_{ref}$$

$$= 20 \log \frac{v_o \omega \rho A}{4 \pi r} + \text{constant}$$

and as both v_o and ω are proportional to vehicle speed (V),

$$SPL = 20 \log \frac{V^2 K \rho A}{4 \pi r} + \text{const.}$$

$$= 40 \log KV + \text{constant where } K = \text{const.})$$

AIR PUMPING SIMULATION - Fig. 6 is a photograph of the piston used to pump air from the tread void. For the pumping simulation a thin rubber membrane was used as an air seal between the piston and the tread void (see Fig. 7). This was done to prevent air from escaping the void anywhere except at the open end, that is, axially. This is an approximation of what happens on the road. Other assumptions made in this test were:

1. All of the volume change in the tread void is a result of radial compression of the rubber, that is, the rubber bulging into the void area is insignificant.
2. The pulse shape or pumping rate can be approximated by the sinusoidal motion of the piston.

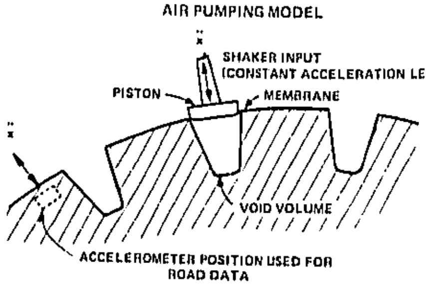

Fig. 7 - Air pumping model

The acceleration of the piston was held constant at 40 g p-p, in these reverberation room tests. Fig. 8 is a sample noise spectrum obtained during an air pumping test. Note that both the frequency and amplitude of the primary peak are above that of the vibration caused spectrum in Fig. 4. This peak @ 1150 Hz strongly supports the theory that the tread void acts as a quarter wave tube (5) (the length of this void is 8.4 cm (3.3 in) therefore, $\lambda = \sim 0.3$ m (1 ft)). The peak at 1150 Hz is clearly an acoustical resonance. When the opening into the void area was closed with a piece of tape the peak was eliminated. Similarly, when the void was partially filled, the peak frequency shifted upward.

TESTS TO DIFFERENTIATE BETWEEN THE NOISE MECHANISMS

NOISE CHARACTER - Tire noise can be characterized as a repetition of impulses. The lug spacing establishes the repetition rate and the shape of the impulse function is determined by the lug shape (or shape of the grooves between lugs). The amplitude of the noise depends on:

1. The excitation amplitude
2. The character and radiation efficiency of the responding system
3. The ratio of the excitation frequency to system natural frequency (ω/ω_n)

The data in the air pumping simulation section might lead one to conclude that air pumping easily predominates over vibration-caused noise. It is not that simple however, as the excitation frequency on the road never reaches the system natural frequencies. The tires used in these experiments had 54 lugs, giving an average lug passage frequency of 417 Hz @ 96 km/h (60 mph). At these frequencies, vibration-caused noise levels are higher than air pumping levels (for 40 g p-p input). At 417 Hz the 40 g p-p input level is approximately equal to a 0.6% volume change. In the Tread Vibration-Input Excitation section it is stated that dynamic volume changes on the order of 2 - 3% could be expected on the road. Thus, if the shaker was capable of acceleration levels high enough to give a 2 - 3% volume change, the noise levels would be of the same order as the vibration-caused levels (@ ~ 400 Hz). Too many approximations are involved in the laboratory test to differentiate between the two mechanisms with confidence.

Various experimental tests have been devised to differentiate between air pumping and vibration caused tire noise.

Water Filled Tire - This test simply involves totally filling the tire with an inelastic fluid (water). This drastically alters the tread vibration, due primarily to increased stiffness. But this should have little effect on the air pumping mechanism which involves primarily compression of the tread rubber. In our tests on the road and on the chassis dynamometer the noise levels were essentially unchanged with water indicating that air pumping predominates with this tire.*

Foam Filled Grooves - GM Research Laboratories have performed tests with the tread grooves filled with acoustical foam. In a shaker experiment similar to ours, this was found to eliminate the amplification caused by the resonant response of the groove (5). Road tests gave similar results, significantly reducing the levels in the frequency bands where air pumping would be expected to dominate (above 1 kHz).

Signal Analysis and Simulation - Some work has been done to differentiate between the mechanism by signal analysis and simulation. Narrow band analysis of cross lug passby data shows a pronounced peak at lug passage frequency and lesser peaks at harmonics thereof. Fourier analysis theory asserts that this type of spectrum can be produced by a repeated impulse-type time function.

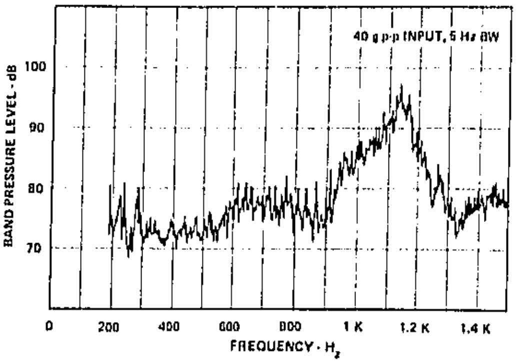

Fig. 8 - Air pumping - noise spectrum

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*In previous tests with water filled car tires, noise levels were significantly reduced.

Function generators in the lab were set up to repeat damped sinusoidal pulses at the lug passage frequency. The frequency of the damped sinusoids were then varied from 650 Hz, that is, the natural vibration frequency, to 1100 Hz, air pumping frequency. The resulting spectra were then compared with tire noise spectra measured on the road. The agreement was good over certain broad frequency ranges. A careful study of the spectra gave the overall impression that both mechanisms are present and contribute to the total spectrum.

Simply examining the spectral character of the radiated noise is sufficient in many instances to determine the predominating mechanism. In the Department of Transportation report "Spectral and Directional Characteristics of Noise Generated by Truck Tires" (6), the rib tire spectra generally peak in the 300 - 600 Hz range, that is, vibration, whereas the cross lug spectra may have peaks both in the 300 - 600 Hz range and in the 1 kHz range, that is, air pumping. The highest depends on the tread wear, road surface, etc.

TREAD PATTERN DESIGN GUIDELINES

We have shown that a number of tests can be employed to determine the dominant noise generation mechanism of an existing tire. Of more benefit would be guidelines to enable tire designers to develop quiet drive axle truck tires. The following guidelines are suggested as a basis for further experimental development work:

1. Eliminate tread patterns that cause air pumping. This can be accomplished by providing multiple paths for the air to escape through, for example, develop a block pattern.
2. If lug or cross bar patterns are indispensable for high tread wear mileage, two steps can be taken to minimize noise:
   a. Randomize the lug spacing as much as possible,
   b. Randomize the lengths of the grooves between lugs.
3. If a block pattern, perhaps with radial carcass will provide adequate mileage and traction, three guidelines should be followed:
   a. use a good block sequence that randomizes the input excitation,
   b. use different (uncorrelated) sequences in adjacent rows or stagger the tread rows to prevent blocks in adjacent rows from hitting the road simultaneously,
   c. use a solid center rib, that is, avoid blocks in the center of the tread area.

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6. W. A. Leasure, and D. M. Corley, "Spectral and Directional Characteristics of Noise Generated by Truck Tires." Dept. of Transportation, TST-75-71, Truck Noise 1-B, September 1974.

DISCUSSION

MR. NILSSON: I am quite anxious to hear your definition of air pumping, because I think what you have shown here is really the most excellent example of how a single groove in a tire can increase the radiation efficiency when it is excited by vibrations.

MR. RICHARDS: I guess my definition, which I thought other people had given, was simply the tread rolling down and sealing the edge around the void and then as the tread compresses, forcing the air out axially.

MR. LIPPMANN: I do agree, although I appeared to be entirely against air pumping before. I have evidence that indicates it is a minor mechanism, so I am not trying to say it doesn't exist. But first of all, one of the experiments on which you base a conclusion is the water-filled tire. Your vibratory experiments are also based on an argument similar to that one, that the vibrations must be shell-type vibrations, and I think Mr. Thrasher indicated that maybe that isn't the total situation. (Discussion following Paper No. 762025 by S. P. Landers).

One thing that is happening, due to the way a tire rolls and the kinematics of the interface, is that a tire builds up shear stresses and these must be released at the exit of the contact. There are vibration modes which can take place under normal rolling conditions of a tire, which are very difficult to excite by a vibrator, particularly in the way you applied it. I am not surprised at all that you didn't find fore and aft displacements.

MR. REITER: I feel compelled to make some general comments about what we are trying to do, What Messrs. Thrasher and Lippmann pointed out is absolutely correct. You have to consider two things concerning the vibration mechanism. One is that this is an acoustically slow problem. That means that the so-called shell vibrations are not important; that is, any noise produced by vibrations in the tire is coming from the region of excitation, which is near the road. That's one of the significant things that we show in our paper. That is where the noise source is located.

Two, the tire is a complex structure with an infinite number of normal modes of vibration or shell vibrations. The response of this structure to any input is some infinite sum of these vibrations. If you fill the tire with water, you will change the numbers of these vibrations; however, the response of the structure is still some series solution of these shell vibrations. The important thing is to look at the response of the structure from the vicinity of excitation. It will be the same, with the exception of different coefficients on the numbers for the shell vibrations.

MR. RICHARDS: I am not sure that requires an answer, but I think if you look at the vibrations, there is definitely frequency content in that range. I just haven't seen any substantial evidence that they are efficient noise generators.

762025

A Vibrational Sound Mechanism of Lug Type Tread Designs

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VIBRATIONAL SOUND MECHANISM OF LUG TYPE TREAD DESIGNS

THE TIRE SOUND MECHANISM presented in this paper is a possible vibrational mechanism in which the forcing function is the result of variations in the circumferential bending stiffness of the tread region of the tire. This theory was initially developed as an explanation for some unexpected test results which showed complex speed dependence of certain test tires. These tires did not follow the expected relationship in which the sound intensity varies as the fourth power of the speed. At lower speeds these tires appeared to follow a relationship in which the intensity increased at a much faster rate than the accepted fourth power of the speed. As the speed approached what appeared to be a critical speed, the rate of increase was reduced below the fourth power relationship. The sound intensity then peaked and actually began to reduce with a further increase in speed as shown in Fig. 1.

When the measured sound levels were first converted to intensity and then divided by the corresponding speed to the fourth power, the resulting values were similar to the response curve of a simple spring-mass-damper system. From this observation the theory was initially developed. It has subsequently been found that not only does it successfully help explain the complex speed dependence of some tires, but it also offers a logical explanation to the observation that in some instances, as a tire wears, it first becomes noisier than when new and then continually decrease in sound level until fully worn.

THE NOISE MECHANISM

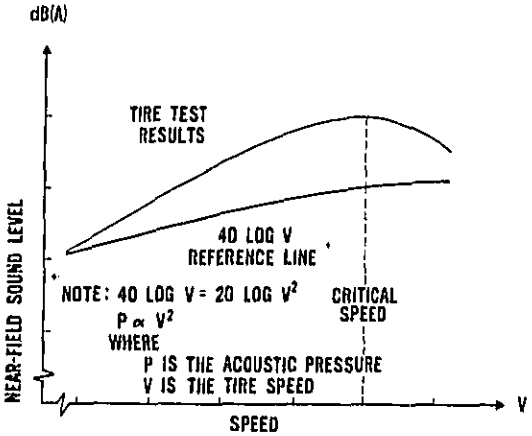

Fig. 1 - Characteristic shape of tire sound test results

The origin of tire generation is highly complex problem. There are many mechanisms that produce tire sounds and any or all of them may be present in a single tire design in varying degrees. The mechanism that is the subject of this paper is a vibrational mechansim in which the driving force originates from changes in the circumferential bending stiffness and tread mass distribution resulting from the changing geometry of tread design as it enters and exits the contact area of a rotating loaded tire. It is similar in concept to a noise generation mechanism that was presented to explain the vibration mechanism for rib type tires(1)*.

The portion of a rolling tire tread that is in con-

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*Numbers in parentheses designate References at end of paper.

ABSTRACT

The results of a carved study of basic design parameters using the on-board noise testing technique indicate that the fundamental noise mechanism of lug type tires is mechanical vibration in nature and exhibits a characteristic spring, mass damper response which is highly dependent on speed. Although the analysis of the data confirms the 40 log V relationship of speed, it indicates that it cannot be solely used to predict the change in sound level because of characteristic resonance sometimes present.

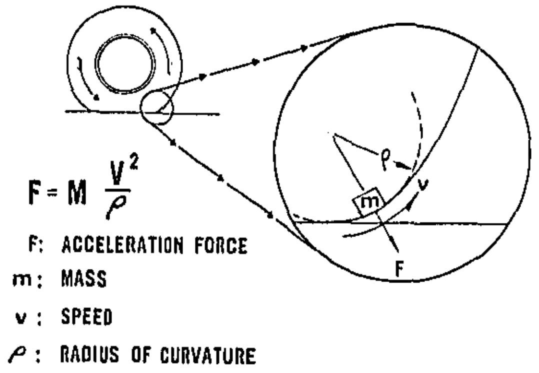


Fig. 2 - The sound generating tread acceleration force

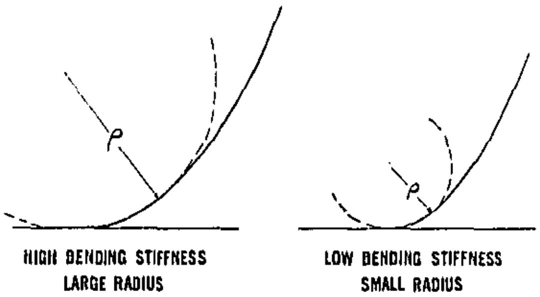


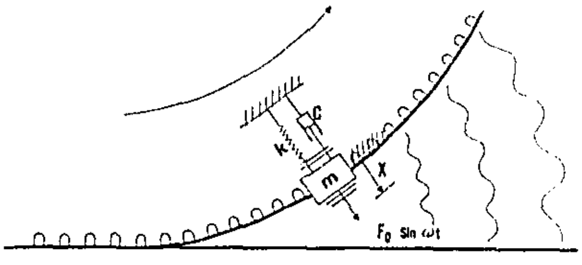
Fig. 3 - The effect of tread bending stiffness

tact with the roadway is compressed and distorted carrying the vertical load and tractive forces. Vibrations resulting from the release of these forces, although also a potential noise mechanism, will not be considered in this paper. The vibrations of interest are generated by acceleration forces. As a tire rotates and a portion of the tread leaves the contact area of the tire/road interface, it must be accelerated away from the flat roadway back into the circular path of the round tire as shown in Fig. 2. The acceleration forces of interest are generated in the portion of the tread that is just about to enter and just leaving the contact interface area of the tire. These forces are similar to centrifugal forces and will be proportional to the tread mass and the square of the speed and inversly proportional to the radius of curvature. The radius of curvatrue of the tread in this area is primarily a function of the circumferential bending stiffness. If the bending stiffness in this area is high, the tire will resist being distorted and the transition will be long and slow with a large radius of curvature. Conversely, if the bending stiffness is low, the tire tread area will be distorted more easily and bent into a sharper, smaller radius as shown in Fig. 3.

Sound will only be produced by this vibrational mechanism if there is an unsteady movement of the tread surface as it enters or leaves the contact area. There must be an air pumping action caused by fluctuations in the displacement of the tread surface. If the circumferential bending stiffness and tread mass are constant around the tire, the acceleration forces and the resulting relative movement will be constant. Little, if any, sound will be produced by this mechanism for a smooth tire. Rib type tires have tread designs which are also generally uniform, with little variation in the circumferential bending stiffness or unit mass. Tires with tread designs composed of large cross grooves cause variations in both circumferential bending stiffness and tread mass distribution. In these tires large portions of their total generated sound may originate from this vibrational mechanism.

The dynamic response of the tire structure is extremely important to the nature of this sound mechanism. The sound produced is a function of the relative movement in the tire surface. The amplitude of this movement is not only a function of the force, but also of the effective mass, stiffness, and damping of the structure. The dynamic response of the tire tread surface can be approximated by a simple spring-mass-damper system, Fig. 4. The structural damping that exists is primarily due to the straining within the tread rubber. In the frequency range under consideration, the damping or rubber is similar to viscous damping, in that it is proportional to the velocity of the distortion. The dynamic response of this type of structure can be approximated by multiplying the maximum static deflection that would result from the input force by a magnification factor, M, shown in Fig. 5.

The acoustic pressure generated by this mechanism should be proportional to the forcing function times the magnification factor. The forcing function is the result of the variations in unit tread mass and circumferential bending stiffness multiplied by the velocity of the tire squared.



INERTIA FORCE + DAMPING FORCE + SPRING FORCE + IMPRESSED FORCE = 0

$$(m\ddot{X}) + (C\dot{X}) + (kX) + (F_0 \sin \omega t) = 0$$

Fig. 4 - The tire tread region modeled as a simple spring-mass damper system

The following simple equation was tested against experimental test data to help verify the theory.

$$P \propto F \cdot M \cdot V^2$$

Where:

P is the effective acoustic pressure,

F is the effective forcing function due to changes in mass and circumferential bending stiffness of the test tire

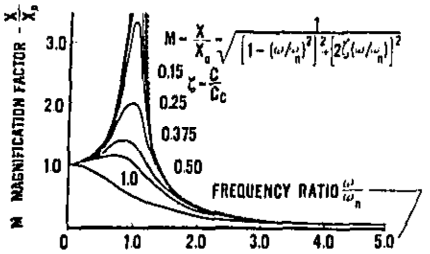
M is the magnification factor for the dynamic response of the test tire

V is the speed of the tire

THE TEST TIRES

The test program was designed to study the effects of speed on tire sound, using hand carved H78-15 bias-belted tires of different tread void volumes. The tires were carved with lug or cross bar type design as shown in Fig. 6. The tire noise mechanism presented in this paper can be used to explain the results obtained from this group. Other design types may include significant sound contributions from other generation mechanisms and cannot be fully explained by this mechanism.

All four tires in this design group contained a different percentage of void volume. They were carved with a constant depth cross groove oriented at 90° with respect to the circumferential direction. The groove width was varied to obtain the different void percentages. Since the cross grooves would cause an abrupt change in the mass distribution and circumferential bending stiffness, it was expected that the tire noise forcing function would be directly related to the width of these cross grooves. It was further anticipated that the effect of the 90° cross grooves would be at a maximum since all of the distortional forces generated would be in phase and additive. The cross grooves in all of the tires were equally spaced, causing the forcing function to be periodic, with a frequency equal to the speed of the tire tread surface divided by the distance between the center of the cross bars.



$\omega_n = \sqrt{k/m}$ - NATURAL FREQUENCY OF UNDAMPED OSCILLATION IN RADIANS PER SECOND
$\zeta = C/C_c$ - DAMPING FACTOR
$C_c = 2m\omega_n$ - CRITICAL DAMPING COEFFICIENT
$X_0 = F_0/k$ - ZERO FREQUENCY DEFLECTION OF THE SPRING-MASS SYSTEM UNDER THE ACTION OF A STEADY FORCE F_0 (NOT TO BE CONFUSED WITH STATICAL DEFLECTION $\Delta = W/k$).

Fig. 5 - The magnification factor, M

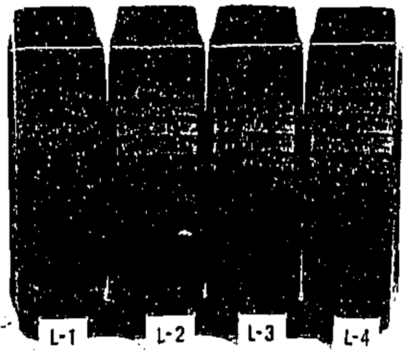


Fig. 6 - The test tires

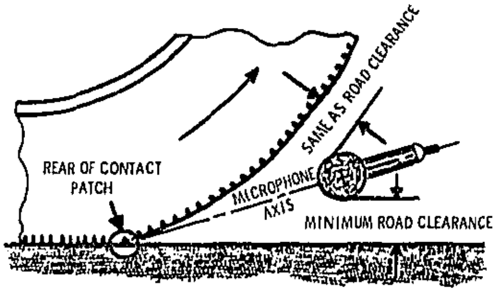


Fig. 7 - The on-board microphone position

The geometry of the cross groove design exaggerated the subject vibrational tire noise mechanism. Other more complex tread designs would not be expected to have such sharply defined forcing functions and would probably not be in phase from shoulder to shoulder.

TESTING PROCEDURE AND DATA

The testing method employed was the on-board testing technique(2). Using this procedure, the microphone monitoring tire sound was located directly behind the test tire, as close as possible, without any interference from the tire or roadway, Fig. 7. This microphone position was ideal for studying the sound produced by vibrations of the tread surface immediately behind the contact patch of the tire. The coast down test was conducted on a new asphalt surface from 55 mph down to 30 mph, with data points taken at 5 mph increments. This produced six sound measurements for each of the four test tires shown graphically in Fig. 8. Note how the more aggressive designs with the wider

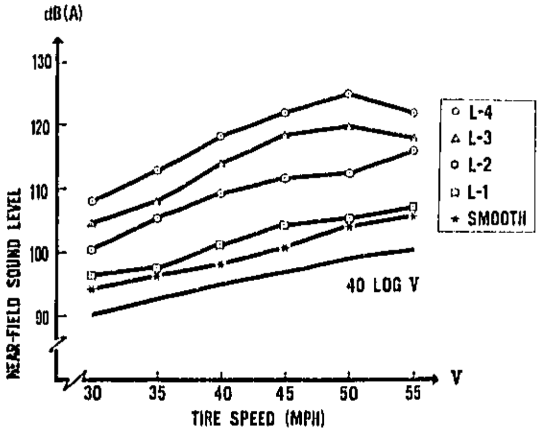


Fig. 8 - The test results

groove width appear to reach a resonant point near 50 mph and then become quieter. A smooth tire and a "40 LOG V" line are provided for slope comparisons.

THE MECHANISM MODELING

The test results were computer analyzed using an iterative technique to solve for coefficients of the noise mechanism formula. The program finds values that minimize the error between the actual measured sound levels and the theoretical predicted results generated by the formula. The resulting coefficients solved for each tire were the effective forcing function, the natural frequency of the structure and the damping coefficient.

The initial run of the program indicated that the calculated natural frequencies of all test tires were nearly equal. This result was unexpected since it was felt that natural frequency would get larger with an increase in cross groove width and reduction of tread mass. Possibly, the effective bending stiffness of the structrue was reduced at approximately the same rate as the tread mass reduction, thus keeping the natural frequency nearly constant. The average calculated natural frequency of 520 Hz was higher than expected. To simplify the computer model, all natural frequencies were set equal to 520 Hz and the data was re-evaluated.

Holding the natural frequency constant, the resulting coefficients are plotted and shown in Figs. 9 and 10. The damping coefficient is seen to decrease as the width or amplitude of the cross groove is increased. This trend is logical because the structural damping is primarily the result of the straining of the tread rubber. As this tread rubber is increasingly carved away, the damping coefficient should become smaller. A closer examination of the damping coefficient results indicate that its value is almost linear with respect to the reducing tread volume.

The effective forcing function also reveals a somewhat predictable trend. The forcing function increased as the width of the cross groove increased, although the relationship did not appear to be linear. It appears to be more nearly a function of the square of the width of the cross groove within the range of the designs tested. It would be expected that, as groove width is increased, somewhere beyond the point where the width is equal to half the distance between cross grooves, the forcing function will peak and begin to reduce. The combined effect of the cross groove on the variation in tread mass and circumferential bending stiffness is very complex and probably cannot be completely expressed with a simple quadratic equation.

The theoretical results predicted by the computer program compared very well with actual measured sound levels as shown in Fig. 11. Nearly all of the values calculated were within 2 dB. Twenty out of the twenty-four values calculated were within 1 dB. The statistical correlation between the calculated and actual values was excellent as shown in Fig. 12. A calculated correlation coefficient for all data points was found to be 0.990. This would indicate a good liklihood that this computer model of the noise mechanism has validity. It seems to fit expecially well for the more aggressive designs in which the vibrational mechanism would be the predominant producer of noise.

THE CHARACTERISTICS OF THE MECHANISM

1. The tire sound generated by this mechanism is very dependent upon the dynamic characteristics of the tire such as the natural frequency and structural damping.

2. The geometry of the tread design is the sound forcing function for this mechanism. The

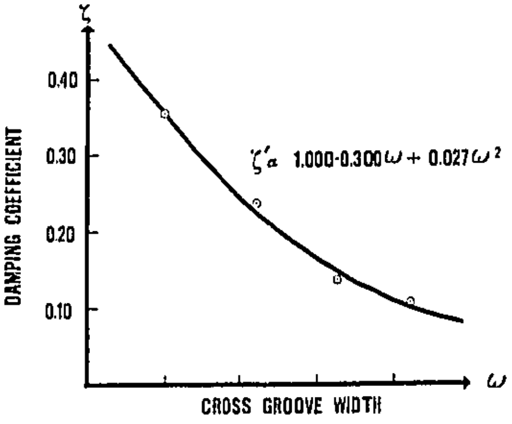


Fig. 9 - The calculated damping coefficients

greater the fluctuations in the tread mass and circumferential bending stiffness, the greater the amount of sound produced.

3. Changes in tire loudness due to changes in speed cannot be predicted solely by the simple "40 LOG V" relationship. Tire resonances can add significantly to the loudness of the sound produced by certain tires. If the resonant speed of a tire is within its operating speed range, there may be problems in trying to rate it for loudness. The single speed at which it is tested and rated may not be representative of its entire speed range.

4. The resonant speed of a given tire is not only a function of the dynamic characterization of a tire's structure, but also of the tread design. The cycle length of the repeating tread design feature determines the period and frequency of the forcing function.

5. It is possible to have more than one resonant speed in a tire. The tire's structure is very complex and has several possible modes of vibration. The forcing function resulting from complex tread designs may contain strong harmonics of the fundamental tread frequency. These harmonics can also excite the resonant characteristic of a tire.

6. As a tire wears, the tire structure will become more resonant. This is because the structural damping, that is the result of the volume of tread rubber being distorted, is being reduced. Also the natural frequency of the structure may increase slightly, as the mass of the tread is reduced. Both of these effects could cause an increase in the resonant response of the structure and a resulting increase in sound loudness. At the same time, the wear of the tire is reducing the variations in mass and circumferential bending stiffness. The road is wearing away the forcing function. For some tires the decrease due to the reduced tread variation may be outweighed initially by the increased resonance response and the tire will first become louder as it wears. There are other effects such as a changing tread radius and irregualr wear that must also be considered. It can be seen that this effect will not occur for all tires, but for those in which it does, the phenomenon is very complex and would be difficult to predict.

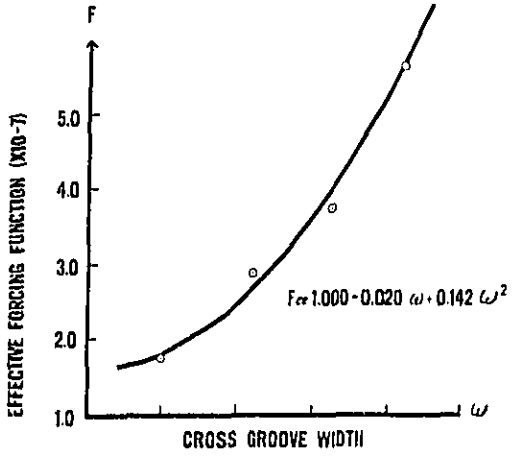


Fig. 10 - The calculated effective forcing function

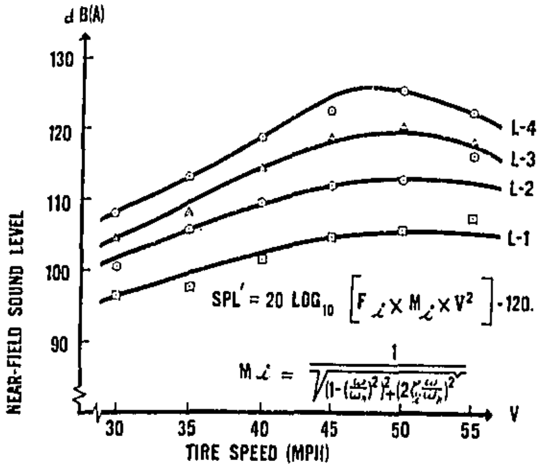


Fig. 11 - A comparison of computer predicted results (lines) and actual test results (symbols)

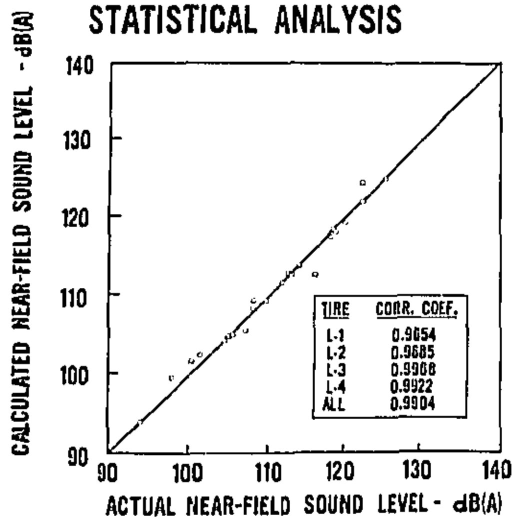


Fig. 12 - A statistical analysis of computer calculated versus actual tire sound levels

7. The tire loudness is affected by the distortion of the tire. This increased distortion can be caused by an increased deflection of the tire due to an increased loading. It might also be caused when

a tire is run on a curved surface such as a lab wheel. Aggressive tires with cross groove type tread designs are slightly louder when tested on a lab wheel than when tested on a roadway(3).

SUMMARY

The tire noise relationship presented in this paper correlated extremely well with experimental test results. The acoustic pressure was modeled as a function of the force variations resulting from tread design geometry, the dynamic response of the tire and the tire velocity. The "40 LOG V" realtionship of tire sound level with respect to tire speed was found to be valid, but other dynamic response characteristics were found to sometimes add significantly to the sound level near resonant speeds. The dynamic response of the tire's structure should be considered in the assessment of a tire's potential loudness throughout its operating speed range or throughout its operating life.

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DISCUSSION

MR. REITER: I would like to make a general comment about the particular example in which you have a non-pitched tire. Certainly this shows that you had a resonant type of phenomenon in the tire, certainly a vibration-type noise. I don't think this is the general vibration source that we are talking about. If you had pitched the tire you wouldn't have observed the result that you obtained. It is, generally speaking, a forced vibrational response problem, a very complex force function, but not a resonant response.

MR. LANDERS: I agree, but not entirely. The tires that I tested here, as I mentioned, are exaggerated. They don't represent commercial tread designs. It just happened that we were able to observe this phenomenon in which the resonance was exaggerated. In an actual tread design, of course, different portions of tread pattern will have different forcing functions. They will be out of phase, and the combination will be very complex.

MR. WOOTTEN: It seems to me that two accelerometers on the axle might have been helpful to resolve the direction of the reaction of the tread acceleration. Also, the dynamic pressure in the tire is another area where additional information could be obtained on dynamics of rubber.

MR. LANDERS: We have not been able to study this with actual accelerometers as yet; that study is to be conducted as soon as I return. I realize that the validity of what I have presented here is not complete until I finish that, but we wanted to present the work to date in order to start people thinking about it as a possible mechanism.

MR. THRASHER: I would like to make one comment about vibration. If you consider the tire as a shell and look at the normal modes of the shell, the radial mode or the lateral mode, and then drive the tire, for a radial tire beyond about 140 Hz you see nothing very exciting happening to that tire.

When you are looking at the shell modes and drop the inflation pressure of the tire by 2 psi, you do shift the frequencies about one cycle and that's a fairly fundamental rule. You can play this game to about 12 psi on a passenger tire.

I think the types of vibrations that you are seeing, as far as noise radiation is concerned, are not the so-called shell modes at all, but perhaps a flexural mode in the tread band itself. I don't have the information, but I think there is some confusion that exists here, in that I don't think that basically the sound radiation modes are really shell modes.

MR. LANDERS: All vibration studies that I know of support what you have said.

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On Generating Mechanisms for External Tire Noise

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TWO DIFFERENT HYPOTHESES concerning the generation of external tire noise dominate the discussion, namely:

1. Noise is generated when air is pumped in and out in tire and road cavities during the contact process; this mechanism is referred to below as "air-pumping".
2. Noise is generated by excitation of vibrations of the tire during the contact process; the vibration in tire and maybe the road can radiate in the form of air-borne sound to the surroundings; this mechanism is abbreviated below as "vibration-radiation".
3. Noise is generated by a combination of mechanism one and two so that the air squeezed out during contact is being modulated by the tire vibrations. By this cross-coupling the radiation efficiency for tire vibrations is highly increased.

Many significant observations can unfortunately be explained by the first two hypotheses mentioned above (See Table 1). Definite and certain information about which generating mechanism is predominating for different speed and frequency ranges seems not to exist.

The analysis of data in pertinent literature seems to indicate what type of mechanism is dominating at different speeds and frequencies. To be really sure that the interpretation presented here is correct we think that further experimental evidences are required. However the Figs. shown are only experimental data. Here we do not deal with mechanisms for speeds exceeding 75 mph.

TIRE NOISE RADIATES FROM THE CONTACT REGION

Many of the tests performed seem to indicate that tire noise is mainly radiated from the tire-road interface.

Experiments performed by Reiter and Eberhardt (2)* show that the tire vibration is greatest in the contact region and some screen tests performed by Tyler, et al. at TRRL, England, show that the effect of low screens near the road is greatest for the high-frequency noise.

Siddon (1) has performed correlation studies between near- and far-field microphones. He found that for normal rib tires on a normal asphalt road the highest cross-correlation coefficient is obtained

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*Numbers in parentheses designate References at end of paper.

ABSTRACT

An analysis of available tire noise data seems to indicate that external noise emission from tires on dry roads is mainly caused by radiation of vibrations from the tire-road interactions. Indications of this are:

1. Speed dependence of random-tonal-and squeal noise.
2. The power spectral density versus speed and frequency (by using a novel data-reducing technique for tire-noise).
3. The connection between n and C in the formula L = C + 10 n log (V)
Where:
L is sound level dB(A),
C is regression constant,
V is vehicle speed, and
n is velocity exponent.
All tires and road surfaces constitute a straight line.
4. External noise dependence on the macro-texture of the road.
5. Connection between the normalized PSD versus structure number and PSD versus space frequency of the roughness of the road surface.

The paper points out the possibility of tangential movements of tread elements as a source of high-frequency external noise from tires on dry road surfaces.

For wet roads, the tire noise normalized spectrum in the lower frequency region would suggest some turbulent fluid-dependent mechanism while transients from braking up the water film may be responsible for the noise at higher frequencies.

Table 1 - Example of How Some Significant Observations Can Be Explained With Help of Both the "Air-Pumping" Theory and the "Vibration-Radiation" Theory.

OBSERVATION	EXPLANATION WITH HELP OF THE "AIR-PUMPING" THEORY	EXPLANATION WITH HELP OF THE "VIBRATION-RADIATION" THEORY
In dry conditions porous road surfaces are quieter than sealed	The velocity of the out-streaming air is reduced which leads to reduced external noise.	Due to the fact that external tire noise is radiated near the road surface the sound absorption of the porous road will reduce the noise.
When a tire was run on a carpet the external noise was reduced.	See above.	With the carpet a higher degree of compliance was obtained which reduced the excitation.
Block-pattern is more noisy than continuous rib-pattern.	Block pattern gives a more rapid out-stream of air from the cavities which cause more noise.	The block-pattern gives "shock-excitation" of the tire which is not the case for continuous rib-pattern. At the same time the circumferential stiffness of the tread elements is reduced which causes more tangential excitation to the tire.
Sound is radiated near the road.	As the entrapped air is streaming "out and in" the cavities near the road, it is natural that the noise also is radiating from the tire-road interface.	As the excitation of the tire occurs near the road and the tire is a very damped construction with acoustically slow waves the radiation must occur near the road.
The harmonics of the tonal noise increase more rapidly than the fundamental when the load is increased.	A sharper wave-form of the in- and outstreaming air is obtained for higher load.	A sharper wave-form for the radial excitation is obtained.
Tire noise is increased when runway roughness is decreased to near zero.	The road surface is sealing the cavities in the tire which leads to a more rapid release and instream of air in the cavities.	Towards extremely smooth road surfaces the tangential movements of the tread elements are increased, which increases the high frequency noise.

for the near-field microphone placed near the exit interface (Fig. 1). Several experiments (1) also show that the sidewall is not the dominating sound radiator.

It is reasonable to conclude that external tire noise is mainly radiating from the tread band in the exit- and entrance interface near the contact patch. For tonal tires it seems that the exit interface is the dominating radiation area.

Due to doppler-shifted wave-length in the tread band relative to the surrounding air it is reasonable to expect that the exit interface would be the dominating radiator for contact patch excitation. See Ref. 15 for the practical case.

RANDOM AND TONAL TIRE NOISE

External tire noise is built up by tonal and random noise components. The tonal part originates from regularities in the tire and the road while the random components can be assumed to originate first by radial excitation due to a random roughness of the road but also from random tangential movements of the tread elements due to a randomly distributed friction coefficient of the road.

Tonal tire noise increases faster with speed than random tire noise according to experiments, (3) See Fig. 2. This probably depends on the

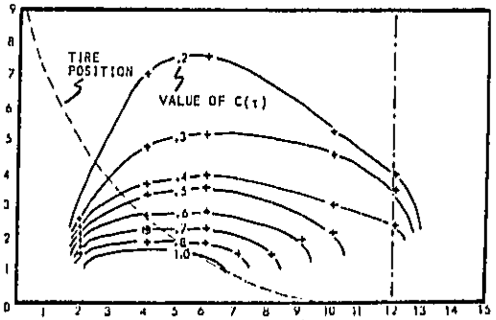

Fig. 1 - Normalized plot of the correlation coefficient $C_{(\tau)_{max}}$, after Siddon, Ref. 1

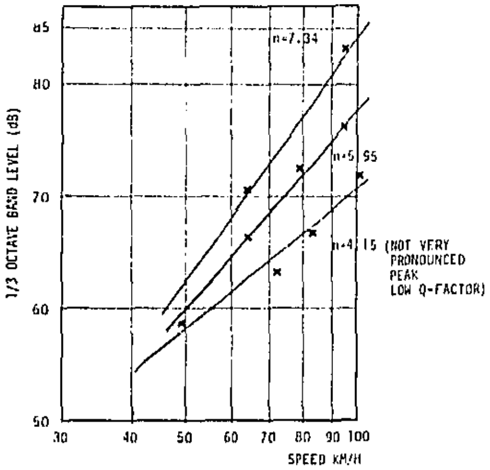

Fig. 2 - Speed dependence of tonal noise from tires, heavily loaded N. R. traction tires. (Data from Underwood, Ref. 4.)

change in wave-forms for the shock occurring when a tire pattern block collides with the road. This trend is reflected by a relationship between n and C in the formula $L_A = C + 10 \log V^n$ for a great variety of tires and road conditions. Tires which give mainly random noise, as for example tires on wet roads, rib-tires on rough road surfaces and studded tires, give low n:s but high C:s. On the other hand tonal tires on smooth roads give mainly high n:s and low C:s.

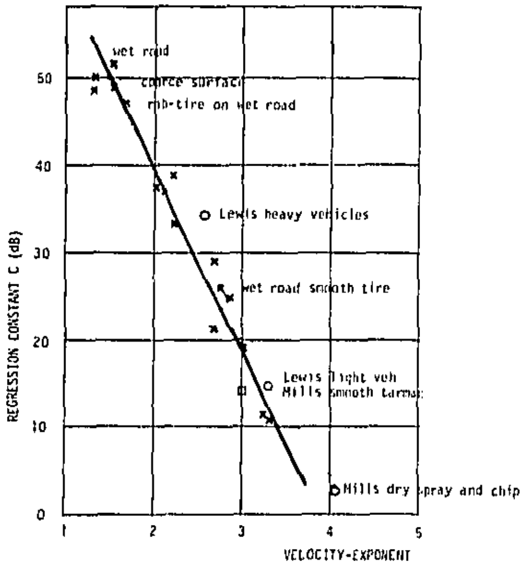

Fig. 3 - Connection between regression - constant C and velocity - exponent N in the formula.
$L_A = C + 10 \text{ Log } (V^N)$. (Data from Ref. 7 - 9.)

Surprisingly enough it has been possible to plot almost all tire noise data in one single diagram! In Fig. 3, C is shown as a function of n. All experimental data collapse to a single line. This line represents all types of tires, road conditions, vehicles and loads. This coast by test was done at the distance of 7.5 m.

If the influence of the tire pattern is taken into consideration a great deal of the scatter in Fig. 3 can be explained (see Fig. 20 in Ref. 12. The distribution of different road-tire-vehicle combinations in the C(n)-diagram can be explained by the "vibration-radiation" theory for external tire noise. It is, for example, plausible that higher load gives more noise from tangential tread element movements which would in turn give lower structure-number exponents.

NORMALIZED TIRE NOISE SPECTRUM

By introducing a novel technique for reducing data from tire noise measurements it is possible to draw some interesting conclusions about the generating mechanisms.

The technique of data reduction consists of a normalization of the sound-pressure-level spectrum (in the case shown, Fig. 4, measured at 7.5 m from the road and for a "coasting vehicle" (4) to a non-dimensional frequency called structure number fd/v and to a specific level due to some assumptions concerning the source strength ($L_{spec} = L_P - 10 \log (V^{n-1}) - 10 \log (\Delta f) - 10 \log d$ where d for this special case is set to one).

In Fig. 4 the source exponent n is allowed to vary throughout the structure-number interval (segmented structure-number analysis). When the correct source-number interval (segmented structure-number analysis). When the correct source-exponent function has been reached all data-points in the entire structure-number interval are reduced to a line (See upper diagram).

What is especially interesting with the segmented structure-number function shown in Fig. 4 is that the exponent is of value four for lower frequencies while of value two for higher frequencies.

In Fig. 5 the corresponding function for flow noise of a straight duct is shown (11). The exponent function for flow noise is found to be a strict increasing function. This type of exponent function seems to be quite different from the exponent function obtained for tire noise on dry road. It appears that pure aerodynamic source mechanisms do not apply to tire noise. Note that the source-exponent function is a continuously increasing function while the corresponding function for tire noise is continuously decreasing.

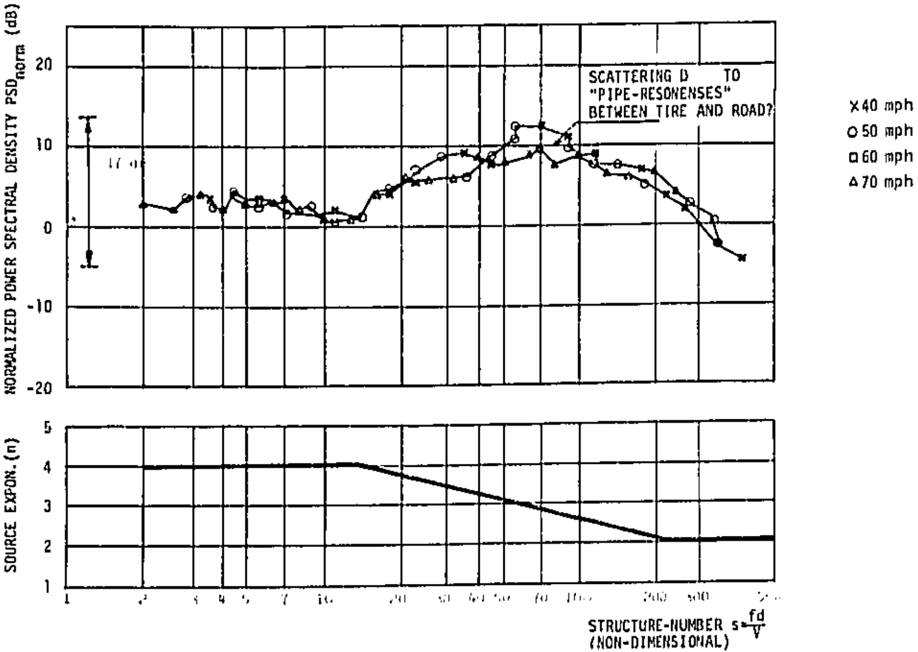

Fig. 4 - S_N - Function. The shown exponent function leads to a good collapse of data in the entire strouhal interval. Data from Ref. 5. (Random tire noise only)

According to a theory by Dr. Ullrich at BASt in Germany (9) it seems reasonable to assume that the radial excitation of a tire would have a source exponent of four. The exponent is somewhat reduced when the tire load is increased. The speed dependence of the radial excitation (9) is shown in Fig. 6.

Our analysis of the data from Ref. 5 shows that tire squeal would have a source exponent of around two. The exponent is dependent on the rubber compound. We think that this reflects the source exponent of noise from tangential movements of the tread blocks even if squeal conditions are not reached. (Fig. 7)

Our hypothesis for the tire-(dry) road interaction noise, based on what has been said in the previous text, is therefore that the lower nor-

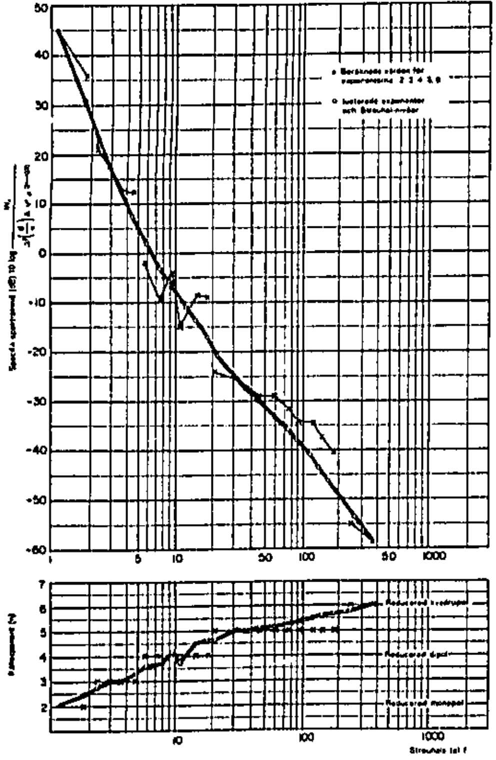

Fig. 5 - Diagram showing a segmented strouhal - function for aerodynamic noise generated by a straight duct

The calculated segmented Strouhal function according to the author. Basic data are from ASHRAE, project NR RP 37. A straight duct with a square crossection and made of 3.7 mm steel sheet coated with visco-elastic damping layer. The length of the duct is 15.6 m. The dimensions are 60 × 60 cm². The generation can be assumed to be practically free from the influence of vibrations in the duct wall for the data concerned. The exponent increases linearly with the Strouhals number from the exponents 2-6. This verifies the theory of the continuously increasing source exponent in the Strouhal interval. In addition it verifies the theory of the reduced source exponent

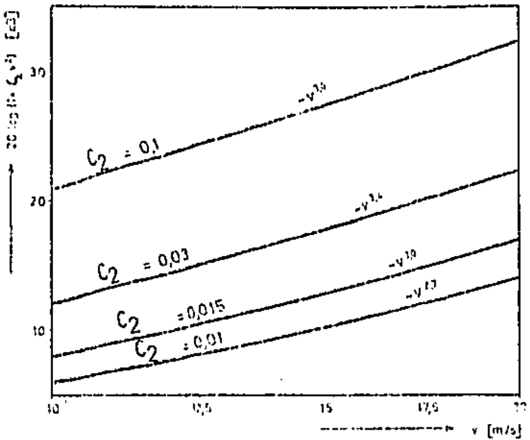

Fig. 6 - Plot of 20 log $(1 + C_2 V^2)$ for different value of C_2. (Ullrich, Ref. 9.)

malized frequencies seem to be dominated by radial excitation in the foot-print region of the tire while tangential (lateral and circumferential) excitation due to scrubbing in the foot-print region seem to be a dominating source for higher frequencies.

The limiting frequency between the two mechanisms is then speed-dependent. At very high speeds tire noise should be totally dominated by radial excitation. At very low speeds tire noise is dominated by tangential excitation.

Experimental data from road-wheel versus road, changed inflation pressure differences between radial- and bias-ply tires can nicely be predicated with the help of Fig. 8.

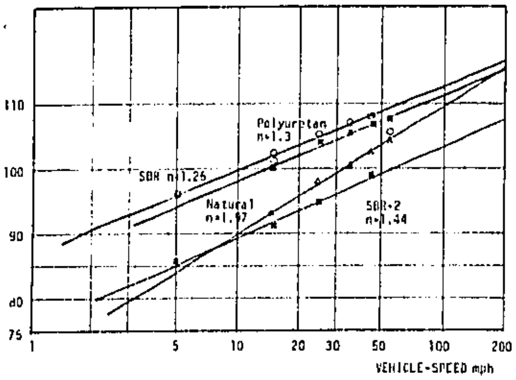

Fig. 7 - Squeal noise levels as a function of vehicle speed for different kinds of tread compounds. (Data from Ref. 6)

CONNECTION BETWEEN ROAD PROFILE SPECTRUM AND RADIATED NOISE

In Fig. 9 is shown the normalized tire noise spectrum where the same source exponent has been used in the whole structure-number interval (with a higher scattering compared to the segmented analysis in Fig. 4) to preserve the spectrum shape. The dotted curve in Fig. 9 is the Fourier transform of the road profile (from Ref 14) (which was obtained by tracing the texture with a profilometer).

As seen from Fig. 9 there is an amazingly good agreement in spectrum shape between the normalized PSD of the road profile and the normalized tire noise function. The limiting frequency between the flat and the falling parts of the two spectrums is occurring at approximately the same values.

We consider this as a further evidence that the vibration-radiation is the dominating source mechanism. Whether this should be interpreted as evidence for either radial or tangential excitation is not clear. It is obvious that the runway roughness can give radial excitation but there is also a possibility that a distributed friction coefficient (which can be represented by the profile spectrum) at higher space frequencies can contribute to the tangential excitation. Thus the coincidence does not eliminate the possibility of higher tire noise frequencies being caused by tangential excitation as Fig. 4 suggests.

ROAD TEXTURE AND THE GENERATING MECHANISMS

In Fig. 8 the radiated external tire noise levels are shown as a function of texture height. As the

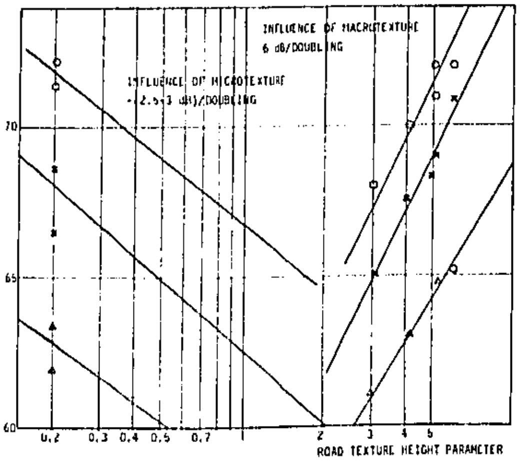

Fig. 8 - Influence of texture - height on external tire noise

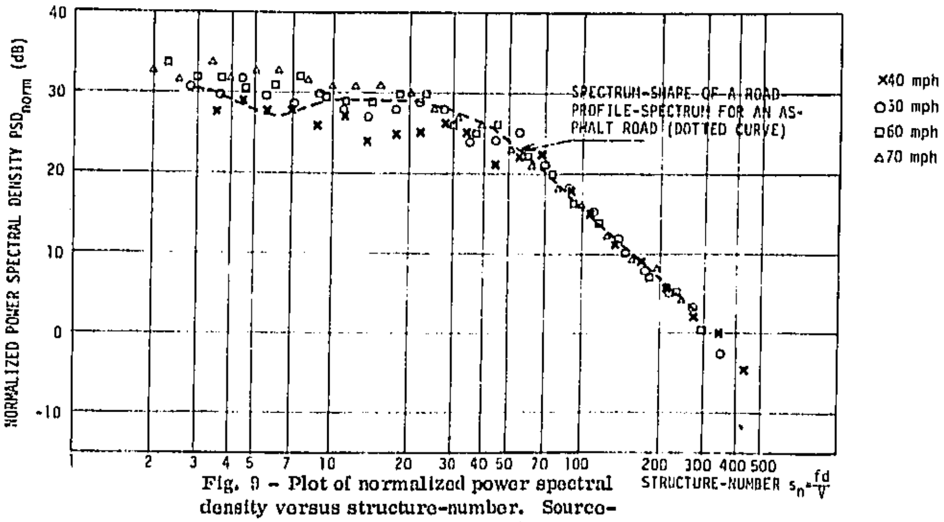

Fig. 9 – Plot of normalized power spectral density versus structure-number. Source-exponent N=2. Rib tire on smooth road. (Hillquist, Ref. 5)

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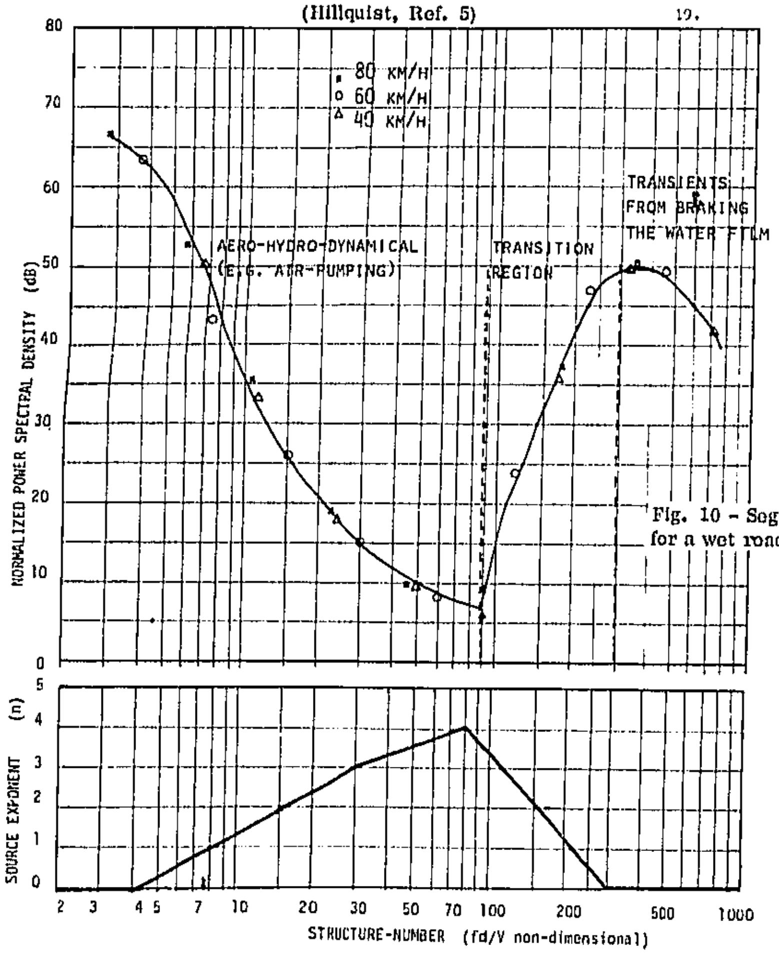

Fig. 10 – Segmented structure number function for a wet road. (Data from Ref. 13, Rathé)

height is increased over value 2 the noise level is increasing with approximately 6 dB per doubling of texture height. Below the texture height value 1, the noise level is surprisingly increasing enough when the texture height is decreased. This phenomenon can be explained by the vibration-radiation theory in the following way.

Higher texture height values (which usually mean bigger stones and thus lower frequencies of the profile spectrum) will give an increased radial excitation to the tire in the audible frequency region. Therefore external noise increases with texture height. On the other hand, when increasing texture height below value one the increased texture gives no additional energy, which increases the dB(A)-level while still giving an additional road friction. Increasing the small scale texture (micro-texture) of the road thus gives no extra radial excitation but decreases the tangential excitation by preventing the tread-elements from scrubbing in the contact region by the increased road friction.

WET ROADS

In Fig. 10 is shown the segmented structure number function for external tire noise from a wet road surface. As can be seen, the exponent function is different from the dry condition. It is obviously two different mechanisms dominating for lower and higher frequencies. This is seen from both the exponent function and the normalized level function.

The exponent function would suggest some aerodynamical or hydro-aerodynamical (for example, air-pumping) source mechanism probably of turbulent character for frequencies up to Sn = 80 (compare with Fig. 5) while transients from breaking up the water-film may cause the noise above Sn = 300. The region between Sn = 90 and Sn = 300 could be a transitional area between the two mechanisms.

NOMENCLATURE

f = frequency
d = characteristic dimension related to radiated noise
V = vehicle velocity
C = regression constant
n = source exponent
Δ f = bandwidth of analyzing filter

ACKNOWLEDGEMENT

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DISCUSSION

MR. REITER: In light of the wealth of information presented on tire vibrations as a noise-producing mechanism, you mentioned air pumping as a mechanism. I should like to ask you what new evidence your investigation has produced that would suggest or would indicate that air pumping is important in tire noise?

MR. NILSSON: My analysis of the literature seems to indicate that tire vibration is the most predominant force mechanism, but for wet roads, it may be an aerodynamic element. Also for a very heavily patterned tire with suction cups on very smooth roads, maybe the air pumping mechanism is still possible, but we think that some more proof is needed in this field.

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Power Train, Tire and Aerodynamic Sound Levels of Automobiles at Steady Speeds

Ralph K. Hillquist
General Motors Corp.

EXPERIMENTAL STUDIES OF SOUND EMISSIONS from highway tires, as evidenced external to the vehicle, have been reported over the last 25 years or so; the vast majority of these have concerned commercial or heavy truck tires. However, several investigations, in whole or in part, have considered automobile tires (1-8, 12)*. Throughout these latter studies, the parameters of speed, load, carcass construction, tread pattern, and pavement surface texture are dealt with in varying degree.

It is becoming somewhat customary to segregate vehicle sound sources into two distinct categories, power train and rolling sounds. The former comprises engine, induction, exhaust, cooling fan, accessories, and transmission; the latter comprises the propeller shaft and rear axle, tires, and aerodynamic sources. Typically, cargo and body rattles, tire squeal, and the like are disregarded. Power train sounds and rolling sounds combine to give the total vehicle sound; of these, only vehicle and rolling sounds are uniquely measurable.

The purpose of this paper is to present the results of a study to determine the magnitudes and characteristics of power train and rolling sounds for typical automobiles and tires. A secondary objective is the possible separation of the tire and aerodynamic constituents of rolling sound.

The test work reported herein was conducted as a continuation of that previously reported by Hillquist and Carpenter (7). Two separate test series, involving different test vehicles, test tires, and test sites, were conducted. Both series will be discussed in this paper.

EXPERIMENTAL WORK

As noted, vehicle and rolling sounds are uniquely measurable, by driving and coasting the test vehicle through a conventional automotive exterior sound measurement test site. Power train sound levels can subsequently be calculated from vehicle and rolling sound levels. This was a basic premise upon which the studies were based and test data acquired. Basically, the experimental procedure was to determine the average peak sound level for replicated coastby and driveby test runs over a range of vehicle speeds, for each of the tires to be studied. From these test data, power train sound levels would be subsequently calculated and averaged.

The first test series utilized a full-size four-door sedan equipped with a 5.7 l (350 CID) engine and single exhaust system. Test tires were of steel-belted radial construction, with both blank and discrete-block tread patterns. The blank tires had full depth of tread rubber, with no grooves or other pattern cut in. The discrete-block pattern, to be designated "TPC" herein, was in accordance with the GM tire specifications. The size of both sets was HR78-15. Vehicle test weight (curb weight plus driver) was approximately 2100 kg (4630 lb).

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*Numbers in parentheses designate References at end of paper.

ABSTRACT

Data from powered and coast passby tests are analyzed to produce sound level versus speed information for the power train and tires as separate sources. Tires with blank, continuous rib, and discrete block tread patterns were used. Test speeds covered the range of 48 - 160 km/h (30 - 100 mph). Fit of the experimental data to a 30 log (Speed) relationship for the power train and a 40 log (Speed) relationship for the tires is exceptionally good. Some evidence of aerodynamic contribution to the rolling (coastby) sound is noted at the upper end of the speed range. These findings support the postulation that tread vibration is the primary mechanism of automobile tire sound generation.

The test site surface (both lane of travel and adjacent reflecting pad) was smooth sand-aggregate asphalt. The test microphone was located 7.5 m (25 ft) from the centerline of vehicle travel, at a height of 1.2 m (4 ft) above the surface.

Tests were conducted at nominal 16 km/h (10 mph) intervals from 48 - 160 km/h (30 - 100 mph). Test speeds were monitored by the vehicle driver, using a calibrated fifth-wheel speedometer. At each test speed, six coastby and two driveby test runs were made, in alternating direction.

All passby runs were recorded on magnetic tape, using a 1 in normal-incidence condenser microphone and amplifier (meeting ANSI Type 1 specifications) and a broadcast-quality audio tape recorder. These tape recordings were subsequently replayed into a Bruel & Kjaer Type 3347 real time analyzer and associated minicomputer, for determination of peak sound levels, the spectrum corresponding to peak A-weighted sound level, and the average of these over the group of test runs. The equivalent of fast dynamic response was used for all level determinations.

The second test series was conducted several months after the first, and in general followed the same format. Because the upper test speed was just marginally attainable with the first test vehicle and because test speeds in excess of 160 km/h (100 mph) were being considered, a sporty two-door coupe equipped with a 7.4 l (454 CID) engine and dual exhaust system was used. Also because of the anticipated upper test speeds, test facility restrictions mandated the use of tires approved for continuous high speed operation (for example, highway patrol tires). Consequently, tires of bias-belted construction, in size F70-14, were used; both a blank and a representative continuous rib tread pattern were tested. Vehicle test weight was approximately 1650 kg (3640 lb).

The test site was surfaced with smooth asphalt, representative of highway construction. (Specifically, the wearing course met Michigan Department of State Highways and Transportation specifications for 31A bituminous concrete, in which the aggregate is 100% crushed stone passing through a 9.5 mm (0.38 in) sieve.) The test microphone was located 15 m (50 ft) from the centerline of vehicle travel, again at a height of 1.2 m (4 ft).

Test speeds were nominally those used in the first test series. For this series, however, an on-site electronic timing system was used to determine vehicle speed. Acoustical instrumentation and recording techniques duplicated those of the first series.

To facilitate comparison of the test data from the two series and also comparison of the data in this paper with other automotive sound level data, the observed sound levels from the first test series have been arbitrarily corrected to a test distance of 15 m (50 ft). This has been accomplished by a uniform five decibel reduction of all sound data; this distance "correction factor" has been shown by other work to be valid for both driveby and coastby circumstances (9, 10). This adjustment of the test data from the first test series serves only to have these data appear numerically like similar data, and in no way affects the subsequent analysis and interpretation of these data.

DATA ANALYSIS

As indicated previously, the peak sound pressure level the peak A-weighted sound level (hereafter, sound level), and the third-octave band spectrum corresponding to the peak sound level were obtained for each test condition (vehicle, tire, speed, operating mode); the average level (on an energy basis) from all test runs for each condition was used for subsequent analyses.

Estimates of the power train sound levels were calculated from the vehicle (driveby) levels and the rolling (coastby) levels. For each vehicle, the two sets of estimated power train levels corresponding to the two tire sets tested were combined for further analysis.

Preliminary examination of the test data indicated that a functional power relationship with vehicle speed could be expected. The exponent, or exponents, of these relationships and the fit of the data to these relationships could be used to draw some insight into the characteristics of the basic sound sources and the possible separation of sources based on their anticipated power relationships. This will be developed further in the following discussion.

Regression coefficients were calculated for the observed coastby data versus speed and for the estimated power train levels versus speed. (These are shown on Table A-1 in the Appendix.) Both the sound pressure level and sound level data were used for this and subsequent analyses. This was done to ensure that the frequency-dependent characteristic response of the A-weighting network was not a factor in determining the exponent in any functional relationship.

The regression slopes indicate that rolling sound varies very nearly as the fourth power of speed (that is, 40 log S) and power train sound, approximately as the third power of speed (30 log S). Consequently, predictive models for rolling and power train sounds were based on 30 log S and 40 log S relationships, respectively.

It should be noted that regression coefficients for rolling sounds were first determined, then a correction based on these coefficients made to the coastby sound levels to account for the difference in coastby and driveby speeds prior to the determination of estimated power train levels.

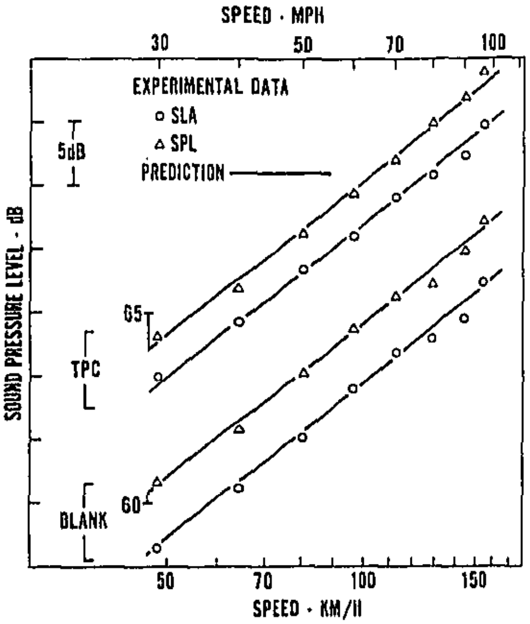

Fig. 1 - Rolling (coastby) sound pressure levels for the full-size four-door sedan on a sand-aggregate asphalt surface

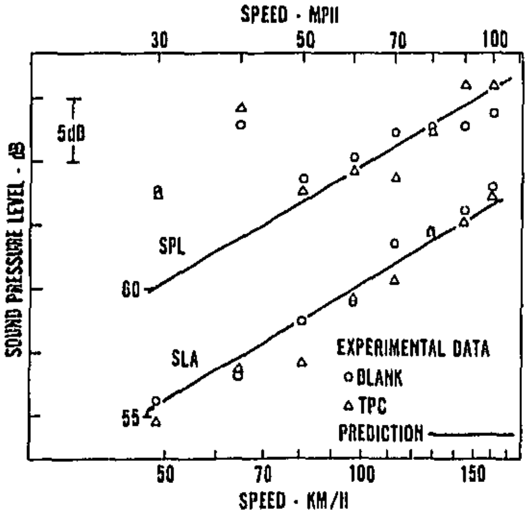

Fig. 2 - Calculated power train sound pressure levels for the full-size four-door sedan

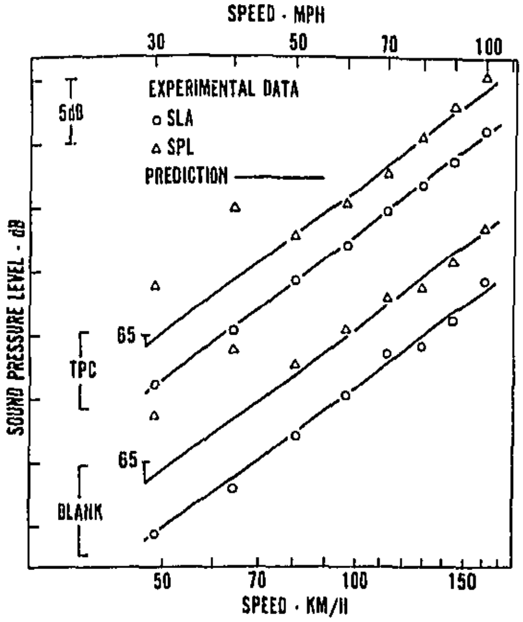

Fig. 3 - Total vehicle (driveby) sound pressure levels for the full-size four-door sedan on a sand-aggregate asphalt surface

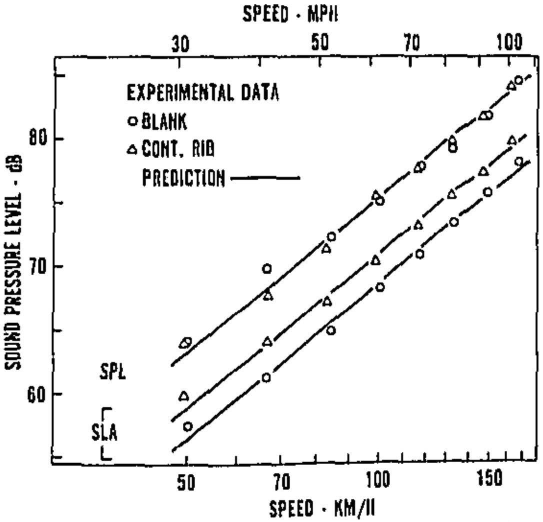

Fig. 4 - Rolling (coastby) sound pressure levels for the sporty two-door coupe on a typical asphalt roadway surface

Intercept values for the prediction, or model, equations for power train and rolling sounds were calculated using a least-squares method and the assumed slope values. (The resulting equations are shown on Table A-2 in the Appendix.) The models for rolling and power train sounds were combined at discrete speeds to provide levels comparable to the observed total vehicle (driveby) levels. The

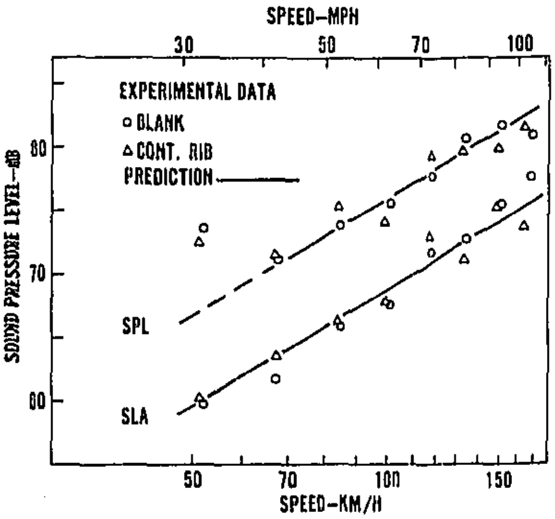

Fig. 5 - Calculated power train sound pressure levels for the sporty two-door coupe

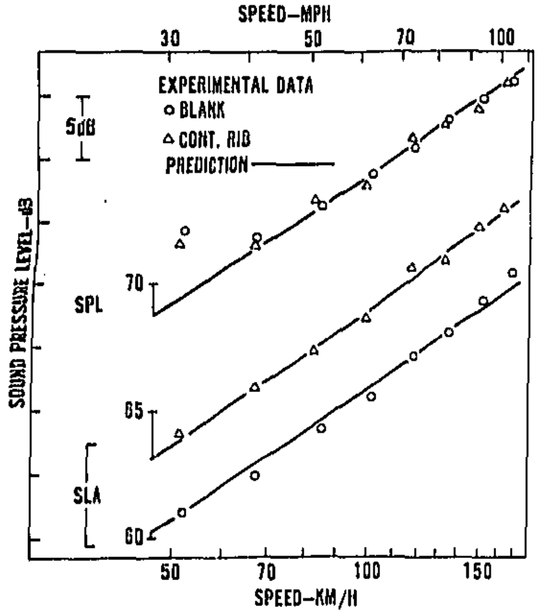

Fig. 6 - Total vehicle (driveby) sound pressure levels for the sporty two-door coupe on a typical asphalt roadway surface

coefficients of determination between predicted and observed vehicle levels were 0.98 or greater, indicating excellent correlation but giving little clue as to the "goodness of fit" of the model to actual data. Consequently, the root-mean-square deviation between predicted and experimental data was calculated for both coastby and driveby operating modes. (This deviation is typically 0.6-0.7 dB; a tabulation of all values is given on Table A-3 in the Appendix.

Fit of the model equations to the test data can be visualized on Figs. 1 - 6. Rolling (coastby) sounds, calculated power train sounds, and total vehicle sounds are portrayed on Figs. 1, 2, and 3, respectively, for the first test series, and Figs. 4, 5, and 6, respectively, for the second test series. For clarity of presentation, some data groups have been plotted offset in level; reference to the absolute level is indicated with each group. Conditions and parameters of each plot are similarly indicated. For simplicity, sound pressure level is designated "SPL" and sound level, "SLA," on the plots.

Comparison of the predicted levels for power train and tire (rolling) sounds at 55 km/h (34 mph) and 90 km/h (56 mph) is shown on Fig. 7. It is seen that the tire sound levels are quite similar between the two test vehicles, but that the power train sound levels differ appreciably. This would be expected because of the differences in engine size, rated horsepower, and exhaust system fitted. Obviously, then, the "crossover" speed from power train to rolling sound predominance is a function of the specific vehicle.

Plots of the third-octave band spectra corresponding to peak sound level for the coastby operating mode, having test speed as the parameter, are shown on Figs. 8 and 9 for the first test series and Figs. 10 and 11 for the second test series. In general, these spectra are reasonably smooth in shape and, quite importantly, spectral shape is essentially invariant with speed for each of the test tire sets. In the first test series, the blank tires exhibit some spectral peaking at 400, 1250, and 6300 Hz, as

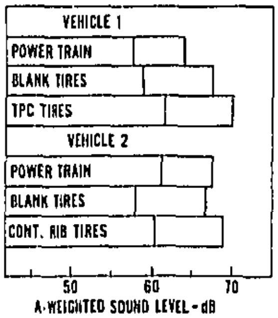

Fig. 7 - Comparison of power train and tire sound levels at 55 km/h (34 mph), designated by the intermediate bar, and 90 km/h (56 mph), based on the prediction models. Vehicle 1 is the full-size four-door sedan and vehicle 2 is the sporty two-door coupe

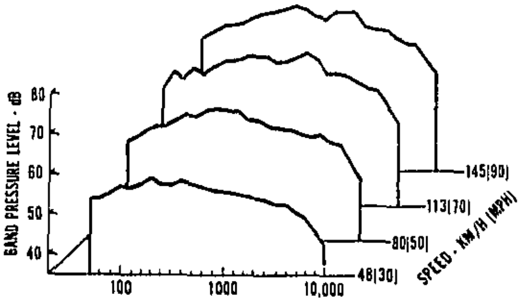

Fig. 8 - Rolling (coastby) spectra for tires with blank tread pattern on the full-size four-door sedan and on a sand-aggregate asphalt surface

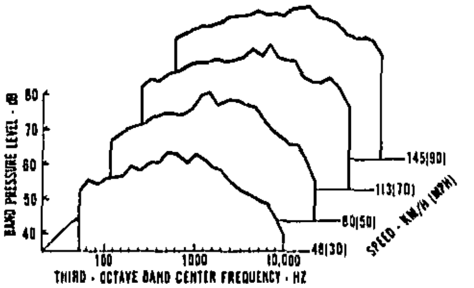

Fig. 9 - Rolling (coastby) spectra for TPC tires on the full-size four-door sedan and on a sand-aggregate asphalt surface

shown on Fig. 8. These latter two peaks are also evident in the spectra for the TPC tires, shown on Fig. 9; a speed-dependent peak starting in the 500 Hz band at 48 km/h (30 mph) and terminating in the 1000 Hz band at 145 km/h (90 mph) is also evident. In the second test series, spectral peaking is exhibited at 80 (albeit spasmodic), 200, 800, and 1250 Hz for the blank tires, as shown on Fig. 10. Only the first three of these are evident in the spectra for the continuous rib tires, as shown on Fig. 11.

DISCUSSION

The results of the two test series and subsequent analysis would indicate that total vehicle sound of automobiles at steady speeds can be characterized as a combination of power train sounds proportional to the third power of vehicle speed and tire (rolling) sounds proportional to the fourth power of vehicle speed. Relative levels, or absolute magnitudes, of power train and tire sounds are dependent on the particular characteristics of each of these sources.

Departures from strict speed-dependent sound level variation of power train sounds were noted for both test vehicles, occurring principally in the sound pressure level at lower test speeds. This can be seen on Figs. 2 and 5. Inspection of the third-octave spectra for these test conditions revealed rather sharp spectral peaking at frequencies corresponding to engine firing frequency; it is suspected that the fundamental acoustic modes of the exhaust system are being excited at these low engine speeds. Note that sound level is not affected in either case. Because of this somewhat anomalous behavior, the few data points affected were not used for the regression analyses.

As mentioned previously, a secondary objective of this study was to obtain some insight into the source characteristics of rolling noise. Of particular interest would be the separation of tire and aerodynamic constituents, or at least some estimate of their relative importance. Aerodynamic sources would be expected to follow a sixth or eighth power of speed relationship and also exhibit a speed-dependent shift in spectral shape. Neither of these conditions were found in this study, although there is suggestion of increased speed dependence of the

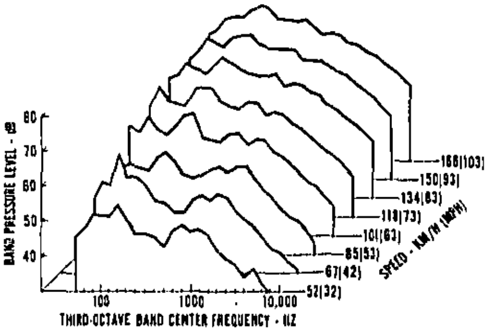

Fig. 10 - Rolling (coastby) spectra for tires with blank tread pattern on the sporty two-door coupe and on a typical asphalt roadway surface

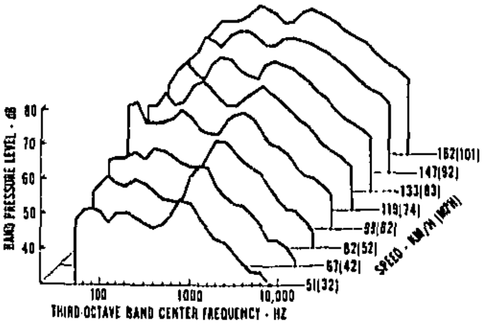

Fig. 11 - Rolling (coastby) spectra for tires with continuous rib tread pattern on the sporty two-door coupe and on a typical asphalt roadway surface

coastby data at the extreme upper end of the speed range.

It must be recognized that aerodynamic sources of the test vehicle and the test tires would be confounded because of the experimental technique used. In an attempt to isolate the tires, a side study was initiated in which the effects of the vehicle body would be removed A large "push cart" was built up using an automobile chassis, suspension, and steering, with a single driver's seat set onto a floor of concrete poured between the frame side rails. Body work consisted only of a small sheet metal fairing at the front of the vehicle and a roll cage, which should have been grossly dissimilar in aerodynamic characteristics than the body. This device was pushed by another vehicle to get to test speed, and then allowed to coast through the test site. For a variety of reasons, test speeds were limited to about 100 km/h (60 mph). Test data obtained using this device were essentially the same as those obtained using an entire vehicle for the same test tires, so further development of this technique was terminated.

In earlier work (9), a series of coastby runs were made up and down wind when the ambient wind was essentially parallel to the direction of travel at the test site and wind speed was reasonably uniform. This gave various combinations of air and ground speed. Spectral differences were observed below 1000 Hz, and were on the order of 2 dB for relative wind speed differences up to 32 km/h (20 mph) at ground speeds of both 80 km/h (50 mph) and 113 km/h (70 mph). These differences are ascribed to air buffeting on the relatively flat surfaces of the vehicle, which can be considered as an aerodynamic source although not in the classical sense.

Consequently, it is concluded that the predominant constituent of rolling sound in the present study is that of the tires, varying as the fourth power of speed. Such behavior is characteristic of a dilatational (monopole) source. In fact, this may be the incoherent combined effect of eight monopole sources, as the tread area forward and rearward of the contact patch is thought to be the radiating surface and of course four tires are involved. These findings support the tread vibration and radiation models of tire sound generation postulated by Richards (8) and Nilsson and Söderqvist (11).

It is interesting to note the consistent behavior of treaded and untreaded (blank) tires, and the small difference in sound levels between them. The sound level differences between the two are seen to be greater than the sound pressure level differences; in fact, the coastby sound pressure level data in the second test series could not be separated statistically and hence were combined for all analyses (refer to Fig. 4). This observation, and the observed spectral invariance with speed, suggest that the tread pattern has but minor importance in determining the sound levels emitted by automobile tires. This of course does not extend to any tonality resulting from regularly shaped or spaced tread elements, as typified by a snow tire, which is superimposed on the basic tire sound.

The invariance of the spectral shape with speed is seen in the near-field measurements on bias-ply tires of Wiener (1) and the far-field measurements of several investigators (4,7,8). All this previous work has involved tires with specific tread patterns. In the present study, comparisons can be made between tires with blank and patterned tread design and of bias-belted and radial-ply construction. Some differences in spectral characteristics can be seen between the two tire constructions, particularly in the frequencies of spectral peaking. With both tire types, however, the presence of the tread pattern results in an emphasis of the spectral peaks which increases with speed. These spectral peaks are typically an octave or more in breadth, implying a broadly-tuned and/or highly-damped phenomenon. Based on these observations, it can be theorized that the presence of a tread pattern increases the vibrational input or excitation of the tread in its entirety, a circumstance which is intuitively plausible.

Recall that the test surfaces used for this study were smooth asphalt, so that vibrational input resulting from tire-road interaction was not augmented by surface irregularity. The effects of road surface texture have been shown previously to have a significant effect on tire sound levels (7, 8, 12).

Findings of the present study, taken with those of other investigators, suggest that the rolling sound of automobiles is comprised primarily of sounds generated and radiated by the tire itself This generation and radiation can be characterized as a simple monopole source, or combination of such sources, with sound intensity varying as the fourth power of vehicle speed. Contributions of aerodynamic flow sources, varying as the sixth or greater power of speed, could not be detected over most of the speed range tested, although suggestion of such sources is noted at the extreme upper end of the speed range.

SUMMARY

A test program has been conducted to determine the magnitude and characteristics of the power train and rolling components of total vehicle sound, for automobiles operating at steady speeds. Two experimental test series were run, involving different test vehicles, sets of test tires and their carcass construction, and test site. Powered (constant-speed driveby) and unpowered (coastby) test runs were made over a speed range of 48-160 km/h (30-100 mph). Peak sound pressure levels and

A-weighted sound levels, and third-octave spectra corresponding to the peak sound level, were determined for all test runs and subsequently averaged for each test speed and operating mode. Estimates of the levels for power train sounds were calculated as the difference between driveby and coastby levels.

Prediction models based on actual regression analyses were formulated for power train sounds and rolling sounds of the individual tire sets. The power train sound is found to vary as the third power of vehicle speed (30 log S), with good agreement to the calculated values except for some anomalous data at low vehicle (and engine) speeds presumably due to acoustic resonances of the exhaust system. Rolling (or coastby) sounds were found to vary as the fourth power of vehicle speed (40 log S), with very good agreement to the observed sound pressure level and sound level data. Predictions of total vehicle sound, obtained by combining power train and rolling sounds at discrete speeds, showed good correlation with the observed driveby levels.

Only slight evidence of higher-order speed dependence was found in the coastby data, indicating that contributions of aerodynamic flow sources involving either the vehicle or the tires are not significant at urban or suburban traffic speeds. The fourth power of speed relationship for tire sound intensity, combined with the invariance of spectral shape with speed, supports recent hypotheses of tread vibration and radiation as the primary mechanism for automobile tires. Further, the effect of properly designed (non-tonal) tread patterns is seen to be small, accounting for perhaps a 2 dB increase in sound levels over those for a blank (untreaded) tire of the same carcass construction.

ACKNOWLEDGMENTS

The Fluid Dynamics Research Department of the General Motors Research Laboratories and the Noise and Vibration Laboratory at the General Motors Proving Ground jointly supported the experimental work, which was very ably conducted by Philip C. Carpenter.

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APPENDIX

TABLE A-1

Actual Regression Equations for Experimental Data

Vehicle 1

Blank Tires - Coast

$\mathrm{SLA} = -3.80 + 40.68 \log S$

$\mathrm{SPL} = 1.46 + 40.49 \log S$

TPC Tires - Coast

$\mathrm{SLA} = 1.76 + 39.16 \log S$

$\mathrm{SPL} = 0.63 + 41.68 \log S$

Power Train

$\mathrm{SLA} = 2.41 + 35.16 \log S$

$\mathrm{SPL} = 27.58 + 23.69 \log S$

Vehicle 2

Blank Tires - Coast

$\mathrm{SLA} = -2.78 + 39.78 \log S$

$\mathrm{SPL} = 9.12 + 36.97 \log S$

Continuous Rib - Coast

$\mathrm{SLA} = -1.84 + 38.50 \log S$

$\mathrm{SPL} = 4.43 + 39.48 \log S$

Power Train

$\mathrm{SLA} = 10.62 + 32.45 \log S$

$\mathrm{SPL} = 28.93 + 26.27 \log S$

(S is in miles per hour)

TABLE A-2

Equations Used for Predicted Data

Vehicle 1

Blank Tires - Coast

$\mathrm{SLA} = -2.44 + 40 \log S$

$\mathrm{SPL} = 2.38 + 40 \log S$

TPC Tires - Coast

$\mathrm{SLA} = 0.31 + 40 \log S$

$\mathrm{SPL} = 3.64 + 40 \log S$

Power Train

$\mathrm{SLA} = 11.67 + 30 \log S$

$\mathrm{SPL} = 15.87 + 30 \log S$

Vehicle 2

Blank Tires - Coast

$\mathrm{SLA} = -3.22 + 40 \log S$

$\mathrm{SPL} = 3.65 + 40 \log S$

Continuous Rib Tires - Coast

$\mathrm{SLA} = -1.03 + 40 \log S$

$\mathrm{SPL} = 3.65 + 40 \log S$

Power Train

$\mathrm{SLA} = 15.08 + 30 \log S$

$\mathrm{SPL} = 22.10 + 30 \log S$

(S is in miles per hour; for metric speeds, reduce the intercepts by 6.20 and 8.27 for 30 log S and 40 log S relationships, respectively)

TABLE A-3

RMS Deviation Between Predicted and Experimental Data

			SLA	SPL
Vehicle 1				
	Coast	- Blank	0.71	0.58
		- TPC	0.51	0.47
	Drive	- Blank	0.66	0.67
		- TPC	0.31	0.56
	Overall		0.57	
Vehicle 2				
	Coast	- Blank	0.56	0.80
		- Continuous Rib	0.60	0.54
	Drive	- Blank	0.77	0.74
		- Continuous Rib	0.46	0.74
	Overall		0.67	

DISCUSSION

MR. COULTER: I believe I have been reading that the blank tire, almost all the tires, show a spectral peaking from 630 - 1000 Hz. Is that correct?

MR. HILLQUIST: There is a peaking in the spectrum from the blank tire that occurs somewhere in the range of 500 - 1000 Hz that is characteristically lower than the peaking of the tire with the treated pattern. This may be brought about by the fact that the higher frequency peaks just seem to be more predominant.

MR. COULTER: I would ask, and I am really not sure about any of the factors here, if there is also a possibility of a coincidence between the speeds of the vibrations traveling through the tire and air, similar to the coincidence effect that allows propagation through a panel, that might increase the radiation efficiency drastically at certain frequencies. Does anybody have any information about the speed of the propagation of vibration through the rubber? It is probably a non-linear function, which would indicate that it is not the same at all frequencies. It might explain why you don't obtain any speed dependence with that peak in the response.

MR. LIPPMANN: The speed, of course, varies with the structure. The speed of propagation in sidewalls is not the same as the speed of propagation in the crown of the tire. For a radial ply tire, it is on the order of about 40 - 45 mph, approximately.

MR. CAMPBELL: Your data showed consistently that the blank tire without any tread design was about 3 dB lower in sound level than the tire with a tread pattern. Then you consistently arrive at the conclusion that tread design has nothing to do with creating noise. This seems to be an inconsistency.

MR. HILLQUIST: I didn't make that statement. What I said was that the presence or absence of a good tread design, ruling out tonality, is minor, because we see only a 3 dB change. It is the initial 60 or 70 dB that I am concerned about, not the differential of three on top of that.

CONTRIBUTED COMMENT

R. Hickling

The possibility that vehicle aerodynamic noise may be a noticeable effect is still a somewhat controversial subject. How controversial it is, is illustrated by the fact that, using the same sets of data, it has been possible to come to entirely opposite conclusions. However, if you look at the nature of the effect, it is not, perhaps, unreasonable that this situation could arise.

Aerodynamic noise is dependent on the 6th to the 8th power of the air velocity. It is to be expected, therefore, that at some speed it will become significant compared to tire noise which is known to be dependent on the 3rd to the 4th power of velocity. The essential question is, does it occur within the normal range of driving conditions of a motor vehicle? The answer appears to be yes, but barely yes.

Recalling the data presented in Ref. 1 on the stake-bed truck with rib tires (Fig. 2), the aerodynamic noise of the truck coasting at 56 mph in still air is about 65 dB(A), which is probably not very important. However, if the vehicle is heading into a 12 mph wind, the vehicle aerodynamic noise rises to 71 dB(A) which is significant in terms of the noise of vehicles at normal cruising speeds. One can expect a similar enhancement of aerodynamic noise if a vehicle is travelling in the wake of another vehicle as is often the case on highways.

REFERENCE

1. L. J. Oswald and R. Hickling, "Possible Effect of Vehicle Aerodynamic Noise on SAE J57a Passby Noise Measurements." P-70 Highway Tire Noise, Paper 762019.

AUTHOR'S CLOSURE TO CONTRIBUTED COMMENT

On the first point, it is quite possible that different conclusions may have been drawn from the same data simply due to the procedures used; a hand (or "eyeball") fit graphical method as opposed to the calculated regression analysis used for my results. However, the "goodness of fit" shown in the paper is of the same relative magnitude as the possible experimental variance, so it does not make sense to flagellate these data further.

The use of test data for a stake-bed truck to dispute my observations on passenger automobiles is curious. In community circumstances ("normal range of driving conditions"), I do not expect that these two vehicle types have equivalent operating characteristics or exposure, aside from their obvious physical dissimilarity. Thus, we may not have conflicting issues.

The comment on enhancement of aerodynamic noise from a trailing vehicle is also of interest. Presumably, the wake of a lead vehicle that is of importance here is the turbulent wake which dispels laterally outward with trailing distance, if I am not mistaken. Hence, if inter-vehicular distances are in keeping with National Safety Council recommendations or prudent driving practice, I cannot imagine that sufficient interference exists to produce sound levels of similar magnitude to those produced by power train or tire/pavement interaction of automobiles at steady traffic speeds.

762028

Tire Noise Screening

G. Gadefelt and P. Voight
IFM Akustikbyrån AB (Sweden)

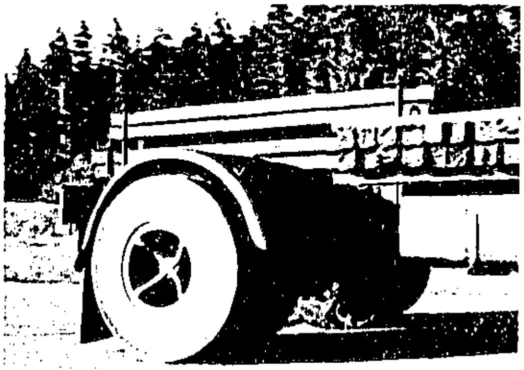

Fig. 1 - Scania-Vabis type L5383 with outer circular discs on the wheels

AN INVESTIGATION is presented here as to what extent tire noise emission from road vehicles can be reduced by attaching special screens to the vehicles.

The tire noise emission from free rolling vehicles on dry and wet road surfaces was studied in the speed range 30 - 90 km/h. The screens studied were:

A. Side dishes of 3 mm steel sheets with rubber in the outer parts,

B. A complete "skirt" of rubber sheet around the whole vehicle, with an air gap of 50 mm between shield and road, and

C. Local enclosures over the single wheels following the movements of the wheel (the construction air gap varied from 5 - 100 mm).

The effect of screens of type "A" was limited to 1 - 2 dB(A) units and was in some cases not statistically significant.

For type "B" reductions at dry roads of 7 dB(A) were recorded at 50 km/h but only about 2 dB(A) at 70 km/h. For wet roads only 1 - 2 dB(A) units in reductions were measured. The limited effect at higher speeds could be caused by a too loose screen design.

Type "C" enclosures were found more promising. Here 5 ± 2 dB(A) were reached on dry roads and $2 {}^{+4}_{-2}$ dB(A) on wet roads. When noise absorbing material was attached inside the screens, the reduction increased to 7 ± 3 dB(A) units on dry roads and 4 ± 2 dB(A) on wet roads. The investigations of the enclosure properties included technical tests like braking tests, splashing tests and tire tread temperature influence. The splash was effectively reduced and the temperature increase in no way critical.

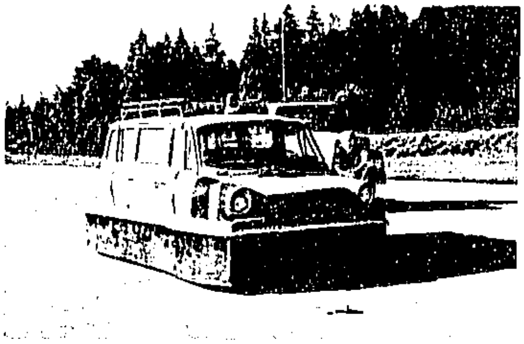

Fig. 2 - Ford Transit with rubber sheets along all sides. Radial tire with block-pattern of all-weather-type

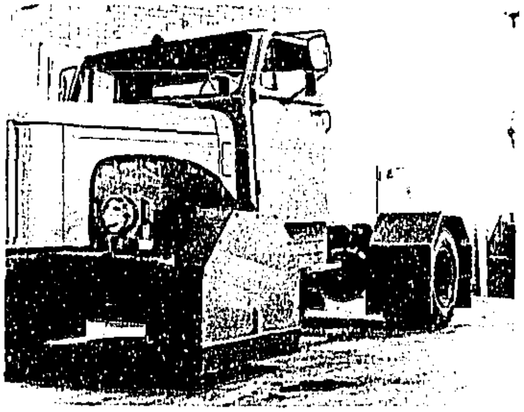

Fig. 3 - Scania Vabis L 5383 with enclosures. The back wheel enclosure is partially removed.
Front wheels: rib tires
Back wheels: winter-tire of cross-bar type

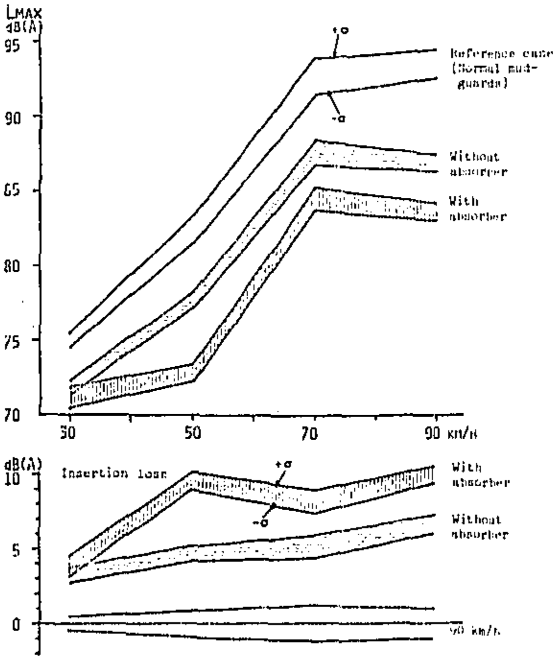

Fig. 4 - Max sound level in dB(A) by a passage distance of 7,5 m. The effect of enclosure with and without absorbers inside; dry road.

Vehicle:	Scania-Vabis L 5383, 1962, coasting by
Reference:	Standard mud guards
Shields:	All wheels enclosed; gap between lower edge and road 50 mm
Absorber:	Mineral wool; 30% perforated steel sheet as mechanical protection

Figs. 1 - 5 depict the experiments for the reader while Table 1 supplies the technical data.

Further investigations are planned for studying the shielding on wet roads and the possibility of eliminating the shields on the front wheels for trucks and buses because the main noise source is located at the (driving) back wheels.

ACKNOWLEDGMENTS

This investigation was made under contract No. 74-4601 from Swedish Board for Technical Development. The mechanical construction of the shields and the application to the vehicles were made by "Swedish National Traffic and Road Research Laboratory".

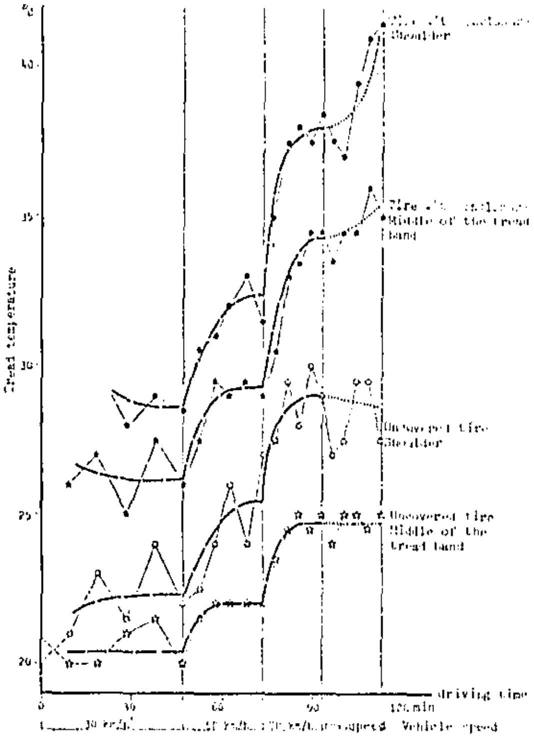

Fig. 5 - Temperature in tire shoulder and in the middle of the tread band. Tire enclosure (air gap 50 mm) compared with completely uncovered tire.

Vehicle:	Scania-Vabis L 5383, 1962, weight 13,3 tons
Tire:	Good-Year winter service 12 ply rating 9.00-20
Road surface:	Fine grained asphalt
Air temp:	+ 7°C (44.6°F)

DISCUSSION

MR. HICKLING: We have had some experience in using shields. We have run with tires inside an enclosure for some period of time and have noticed that the wear on these tires is greater than we would have expected normally. This kind of result goes against the results that you observed of increased temperatures.

MR. NILSSON: We have not examined the tread wear of the tire, just the temperature. I think further steps must be taken in this regard.

MR. LANDERS: Concerning the temperature rise, how many miles was this run?

Table 1 – Insertion loss in dB(A) at 7,5 m:s distance by different screen alternatives and road conditions. Road: fine grained asphalt.

Road Condition	Velocity km/h	Scania Vabis L5383							Ford Transit	
		Enclosure without absorber			Enclosure with absorber					
		20 mm dB(A)	50 mm dB(A)	100 mm dB(A)	20 mm dB(A)	50 mm dB(A)	100 mm dB(A)	Wheel dish dB(A)	Skirt all over dB(A)	Skirt only on the long sides dB(A)
Dry	30	-	3,2	-	-	3,8	-	-	-	-
	50	5,7	4,7	5,3	6,6	9,6	7,9	0,5	6,5	3,2
	70	5,5	5,1	5,2	8,3	8,2	8,7	0,9	1,7	0,9
	90	-	6,7	-	-	10,0	-	-	-	-
	Mean value	5,6	4,7	5,2	7,4	7,1	8,3	0,7	3,5	1,9
Wet	30	-	0,9	-	-	6,4	-	-	-	-
	50	2,5	6,4	4,8	7,8	5,0	6,0	1,6	0	1,0
	70	1,7	0,3	2,0	2,4	1,9	2,9	1,1	1,5	1,6
	90	-	2,1	-	-	2,5	-	-	-	-
	Mean value	2,1	1,9	3,2	4,3	3,6	4,2	1,3	0,7	1,3

MR. NILSSON: It was run for about 2 h. We drove with a constant speed for awhile until we reached equilibrium, then increased the speed again until we reached equilibrium, and then until we reached 90 km/h.

MR. CAMPBELL: I don't believe we should allow the record to stand unchallenged with respect to the disastrous effect of a 10°C rise in tire temperatures for truck tires. The predominant mode of failure for truck tires in this country is heat failure. Heat failures on truck tires are particularly disastrous on the front wheel. Any increase in the incidence of failures due to heat would be very detrimental to safety. It is inconceivable for me to think that we could talk about increasing running temperature of tires 10°C in a meeting where safety is of at least some concern.

MR. NILSSON: We think that our investigations show that acoustically, the tire enclosure works. What is in front of us now is to fit them in order that the car manufacturers and the others are able to use them. This application to the vehicle will, of course, include some kind of cooling, intake of air, or something similar, which will deal with that kind of problem. I think that the temperature problem can be solved, if it is a problem.

PART V
RELATED PERFORMANCE CHARACTERISITCS

762029

The Noise and Highway Traction Properties of Heavy Truck Tires

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Highway Safety Research Institute
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THIS PAPER PRESENTS THE RESULTS of two research projects (1, 2)* conducted to examine both the noise and highway traction properties of heavy truck tires. In this context, tire "noise" refers to the sounds emitted by the freely-rolling tire, under load, while traveling at highway speeds on paved surfaces. Highway "traction" is a term used rather broadly to include the longitudinal and lateral shear force generation of tires operating over the entire range of wheel slip conditions, on paved surfaces. Experimental measurements of these properties reported here constitute a new contribution to the literature only insofar as they have been obtained for a common sample of tires. The reader should note that other publications have treated truck tire noise generation behavior (3, 4) and traction behavior (5, 6) separately. Likewise, test methodologies employed in the gathering of data reported here have been documented previously (1, 6).

The thrust of this paper, then is centered around a comparison of tire construction types so as to shed light on the relationship between tire noise and the tire's role in determining the pre-crash safety quality of heavy trucks and tractor-trailers. Put another way, the paper is intended as a reference material to those concerned about the possible safety implications of truck tire noise regulation. If the regulation of tire noise results in a revision of the range of marketable tire designs, the related question is: "Will this market revision result in a greater incidence of commercial vehicle accidents?"

To address this question, albeit in a very indirect way, the hypothesis was taken that the truck tire's role in commercial vehicle safety is subsumed within its ability to generate shear forces in the ground plane. By this notion, the shear force behavior of tires is seen as linked to vehicle controllability insofar as it determines vehicle response to steering and braking. Accordingly, the safety implications of a measured set of tire shear force properties are interpreted in this paper on the basis of generalizations deriving from the discipline of vehicle mechanics (an approach which, lacking considerations of the driver's loop closure role, has a limited scope of utility). The conclusions, then, are confined within a rather narrow context. Fortunately, the results presented here suggest that the exclusion of the noisier type tires may actually serve to benefit the safety picture rather than to degrade it. Thus there is no need to "split hairs" over relative levels of safety which may be lost to assure certain gains in the noise environment.

To balance the following discussion of noise and traction measurements, it should be stated that the confinement of the related research projects to only those two considerations in no way presupposes that traction properties constitute the most important tradeoff to be addressed in formulating tire noise regulations. Rather, it is presumed that the other tire performance properties which are likely

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*Numbers in parentheses designate References at end of paper.

ABSTRACT

This paper provides a common data base of noise and traction properties for a sample of heavy truck tires. It provides objective information which contrasts these characteristics.

It postulates that tires exhibiting improved traction performance are generally those whose tread patterns yield lower noise output. Conversely, the tire which exhibits less desirable peak longitudinal traction properties has been found to be noisier.

The degree of disadvantage incurred by the bias lug-rear, bias or radial rib-front configuration cannot yet be objectified within current technology.

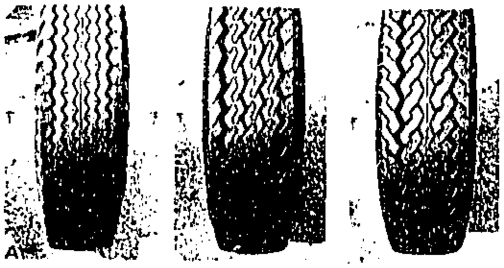

Fig. 1A - Sample of bias-ply, rib-tread tires

Fig. 1B - Sample of bias-ply, lug-tread tires

to be influenced by a noise emissions rule will be examined elsewhere.

RESEARCH METHODOLOGY

Research programs yielding noise and traction data were supported under two separate projects at the Highway Safety Research Institute (HSRI) of The University of Michigan. In the first study, supported by the Motor Vehicle Manufacturers Association (MVMA), traction-type testing of bias-ply truck tires was conducted using facilities and methods developed by HSRI, while noise generation measurements were conducted according to the SAE J57a test procedure at the facilities of the International Harvester Co. in Fort Wayne, Indiana. As a complement to the MVMA study, a second study supported by the U.S. Dept. of Transportation's Office of Noise Abatement (ONA) involved duplicate methodologies, but using radial-ply tires. In the ONA study, noise measurements were conducted by personnel of the National Bureau of Standards.

Altogether, a sample of six bias-ply and six radial-ply tires have been subjected to the common set of noise and traction tests. Five specimens of each selected tire sample were obtained, each from a single production lot. Shown in Figs. 1 and 2, the bias- and radial-ply sample sets were each configured to provide three models of rib-tread types and three models of the more aggressive, or lug-tread variety. In the sample of radial-ply tires, however (Fig. 2), the third aggressive tread tire would not be commonly characterized as a "lug" tire since it does not employ primarily lateral tread elements. All tires were selected to afford a reasonable representation of the commercial tire market, while the sample of bias-ply tires was also configured to duplicate as closely as possible the test sample employed in an earlier noise measurement study (3). All specimens were of size 10.00 x 20 with the bias-ply tires constructed in load range F and the radial-ply tires in load range G.

NOISE MEASUREMENT PROCEDURE

All twelve of the selected tire types were tested according to SAE J57a, "Sound Level of Highway Truck Tires." The basic procedure requires, first, the installation of the subject tires as duals on the rear axle of a loaded, two-axle truck. The front axle of the vehicle is outfitted for these tests with a so-called "quiet" tire. The vehicle is coasted by the noise measurement site at a speed of 50 mph, while a measurement of the peak A-weighted noise level is made using a single microphone located 50 ft from the centerline of the traveled lane.

Only fully-treaded tire samples were subjected to the matrix of coast-by measurements. Noise tests were conducted first, following which the same tire specimens were utilized in the various traction experiments.

TRACTION MEASUREMENTS

Traction measurements were made on each of the sample tires using three different test devices.

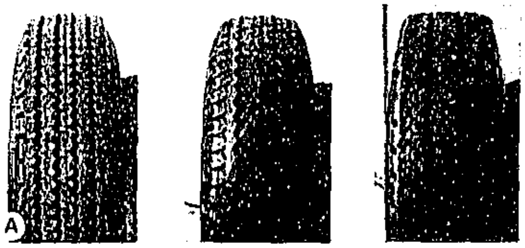

Fig. 2A - Sample of radial-ply, rib-tread tires

Fig. 2B - Sample of radial-ply, lug-tread tires

The first machine, the HSRI Flat-Bed Tire Tester, is a low-speed laboratory dynamometer which was used to obtain precision measurements of the "cornering stiffness" parameter (C_α), defined as the slope of the side force (F_y) versus slip angle (α) relationship through the origin, viz.,

$$C_\alpha = \frac{\partial F_y}{\partial \alpha}_{\alpha=0}$$

In addition to measuring C_α, a tire property bearing on the directional response of trucks in normal driving maneuvers, other traction tests were conducted to characterize tire properties relevant to emergency braking and steering maneuvers. These other tests involved the use of two mobile traction dynamometers which were developed at HSRI. One machine measures a tire's longitudinal force (F_x) response to longitudinal slip (s), while another device measures the F_y versus α relationship, comparable to the flat-bed machine, but now obtaining data on real pavements at actual highway speeds.

All mobile tests were conducted on a Portland cement concrete track at the Dana Automotive Test Facility in Ottawa Lake, Michigan. This surface is characterized by ASTM skid numbers (dry) of 87 and (wet) of 62, as measured with the E-501-73 standard tire. Texture depths have been measured on this surface using the so-called "sand patch" tests, indicating an average texture depth of 0.014 - 0.024 in. These surface properties are reasonably representative of concrete pavements making up the federal interstate highway system in the United States.

FLAT-BED TESTS - The HSRI Flat-Bed Tire Tester, shown in Fig. 3, mounts a single tire specimen within an instrumented support assembly from which force and moment reactions are measured. The tire is caused to operate at the desired slip angle on a flat plate at a velocity of 1.44 mph. The vertical load (F_z) condition is maintained constant throughout the traverse of the flat plate, while a computerized data acquisition system samples the output of various measurement transducers.

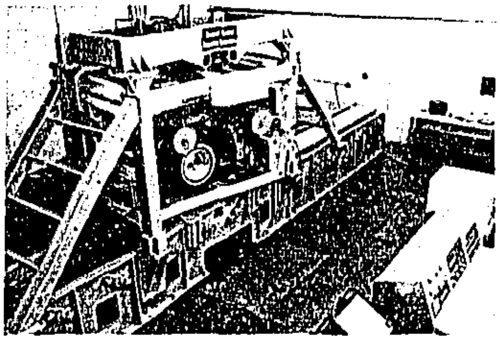

Fig. 3 - HSRI Flat-Bed Tire Tester

Table 1 - Vertical Load (F_z) Values of Tires in Flat-Bed Tests

Bias Tires (Lb)	Radial Tires (Lb)
5430	6040
3260	3020
1630	1510

In tests performed for this study, each tire was operated at ±1° slip angle orientations, and at vertical load (F_z) values shown in Table 1.

Varying F_z conditions were chosen to cover tire loadings such as prevails over the empty to fully-loaded usage of commercial vehicles. Since F_z is known to have a first-order influence on C_α, it is pertinent to examine this sensitivity as it signifies a sensitivity of vehicle directional behavior to loading.

One specimen of each tire was employed in the flat-bed tests; all tires were tested at their rated cold inflation pressures of 85 psi for bias-ply tires and 105 psi for radials.

MOBILE TRACTION TESTS-LONGITUDINAL - The HSRI Mobile Longitudinal Force Tester, shown in Fig. 4, is a semi-trailer device which mounts a single tire sample along its centerline. The test wheel is braked by a large commercial air-actuated brake as the trailer is towed at various velocities over the test pavement. The test wheel suspension incorporates a multi-component force transducer and an air spring loading system. The rotational velocity of the test wheel is transduced by a DC tachometer, which output signal is used in computing longitudinal slip.

Using this machine, each tire specimen was subjected to a sequence of velocity and load conditions covering the range from 20 - 55 mph and from 0.5 - 1.5 times the Tire & Rim Association load

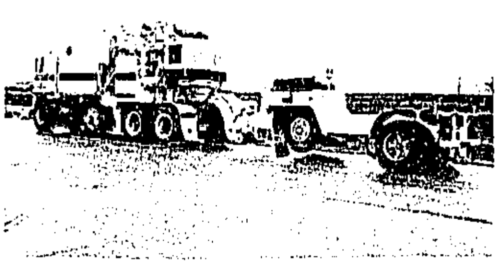

Fig. 4 - HSRI Mobile Truck Tire Dynamometer

rating for the tire used as a single. For each "run" in the sequence, the test-wheel brake is applied so as to approximate a ramp input of torque. The wheel is braked until "lockup," (slip, s=100%) is achieved, following which the brake is automatically released. This "lockup cycle" is repeated five times at each test condition. In later processing of the tape-recorded data, the F_x versus s function is determined as an average of the tire's behavior over the five cycles.

One specimen of each tire was subjected to the indicated matrix of test runs on a dry concrete surface. A second specimen was tested per the same test matrix but on a concrete surface which was wetted by a water film of 0.020 in nominal thickness. The wet pavement condition was achieved by means of an on-board watering system delivering a calibrated flow of water ahead of the test tire. A nozzle is employed just ahead of the test wheel position to deliver a flow rate which is adjusted at each test velocity condition to yield a nominal 0.020 in thickness to the deposited film. The nozzle is segmented to assure a uniform flow distribution across an 18 in swath. The wet test process, itself, involves an initial pass over the test course to provide a preliminary wetting of the test pavement. On successive passes, the water delivery system is activated about 2 s prior to the initiation of the slip process. The elapsed time between runs is maintained reasonably constant throughout the test sequence.

MOBILE TRACTION TESTS-LATERAL - A second mobile device, namely, a tire side force dynamometer, is incorporated within the tractor-trailer system described previously. This dynamometer assembly is attached to the frame of the tractor which was shown in Fig. 4 and applies two test tires to the roadway at a controlled slip angle, α. Lateral and vertical reaction forces are transduced through a load cell mounted in the test-wheel spindle. The test tire is loaded by an air spring system, as with the trailer device. The slip angle is servo-controlled through a program of "slow and pause" increments, causing the test wheel to experience a predetermined set of steady-state levels of α. In later reduction of the data from magnetic tape, the time history of recorded signals is sampled and averaged over each of the "pause" intervals, yielding a set of F_y, F_z, and α numerics characterizing the tire's lateral traction response to the stated conditions.

Lateral traction measurements were conducted on specimens of each tire under both dry and wet pavement conditions. The matrix of vertical loads and velocities duplicated the conditions for longitudinal traction tests. Slip angle was incremented in each lateral force run to cover the values α = -1°, +1°, 2°, 4°, 6°, 12°, 20°. Each α level was maintained for a period of 1.0 s, while velocity and vertical load were held constant. As with the longitudinal measurements, one specimen was employed in tests on dry concrete and a second specimen was employed on concrete which was wetted via the on-board technique with a water film of 0.020 in thickness.

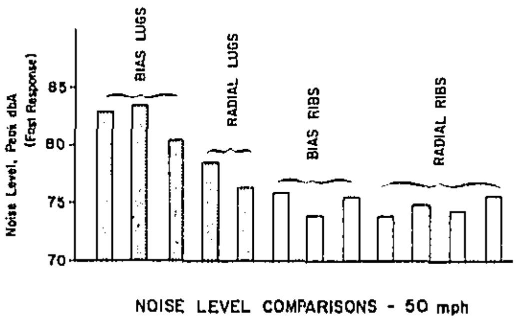

Fig. 5 - Noise level comparisons - 50 mph

TEST RESULTS - NOISE

Noise level measurements obtained according to SAE J57a are shown in terms of peak levels of dbA in the bar graph of Fig. 5. In general, the bias-ply, lug-type tires are seen to be an average of 6.9 dbA higher in sound level than the rib tires when using a "fast response" sound level measure. The radial-ply, lug-type tires are seen to register a fast response meter reading which averages 2.9 dbA higher than the rib-type radials.

Noise level measurements of the bias-ply tires were seen to confirm the results obtained on the same respective tire selections of Ref. 3 within 1 db when comparing data taken on brushed concrete. No reference measurements were available to confirm the noise data taken on radial-ply tires. In general, however, we find that the bias-ply lug tire, to the extent represented by the selected samples, is distinctly the noisiest generic type. No explanation is offered for the significantly lower noise output of the comparably aggressive radial-ply lug tires which were tested.

TRACTION TEST RESULTS - CORNERING STIFFNESS

A composite plot of the cornering stiffness (C_α) measurements as a function of vertical load, F_z, is shown in Fig. 6. While there is a clear separation between the rib- and lug-type bias-ply specimens, no similar distinction was seen in the results with radial-ply tires. Characteristically, the radial tire exhibits a steeper C_α / F_z slope and registers absolute values well above those of any bias-ply tire at elevated levels of load.

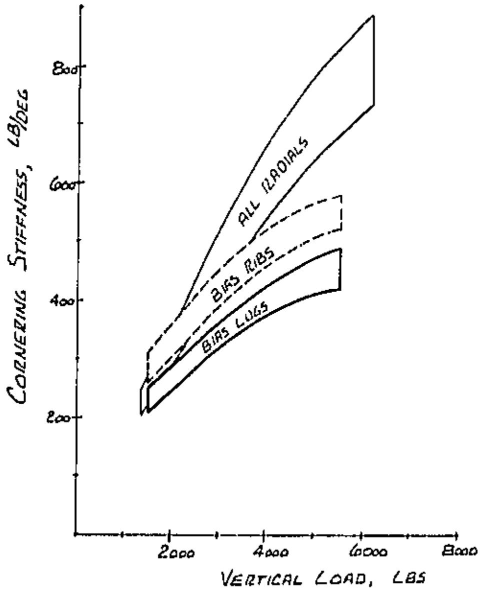

Fig. 6 - Envelopes of the cornering stiffness parameter measured over a range of vertical load

By way of interpretation of these data, the C_α parameter is relevant to a vehicle's response to steering in the range of normal path-keeping maneuvers. For vehicles with the same tire installed at all wheel positions, the absolute level of C_α principally determines the speed of yaw response in a transient steering maneuver. Thus, the absolute level of C_α determines a sort of "yaw stiffness" property of the total vehicle. Alternatively, for vehicles which are configured with dissimilar tire installations at the various axle positions, the directional gain, or "understeer," characteristic becomes peculiarly sensitive to the relative levels of C_α which characterize tires employed on front and rear axles. This latter case makes the range of C_α parameters particularly important to heavy trucks and truck-tractors because of the widespread usage of lug-type tires on rear-located driving axles. A measure of the significance of varying C_α distributions at front and rear axles can be derived from the definition of the understeer coefficient, U, which determines a vehicle's basic linear range yaw behavior as a function of certain parameters of the tire/vehicle configuration, per the relation:

$$U = \frac{W}{\ell}\left(\frac{a}{C_{\alpha_2}} - \frac{b}{C_{\alpha_1}}\right) \text{deg/g}$$

Where:

ℓ = wheelbase

W = vehicle weight

a = longitudinal position of mass center aft of the front axle

b = $\ell - a$

C_{α_1} = sum of the cornering stiffnesses of all tires mounted on the front axle

C_{α_2} = sum of the cornering stiffnesses of all tires mounted on the rear axle

For purposes of evaluating the C_α measurements shown in Fig. 6, the usage of bias lug-type tires on the drive axle with either Case A, bias- or Case B, radial-ribs on the front axle of a two-axle truck can be compared with the usage of a common tire at both axle positions. The influence of these tire installations can be expressed in terms of the difference in U which derives, considering (from Fig. 6) that for tires on a fully-loaded vehicle:

$$\begin{aligned} C_{\alpha_{(\text{Bias-Ply Lug Tire})}} &\approx 0.80\, C_{\alpha_{(\text{Bias-Ply Rib})}} \\ &\approx 0.60\, C_{\alpha_{(\text{Radial-Ply Rib})}} \end{aligned}$$

With four rear tires (mounted as duals) on the rear axle and two front tires, we have that:

$$\begin{aligned} C_{\alpha_2} = 4C_{\alpha_{(\text{Bias Lug})}} &= 3.2C_{\alpha_{(\text{Bias Rib})}} \\ &= 2.4C_{\alpha_{(\text{Radial Rib})}} \end{aligned}$$

and

$$\text{Case A)}\quad C_{\alpha_1} = 2C_{\alpha_{(\text{Bias Rib})}}$$

$$\text{Case B)}\quad\quad = 2C_{\alpha_{(\text{Radial Rib})}}$$

As a simplification, let us consider a perturbation in U about a configuration in which $a = 2b$; a configuration yielding a neutral steer behavior, that is, $U=0$, for the case when tires with the same value of C_α are installed at all wheel positions. Evaluating U for "Case A" we find that the usage of bias lugs at the rear with a typical bias rib at the front yields a 2 deg/g reduction in the understeer level below that which would derive from common tire installations all around. Similarly, for Case B, the bias lug-rear, radial rib-front configuration would typically yield a 5.3 deg/g reduction in U below that obtained with an all-common tire installation.

The point of this approach toward interpreting cornering stiffness differences is that heavy trucks

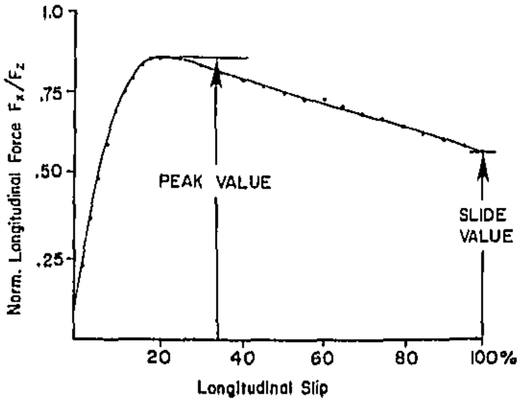

Fig. 7 - Example "μ-slip" curve, providing definitions of the "peak" and "slide" numerics

typically employ tires in such a way that the C_α variations shown previously can have a profound impact on yaw response properties. Additionally, there is reason to believe, on the basis of other recent research findings (6), that certain trucks and tractor-trailers exhibit a sufficiently narrow margin of directional stability that the above-cited results of the lug/rib mix are indeed significant to the determination of a safe operating range in turning maneuvers. It has been shown, for example, that a heavy truck may begin to spin out at a turn severity substantially below that needed to directly induce rollover. It is further clear that the basic understeer level of the vehicle can play a significant role in determining the turn severity level at which the premature spin-out type limit is reached.

Since the typical, loaded, heavy truck or tractor-trailer exhibits a rather low understeer level, even with common tires all around (in the range of U = 3 to 6 deg/g), the decrement suffered by the use of bias-ply lug tires on drive axles is a matter deserving of concern. Further, the consideration of the bias lug-rear, radial rib-front configuration is of increasing relevance due to the continuing changeover of much of the American truck fleet to radials. Moreover, we conclude that the increased noise levels characterizing bias-ply, lug-type tires is not offset by any discernible benefit in the cornering stiffness property, given that such tires are typically installed on rear axles.

MOBILE TRACTION RESULTS - LONGITUDINAL

Measurements of the longitudinal traction properties of the bias and radial tire samples were obtained according to the matrix of load and velocity conditions described earlier. For each tire and test condition, a graphic display of the so-called "μ-slip" behavior was obtained, as shown for an example tire in Fig. 7. The μ-slip curve shape illustrates the classic features of longitudinal force generation. The initially-steep increase of longitudinal force with increasing slip reflects the circumferential elasticity of the tire's carcass and tread structure. Beyond the elastic region, the force output reaches a peak as all of the tread elements traversing the contact patch begin to slide relative to the roadway. As slip increases further, the frictional coupling between tire and road degrades due to rubbing speed and heating effects, hence the characteristically negative slope at high slip.

With regard to limit braking capability, the pertinent features of the μ-slip curve are the peak value of F_x/F_z and the value which accrues under the locked-wheel condition, at s = 100%. Accordingly, the longitudinal traction data obtained for the tire sample are presented as plots of "peak" and "slide" values of F_x/F_z as a function of test velocity on each of the two surface conditions.

As shown in Fig. 8, envelopes of the peak values of F_x/F_z obtained on dry concrete reveal the following:

1. Peak longitudinal traction values are rather insensitive to velocity, for all tire types.
2. The bias-ply tires determine both the upper and lower bounds of the data, with no overlap occur-

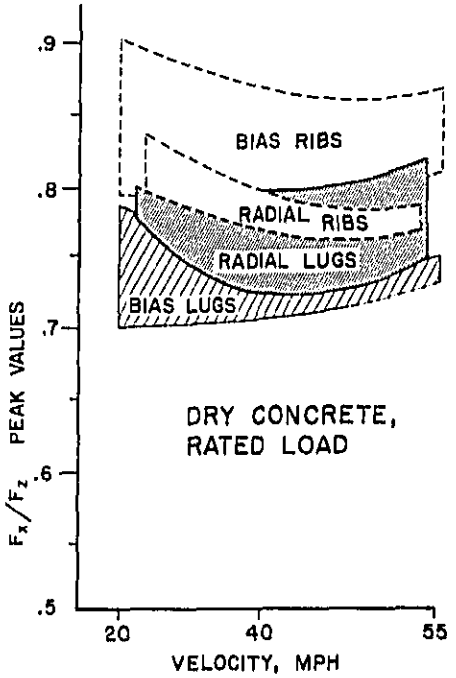

Fig. 8 - Envelopes of peak longitudinal traction values obtained on dry concrete

ring between the bias-rib and bias-lug type constructions. The average bias lug is some 13% lower in traction capability than the average bias rib.

3. Radial-ply tires assume a median level of performance and indicate a less distinctive separation of rib and lug tread performances.

Looking at the corollary peak traction measurements obtained on wetted concrete, the data of Fig. 9 indicate the following features:

1. As expected, peak longitudinal traction values indicate the characteristic negative slope with increasing velocity, thereby suggesting a certain hydrodynamic effect.
2. Again the bias-ply tires illustrate no overlap between rib and lug treads. On this wet surface the average bias-lug tire is found to yield peak traction values some 23% below those obtained with the average bias rib.
3. As on dry concrete, the radial tire samples provide a median level performance and indicate substantial overlap between peak capabilities of the respective lugs and ribs.

The contrast among tire types, as seen in the "slide" traction level data of Fig. 10, is much less pronounced. While, again, these dry surface data show the bias-rib tire to be defining the upper bound, a sufficient degree of overlap exists among the performances of the other three constructions that little generalization is possible. Perhaps of some significance is the observation that the average radial tire yields about 6% lower slide traction performance

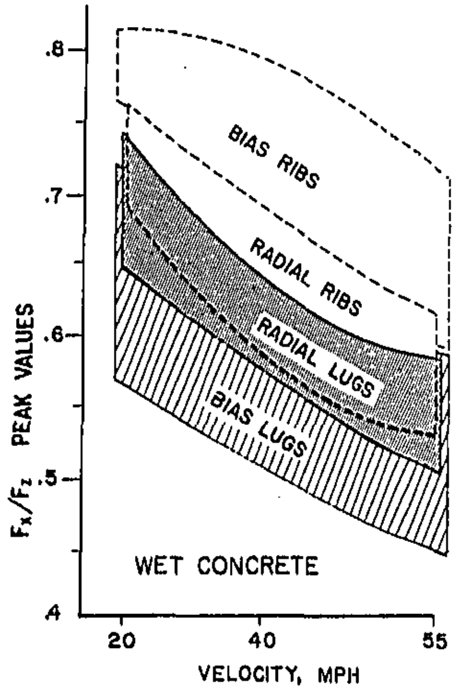

Fig. 9 - Envelopes of peak longitudinal traction values obtained on wet concrete

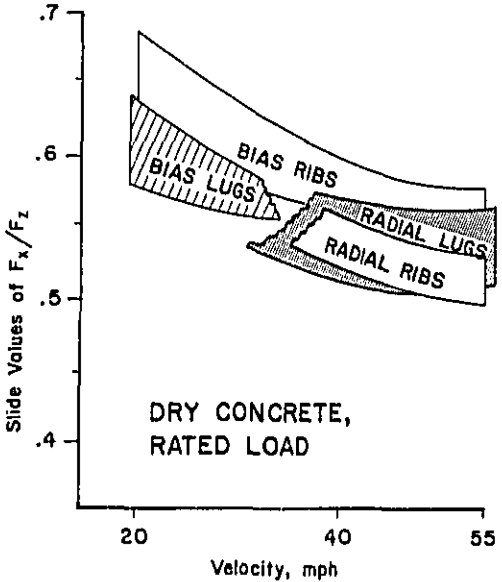

Fig. 10 - Envelopes of slide values of F_x/F_z obtained on dry concrete

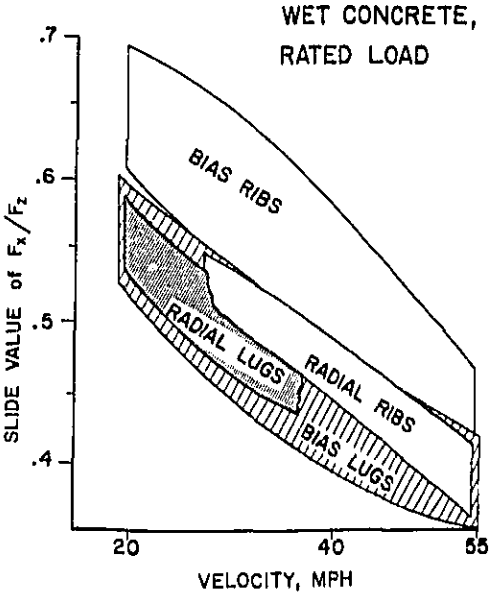

Fig. 11 - Envelopes of slide values of F_x/F_z obtained on wet concrete

than that of the average bias-ply tire.

The corresponding envelope of slide traction levels observed on wet concrete are shown in Fig. 11. As with the peak traction data, a more pronounced velocity sensitivity is observed than on the dry surface and a more distinctive spread between bias-rib and bias-lug type samples is noted. Radial ribs and lugs are, as before, not clearly delineated from one another. In these data, the radial tire samples occupy the lower range of the performance spectrum.

An evaluation of these data as they relate to limitations in vehicle braking capability must be accomplished with the peculiarities of heavy truck brake systems in mind. While a rigorous treatment of this evaluation is not possible here, certain generalized approximations are offered.

With regard to traction peaks, for example, an approximation of the stopping distance constraints imposed by lug versus rib tires can be obtained through analogy to a sensitivity analysis recently reported by Fancher and MacAdam (7). Through computerized simulation of a three-axle antilock-equipped heavy truck, these researchers found that a 10% reduction in peak traction capability on all 10 installed tires resulted in 8% and 3% increases in stopping distance for the unloaded and loaded configurations, respectively. Taking into account the specific brake system being simulated, these findings suggest that a bias lug-rear and bias rib-front tire distribution might be expected to increase stopping distances on a dry surface on the order of 3% unloaded and 3% loaded in comparison with a baseline, bias rib-only tire distribution. On a wet surface, minimum stopping distance of the bias lug-rear, bias rib-front configuration would be extended significantly beyond these percentage increases. While this example is of an antilock-equipped truck, such as represents an increasing portion of the truck fleet since promulgation of FMVSS 121, the larger (non-antilock-equipped) percentage of the truck population is more directly affected by the lug tire/rib tire traction differences. Most significantly, the use of bias-lug tires on the more heavily braked drive axle(s) of "pre-121" trucks imposes a lower ceiling on the controllable braking range of such trucks, since rear axle lockup will typically determine the vehicle's braking limit. Accordingly, the choice of installing bias lugs on rear axles as opposed to, say, bias ribs all around would suggest an effective reduction in deceleration capability on the order of the 13% (dry) and 23% (wet) range of difference observed between the peak traction performances of bias rib and lug tires.

In summary, then, lug- and rib-type tires of cross-bias construction are clearly differentiable in the friction-limited regime of their longitudinal traction behavior. Further, the differentials in both regimes render the rib tire more beneficial, particularly when the commonly-rearward (drive axle) installation of lug tires is considered. Radial ribs and lugs, however, are not clearly differentiable in terms of longitudinal traction performance. Considering all of the examined tread designs together, radial tires are found to yield peak and slide values of F_x/F_z which are a few percentage points below the values exhibited by the average bias-ply tire. It should be noted that the context of these remarks is that of wet and dry longitudinal traction on paved surfaces and does not imply any conclusions for deformable surfaces such as mud or snow.

MOBILE TRACTION RESULTS - LATERAL

Tests were conducted on the lateral traction dynamometer to permit examination of the friction-limited lateral force behavior of the tire sample. Data resulting from such tests are typically presented as plots of normalized lateral force, F_y/F_z versus slip angle, α. As with longitudinal force versus slip characteristic, the envelopes of data taken on dry concrete, Fig. 12, illustrated the steeply rising (elastic) behavior followed by a friction-determined saturation. In the case of lateral traction, the angular slip range of interest is limited to about α=20°, thereby eliminating any need to characterize performance at high slip velocities such as are relevant to longitudinal traction. The envelopes, in Fig. 12, of bias and radial tire performances illustrate that:

1. No distinctions between the high slip angle behavior of rib- and lug-type treads could be found - either among radial- or bias-ply constructions.

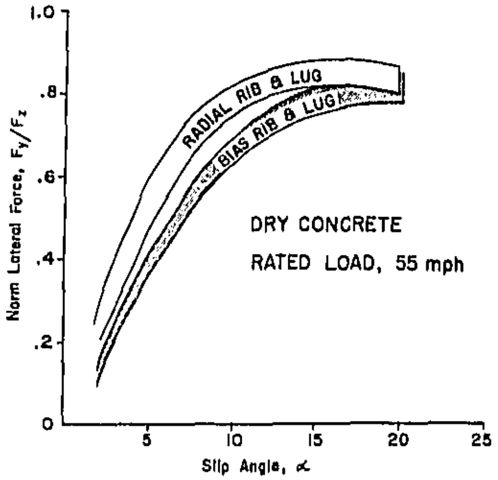

Fig. 12 - Envelopes of lateral traction performance on dry concrete

2. Radial-ply samples, with their characteristically higher values of cornering stiffness rise more steeply to saturate at lower values of slip angle than is the case with the bias-ply samples.

3. The saturation level side forces attained on dry concrete by tires of both radial- and bias-ply construction are comparable.

Looking at lateral traction performance on wet concrete, Fig. 13 breaks down the data into bias and radial envelopes, again reflecting the observation that F_y/F_z performances of rib- and lug-type treads are not differentiable. While we do see a broader band of data than that found on dry concrete, the significant item is that the radial samples illustrate a greater side force loss due to the wet surface condition.

Taken together, the lateral traction performances at elevated levels of slip serve to indicate the extent to which severe turning maneuvers are affected by tire selection. Since we observe no general correlation between these lateral traction measures and the tread constructions which are culpable in noise generation, no tradeoff between truck tire noise properties and tire behavior in severe cornering maneuvers seems to exist.

CONCLUSIONS

This paper has served to provide a common data base of noise and traction properties for a sample of heavy truck tires. As such, it has provided an objective set of information to assist the decision making of those who are concerned with the contrast in these characteristics.

Measurements of peak dbA noise levels per SAE J57a have shown bias lug-type tires to be an average of 7 db higher and radial lug tires 3 db higher in noise level than tires in the respective constructions with rib-type patterns.

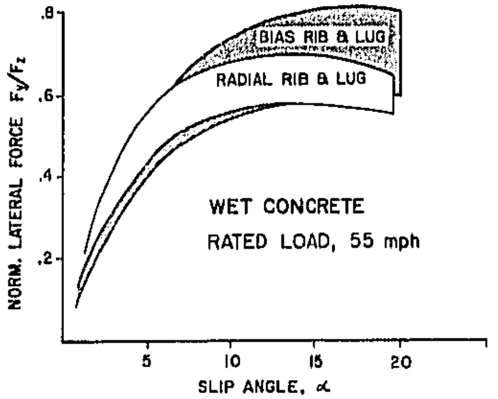

Fig. 13 - Envelopes of lateral traction performance on wet concrete

Insofar as peak longitudinal traction is concerned, it has been shown that tires exhibiting improved traction performance are generally those whose tread patterns yield lower noise output. Conversely, the tire which exhibits characteristically less desirable peak longitudinal traction properties has been found to be noisier as well. Regarding both directional and longitudinal traction properties, the common usage of bias lug-type tires on rear driving axles (only) results in a typically disadvantageous arrangement, from a vehicle control point of view. The radial-type lug tire, on the other hand, is seen to provide lateral force properties which are virtually interchangeable with those afforded by the radial rib, thus rendering no apparent disadvantage to vehicle controllability when installed on driving axles with radial ribs located at the steering axle.

The degree of disadvantage incurred by the bias lug-rear, bias or radial rib-front configuration cannot be objectified within current technology. Indeed, it might be argued that the professional truck driver is quite capable of maintaining an acceptable level of control over his vehicle when it is configured with the common rib-front, lug-rear tire installations. It cannot be argued, however, that such a configuration, per se, promotes controllability. Rather, it would seem that the trucking community opts for bias lug tires on driving axles for reasons other than can be justified on the basis of the resulting influences on vehicle control quality.

While it has not been the intent of this paper to discuss the relative merits of lug and rib tires beyond the context studied here, the reader should note that significant other areas of tire performance do exist and should be duly accounted for in any program which seeks a comprehensive comparison.

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DISCUSSION

MR. LANDERS: Did you say your water depth was twenty thousandths?

MR. ERVIN: Yes.

MR. LANDERS: Did you test any deeper?

MR. ERVIN: No, we didn't. We didn't test at greater water depths. I think that twenty thousandths of an in is a number that is maybe somewhat characteristic of a rather severe rainfall, as will be manifested in a water film on an interstate highway type highway design guide with the accompanying crown.

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Power Loss of Truck Tires Under Equilibrium and Transient Conditions

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Calspan Corp.

THIS PAPER PRESENTS RESULTS from a test program which was conducted on the Calspan Tire Research Facility (TIRF) wherein power consumption characteristics of selected heavy truck tires were determined. Much work is being carried out in industry in the area of truck tire noise performance and early conclusions are favoring radial ply constructions and rib tread designs for minimizing noise emission. The DOT/EPA Panel 7 Report(1)* states that "a 10 decibel reduction in the noise level (or halving the loudness)" can be obtained on a truck by simply using radial tires instead of crossbar bias ply tires. It is interesting to speculate as to whether tire design properties similarly affect rolling resistance in a favorable manner. Tire rolling resistance directly affects fuel consumption which in turn relates to the depletion rate of the nation's fuel resources. It is therefore important to be cognizant of the factors which influence rolling resistance so that a more comprehensive understanding of tire behavior can be established.

Quantitative values of truck tire rolling resistance have been very scarce to date. As a consequence, a reduced effectiveness has prevailed in attempts to evaluate tire power consumption and its relationship to fuel economy. The importance of such information is amplified in the Panel 7 report (1). It states in part, "In the search for improved fuel economy, one area of high potential is the substitution of radial ply tires for conventional bias ply tires." It continues, "Many of the more convenient tests (to determine rolling resistance) incorporate shortcomings in accuracy and applicability of the data. And to date only limited data have been generated and published in the open literature which evaluate the true potential of radial tires applied to trucks and buses specifically to achieve improved fuel economy." It may be concluded from this that a larger data base is required before truck tire power consumption can be estimated with reasonable confidence. The study which is the subject of this paper has resulted in a contribution to such a data base.

The effects of tire wear, inflation pressure, load, replication, tire variations, test drum curvature, speed, driving and braking torque and distance traveled were investigated. A brief description of the test program is presented and is followed by salient results from the study. A final report which will contain the full scope and results of this program is in preparation at the time of this writing.

DESCRIPTION OF ROLLING RESISTANCE

It is convenient to think of rolling resistance as that portion of the tire input energy which does not

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*Numbers in parentheses designate References at end of paper.

ABSTRACT

A test program to measure the rolling resistance characteristics of selected 11 x 22.5 truck tires was conducted at the Calspan Tire Research Facility (TIRF). Test data from this study provide a data base which contributes to the understanding of truck tire rolling resistance and its relationship to operating variables. The influences of tire wear, speed, load, torque, slip angle, inflation pressure, temperature, construction, tread pattern and distance traveled on rolling resistance were investigated. A short description of the test program and a brief summary of the results are included in this paper.

produce useful work. This energy is lost because of hyteresis and friction. No attempt will be made to define the mechanism or discuss the physics of rolling losses of tires; instead, descriptions of these losses in terms of forces and moments acting on the tires will be presented.

For a flat road or test surface, the rolling loss power, P_F, of a free rolling tire is:

$$P_F = (FXO_F)(V_F), \qquad (1)$$

Where:

FXO = the longitudinal force,

V_F = the road speed, and

F = a flat surface.

In the case of a curved surface such as encountered on a drum, a D subscript is used. The rolling power loss, P_D, on a curved test surface (2) is

$$P_D = FXO_D\ (1 + RL_D/R)V_D, \qquad (2)$$

Where:

RL_D = the tire loaded radius,

R = the drum radius, which in the case of TIRF is 0.85 m (33.61 in).

A free body diagram of the tire on a flat and curved test surface is shown in Fig. 1.

It should be recognized that the longitudinal forces FXO_F and FXO_D are not necessarily equal under the same load conditions and that they can only be known through tests. The ratio of rolling loss power, P, to the road speed, V, is called rolling resistance, FR, and conforms to the SAE definition of Ref. 3. For the flat surface,

$$FR_F = P_F/V_F = FXO_F \qquad (3)$$

and for the curved surface,

$$FR_D = P_D/V_D = FXO_D\ (1 + RL_D/R). \qquad (4)$$

Equations 3 and 4 were employed in the determination of rolling resistance for free rolling tests with zero slip angle and wheel torque in this study.

When slip angle, α, and longitudinal slip, S, are introduced, the expression for rolling loss becomes more complex and the definitions used for straight ahead and free rolling conditions no longer apply. In fact, it was pointed out in Ref. 4 that according to the SAE definition of rolling resistance, "... the rolling resistance force becomes negative at large braking torques - a result clearly inconsistant with the energy principle." As a consequence, the following relationship from Ref. 4 was used to compute rolling resistance for the conditions where α and wheel torque were not zero:

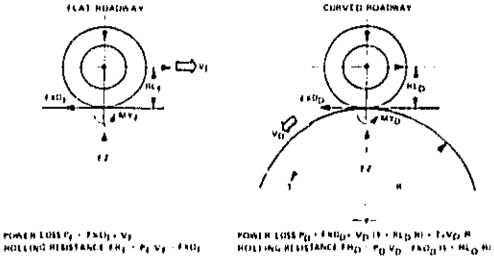


Fig. 1 - Rolling resistance of a free rolling tire measured on flat and curved roadways

$$e_R = \left[(T/RL)(1 + S) - FX - FY \tan \alpha\right] \cos \alpha \qquad (5)$$

Where:

e_R = the tire energy loss per unit distance traveled and is reported as FR in this study for the applicable results

T = the wheel torque,

FX = the longitudinal force,

RL = the tire loaded radius,

FY = the lateral force,

α = the slip angle,

S = the slip ratio.

The slip ratio is defined by the expression:

$$S = (\omega RL/V \cos \alpha) - 1, \qquad (6)$$

Where:

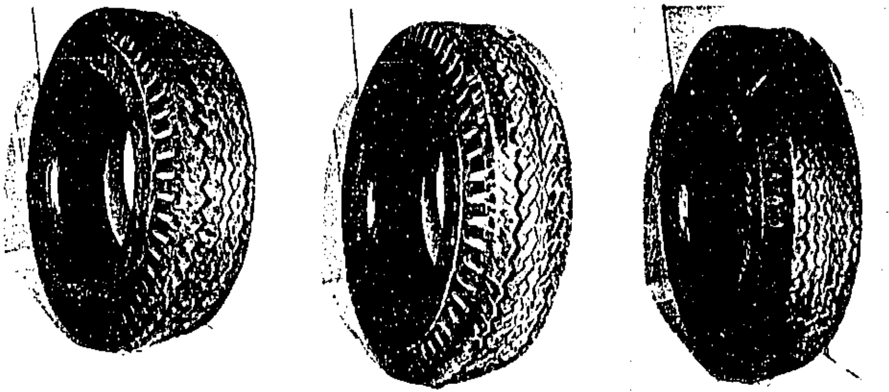
ω = the wheel spin velocity

V = the road speed.

TEST PROGRAM

Ten types of 11x 22.5 truck tires were tested for rolling resistance under selected conditions. These tires were chosen because they represent popular brands which are currently in highway use and because many of them were tested in other DOT programs involving noise investigations. Figs. 2 - 5 show representative samples of these tires.

Fig. 2 shows the three bias ply rib type tires which are a Goodyear Super Hi Miler, a Firestone Transport 1 with a zigzag center rib and a Firestone Transport 1 with a diamond center rib pattern. Bias ply bar type tires are shown in Fig. 3 and include a Goodyear Custom Cross Rib, a Firestone Power Drive and a Uniroyal Fleetmaster Super Lug. Radial rib tires which include a Michelin XZA, a Firestone Transteel and a Goodyear Unisteel R-1 are shown in Fig. 4. One radial bar type tire, a Firestone Transteel Traction, was tested and is shown in Fig. 5.



FIRESTONE TRANSPORT 1
ZIGZAG CENTER RIB

TIRE NUMBER
7
8 (50% FLEETWORN)

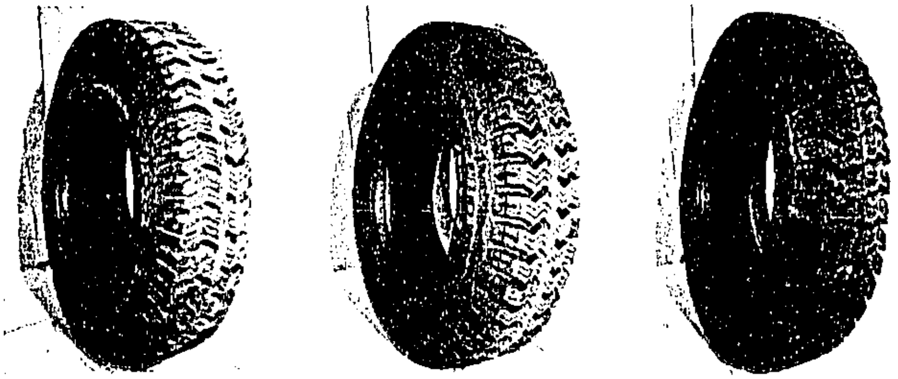
FIRESTONE TRANSPORT 1
DIAMOND CENTER RIB

TIRE NUMBER
18
19
20

GOODYEAR SUPER HI MILER

TIRE NUMBER
11

Fig. 2 - Bias ply rib tires



GOODYEAR CUSTOM CROSS RIB

TIRE NUMBER
1 (50% FLEETWORN)
2 (100% FLEETWORN)
3
12
13

FIRESTONE POWER DRIVE

TIRE NUMBER
10

UNIROYAL FLEETMASTER
SUPER LUG

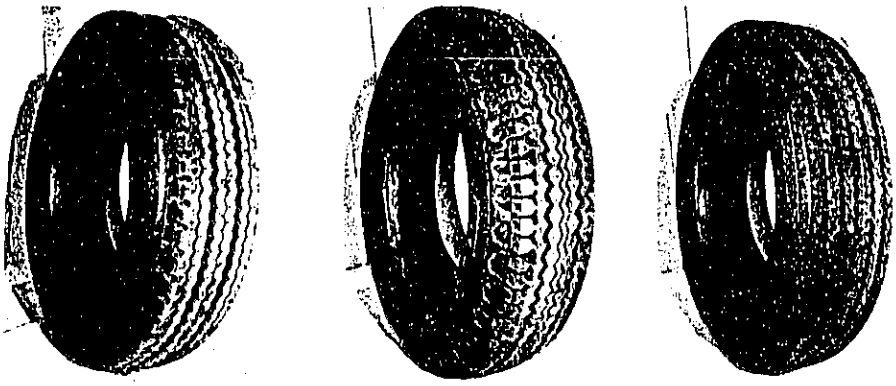
TIRE NUMBER
14

Fig. 3 - Bias ply bar tires

The Firestone Transport 1, Goodyear Custom Cross Rib and Michelin XZA were considered baseline tires and were tested under all conditions except tire variations in the program. For tread and tire model variations, a Goodyear Super Hi Miler, Firestone Power Drive, Uniroyal Fleetmaster Super Lug, Firestone Transteel, Goodyear Unisteel R-1 and a Firestone Transteel Traction were tested.

Table 1 contains a summary of the tests which were conducted and the corresponding tires which were used.

Except for slip angle and driving/braking torque tests, each test was conducted in the same manner with respect to distance traveled and load and speed variations. Fig. 6 shows these variations as they occurred in each test run. A constant load of 100%



MICHELIN XZA

TIRE NUMBER
4 (50% FLEETWORN)
5 (100% FLEETWORN)
6
17
22

FIRESTONE TRANSTEEL

TIRE NUMBER
15

GOODYEAR UNISTEEL R-1

TIRE NUMBER
21

Fig. 4 - Radial ply rib tires

FIRESTONE TRANSTEEL TRACTION

TIRE NUMBER
16

Fig. 5 - Radial ply bar tire

of T&RA for the F load range (21174N (4760 lb)) was established and maintained throughout the warm-up interval for 94.6 min. Speed was linearly ramped from 0 - 88.5 km/h (55 mph) over a time period of 4.8 min at the beginning of the run. Data were recorded during the entire test run, which permitted evaluation of transient and equilibrium rolling resistance characteristics of the tires. Once up to speed, test conditions were maintained for 89.8 min. At this point in the run, load was changed in the sequence 75%, 125% and 100% T&RA. Upon completion of the load variations, the speed was ramped to zero in 5 min concluding the test run. Inflation pressures of 517 kPa (75 psi) were used with bias tires and 551.6 kPa (80 psi) with radials. The influence of increasing and decreasing inflation pressure by 69 kPa (10 psi) on rolling resistance was investigated in the pressure tests.

Table 1
TEST SUMMARY

TEST	TIRES
• WEAR	FIRESTONE TRANSPORT 1, NUMBERS 7 AND 8 GOODYEAR CUSTOM CROSS RIB, NUMBERS 1, 2 AND 3 MICHELIN XZA, NUMBERS 4, 5 AND 6
• INFLATION PRESSURE • DRUM EQUIVALENT FLAT PLAT LOAD • DRUM - COOL TEMPERATURE • DRUM - TEMPERATURE MATCHED TO FLAT ROAD TESTS • DRUM - WARM TEMPERATURE • SLIP ANGLE • TORQUE	FIRESTONE TRANSPORT 1, NUMBER 18 GOODYEAR CUSTOM CROSS RIB, NUMBER 12 MICHELIN XZA, NUMBER 17
• REPLICATION	FIRESTONE TRANSPORT 1, NUMBERS 19 AND 20 GOODYEAR CUSTOM CROSS RIB, NUMBER 13 MICHELIN XZA, NUMBER 22
• TIRE VARIATIONS	GOODYEAR SUPER HI MILER, NUMBER 11 FIRESTONE POWER DRIVE, NUMBER 10 UNIROYAL FLEETMASTER SUPER LUG, NUMBER 14 FIRESTONE TRANSTEEL, NUMBER 15 GOODYEAR UNISTEEL R-1, NUMBER 21 FIRESTONE TRANSTEEL TRACTION, NUMBER 16

Wear investigations were conducted on the baseline tires. Fleetworn tires with 50% and 100% wear were used in these tests for the Goodyear Custom

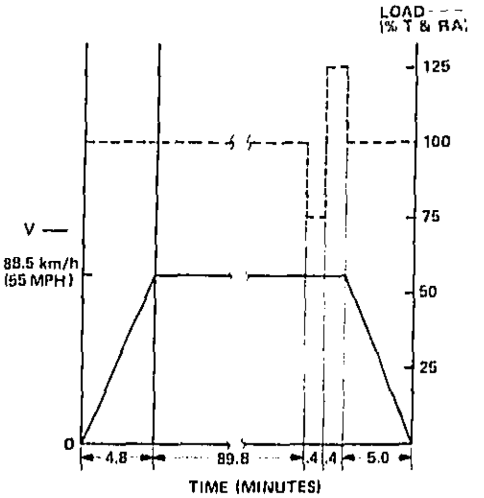


Fig. 6 - Free rolling test load and speed variation

Cross Rib and Michelin tires. A 100% worn Firestone Transport 1 was not available for these tests so consequently it was tested only in the 50% worn condition. The new tires were also tested in shaved conditions which simulated 50% and 100% worn tires. Tires were shaved to two configurations for each wear level. These were designated TD and TD & TR. TD represents a tire condition in which it was shaved to the same tread radius or contour as the new tire but the tread depth was reduced to either 50% or 100% of the new configuration. TD & TR represents a tire condition in which the tire was shaved to duplicate the tread radius of the fleetworn tires at the 50% and 100% wear levels.

Replication effects on rolling resistance were investigated by testing an additional carcass of each baseline tire. Two additional Transport 1 tires were tested and one of each of the Custom Cross Rib and XZA.

Variations due to tires which have different constructions, tread patterns and other model features were tested. Six tires were used in this portion of the testing and are listed in Table 1.

Tests were conducted on the baseline tires to determine the effects of road curvature. The first drum tests on the 1.708 m (67.23 in) diameter drum, were under the same loads and road surface temperature conditions which existed during the flat road tests. Temperature control was achieved by directing controlled air flow over the drum surface to duplicate the temperature recorded during the equivalent flat road tests. Cool temperature tests were conducted by directing maximum air over the drum and warm temperature tests were conducted by not cooling the drum at all and letting it operate in the normal room environment. Drum tests were also conducted under the flat plate equivalent loads which represented the same loaded tire radius on the flat and drum surfaces at zero speed.

Slip angle tests were conducted over a slip angle range of ±4 deg and a load of 100% T & RA. A warm-up period of 45 min was followed by the slip angle sweeps.

Braking and driving torque tests were conducted over a torque range of ±2712 Nm (1000 ft-lb) for 75%, 100%, and 125% T & RA loads. A warm-up period of 45 min under zero torque was followed by the three torque sweeps.

RESULTS

Results are presented in the form of plots which show the Rolling Resistance Coefficient (FR/FZ) on the vertical axis and the corresponding variable of interest on the horizontal axis. The intent of these plots is to show a representative summary of results and not to explicitly present all pertinent results. These will be contained in the final test report.

WEAR - Fig. 7, 8 and 9 show the variation of equilibrium Rolling Resistance Coefficient under the influence of wear. There was a reduction in rolling resistance for all shaved tires with an increase in simulated wear. The effects of simulating tread depth (TD) as compared to tread depth and tread radius (TD & TR) are also shown in the plots. The Firestone Transport 1 tire showed little sensitivity in rolling resistance to tread radius whereas both the Custom Cross Rib and XZA exhibited less rolling resistance for the tires shaved to TD & TR than did those which were shaved to TD. Comparison of the fleetworn tires shows that the Firestone Transport 1 was in good agreement with the shaved tire and the Michelin XZA was in good agreement at 100% wear. There was not as good agreement with the Goodyear Custom Cross Rib and the XZA at 50% wear. It must be remembered that each fleetworn tire was a different physical carcass whereas the shaved tires were the same carcasses at each wear level. Later it will be shown that tire variations within the same brand were as large as the differences between fleetworn and shaved tires. Shaving tires for the purposes of simulating wear in rolling resistance tests appears to be in generally satisfactory practice producing results which tend to be within the tire to tire variations experienced in a sample of a given brand.

INFLATION PRESSURE - The influence of pressure on rolling resistance is shown in Fig. 10 for three baseline tires. For all three tires, the equilibrium rolling resistance decreased with increasing pressure. Only pressures which were 69 kPa (10 psi) above and below the nominal values were used with these specific tires. Nominal pressures were used in the baseline tests, but on other physi-

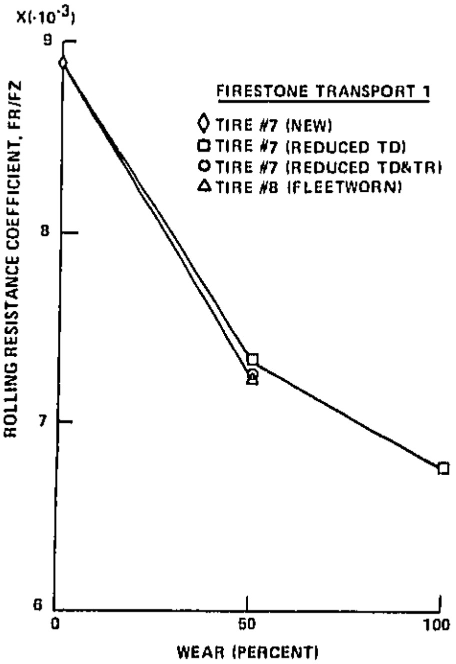


Fig. 7 - Rolling resistance variation with wear

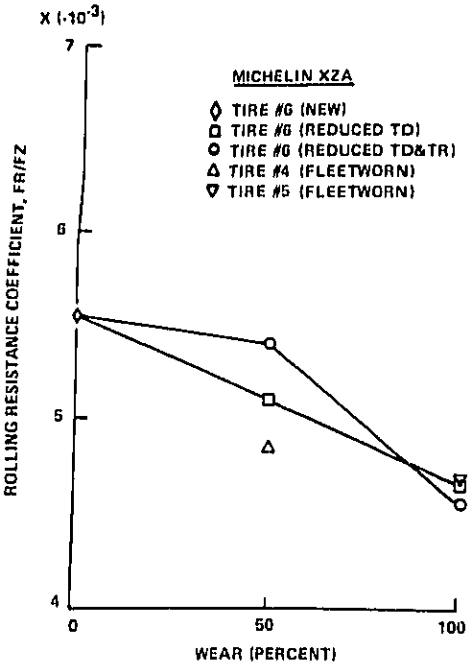


Fig. 9 - Rolling resistance variation with wear

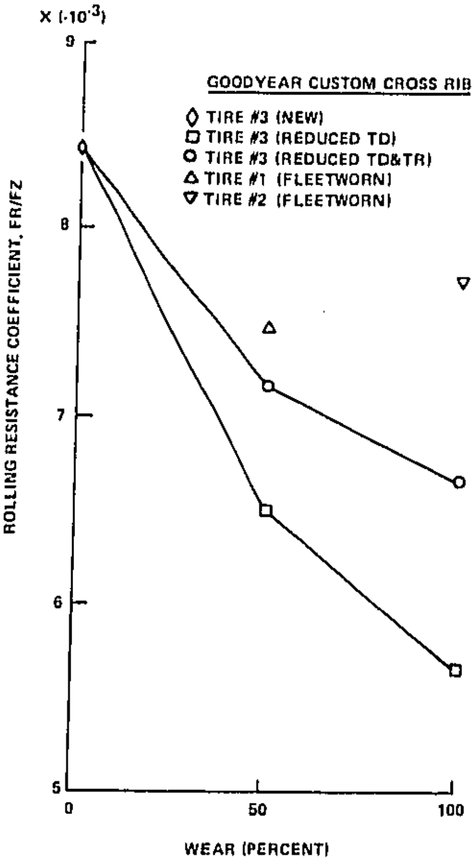


Fig. 8 - Rolling resistance variation with wear

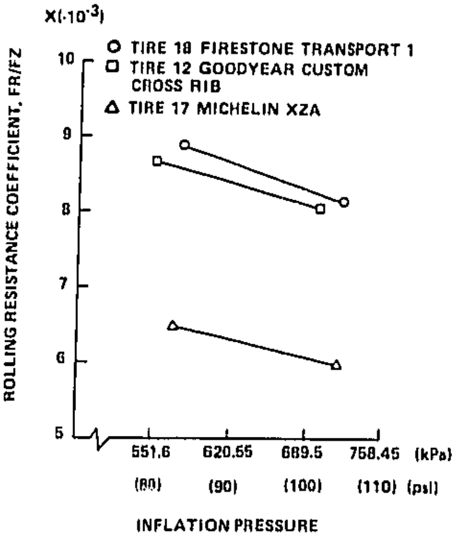


Fig. 10 - Rolling resistance variation with inflation pressure at 100%T&RA load

cal tire carcasses, and consequently were not plotted in this Figure. Nominal pressure for bias tires was 517 kPa (75 psi) and 551.6 kPa (80 psi) was used with the radials in these tests.

REPLICATION - Tests were performed on additional tires of the same brand as were used in the baseline tests. Fig. 11 shows the variations in rolling resistance which resulted for four Firestone Transport 1 tires. One of these tires had a zigzag center rib while the other tires had a diamond pattern center rib. An 8% variation in the rolling resistance coefficient existed for this four tire sample. Fig. 12 shows the same relationship for three Goodyear Custom Cross Rib tires. The variation was less than for the Transport 1, on the order of 3%, but still significant. Fig. 13 shows the variation for three Michelin XZA tires. This tire had a variation of approximately 13% among the three tire sample.

These variations among tires of the same model are significant to conclusions that may be considered about rolling resistance values which are determined for different tires.

OTHER TIRES - Fig. 14 shows the variations in equilibrium rolling resistance coefficient for six other tires. Three were radials and three were of bias ply construction. It is clear that the rolling resistance coefficient of the bias ply tires was about 50% more than that of the radial ply tires. Also, bias ply tires exhibited an increasing rolling resistance coefficient with increasing load whereas the rolling resistance coefficient for radials generally tended to decrease with increasing load. The results obtained for the baseline tires also fit into the characteristics exhibited by the corresponding groups.

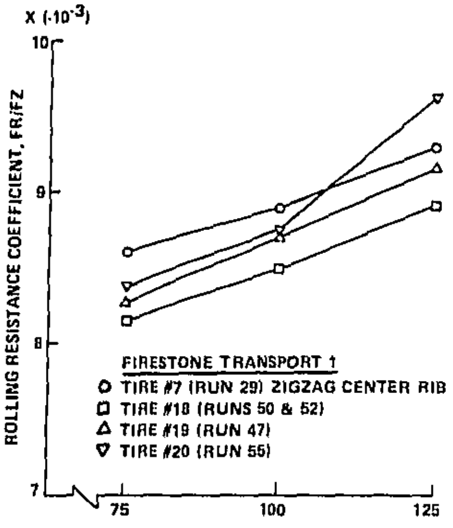


Fig. 11 - Rolling resistance variation with load for four tires of the same model

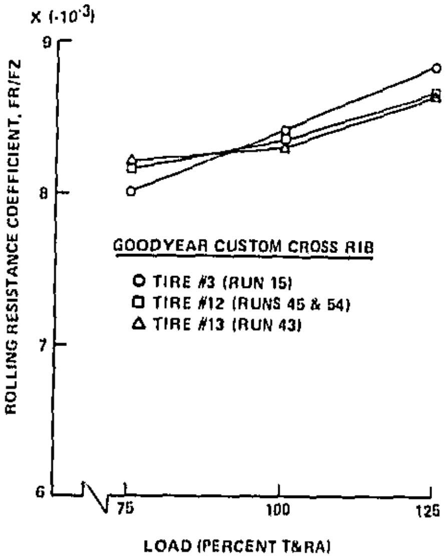


Fig. 12 - Rolling resistance variation with load for three tires of the same model

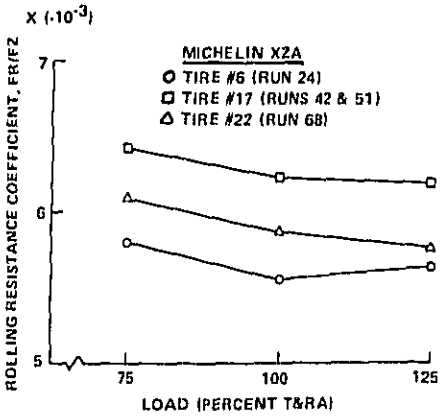


Fig. 13 - Rolling resistance variation with load for three tires of the same model

To show the general characteristics of bias and radial tires, the results of measurements on 10 bias ply tires and six radials were plotted in Fig. 15. The plotted points represent averages of the representative tire types. The vertical lines indicate the range of extreme maximum and minimum values obtained in the tests.

DRUM - Figs. 16, 17 and 18 show the variations in equilibrium rolling resistance coefficients when

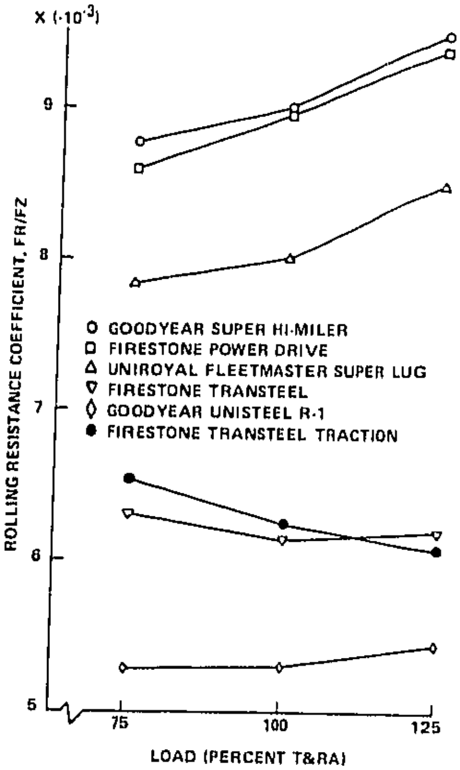


Fig. 14 - Rolling resistance variation with load

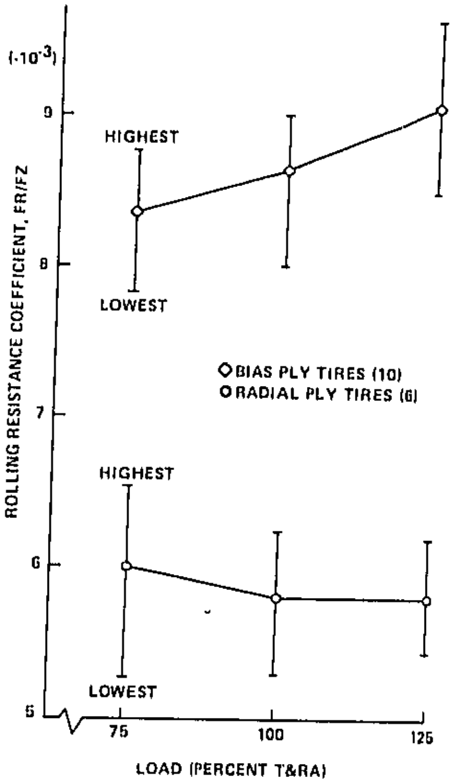


Fig. 15 - Rolling resistance variation with load for all new tires

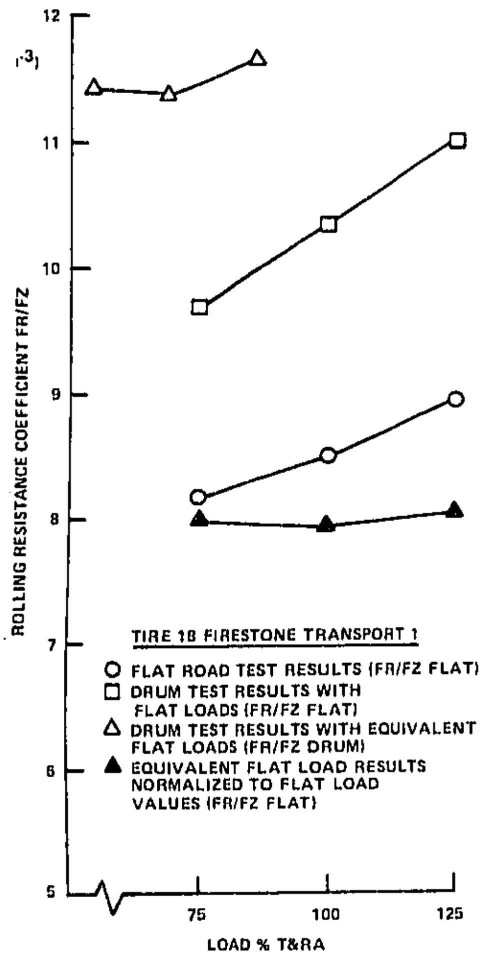


Fig. 16 - Rolling resistance variation with road curvature for a 1.708 m (67.23 in) diameter drum

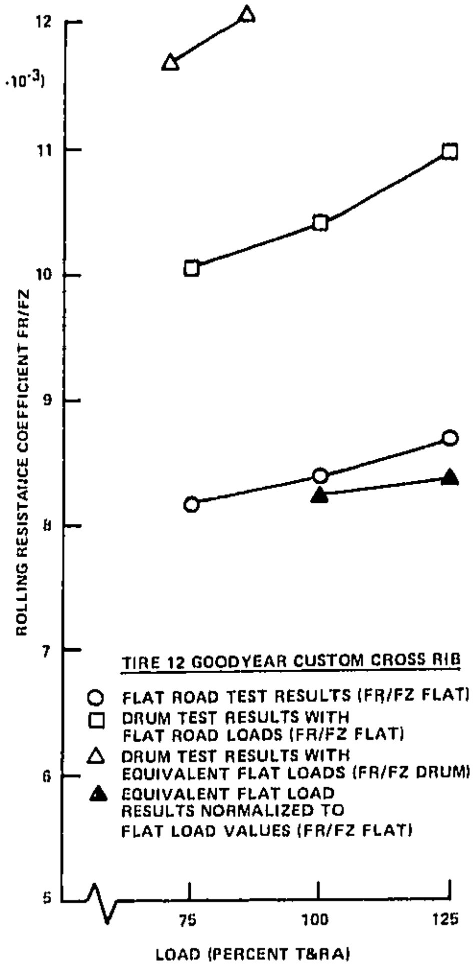


Fig. 17 - Rolling resistance variation with road curvature for a 1.708 m (67.23 in) diameter drum

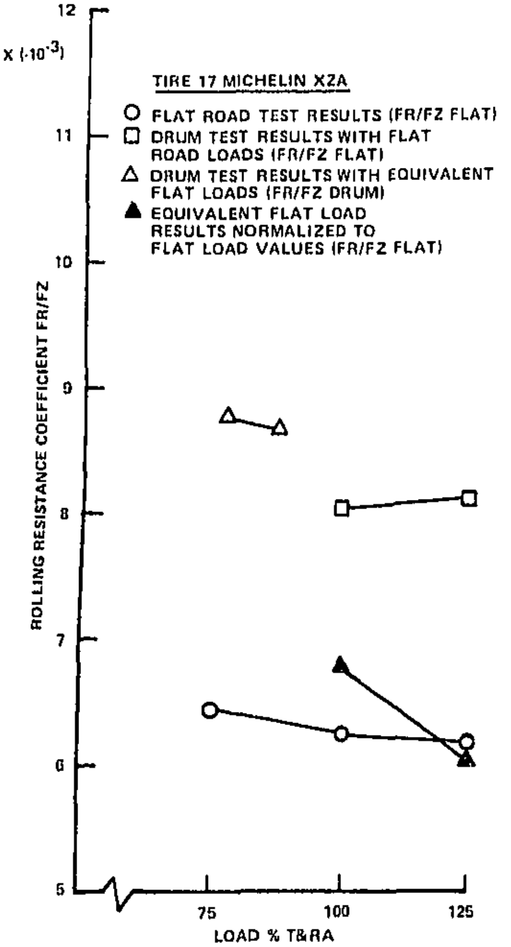


Fig. 18 - Rolling resistance variation with road curvature for a 1.708 m (67.23 in) diameter drum

measurements were made on flat and curved test surfaces. Values obtained on the drum were higher in magnitude than those obtained on a flat surface when the same loads were used in both tests. When equivalent flatplate loads were used, the values of rolling resistance coefficients computed on the basis of actual loads used were higher than those obtained from the flat road load values. When rolling resistance coefficient values were computed by dividing the measured FR values by the original flat road loads, the results were more nearly in agreement with the flat road tests.

SPEED - The influence of speed on rolling resistance is shown in Figs. 19, 20 and 21 for the Transport 1, Custom Cross Rib and XZA tires respectively. In each Figure, the top data represent

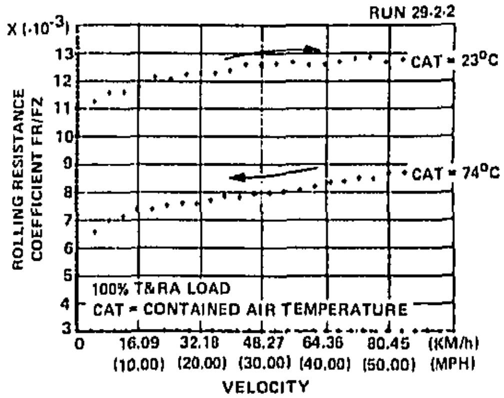


Fig. 19 - Rolling resistance variation with speed - Tire 7 Firestone Transport 1

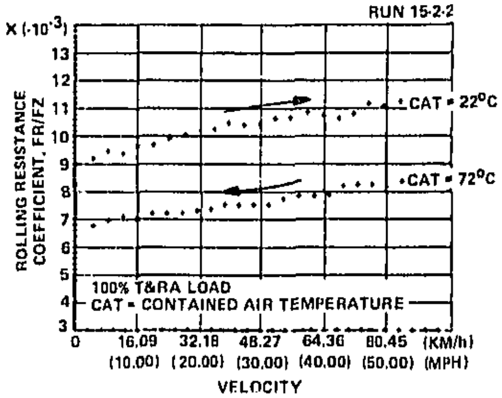


Fig. 20 - Rolling resistance variation with speed - Tire 3 Goodyear Custom Cross Rib

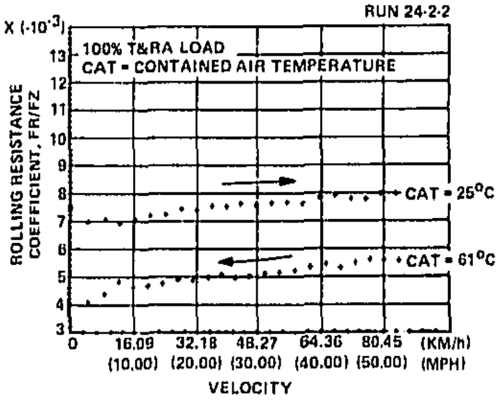


Fig. 21 - Rolling resistance variation with speed - Tire 6 Michelin XZA

the beginning portion of the test during the ramp from 0 - 88.5 km/h (55 mph). The bottom data represent the ramp down portion of the test at the end. These results do not represent equilibrium conditions since the tires were warming up during the ramp and were cooling during deceleration. These data do, however, reflect essentially constant contained air temperature (CAT) and corresponding values are shown on the plots. The radial tire exhibited the least sensitivity of rolling resistance to speed; however, the percentage change was about the same for all three tires.

DRIVING AND BRAKING TORQUES - When driving and braking torque was applied to the baseline tires, rolling resistance increased for large torques. This variation is shown in Fig. 22. It is significant that the minimum rolling resistance did not occur at zero torque, in fact, it occurred at a substantial level of driving torque for these tires. Each tire had been exposed to 45 min of warm-up at zero torque prior to making these measurements.

SLIP ANGLE - Application of slip angle to the baseline tires caused the rolling resistance to increase rapidly for increasing slip angles. Fig. 23 shows the influence of slip angle on rolling resistance for these three tires. Minimum rolling resistance did not occur at zero slip angle for these tires.

DISTANCE - Transient variations in rolling resistance are shown in Figs. 24 - 26 as plots of CAT, inflation pressure and rolling resistance coefficient with distance traveled for the baseline tires. Fig. 24 shows the variation in contained air temperature as a function of distance traveled. The radial tire incurred the least temperature rise of the three tires. It is also significant that even with 138 km (86 miles) of travel, the temperature was still rising for the tires and complete thermal equilibrium had not been obtained.

Pressure characteristics were similar to those of temperature for these tires. Fig. 25 shows the relationship between inflation pressure and distance

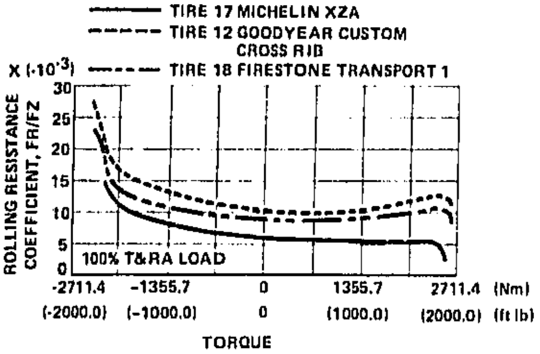


Fig. 22 - Rolling resistance variation with torque

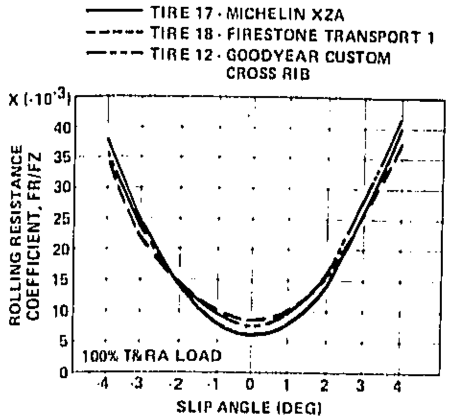


Fig. 23 - Rolling resistance variation with slip angle

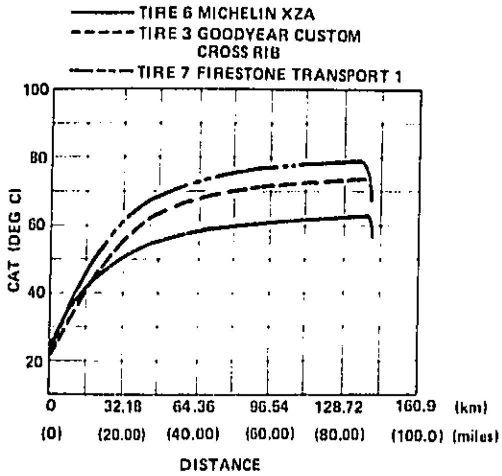


Fig. 24 - Contained air temperature (CAT) variation with distance

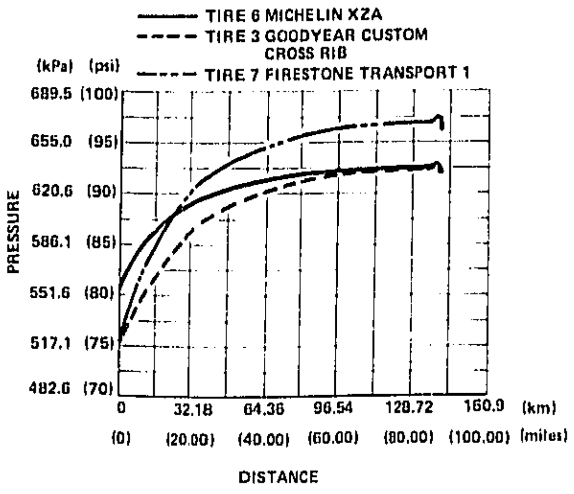


Fig. 25 - Inflation pressure variation with distance

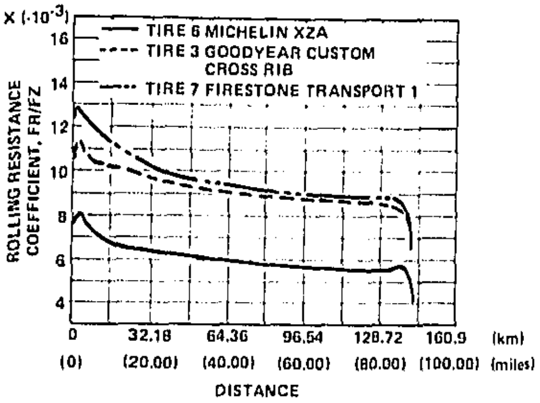


Fig. 26 - Rolling resistance variation with distance

traveled for these tires. The radial tire exhibited the smallest pressure increase of the three tires. Again the pressure did not come into complete equilibrium in 138 km (86 miles) of travel.

The influence of distance traveled on rolling resistance for the Firestone Transport 1, Goodyear Custom Cross Rib and Michelin XZA is shown in Fig. 26. The significant point in these results is that the radial tire experienced the least change in magnitude of FR/FZ with distance. It is also evident that the radial and Transport 1 tires has essentially reached equilibrium in rolling resistance whereas the Custom Cross Rib tire had not in 138 km (86 miles) of travel.

Inspection of the plots of rolling resistance coefficient and CAT, Fig. 24 and Fig. 26, shows that rolling resistance decreased with increasing contained air temperature.

CONCLUSIONS

The rolling resistance of truck tires decreases with wear. The amount of decrease is about twice as much for bias tires as for radial tires.

The rolling resistance of truck tires decreases with increasing inflation pressure.

Rolling resistance of bias ply tires is greater than that of radial ply tires. In general, the rolling resistance coefficient is about 50% greater for bias tires than it is for radial ply tires.

Rolling resistance coefficients of a tire measured on a 1.708 m (67.23 in) diameter drum are greater than those measured on a flat road under the same loads. If flat plate equivalent loads are used then the measured values are more nearly similar.

Rolling resistance coefficients of bias ply tires increase with load whereas for radial tires they generally decrease.

Tire replication showed variations in rolling resistance of up to 13% for radial tires and up to 8% for bias tires.

Rolling resistance increases with increasing speed.

Minimum rolling resistance does not necessarily occur at zero wheel torque.

Minimum rolling resistance does not necessarily occur at zero slip angle.

ACKNOWLEDGMENTS

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Appreciation is expressed to William A. Leasure of the Office of Noise Abatement at DOT for his able and informative assistance in establishment a meaningful test program. His contributions to tire selection and test definitions were welcome inputs.

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2. D. J. Schuring, "Rolling Resistance of Tires Measured Under Transient and Equilibrium Conditions on Calspan's Tire Research Facility." U.S. Department of Transportation, Report Number DOT-TSC-OST-76-9 under Contract Number DOT-HS-4-00923, Amendment 2, March 1976.

3. SAE Recommended Practice, Vehicle Dynamic Terminology - SAE J670d, SAE Handbook.

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DISCUSSION

MR. CLARK: A couple of quick questions, Mr. Gusakov: The 90-min warmup time did result in temperature equilibrium and the tires were basically in equilibrium at that point?

MR. GUSAKOV: The 90-min warmup period was sufficient to bring the rolling resistance into equilibrium, but the temperatures were still climbing.

MR. CLARK: The tests were conducted with trapped air, I take it? You didn't monitor the inflation pressure at the figure indicated?

MR. GUSAKOV: Yes, we monitored inflation pressure, but the cavity volume, or the mass of air, was kept constant during the test.

MR. CLARK: So you neither added nor subtracted air?

MR. GUSAKOV: No.

MR. CLARK: - from the test?

MR. GUSAKOV: No.

MR. CLARK: The last question concerns the conclusion you made about the variation with speed, which I suppose to a certain extent seems to be true with passenger car tires. In this case, however, the speed variation that you ran was not allowed to come into equilibrium, was it, or did I understand that correctly?

MR. GUSAKOV: That's correct. It was not at equilibrium.

MR. CLARK: So it might have been a somewhat different picture had it been allowed to come into equilibrium?

MR. GUSAKOV: To a certain extent, yes.

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The Reduction of Noise by Applying Basic Design Principles to Roads and Tires

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Dunlop Limited (England)

IN THE TOTAL VEHICLE NOISE PROBLEM, especially that of heavy trucks on urban high speed traffic flow roads, a reduction of 10dB(A) of the engine associated noise sources is thought to be within reach of our existing technology. However, the benefits of such changes will not be fully realized unless at the same time tire/road noise can be reduced (1)[*].

The approach to this is in four main parts in this present work:

1. Measure and analyse vehicle coasting noise on the road.
2. Measure and analyse tire/surface noise on a drum in the laboratory.
3. Develop a mathematical model in the computer in order to predict results.
4. Obtain as close a correspondence as possible between the above different parts of the work, and apply the knowledge gained to produce quieter tire/road interfaces, bearing in mind other tire/road properties.

Other factors which must be optimised are wet grip, irregular wear, endurance, stone trapping and chunking. These are fairly easily overcome on car tires, but more skill and research is needed to obtain optimisation on truck tires.

Consider the units of measurement of noise level. The traffic can be considered as a line source when the distance from the highway is greater than half the average headway between the vehicles. A 3dB reduction which is halving of sound intensity, is equivalent to doubling the distance from the highway or to halving of traffic volume or to reducing the traffic speed by 25%. Although 1 dB is fairly insignificant from a subjective point of view, it is of great importance to United Kingdom (U.K.) authorities paying compensation under the British Land Compensation Act when the measured noise is close to the limit.

TRANSPORT AND ROAD RESEARCH LABORATORY TESTS

Fig. 1 (Ref. 3) summarises the main dB(A) results published in the Transport and Road Research

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[*] Numbers in parenthesis designate References at end of paper.

ABSTRACT

Noise level results for a range of types of truck tire tread patterns and road surfaces are discussed. Some of the results of noise level in dry conditions are related to braking grip in wet conditions, showing that it is possible to increase wet grip and still reduce noise level.

Computer studies using the mechanical frequency modulation method of predicting dominant tread pattern frequencies from tread segment pitch variations are dealt with including an automatic optimization procedure.

A further development which includes the detail of the tread pattern in the segment as input to the computer gives closer prediction of higher harmonics of more complex tread patterns.

Recent tests on total traffic noise after resurfacing the Hammersmith fly-over in London, England, have shown almost a 3dB(A) reduction with Delugrip Road Surfacing Material compared with the original British Standard Hot Rolled Asphalt.

Laboratory U.K. quiet truck project work (2). It shows the coasting noise levels in dB(A), fast response, at the standard distance of 7.5 m (25 ft) - the European Standard - from the centre line of the vehicle for a laden truck 13,200 kg (29,000 lb) traveling at 100 km/h (62 mph).

Here there are three dry surfaces, polished smooth concrete, coarse quartzite and motorway surfaces, and three types of tire pattern, blank tread, ribbed pattern and tractive pattern, on the 10.00-20.00 cross-ply tires. A blank tread is one of full tread thickness without a tread pattern.

The polished smooth concrete surface shows a much greater contrast in tread pattern road noise than the surfaces with the greater macrotexture - this is the large-scale texture of the road surface for water drainage. In the latter cases, ribbed tires are 1 - 2 dB(A) noisier than smooth tires and traction tires are 3 dB(A) noisier than the ribbed tires. Thus, the total effect of any major pattern feature is of the order of 3 dB(A).

This Figure shows two distinct effects of the road surface on the tire/road noise.

First, the excitation effect - the greater the macrotexture the more the tire is excited and the greater the noise emitted, unless the frequency is high enough to be outside the sensitive region for the tire. This is seen in the blank tire results which get noisier as the macrotexture increases. There is no tread pattern effect in this case.

Second, the breakup of the tread pattern effect - up to a point, the greater the macrotexture the less the tread is in contact with the road, it contacts just the tops of the stones, then the greater is the breakup and the less will the noise be due to the tread pattern. This is shown in the traction pattern results, where because of the transverse lug tread pattern (no centre rib) the effect of breakup dominates over the excitation effect and the tire gets quieter as the macrotexture gets greater.

The coarse quartzite surface is 3 - 4 dB(A) quieter than the motorway surface for all tread patterns.

The effect of high hysteresis tread rubber was also measured, and as compared to natural tread rubber the average differences were less than - 1 - 1.5 dB(A).

SNOW TRACTION TESTS - CROSS BAR VERSUS RIBBED PATTERN

A related performance consideration of the cross bar pattern is its advantage in snow conditions. Results from snow tests in Austria in the 1975/76 winter, on truck radial tires, showed that a cross bar pattern, with centre ribs and shoulder blocks, similar to those used in the following noise tests, is better than a ribbed pattern. On packed snow (snow temperature -1° - -3°C), the cross bar pattern gave 13% better draw bar pull at 40% slip which is an important operating region. On packed and loosened snow - snow temperature -9°C - it gave 8% better braking. The differences are quite substantial, since, for these properties, a 6% improvement is considered commercially worthwhile.

TRUCK COASTING NOISE

Fig. 2 shows the coasting noise levels in dB(A) at 7.5m (25 ft) for a laden truck 16,200 kg (35,600 lb) traveling at 64 km/h (40 mph). The figures are the average from 8 runs. The noise measurements were taken with a Bruel and Kjaer

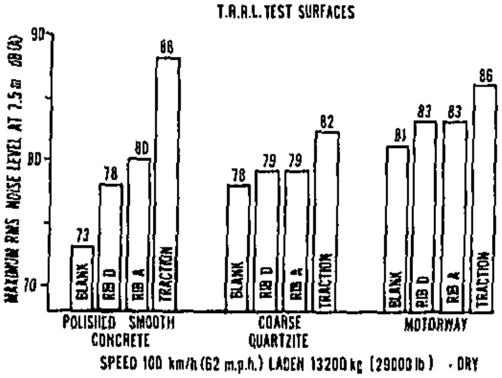

Fig. 1 - Truck coasting noise for various tire road combinations

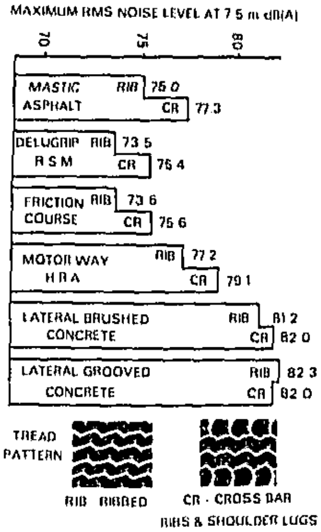

Fig. 2 - Dry truck coasting noise for various road tire combinations [Speed 64 km/h (40 mph) Laden 16,200 kg (35,600 lb)]

precision Sound Level Meter Type 2209 using the fast response. Wind velocity was below 5 mph. The tests are under J57a conditions except where otherwise stated.

DR 22.5 radial ply tires were used. Ribbed pattern tires were fitted to the front truck axle in all tests, and the ribbed pattern or the traction pattern (centre ribs and shoulder lugs) were fitted to all four wheels of the rear drive axle respectively. There are six road surfaces:

1. Mastic Asphalt - a skidding test strip.
2. *Delugrip Road Surfacing Material (R.S.M.) with maximum aggregate size of 10 mm.
3. Friction Course - previous Macadam.
4. Motorway - Hot Rolled Asphalt BS 594 with 19 mm precoated chippings.
5. Lateral Brushed Concrete - Brush marks 1 to 2 1/2 mm deep and 3 to 10 mm apart.
6. Random Lateral Grooved Concrete - grooves 10 mm wide and 30 to 55 mm apart.

The surfaces 2 to 6 are from 1 - 3 years old with medium traffic density up to 500 commercial vehicles/day.

The tire pattern effects are shown in perspective with the road surface effects. Starting on the left hand side of Fig. 2 a certain amount of macrotexture decreases the pattern effect and then added macrotexture excites more noise. In the cases of the lateral brushing and grooving of the surface, the tire impacts the lateral ridges at the same time across the width of the tread, which is the worst way for noise generation.

In the case of automobile tires ranging from blank to snow tread patterns, tested on a 3M Safety Walk surface on a drum in the laboratory, we found the difference between a range of patterns to agree well with vehicle pass-by tests on the very smooth Mastic Asphalt (3).

DELUGRIP ROAD SURFACING MATERIALS

In order to optimise wet grip at the tire/road interface, the wet grip of tires was steadily improved over the years. It was then realised that the greatest room for substantial improvement lay in the second half of the problem. That is, the potential grip of the road surface, and work was then directed towards improving this.

Delugrip Road Surfacing Materials have been developed after eight years of joint research between Dunlop and Birmingham University. These materials have increased wet skid resistance, reduced spray generation and reduced tire/road noise. These properties are maintained throughout their life.

The large scale texture of the surface, the macrotexture, is optimised for the drainage of bulk water across the surface and to aid water drainage from under the contact patch as shown by Bond et al. (4).

The microtexture for adequate skidding resistance at any speed by rupture of the thin remaining water film should have a specific level as shown by Williams and Lees (5, 6).

The Delugrip type of surface is a wearing course material designed to a rational method of aggregate grading (7) and complies with the above requirements for macrotexture and microtexture. The microtexture is achieved through mix design principles to give adequate sub-tire drainage for the average traffic speed of the site and is maintained by differential wear rates of the aggregates. The microtexture required is achieved and maintained by selection of suitable aggregates having resistance to polishing.

The substantial benefit in wet grip is illustrated by the sideways (lateral) force coefficient figures in Fig. 3. They were taken over a three year period for a trial area of the A4, London comparing the Delugrip type of surface with Hot Rolled Asphalt. The traffic is very heavy. The values were measured using the Sideway Force Coefficient Routine Investigation Machine (S.C.R.I.M.) (8) which has become the standard wet grip testing machine for road authorities in the U.K. In this machine the lateral force coefficient of a blank tread motorcycle tire at a slip angle of 20° is measured in the wet at a speed of 50 km/h (30 mph).

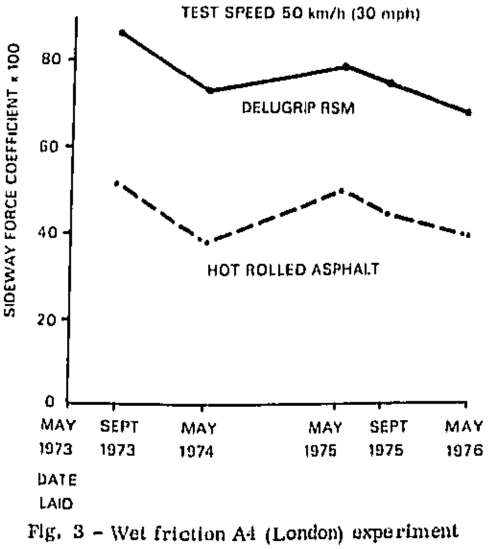

Fig. 3 - Wet friction A4 (London) experiment

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*'Delugrip' is a registered Trade Mark of Dunlop Limited.

NOISE AND WET GRIP

Fig. 4 shows the increase in automobile coasting noise level with speed at 7.5 m (25 ft) distance with blank tread tires and ribbed and multislotted tread tires. The peak braking force coefficient figures in the wet are shown for the latter.

With doubling of speed, the increase with speed ranges from 9 - 12 dB(A). The truck tire tests previously discussed show an average of 10 dB(A) increase with doubling of speed. This corresponds to 3 dB(A)/25% increase in speed.

The surfaces range in coarseness from the random spacing grooved concrete, which has good wet grip but is the noisiest, through British Standard Hot Rolled Asphalt BS 594 which has lower wet grip when worn and is noisy, through Delugrip Road Surfacing Material which has good wet grip when worn and is quieter, to the Smooth Mastic Asphalt Skidding test track surface which has poorest wet grip and is the quietest. Thus, Delugrip Road Surfacing Material is an attempt to optimise both wet grip and noise.

Fig. 5 shows the form of the relationship between wet grip and noise in the dry for various tire/road combinations for both truck and automobiles. The truck figures are from Transport and Road Research Laboratories work and the coasting noise levels are those which were shown in Fig. 1. The13,200 kg (29,000 lb) truck at 100 km/h (62 mph) with blank tires on polished smooth concrete has a low value for peak braking force coefficient of 0.03 and a low noise level of 73 dB(A).

Consider the following ways of increasing grip. First, when road texture is increased and a rib pattern is used on the tires the noise rises 10 dB(A), the texture contributing more to the noise than the tire pattern. However, this is not necessarily inevitable since the grip can be increased and the noise reduced, in the case of our work with a 1280 kg (2800 lb) automobile traveling at 64 km/h (40 mph) on surfaces after one year of heavy traffic (approximately 1000 commercial vehicles/day); with increasing grip the noise level reduces by 4.7 dB(A) when changing from standard compound tires on the motorway to high friction tread compound tires on the Delugrip type of surface. There is a 1.7 dB(A) reduction due to the tread compound change and a 3dB(A) reduction due to the road surface change. The Delugrip type of surface also gives a significant improvement in comfort.

It will be noted that the braking force coefficients are rather higher with the truck on the test track motorway surface, than with the automobile on the actual motorway. This is because on the track the roughening, due to weathering, dominates any traffic polishing whereas on the motorway the reverse is true. In fact, an automobile has a higher grip than a truck on the same surface.

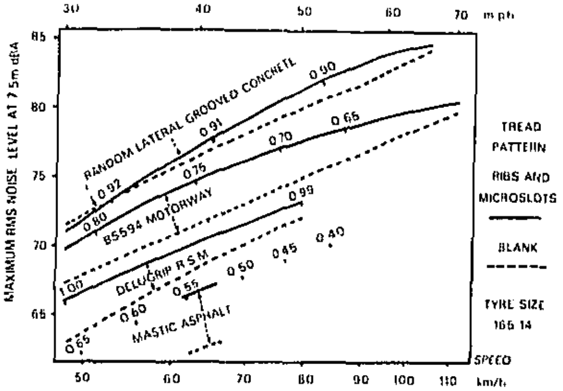


Fig. 4 - External car coasting noise generation on dissimilar surfaces - Dry with blank and patterned tires and peak braking force coefficient figures - wet

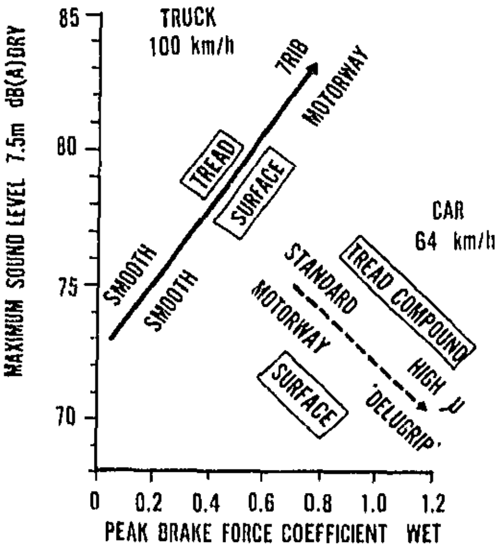


Fig. 5 - Vehicle coasting noise related to wet grip

WET ROAD

If bulk water does lie on the surface then the noise can be 7 - 11 dB(A) higher than in the dry with truck tires. However, if the road surface has enough drainage to drain away the surface water, such as the porous surface of friction course of the Delugrip type of surface, then noise in the wet is hardly any higher than the noise in the dry, and the spray is greatly reduced.

TIRE TREAD PATTERN/ROAD SURFACE NOISE SYNTHESIS

It is possible to synthesise, analyse and listen to the noise from a tread pattern at the design stage, using the digital computer and also get some indication of the effect of the contact patch on a rough road surface.

PITCH SEQUENCE

The first step in this work was to take account of only the tread segment pitch lengths and the pitch sequence round the tire. A sawtooth wave is used as the effect of a tread segment. From these, the program constructs the waveform for the complete periphery of the tire. This waveform is then frequency analysed. This is similar to the system proposed by Varterasian (9). Although it does not differentiate between different tread patterns within the segment they both have many high harmonics and it is a powerful method of optimising the sequence.

Fig. 6 shows the effect on the dominant harmonic of increasing the pitch ratios of the three pitch sequences shown.

Starting with the harmonic corresponding with the number of segments 62, different harmonics take over as the dominant harmonic, each at a lower level, as the pitch ratio increases. P. S. D. (Power Spectral Density) is the power per Hz bandwidth.

The next step was to include in the computer program an automatic search for a better sequence by permuting the order of groups of segments.

Fig. 7 shows the effect on the dominant harmonics of increasing the pitch ratios for two pitch sequences. One has a maximum of three identical length adjacent segments, and the other a maximum of seven. For each ratio the order of the blocks was permuted and the minimum and maximum values of the dominant harmonic shown.

The danger of having too many identical length segments adjacent is that an undersirable warble will appear in the noise. As pointed out by Thurman (10) on automobile tires, pitch ratios up to two to one can be used, but since in truck tires the flexibility of the shortest segment can cause non-uniform wear then only small ratios can be used.

If at a certain speed, a dominant tone coincides with a resonance, then the noise level will be greater. By reducing dominant tones and spreading the noise energy into other parts of the frequency spectrum this possibility is avoided and also the noise blends better with the background.

TREAD PATTERN INPUT

A major extension of the scope of the program is to replace the simple sawtooth wave used for repre-

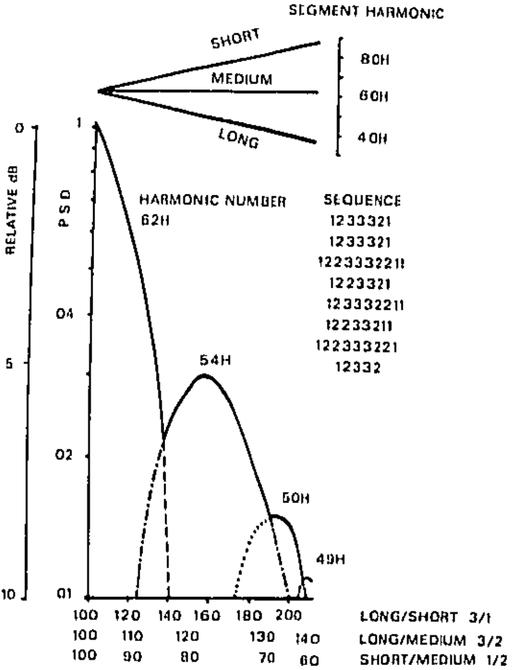


Fig. 6 - Effect of Segment Length Ratio on dominant harmonics of sequence

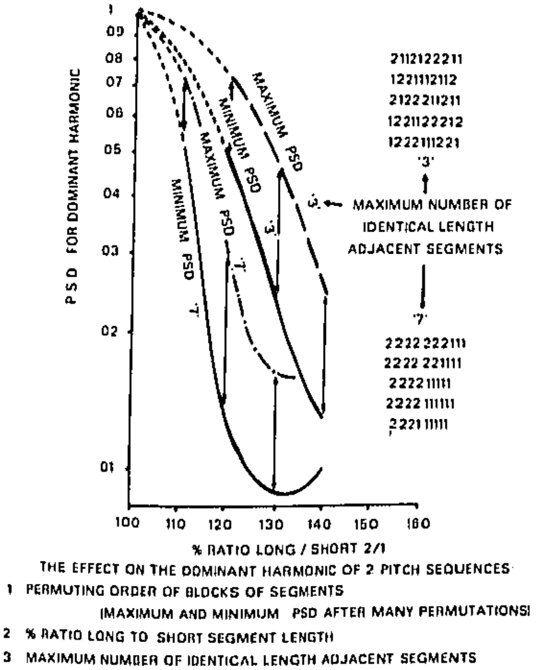


Fig. 7 - The effect on the dominant harmonics of increasing the pitch ratios for two pitch sequences

senting a tread segment by a wave derived from the tread pattern.

In a tire noise simulator described by Mukai (11), the tread pattern is painted with grooves black and the remainder white, on a sheet of paper positioned around the inside of a drum. As the drum rotates, a line of photocells across the tread pattern responds to the black and white pattern and gives an electrical wave form. This is fed to a loudspeaker to give simulated noise.

In the present computer noise simulator, the total groove width along a lateral line across the tread is calculated at millimeter intervals along a tread segment. This total groove width variation along the segment is fed into the computer together with the segment sequence and segment lengths to produce the simulated noise. A frequency analysis is obtained together with a loudspeaker output for subjective assessment. This differentiates between different tread patterns. Angling grooves and anti-phasing the pattern on opposite sides of the tread will give less total groove width variation and quieter tires.

The effect of tire resonances is kept in mind when comparing the simulated spectra with measured spectra.

Although the model is simple, it does give help in reducing tread pattern noise. It is felt that computerised simulations are particularly suitable for further sophistication as further insight is gained into the mechanisms of tire noise generation.

ROAD SURFACE CONTACT

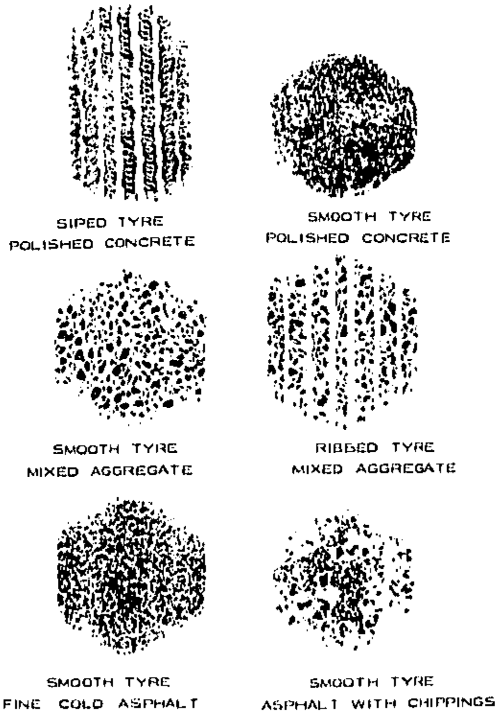
Fig. 8 which is taken from Ref. 12 shows automobile tire/road contact prints. The variation of non-contact width or conversely true contact width can be seen. In terms of the model, increased macrotexture would increase the noise of a blank tire, and decrease the noise of a traction pattern.

In the case of lateral grooved concrete and lateral brushed concrete, the tire/road non-contact will be in lines across the tread between the road ridges and this contributes strongly to the contact width variation and hence the noise.

NOISE DUE TO ROAD SURFACE TEXTURE

Fig. 9 (3) shows the relationship between length of tire tread pitch or mean aggregate spacing, vehicle speed, and the corresponding frequency generated. The aggregate spacing is shorter on the Delugrip type of surface than Hot Rolled Asphalt resulting in higher frequencies from Delugrip for a given speed.

Fig. 9 shows in addition the third octave spectrum of a plain rib steel breaker radial ply automobile tire on Delugrip. A broad peak in the order of 1000 Hz which is independent of speed together


SIPED TYRE
POLISHED CONCRETE

SMOOTH TYRE
POLISHED CONCRETE

SMOOTH TYRE
MIXED AGGREGATE

RIBBED TYRE
MIXED AGGREGATE

SMOOTH TYRE
FINE COLD ASPHALT

SMOOTH TYRE
ASPHALT WITH CHIPPINGS

Fig. 8 - Tire/road contact patch various combinations of tire and surface (Reproduced from Reference 2)

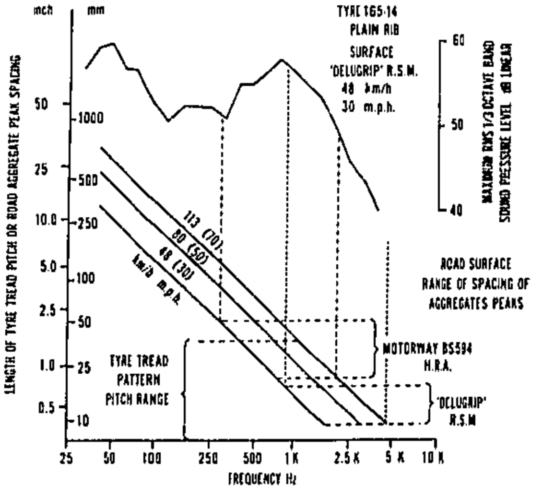


Fig. 9 - Relationship between tire/road noise and frequency generation due to vehicle speed, tire tread pitch and road aggregate spacing

with a rapid decay rate as frequency rises further is shown in this spectrum. It also occurs with the blank treaded tire on a smooth asphalt sand carpet surface at lower levels. Blank treaded truck tires also show a fall in the noise in the high frequency region.

The higher frequencies from the Delugrip type of surface are in the less sensitive region for the tire/road noise. It is evident that both the road designer and the tire designer have to be careful in choice of aggregate size and tire tread element pitch so that excitation is, as far as possible, in the less sensitive high frequency region.

TOTAL TRAFFIC NOISE - THE RESURFACING OF HAMMERSMITH FLY-OVER U.K.

In March 1975 the eight year old Hot Rolled Asphalt surface on the Hammersmith fly-over or overpass U. K. was re-laid with Delugrip. This opportunity was taken to carry out an exercise to investigate traffic noise before and after resurfacing (13). The traffic flow is very high at 69,000 vehicles/day and approximately constant from week to week. Tape recordings of the noise were taken in January over two half-hour periods, namely early and late afternoon. Recordings were repeated on the same day of the week in April after resurfacing. Each day was similar in weather conditions. The average traffic speed was fairly consistent - 55 km/h (40 mph) during the test periods.

In addition to measurement of the total traffic noise, advantage was taken of the closed periods of the fly-over to carry out individual noise tests. These involved an automobile coasting past a microphone at 7.5 m (25 ft) distance, over a range of speeds.

The microphone position for the traffic noise tests was on the roof of the local Odeon Cinema. This gave a good position some 9.1 m (30 ft) above the carriage way and approximately 18.2 m (60 ft) from the centre of the road.

The difference in surface texture is shown in Fig. 10 the scales being compressed horizontally and expanded vertically to show the difference with clarity. These sections were obtained by taking a cast of the road surface in the wheel rut area along the direction of travel. The casts were sectioned, photographed, and the profile trace digitised to produce punched tape. This was fed to the IBM 370 computer and the magnetic tape output was fed to the autodraft equipment.

The upper trace shows the Hot Rolled Asphalt with the binder worn away. The tops of the stones were severely polished giving poor wet grip. This surface will excite considerable tire vibration and hence, considerable tire/road noise.

The Delugrip type of surface shown below has a much finer macrotexture, which causes much less tire vibration and this is at higher frequencies in the less sensitive region of the spectrum and thus gives quieter tire/road noise. The valleys in this profile are interconnecting water ways for good drainage. In the case of the individual noise tests with a coasting automobile a 3dB(A) improvement was obtained.

Fig. 11 shows s distribution or histogram of the traffic noise levels for both Hot Rolled Asphalt and the Delugrip Road Surfacing Material. The tape recording of traffic noise was fed to the Sound Level Meter which provided the input to the digital mini computer which calculated the distributions shown.

The vertical scale represents the percentage of the time that each particular dB(A) level was recorded over the total period of 1 h. The horizontal scale shows increasing dB(A) levels to the right. This Delugrip type of surface is 3 - 4 dB(A) quieter than Hot Rolled Asphalt over a large part of the distribution. At the noisiest end, corresponding to a noisy truck engine the difference is much less since the engine noise dominates. However when the quiet lorries have been produced, the quieter surface is already available.

To investigate frequencies at which the difference between the two surfaces was greatest each tape was analysed through the 1/3 octave bands in the range 40Hz - 3.15 kHz. This enabled curves to be plotted for each frequency, thus a frequency analysis could be obtained for various percentages of time.

Fig. 12 shows the curve for 50% and is an average of both tapes.

In this diagram the various 1/3 octave levels

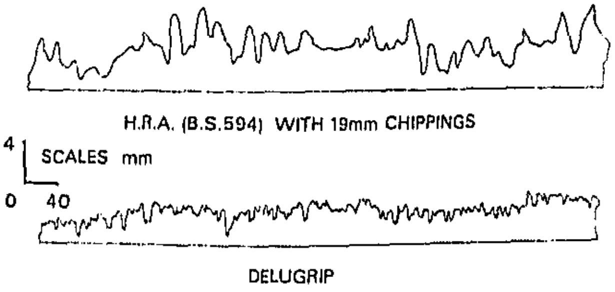


Fig. 10 - Road section profile

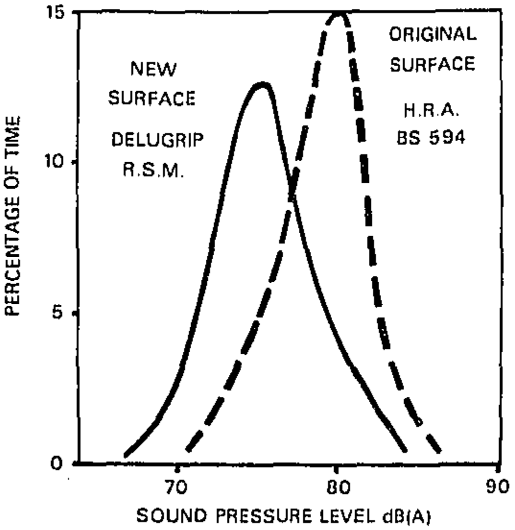


Fig. 11 - Histograms of noise on Hammersmith Fly-over before and after resurfacing

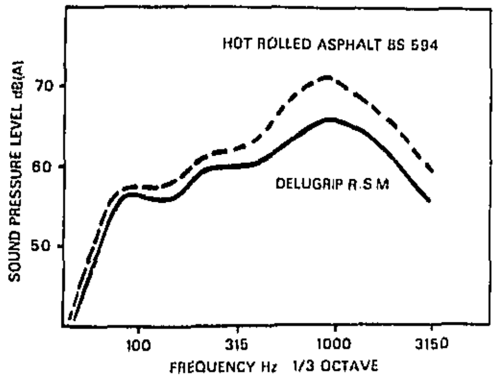


Fig. 12 - Average frequency spectrum over two half-hour periods for 50% of time

have also been weighted using the dB(A) scale in order to give a closer correspondence to that experienced by the human ear. This procedure attenuates the high noise at the lower frequencies due to heavy goods vehicle exhausts etc.

It can be seen from Fig. 12 that at 1 kHz the difference between the two surfaces in 5 dB(A) thus showing that the frequency range in which the Delugrip surface is most effective is from 500 Hz - 2.0 kHz. As already noted the Hot Rolled Asphalt surface generates frequencies in the range 300 Hz - 2.0 kHz whereas the Delugrip type of surface generates frequencies from 1 - 5 kHz over a normal range of road speeds. Therefore, the noise generation is taken out of the sensitive area around 1kHz, where the tire acts as a good emitter.

CONCLUSIONS

The computer noise simulation model, including tread pattern details, is an aid to tread pattern design and is potentially capable of considerable sophistication as more becomes understood about the mechanisms of noise generation.

Although in automobile tires, wide pitch ratios and high friction compounds can be used, in truck tires the designer is much more restricted because of having to compromise with other properties.

Cross texture in a road surface such as laterally brushed or grooved concrete causes increased tire/road noise. Smooth road surfaces emphasize tread pattern noise effects but this type of surface is now technically outdated. In the design of the polishing resistant Delugrip road surfacing materials, we find an attempt at a balance between a surface coarse enough to give adequate bulk water drainage and fine enough to give low noise.

ACKNOWLEDGMENTS

The author wishes to thank his colleagues and particularly D. J. Major and F. G. Court for their help in this work and to Dunlop Limited for permission to publish it.

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DISCUSSION

MR. SMITHSON: I really don't have a question as much as a statement. First, I think that Mr. Walker and his comrades at Dunlop should be congratulated on one of the most sound approaches to this area. I have met many of their people and talked with them. I would like to expand on that a moment. Much of my career has been dealing with the problem of traction, and it was outlined here in discussion that the development of tread design should improve traction. The problem we have in the tire area is that we are trying to improve traction, but on what roads? We are going to wear out the tires on our vehicles. When they wear out, the traction is gone, so we are only improving traction on the average over the life of a tire, and the end result - no matter where you start - is the same, and that's very poor. It has been well documented that the worn tire is the area in which we are having the accident problem. In a way, I think we may not be helping ourselves by creating such a large difference between new tires and worn tires by making improvements in new tires. When we look at it, we realize that it is a fairly simple problem, in that we need texture. We need texture to dissipate water, and we can obtain it in the tread design, or we can obtain it in the road surface. In very simple terms, we can end up with very rough road surfaces that can create noise problems. Dunlop has looked at putting the tire and the road together to maximize traction, and minimize noise. They have proven that technology exists to do that. I suggest that there is a problem beyond what this addresses. We have not discussed, today, the effect of texture on rolling resistance of tires. I would like to point out that there is an effect and it is a negative effect. The more we increase texture, the more we increase the rolling resistance of tires. Therefore, we have another national goal, one that is very dear to the automobile companies - and I can assure you the rubber companies - to reduce rolling resistance of tires, and again we are working at cross purposes. I believe, therefore, that work being done here also enters into that. Another issue which is a consumer problem that concerns me, is that increasing textures will increase wear rates. That strikes the tire companies with rather mixed emotions, but indeed it is going to result in some irate customers, and I believe you will find that the work done by Mr. Walker in the Delugrip type surface will probably mitigate some of the effect of the real gross textured surfaces. I think it all boils down to a system problem. It is a problem that is going to have to be dealt with by people who are experts in tires and vehicles, and in the road, and I think the technology exists to make great benefits. There will be a great amount of practical problems that highway people will have to solve concerning road carrying capability and weathering effects in various climates, and how much it will cost to obtain high friction aggregates and have them moved into parts of the country where they are not available. Those are the kind of logistics problems, however, that can be solved if you look at them in terms of a system.

MR. CLOSE: I would like to ask a question that might be of a shorter term than Mr. Smithson's. With this highly controlled and defined surface, I wonder if Delugrip might not be a suitable candidate for a tire noise test surface that would have slightly more track than the composite materials we heard about from Mr. Long earlier. Could you address the question of availability of segments of this material for tire companies to do their testing?

MR. WALKER: I think it would be a good test surface. It is a good ball-park surface. You have grip, and it does maintain it throughout a very long life.

MR. CLOSE: I gather it can be laid with high consistency from one side to the other?

MR. WALKER: Yes, quite well.

MR. FULLER: Mr. Walker, I believe on one of your charts you showed two tire types. You compared cost by load levels or varying surfaces, and I believe you ranked those surfaces in order of increasing maximum texture, is that correct?

MR. WALKER: I just placed them in the order that the noise levels became greater, and, yes, it is more or less in that order.

MR. FULLER: So it is in terms of just increasing those levels, and not in terms of increasing roughness?

MR. WALKER: It is true what you said, yes, both.

MR. FULLER: How exactly did you measure, or what measure did you use to compare the roughness? What is the friction coefficient?

MR. WALKER: I didn't actually measure it.

MR. FULLER: It is just visual?

MR. WALKER: Yes.

CONTRIBUTED COMMENT

F. D. Smithson

Studies have been made to relate rolling resistance of passenger car tires and road surface texture, as indicated by my comments at the Symposium. The results of these studies are summarized in the following Table:

Road Surface Texture Definition	Relative Tire Rolling Resistance
Medium concrete	100
Smooth asphalt	110
Medium asphalt	112
Coarse asphalt	130
Very coarse asphalt	157
Crushed rock over asphalt	170
Hard-packed dirt	176
Gravel	209

All tests were conducted on public highways in one locale. The first column above is the subjective texture definitions of the road surfaces used. The second column is the rolling resistance normalized to the "medium concrete" surface and expressed in percent.

These data show that significant differences in rolling resistance occur with differing road surface texture.

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Predicting Tire Noise and Performance Interactions

L. T. Dorsch
Firestone Tire and Rubber Co.

THE PURPOSE OF THIS PAPER is to describe the conflicting relationship between various tire performance characteristics associated with changes in tread design. Using mathematical equations developed from testing tires handcut with specific combinations of cross slot angle, percent tread void, and number of cross slots, one can show the effect that selecting tread designs for reduced tire noise has on other performance characteristics. While the factors studied do not cover all possible tread design changes which could affect noise levels, the three chosen are certainly significant factors. Remaining tire design variables not included in the study were set comparable to present original equipment radial tires.

TIRE DESIGN

The test chosen was a three factor, patched orthogonal, central composite design. The tires, designed for Table 1, cover the following range of variables:

Cross slot angle	30° - 90° (0° implies circumferential)
Percent void*	26% - 36%
Number of cross slots	32 - 96

The center of the design was chosen to approximate present original equipment radial tread patterns. All tires were handcut from steel belted radial plain treads contoured with dimensions of similar size original equipment tires. The following common features were incorporated into all tires (Fig. 1):

Tread arc = 6.84 in
Tread radius = 16 in
Cross slot width = 0.12 in
7-Rib
Circumferential grooves
Straight cross slots
Non-directional tread design
No sipes
Plain shoulder ribs
Equal tread element lengths (no noise treatment)
JR78-15

Shoulder ribs were left plain since most radial tire cross slots in this area are relatively shallow based on wear resistance and durability considerations. Variations of percent tread void were achieved through changes in groove width. The reasoning used in this decision was twofold:

First, passenger tire tread designs can be generally described by specifying six of the following seven features:

1. Cross slot angle,
2. Percent void,
3. Number of cross slots,
4. Arc width,
5. Number of grooves,
6. Width of cross slots,
7. Width of grooves.

The first three features are those being studied. Arc width and number of grooves do not offer sufficient opportunity for change within the realm of current designs. This leaves varying the width of the cross slots or the width of the grooves to change tread void.

Second, there is approximately 540 in of total groove length in the average tire versus

ABSTRACT

A computer program has been developed which predicts tire performance characteristics related to tread design. Handcut tires were tested with specific combinations of cross slot angle, percent void, and number of cross slots. Mathematical equations generated from the test results are used to show that some performance sacrifices may be required to achieve tire noise reductions.

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[*] Surface area of grooves and cross slots divided by total tread area around circumference of tire.

Table 1-Design Table Showing Angle, Void, and Number Of Slots For Each Handcut Tire.*

Tire Number	Slot Angle		Percent Void		Number of Slots	
	Actual deg.°	Expt.	Actual %	Expt.	Actual	Expt.
1	35.3	-1	26.9	-1	37	-1
2	84.7	1	26.9	-1	37	-1
3	35.3	-1	35.1	1	37	-1
4	84.7	1	35.1	1	37	-1
5	35.3	-1	26.9	-1	90	1
6	84.7	1	26.9	-1	90	1
7	35.3	-1	35.1	1	90	1
8	84.7	1	35.1	1	90	1
9	30.0	-1,215	31.0	0	64	0
10	90.0	1,215	31.0	0	64	0
11	60.0	0	26.0	-1,215	64	0
12	60.0	0	35.0	1,215	64	0
13	60.0	0	31.0	0	32	-1,215
14	60.0	0	31.0	0	96	1,215
15	60.0	0	31.0	0	64	0

NOTE: The table is originally established in experimental units for ease in checking for independence of the design factors (orthogonality of the design). These experimental units are then applied to the specific experiment by appropriately scaling the actual factors of interest in a corresponding fashion. Test results for the 15 tires handcut to this Table are used to determine mathematical equations describing the performance through regression analysis as shown in the Appendix.

250 in of total cross slot length. Therefore, a smaller range of width variation is required by changing grooves. Consequently, with a wide range of tread voids required, groove widths are the best way to make the change and still keep the designs close to present tires.

PERFORMANCE TERMINOLOGY AND TEST PROCEDURES

The following descriptions apply to all performance levels/ratings that are shown throughout this paper.

SOUND-Indoor dB levels were measured 14 in in front of the center of the footprint-the area where noise levels were highest. (Note: Outdoor testing of several of the test tires produced the same ranking and approximate sound level differences between these basic, non-noise treated designs.)

TRACTION-Testing and data analysis were handled in general compliance with SAE J 345a. The first tire of the designed experiment was arbitrarily established as the control and tires were rated against it using the general industry practice of comparing traction coefficients of the test tires and the control tire on a percentage basis. The traction numbers shown are projected ratings and should be used only to compare one design relative to another design. These ratings apply to the particular surface conditions used in this experiment.

HYDROPLANING-Drop in revolutions per mile of the test tire free rolling through 0.25 in of water divided by the revolutions per mile of the same tire free rolling at the same speed on dry pavement (Outdoor test).

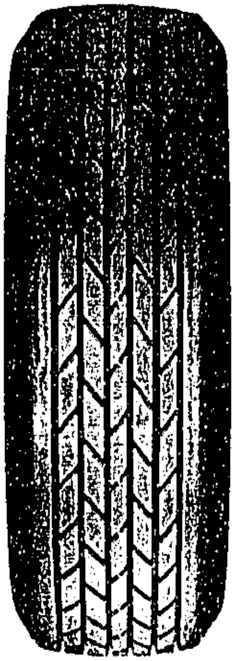


Fig. 1 - Sample tire with handcut tread design

ROLLING RESISTANCE, CORNERING COEFFICIENTS, AND ALIGNING TORQUE- Discussion deleted since tread design changes were found to have only minimal effects on these parameters.

COMPUTER OPTIMIZATION INPUTS

The most efficient way to examine all combinations of cross slot angle, percent void, and number of cross slots within the range of the experiment is to use the computer to determine and display optimum combinations. The optimization program used for this experiment (Fig. 2) selects combinations based on the following information:

1. Maximum and minimum value for the three design parameters, that is, search combinations from 26 - 36% void.
2. Size of increment to be used for each design parameter during search, that is, search between 26 - 36% void in steps of 1%.
3. A goal (maximize, minimize) for selecting each predicted performance level. These goals are used for determining the optimum design within the range of design variables.
4. Critical performance levels which any combination selected must meet, for example, any combination selected must have a 50 mph sound level of 100 dB(A) or less at the 14 in distance. Performance levels not of prime consideration are set such that all solutions are acceptable.

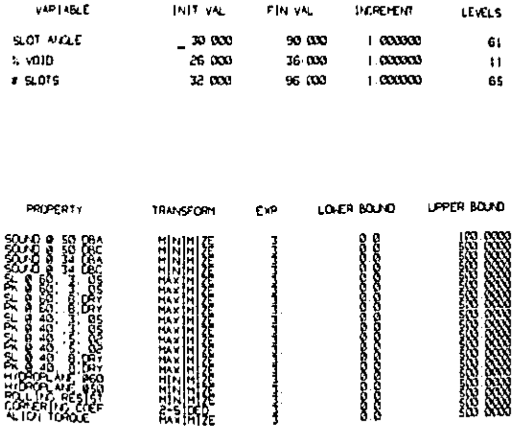
PERFORMANCE TRADE-OFFS

Table 2, showing the results of several computer optimization runs, illustrates the performance changes required to reduce 50 mph sound levels. For each line of data, the computer has calculated the optimum tire design with a 50 mph sound level equal to or less than the value shown in the box.

When reducing noise levels, the biggest sacrifices occur in 60 mph slide traction (deep water, slippery surface) and hydroplaning. The wet traction rating diminished from 255% better than the control to 160% better than the control and a 15% increase in the tendency to hydroplane resulted while achieving a 3dB sound reduction. In addition, changes made to achieve 50 mph noise reductions increase 34 mph noise levels.

Conversely, 60 mph peak wet traction improves as a result of design changes made to reduce 50 mph noise. Some improvement is also achieved in 40 mph slide traction.

Another approach to noise reduction is to maintain upper limits on 34 mph noise levels and then progressively reduce 50 mph noise. Table 3 shows that this approach is limited since only small reduction in 50 mph noise can be achieved without relaxing 34 mph noise requirements.



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    VARIABLE             INIT VAL     FIN VAL     INCREMENT      LEVELS

SLOT ANGLE              _30 000       90 000     1 000000          61
% VOID                   26 000       36.000     1.000000          11
# SLOTS                  32 000       96 000     1.000000          65
```

```
    PROPERTY           TRANSFORM    EXP     LOWER BOUND     UPPER BOUND

SOUND @ 50 DBA         MINIMIZE      3         0.0          100.0000
SOUND @ 50 DBC         MINIMIZE      3         0.0          500.0000
SOUND @ 34 DBA         MINIMIZE      3         0.0          500.0000
SOUND @ 34 DBC         MINIMIZE      3         0.0          500.0000
PK @ 60. .3 .05        MAXIMIZE      3         0.0          500.0000
SL @ 60. .3 .05        MAXIMIZE      3         0.0          500.0000
PK @ 60. .8 DRY        MAXIMIZE      3         0.0          500.0000
SL @ 60. .8 DRY        MAXIMIZE      3         0.0          500.0000
PK @ 40. .3 .05        MAXIMIZE      3         0.0          500.0000
SL @ 40. .3 .05        MAXIMIZE      3         0.0          500.0000
PK @ 40. .5 .05        MAXIMIZE      3         0.0          500.0000
SL @ 40. .5 .05        MAXIMIZE      3         0.0          500.0000
PK @ 40  .8 DRY        MAXIMIZE      3         0.0          500.0000
SL @ 40  .8 DRY        MAXIMIZE      3         0.0          500.0000
HYDROPLANE @60         MINIMIZE      3         0.0          500.0000
HYDROPLANE @50         MINIMIZE      3         0.0          500.0000
ROLLING RESIST         MINIMIZE      3         0.0          500.0000
CORNERING COEF         2-SIDED       3         0.0          500.0000
ALIGN TORQUE           MAXIMIZE      3         0.0
```

Fig. 2 - Computer input data for selecting optimum designs

Table 2-Performance Levels For Optimum Design Combinations Within 50 mph Noise Constraint (Boxed Value)

Design Combinations	Sound Levels dBA @ 50 mph	dBC @ 50 mph	dBA @ 34 mph	dBC @ 34 mph	Traction Ratings* Slide 60 mph	Peak 60 mph	Slide 40 mph	Peak 40 mph	Hydroplaning 60 mph	50 mph
	$\boxed{101.0}$									
86.8°, 35.1%, 32 Slots	100.917	103.016	87.815	90.109	255.696	130.583	114.396	111.846	45.183	4.709
	$\boxed{100.5}$									
84.3°, 34.2%, 32 Slots	100.451	102.390	88.596	90.823	248.471	137.885	116.345	112.715	48.910	9.220
	$\boxed{100.0}$									
84.3°, 33.4%, 32 Slots	99.972	101.763	88.872	91.042	238.743	140.949	117.066	112.864	53.644	13.334
	$\boxed{99.5}$									
80.3°, 32.6%, 32 Slots	99.411	101.030	88.248	90.359	222.457	136.503	115.579	111.830	61.092	17.520
	$\boxed{99.0}$									
71.9°, 33.0%, 93 Slots	98.919	100.531	98.430	100.126	171.130	148.822	119.568	108.474	59.377	22.388
	$\boxed{98.5}$									
60.5°, 33.4%, 95 Slots	98.494	100.072	98.417	100.199	166.610	149.370	118.886	109.231	59.803	22.585
	$\boxed{98.0}$									
60.5°, 33.0%, 96 Slots	97.998	99.642	98.343	100.187	159.978	149.287	118.154	108.920	60.899	23.810

* 0.3 Coefficient Concrete Pad
.05 in. Water Depth

Table 3-Performance Levels For Optimum Design Combinations Within 34 and 50 mph Noise Constraints (Boxed Values)

Design Combinations	Sound Levels				Traction Ratings*				Hydroplaning	
	dB_A @ 50 mph	dB_C @ 50 mph	dB_A @ 34 mph	dB_C @ 34 mph	Slide 60 mph	Peak 60 mph	Slide 40 mph	Peak 40 mph	60 mph	50 mph
	$\boxed{100.5}$		88.0							
90,0°, 34. 6%, 32 Slots	100,412	102,427	87,229	89.536	247,722	128,747	113,795	111,361	50,831	7,443
	$\boxed{100.0}$		88.0							
90,0°, 33. 8%, 32 Slots	99,897	101,750	87.546	89,791	237,693	132,487	114,706	111,659	56,075	11,966
	$\boxed{99,75}$		88,0							
90,0°, 33. 4%, 32 Slots	99,690	101,465	87.721	89,927	232,425	133,830	115,001	111,720	58,386	14,002
	$\boxed{99.5}$		88.0							
	← NO SOLUTION →									
	$\boxed{99.5}$		88.25							
90,0°, 32. 6%, 32 Slots	99,377	101.000	88.102	90.215	221,381	135,460	116,271	111,667	62,389	17,622
	$\boxed{99.0}$		88.25							
	← NO SOLUTION →									
	$\boxed{99.0}$		90.0							
30,0°, 29. 7%, 96 Slots	94,222	95,760	89.996	91,546	61,733	111,805	90,609	99,601	79,326	46,518
	$\boxed{94.3}$		90.0							
32,5%, 29. 7%, 96 Slots	94,222	95,760	89,996	91,546	61.733	111,805	90,609	99,601	79,320	46,518

* ,03 Coefficient Concrete Pad
,05 In Water Depth

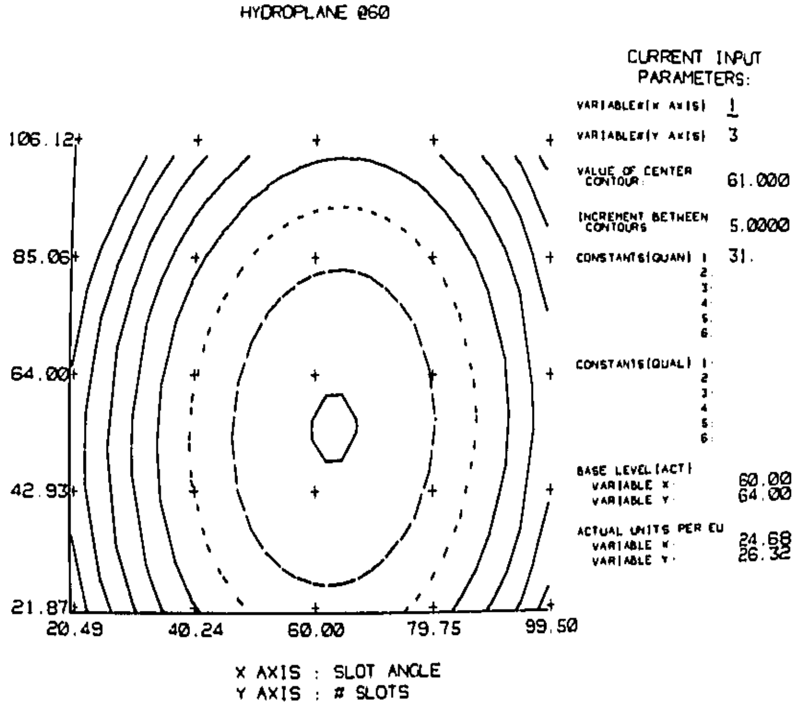

Fig. 3 - 60 mph hydroplaning contours of slot angle versus number of slots for 31% void designs

Attempts to place restrictions on both high and low speed noise levels can have disastrous effects on tire traction. Restriction of 99 dB(A) at 50 mph and 90 dB(A) at 34 mph, arbitrarily placed without considering tire performance, would require severe reductions in 60 mph slide traction.

Another technique available for examining the relationship between tire performance characteristics is to plot two of the design variables against tire performance - holding the third design variable at some constant value.

Fig. 3 is a plot of slot angle versus number of cross slots versus percent hydroplaning at 60 mph for tires with 31% void. The short dash line represents all design combinations with 61% hydroplaning. The long dash line is the next increment lower or combinations with 56% (61 - 5%) hydroplaning. The center of the hydroplaning contours represent the best possible combination of cross slot angle and number of cross slots (minimum amount of hydroplaning) for a 31% void tire.

Similar analysis of the 60 mph slide traction graph, Fig. 4, and the 60 mph peak traction graph, Fig. 5, shows the center of the contours to represent the maximum traction rating in both cases. Analysis of the 50 mph noise data, Fig. 6, indicates the center of the countours to be the highest possible noise level for a tire with 31% void. By overlaying the four plots, Fig. 7, one can see that the best possible design combinations for slide traction, peak traction, and hydroplaning nearly corresponds with the worst possible combination for noise. It must be kept in mind that these graphs apply only to tires with 31% void. Changing the percent void can and will change the relationships.

While the designs used for the experiment are skeletal in nature (circular grooves, straight cross slots, and no sipes), it is still possible to predict performance levels for many of the current radial tire designs. As a specific example of the interacting tire performance considerations, the G. M. part number radial, designed by several tire companies in cooperation with G. M., is an excellent example. Table 4 shows several optimum designs within present G. M. restrictions (20 - 50° slot angle, 30 - 34% void, and 48 - 64 cross slots) listed in the order of decreasing 50 mph noise levels. As was obvious in previous design tables, there is a point where small decreases in noise level require large sacrifices

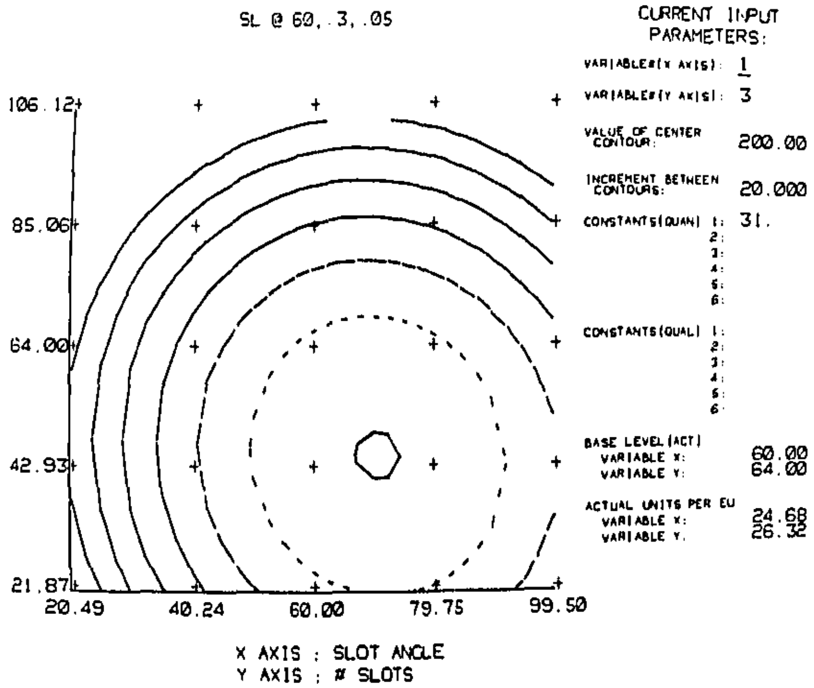

Fig. 4 - 60 mph slide traction contours of slot angle versus number of slots for 31% void designs

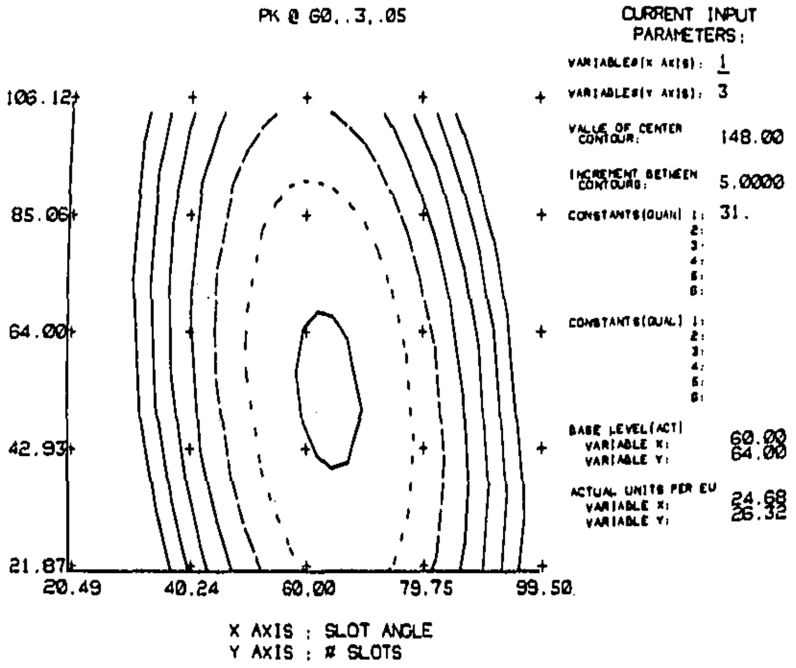

Fig. 5 - 60 mph peak traction contours of slot angle versus number of slots for 31% void designs

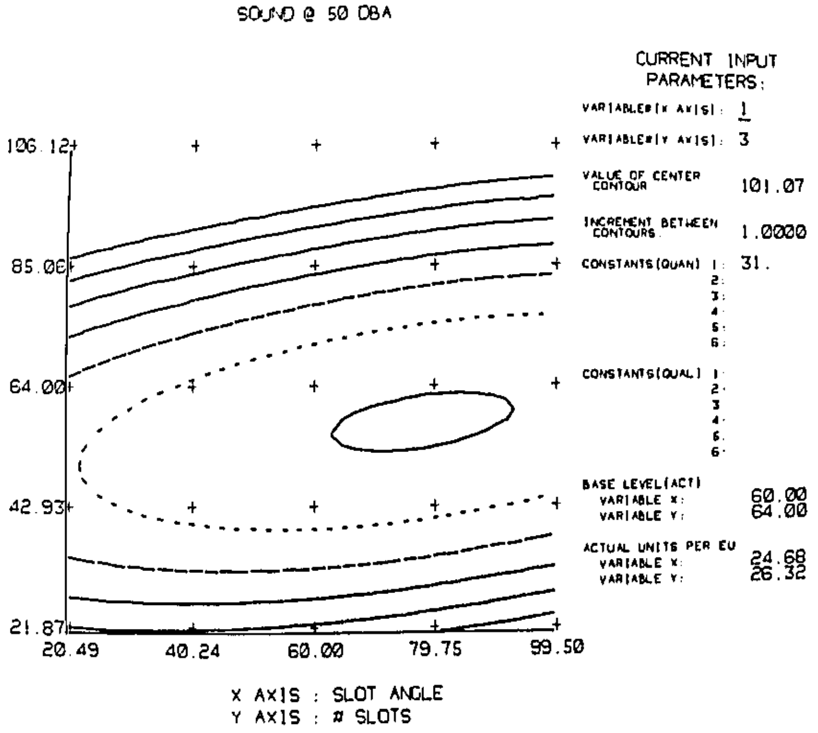

Fig. 6 - 50 mph noise contours of slot angle versus number of slots for 31% void designs

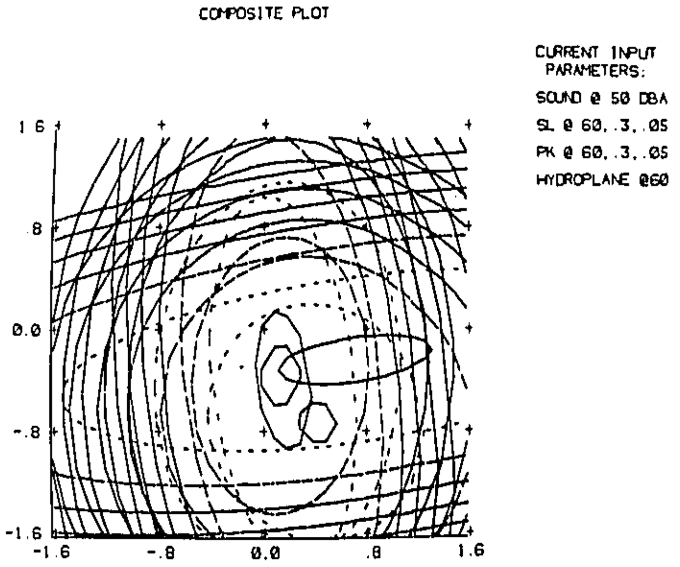

Fig. 7 -- Overlay of Figs. 3, 4, 5 and 6

Table 4–Performance Levels For Optimum Combinations Within 50 mph Noise Constraints and G. M. Design Restrictions

Design Combinations**	Sound Levels dBA @ 50 mph	 dBC @ 50 mph	 dBA @ 34 mph	 dBC @ 34 mph	Traction Ratings* Slide 60 mph	 Peak 60 mph	 Slide 40 mph	 Peak 40 mph	Hydroplaning 60 mph	 50 mph
60°, 31%, 64 Slots (G. M. Tire)	101, 864	103, 188	95, 906	96. 832	205. 595	153, 160	120, 780	107. 604	51, 407	26, 906
	103, 0									
50, 0°, 33, 3%, 51 Slots	102, 994	104, 173	95, 742	96, 613	220, 203	147, 712	119, 443	110, 132	49, 477	18, 384
	102, 5									
50, 0°, 32, 5%, 51 Slots	102, 445	103, 608	95, 580	96. 488	213, 721	148, 811	119, 414	109, 640	51, 921	20, 827
	102, 0									
50, 0°, 31. 7%, 48 Slots	101, 912	103, 077	95, 368	96, 351	206, 860	148, 122	118, 856	109, 277	53, 629	21, 586
	101, 5									
50, 0°, 30, 0%, 48 Slots	101, 405	102, 647	95, 290	96, 234	190, 465	143, 436	116, 776	107, 170	54, 594	23, 542
	101, 0									
37, 3°, 30, 0%, 64 Slots	100, 912	101, 944	94, 684	95, 292	152, 990	128, 772	108, 754	102, 477	63, 158	30, 776
	100, 5									
27, 4°, 30, 0%, 64 Slots	100, 430	101, 222	93, 370	94, 274	120, 156	110, 207	101, 252	99, 310	74, 298	32, 027

* .3 Coefficient Concrete Pad
.05 In, Water Depth

** Within G. M. restrictions - 20-50°, 30-34%, 48-64 slots.

in deep water, slippery pavement traction. Within the G.M. design restrictions this (transition) break-off occurs between 102 dB(A) and 101.5 dB(A). To achieve 0.5 dB(A) reduction requires approximately a 16% loss in wet tractive capabilities.

This drop-off point aligns with the current G.M. tire design. Fifty mph tire noise has been reduced as far as possible while still maintaining a good degree of wet traction. Thirty-four mph noise appears to have suffered some in the skeleton design; however, the overall noise levels at 34 mph are much lower. Also, siping and slight groove modifications can be used to fine tune tread designs in the noise and traction area.

However, the G.M. tread design, as with all other tread designs, can be seen to be a compromise. The goal is to achieve the lowest noise levels possible while still maintaining maximum performance in the areas shown on Table 4 as well as other traction tests, durability, tire related vehicle handling, and tread wear.

It should be pointed out that this computer program was not available during the design phases of the G.M. tire. This tread design is used as an example because it is common to all original equipment tire suppliers.

ADDITIONAL PERFORMANCE CONSIDERATIONS

In addition to the traction, hydroplaning, and noise levels discussed, the other tire performance levels studied were 40 mph dry traction, 40 mph shallow water traction, 60 mph dry traction, rolling resistance, cornering forces, and aligning torques.

Discussion of these parameters has been deleted since it was found that tread design variations of the type studied have only minimal effects on the above performance parameters.

SUMMARY

Within the range of this designed experiment, it is mathematically possible to predict tire performance levels that are related to cross slot angle, percent void, and number of cross slots. It has been shown that changes which affect noise levels also have significant effect on traction and hydroplaning. Complicating the picture is the fact that improvements in one area do not always correspond with improvements in other areas. It is not advisable to arbitrarily restrict one or two areas of performance without considering other areas of performance.

Although not included in this study one cannot deny the importance of tonality, tread wear, and tread durability, etc. These performance factors must also be considered in any tread design project.

REFERENCES

1. O. L. Davies, Editor, "Design and Analysis of Industrial Experiments." New York: Hafner Publishing Co., 1956.

APPENDIX

GOVERNING EQUATION-By using test data from the 15 tires designed per Table 1, coefficients can be determined for an equation of the form shown below. Separate equations are required for each performance test.

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_3 + a_{11}X_1^2 + a_{22}X_2^2 + a_{33}X_3^2 + a_{12}X_1X_2 + a_{13}X_1X_3 + a_{23}X_2X_3$$

Where:

X_1 = Cross slot angle
X_2 = Percent void
X_3 = Number of cross slots
Y = Performance level from test
$a_1 = \Sigma\ X_{1i}\ Y_i/10.952$
$a_2 = \Sigma\ X_{2i}\ Y_i/10.952$
$a_3 = \Sigma\ X_{3i}\ Y_i/10.952$
$a_{11} = \Sigma\ X_{4i}\ Y_i/\ 4.36$
$a_{22} = \Sigma\ X_{5i}\ Y_i/\ 4.36$
$a_{33} = \Sigma\ X_{6i}\ Y_i/\ 4.36$
$a_{12} = \Sigma\ X_{7i}\ Y_i/\ 8$
$a_{13} = \Sigma\ X_{8i}\ Y_i/\ 8$
$a_{23} = \Sigma\ X_{9i}\ Y_i/\ 8$
$a_0 = \bar{Y} - .73\ (a_{11} + a_{22} + a_{33})$
$Y = \Sigma\ X_{0i}\ Y_i/15$
i = Trial 1 through 15

Further discussion regarding designed experiments and data analysis is contained in Ref. 1.

DISCUSSION

MR. THRASHER: I am amazed that the noise increases 10 dB(A) by obtaining a level, a drop of 3 dB(A) at 50 mph. Have you any physical explanation as to why that happened?

MR. DORSCH: No, it would only be conjecture on my part. I don't know.

MR. THRASHER: Allow me to ask the question in a slightly different manner. In your formulation of the equation for sound level pressure, is your equation a form of regression analysis?

MR. DORSCH: The equation is based on the performance level of the 15 tires; it is a regression.

MR. THRASHER: It is not a mechanistic type of equation that you are using then? You are strictly using a regression?

MR. DORSCH: Regression.

MR. THRASHER: Perhaps that's part of the problem.

MR. DORSCH: I don't know if there is a problem. It seems to work. We have tested tires, and we have noticed this inverse relationship on the tires we have tested.

MR. THRASHER: Do you have any experimental data on a tire that you cut that went up 10 dB at 35 or 40 mph?

MR. DORSCH: It did, in fact, do that when we tested the tire.

MR. CLOSE: I think it is extremely interesting to see the overlay of the many targets and to see that the optimum points do seem to fall so close together. I wonder if now that this information is generally available within the tire industry we might actually expect to find a much greater coalescence in trend pattern than the many thousands that are available for sale today. Indeed, we will see a rather standardized trend in the future. Do you think that is what this program tends to indicate?

MR. DORSCH: Well, the designs we are looking at are very basic. We are just looking at three factors of design. Also, you have change in circumferential groove, for simplicity, so there are so many more factors in tread design that we have not even looked at yet; not even begun to analyze. You can only proceed so far with just three factors. You can make tires that don't look anything alike, but that do have the same three factors.

MR. CLOSE: However, the movement away from the target point seems to produce rather substantial or drastic, or perhaps even disastrous effects. It would seem that if this kind of tool is really available through the industry, that they certainly wouldn't choose to move out of the high performance areas, and, indeed, we would expect to see a greater similarity in trend pattern in the future using these tools, as opposed to appearance features, and such things, to design trends.

MR. DORSCH: I suppose it is possible.

MR. CLOSE: One final point. I wonder if in working with your input data from the dynamometer rolls, and the sound levels that were generated, there was any attempt to correlate this near field sound and variation that you obtained in your test tires with very small variations in passby sound levels that had been measured for passenger car tires?

MR. DORSCH: The correlation we made was "in-car." The outdoor correlation was "in-car" rather than "passby." We were trying to predict or associate with customer acceptance of the tire, rather than the community acceptance of the design. Therefore, the correlation we obtained was indoor and within car, both subjective, rather than passby.

MR. CLOSE: The numbers that you represented for noise, however, were exterior measurements?

MR. DORSCH: They were at 14 in.

MR. CLOSE: They presumably would relate in some way to the 2 or 3 dB spread from your blank tires to your fully-treaded rib tires that have been measured in that range?

MR. DORSCH: Yes.

MR. CLOSE: So when you try to force from 101 down to 98, a 4 or 5 decibel difference, are you perhaps forcing it beyond the realm of reason, since the full range of tires that have been measured to date just don't exhibit that kind of 25 or 250 ft passby variation?

MR. DORSCH: The variation from a difference would be compressed. The scale would be compressed considerably, like you are saying. I don't know the answer to that question. When you are 14 in from a tire you can distinguish somewhat better and obtain a better spread on the data than when you are away, because you are probably picking up something that is not being projected from the tire.

MR. CLOSE: This will give the engineers a chance to defend tread patterns in the future.

MR. EAGLEBURGER: On the first point Mr. Dorsch, as far as the solutions to your computer programming, isn't it possible that there would be several different tread face interpretations within the same constraints of the parameters that you identified?

MR. DORSCH: Certainly.

MR. EAGLEBURGER: They would look differently, but contain the same parameters?

MR. DORSCH: There are seven factors that make up a passenger tread design, of which we have examined three. Also, your siping, your groove proportions, we have treaded tires to hold the groove proportions constant with original equipment tires, but still have the same angle, and have one wide rib and one narrow rib, or two narrow ribs and still achieve it. There are many variations within these three factors.

MR. SMITHSON: Mr. Dorsch, it is good to obtain all that hindsight approval for what we did there. I am not sure how we did it. I would like to point out, though, that the point that was made is that if you look at most modern, particularly the five major, and most all tread designs, and get by the siping effects on the surface and look at the basic design, you will begin to see a considerable amount of similarity. I would like to ask Mr. Dorsch a particular question. How did you deal with the ratio of block sizes in sequence? Was that held constant for all of these?

MR. DORSCH: Yes, they were all equal element lengths. We went back in the tires for which we predicted noise level, and we noise-treated them. We ran equal element length versus distinct element lengths, and basically we found that when you noise-treat a tire the meter gives it nearly the same value. The decibel reading for the tire, in essence, the sound power coming out of the tire, is fairly close where it is noise-treated. It is much better and it is more pleasing to the ear, because you have several frequencies, as opposed to one whine or scream.

MR. SMITHSON: Depending on which of these values is most pertinent to the community. You obtain an optimization of this tire dependent very highly on the water depths selected for the wet traction tests, of course. A tire's ability to handle water continues to a point where it can no longer pass water, and we start obtaining groove resistance; therefore, at that point you would need more void area to continue to have improved wet traction. You have a limiting condition based on water depth and speed. If you select a design or a water depth of relatively low depth, twenty thousandths, in my opinion, such as many of the tires you looked at here, you would not reach large limiting conditions, because the tires would handle that kind of water depth through 50 or 60 mph very easily. I would suggest that this would be the reason why you did not see a large difference in the tires that you tested. If you had been in higher water tests, I think the literature would address the fact that you obtain much higher than twenty thousandths. You would probably start to separate the designs as each of them run into a limiting condition in their ability to handle the water.

MR. DORSCH: Right. In a highway passenger tire you have enough void area in that tire, in a new tire that is, to handle nearly a 1/4 in of water, so theoretically, if you can move the water into the groove you can drive through a 3/4 in of water without filling the groove, or at that point your groove would be full.

MR. CLARK: I have heard a great deal at this meeting about tread pattern design, but how general do you think a study like you presented is in terms of the other factors that go into the design of a tire, such as cord textile material, aspect ratio, belt width, and things of that nature? Is it going to have to be done over again, or is this general conclusion really general?

MR. DORSCH: This handles certain aspects of performance. Your fabric, etc., would probably have a more significant effect on cornering coefficients and rolling resistance. The tread design we looked at really correlates more with water, wet traction and hydroplaning-type features. These other features would have to be done again in a separate study. I did not report on rolling resistance, cornering coefficients and aligning torque, because tread design changes of the nature we studied, within the range we studied, do not have a significant variation in rolling resistance, due to these types of changes. There are other changes that account for that type of performance.

PART VI
REGULATORY AND ENFORCEMENT CONSIDERATIONS

762033

Tire Noise Regulations–Technical and Economic Implications

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U. S. Dept. of Transportation

VEHICULAR TRAFFIC NOISE continues to be a major source of community annoyance, especially near high-speed highways. Many consider trucks to be the major offender. Truck noise can be categorized as the noise produced by the power plant (including the engine, exhaust, intake, cooling system, etc.) and by the tire-road interaction. The noise from the power plant increases as the engine speed increases while the noise from tires increases as the vehicle speed increases. Trucks tend to operate at a nominally constant engine speed so that engine and exhaust noise do not vary appreciably with vehicle speed. Therefore, at the lower highway speeds the engine-exhaust noise is dominant while at the higher highway speeds tire pavement interaction becomes the dominant source of noise. The exact speed at which the tire-roadway noise starts to predominate power plant-associated noise is a highly complicated function of tire characteristics, engine-exhaust characteristics, road surface, vehicle condition, etc.

In developing the noise emission regulations for new medium and heavy trucks, EPA considered two alternative approaches to controlling truck noise: regulation of the complete truck, including tires, and secondly regulation of truck and tires separately. Since inclusion of a high speed sound emission test procedure as part of the new truck regulation (to account for tire noise) would not ensure a decrease in overall truck levels at highway speed* and therefore, would not satisfy the need to protect health and welfare by lowering community noise levels, EPA decided to regulate trucks and tires separately.

Two governmental actions signal the imminency of tire noise regulations. The California Legislature has enacted a law (1)** which requires the California Highway Patrol to establish noise standards for tires offered for sale within the State and to prohibit the sale of non-complying tires. Also, EPA has identified tires as a candidate major noise source (2).

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*The breakdown of shipments of new truck tires in 1974 which totaled over 34 million indicated 34.6% were original equipment, 62.2% were for after-market replacement and 3.2% were for export. When one also takes into consideration the number of retreads in use - 13 million sold in 1974 - it is obvious that the number of original equipment tires on the road is small (25%). This coupled with the fact that the majority of tires on the market today could meet the new truck regulation when new, but might exceed the allowable limit after some wear, indicates that regulating total truck noise - new trucks equipped with new original equipment tires - would not be a very effective means of controlling tire noise.

**Numbers in parentheses designate References at end of paper.

ABSTRACT

Operational noise emission standards are presently in effect for interstate motor carriers. Point-of-sale noise standards for medium and heavy duty trucks have been promulgated with an effective date of January 1, 1978. Although "fixes" have been demonstrated for most of the engine-related noise sources on trucks, tire noise remains an unsolved problem at highway speeds. If community noise levels are to be reduced near highways, tire noise must also be reduced. This paper reviews the operational and design variables affecting tire noise and investigates the technical and economic factors associated with current tire use practices and with revisions to these practices which may be necessary to comply with future tire noise regulations.

The remainder of this paper discusses the technical and economic implications of tire noise regulations including:

1. A review of the operational and design variables affecting tire noise,
2. A cost scenario of current tire use practices and revisions to these practices which may be necessary to comply with future tire noise regulations, and
3. An evaluation of the safety, that is, traction, implications of various alternatives to meeting these regulations.

TIRE NOISE

Extensive research on the operational and design variables affecting commercial vehicle tire noise has established a rather complete picture of the parametric variations as illustrated in Figs. 1 through 7. These data have been acquired utilizing procedures similar to those specified in Society of Automotive Engineers Recommended Practice J57a, Sound Level of Highway Truck Tires (3). This standard establishes a test procedure for the measurement of sound generated by a set of test tires mounted on the rear (drive) axle of a single-chassis test vehicle which is operated at 50 mph (80.5 km/h) on a relatively smooth, semipolished, dry Portland concrete surface that is free of extraneous surface material. In order to isolate tire noise, the test vehicle is coasted through the test zone with the engine shut off and the transmission in neutral. One very important fact that must be pointed out is that the data reported here, and the vast majority of the

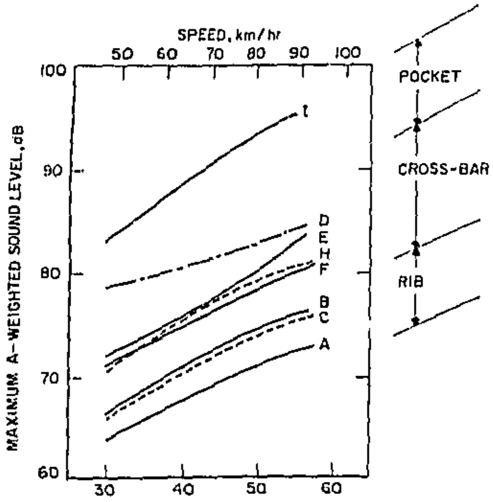

Fig. 1 - Maximum A-weighted sound level, as measured at 50 ft (15.2 m), versus speed for a loaded single-chassis vehicle running on a concrete surface. Various types of new tires were mounted in dual pairs on the drive axle (I, pocket-tread; D, E, F, and H, cross-bar; A, B and C, rib) (5)

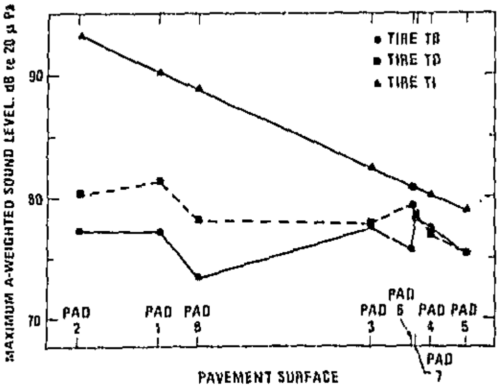

Fig. 2 - Maximum A-weighted sound level, as measured at 50 ft (15.2 m), versus pavement surface with tread design as a variable. The abscissa was adjusted such that the sound level data versus surface for the pocket-tread tire formed a straight line. Vehicle speed (coastby) was 50 mph (80.5 km/h) (TI, pocket-tread; TD, cross-bar; TB, rib) (7)

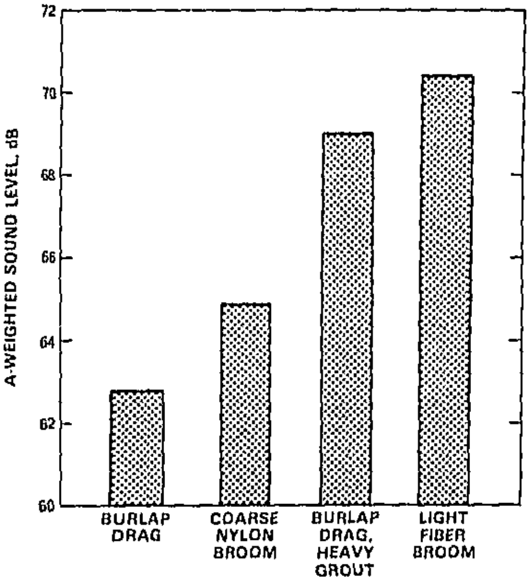

Fig. 3 - Comparison of A-weighted sound level data for four Portland cement concrete pavements with various surface finishes. The automobile speed was 60 mph (96.5 km/h). The microphone distance was 50 ft (15.2 m) (8).

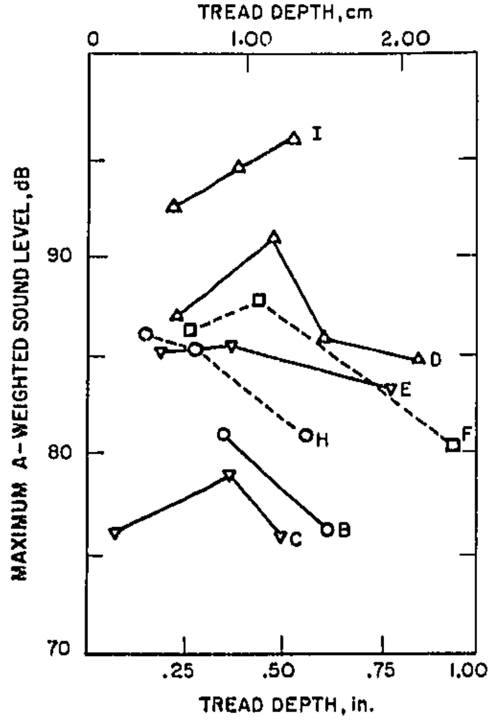

Fig. 4 - Maximum A-weighted sound level, as measured at 50 ft (15.2 m), versus nominal tread depth of the tires on the drive axle. The loaded, single-chassis vehicle was running on a concrete surface at a speed of 55 mph (88.5 km/h) (I, pocket-tread; D, E, F and H, cross-bar; B and C, rib) (5)

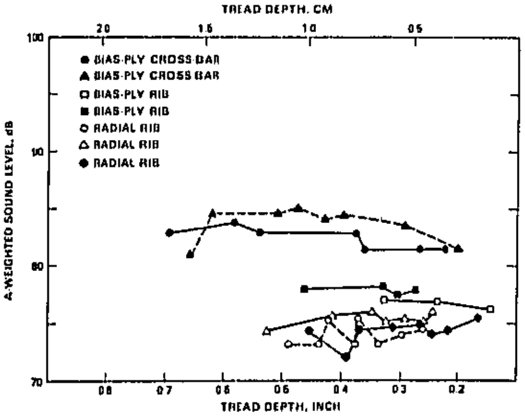

Fig. 5 - Maximum A-weighted sound level, as measured at 50 ft (15.2 m), versus nominal tread depth of the tires on the drive axle. The loaded, single drive-axle tractor was running on an asphalt surface at a speed of 50 mph (80.5 km/h) (9)

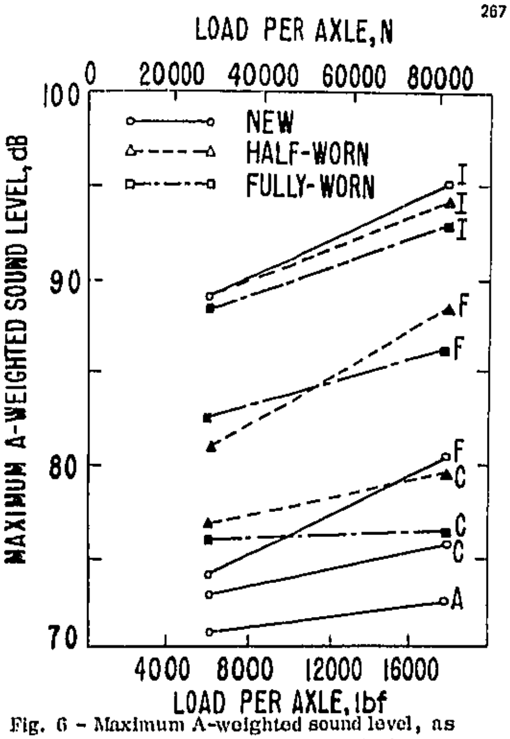

Fig. 6 - Maximum A-weighted sound level, as measured at 50 ft (15.2 m), versus the load on the drive axle. The single chassis vehicle was running at 55 mph (88.5 km/h) on a concrete surface (I, pocket-tread; F, cross-bar; C and A, rib) (5)

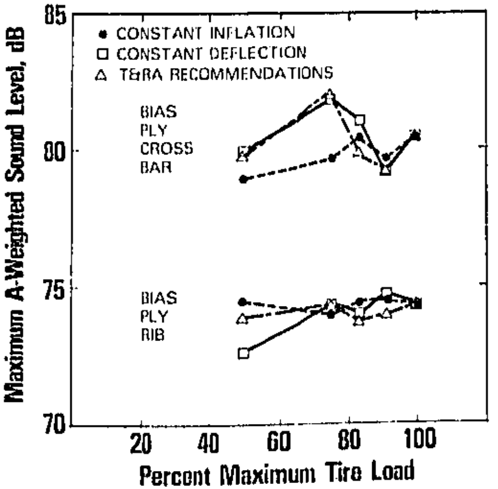

Fig. 7 - Effect of inflation pressure and load on the A-weighted (fast response) sound level measured at 50 ft (15.2 m) under the conditions of (a) constant inflation pressure (75 psi, 5.2x10^5 Pa), (b) constant deflection maintained by altering pressure with load, and (c) T&RA recommended load/inflation pressure (11).

existing data in the open literature, were obtained using "fast" sound level meter response characteristics. SAE J57a, on the other hand, specifies the use of "slow" response. A study by the National Bureau of Standards (4) has shown slow response tire noise levels to be several decibels lower than fast response levels. It is important to keep these facts in mind when utilizing existing data to establish the regulated level for tire noise emission regulations.

EFFECT OF SPEED, TREAD DESIGN, AND ROAD SURFACE - The level and spectra of tire noise are affected by speed, tread design, and road surface; therefore, maximum A-weighted sound level is plotted in Fig. 1 versus speed on a concrete surface with tread design as a variable.

From these data it can be seen that tire noise varies as a function of the third to fourth power of vehicle speed. It is also evident that a wide variation exists depending upon the tire tread type. Levels range from the quiet control tire, "A", with its characteristic circumferential rib pattern to the noisiest pocket-tread tire, "I" (use of which is now prohibited by the Federal Interstate Motor Carrier Regulations (6)). Tread design is not as significant a factor in passenger car noise as it is for trucks.

The effects of road surface macrotexture on selected tires are shown in Fig. 2. No quantifiable road surface descriptor has been postulated which permits reliable prediction of tire noise as a function of pavement surface. The most orderly representation means found to date derives from plotting the maximum A-weighted sound levels against pavement surface, with the location of the various surfaces on the abscissa being selected such that the data for the pocket-tread tire forms a straight line. It is believed that the "suction cup" effect of the pocket-tread tire becomes less effective as the road surface becomes rougher. The sound level of this tire, then, is a fairly sensitive indicator of the road surface parameters which affect tire noise. These data show that significant differences in noise levels are produced by tests run on smooth road surfaces depending on the type of tire used, but when similar tests are performed on progressively rougher road surfaces the differences in sound level attributable to tire type tend to be reduced. It is thought that the road surface material itself is not the important variable, but rather the scale roughness of the surface (surface macrotexture) is the determining factor in the level of noise generated by a given set of tires. For example, Fuller (8) observed a difference of 7.6 dB for circumferentially-grooved passenger car tires running on Portland cement concrete surfaces with four typical surface finishes (see Fig. 3).

EFFECT OF TREAD WEAR - Data on another variable which can greatly affect truck tire noise, namely, tread wear, are presented in Fig. 4. The data shown are for measurements made on a set of tires with identical tread designs when the tires were new, approximately half-worn, and when fully worn. In general, tire noise increases as the tread is worn, reaching maximum levels somewhere near the half-worn point. The noise level with further wear declines or remains nearly constant. The growth in noise levels is seen to be as high as 8 dB from new to half-worn. In contrast to these data, the results of an ongoing tire wear/noise test program (9), as shown in Fig. 5, indicate less variation in noise level with tire wear over the lifetime of the tire. These trends, however, do not hold in the case of passenger car tires. Data (10) show that automobile tire noise may either slightly increase or slightly decrease with tire wear, but the changes are not significant. In general, the noise levels for tires in the half-worn state of tread depth are within 2 dB of the levels measured when the tires are new. Therefore, it appears that tread wear is not as significant a parameter for automobile tires as it is for truck tires.

From a certification standpoint, one is primarily interested in the state of tire wear that results in the maximum noise level for a particular tire type. Since neither proper grinding techniques which simulate normal wear nor analytical techniques for predicting the radiated noise from tires as a function of tread wear exist today, it is necessary to either conduct costly and time-consuming noise measurements with in-service worn tires in order to establish a relationship between tread wear and tire noise or as an alternative to full wear cycle testing, new tire certification could be accomplished by testing new tires against a maximum allowable noise level limit adjusted downward from the "pass level" by the largest difference encountered between new and worn tires tested through the wear cycle. Reported differences in noise levels between the new state and that tread wear point at which maximum noise is produced are (6, 10): bias-ply rib, 0.5 - 5.0 dB; bias-ply cross-bar, 2.5 - 8.0 dB; radial rib, 1.5 - 3.5 dB.

EFFECT OF LOAD - In general, an increase in load results in an increase in the maximum A-weighted sound level for truck tires. Load has been found to significantly affect the noise generated by tires with cross-bar tread patterns while noise from tires with rib tread patterns are relatively unaffected by load changes (see Fig. 6).

Additional load/deflection/noise data indicate that if the tire loading is maintained in the 80 - 100% range and the inflation pressure is either held constant or is adjusted to Tire and Rim Association specifications, the noise level produced will not be significantly affected (see Fig. 7).

EFFECT OF TIRE DIMENSIONS - The effect of tire size is another important parameter to consider since it impacts the certification test procedure.

The question to be addressed is whether the measurement of noise level for every size tire is needed or whether a single tire size can be measured which represents the maximum noise level for a particular carcass construction/tread design combination.

Data from a recent experimental investigation (11) of the noise generation characteristics of a wide range of tire sizes (all tires of a particular type, for example, bias-ply rib, with the same tread pattern) currently available for passenger cars and trucks are presented in Table 1. No significant differences in A-weighted sound levels were observed.

TIRE LIFE CYCLE COSTS

Tire use practices have a great deal of bearing on both the inservice noise level generated by truck tires and the economics of truck tire noise regulation. Due to the variety of truck configurations, geographic routes (that is, flat versus mountainous terrain, rain and snow covered versus clear roads, high abrasion versus low abrasion roadways, etc.), fleet maintenance practices, and fleet recapping policies, there is an inherently wide variety of tire use practices. However, there are certain reliable trends which can be addressed in the assessment of tire noise regulations insofar as the relationship of certification noise levels to highway community noise levels and the economics of tire use

Use patterns and wear rates (see Figs. 8 - 10) can be evolved on the basis of data developed by the Western Highway Institute (12) and by the Department of Transportation in its ongoing study of truck tire wear/noise characteristics. (Details of the cooperative tire wear/noise study are discussed in Appendix A.) These data can serve as a guide for assessing the cost impact of factors which would change tire use. The cost picture is centered on tire placement and rotation, resultant revenue mileage and the original costs of tires and recaps. Initial cost is, of course, only one element of the life cycle costs of truck tires.

Six tire use/cost scenarios (see Appendix B.) -- 4x2 and 6x4 tractor double axle trailer combinations with the tractor drive axle(s) equipped with either bias-ply rib, bias-ply cross-bar, or radial rib tires - have been postulated in order to gain some insight into the costs associated both with current tire practices and with revisions to those use practices which may be necessary to comply with tire noise regulations.

Tire costs are highly variable depending on the particular arrangements made between a fleet operator and a tire supplier. A review of commercial prices published by tire manufacturers has shown that, in general, the bias-ply cross-bar costs approximately 15% more than a bias-ply rib while the radial rib costs approximately 20% more than a bias-ply rib. A top tread "cold" recap for a radial

Table 1. A-weighted sound levels for passenger car and truck tires of various sizes having the same tread design.*

Tire Size	A-Weighted Sound Level, dB			
	Bias-Ply Rib	Radial Rib	Bias-Ply Cross-Bar (Snow)	Radial Snow
A 78 - 13**	71.1	70.6	72.2	70.3
B 78 - 13	71.5	69.6	72.4	69.1
C 78 - 14	70.6	70.2	72.0	70.3
E 78 - 14	72.2	70.6	73.4	72.1
H 78 - 15	71.6	70.2	72.5	71.8
L 78 - 15	71.5	70.5	73.7	70.9
9.00 - 22.5 †	75.1		79.6	
10.00 - 22.5	75.5		80.2	
11.00 - 22.5	75.2		80.1	
11.00 - 24.5	75.9		80.6	

*Tires were tested at rated load and inflation pressure and at a speed of 50 mph (80.5 km/h).

**In the case of passenger cars, when rib tread patterns were tested, test tires were mounted at all four wheel positions. When snow tread patterns were tested two test tires were mounted on the powered axle while the remaining axle was equipped with two blank tires.

† In the case of trucks, four rib tread or cross-bar tread test tires were mounted on the drive axle and two blank tires were mounted on the steering axle.

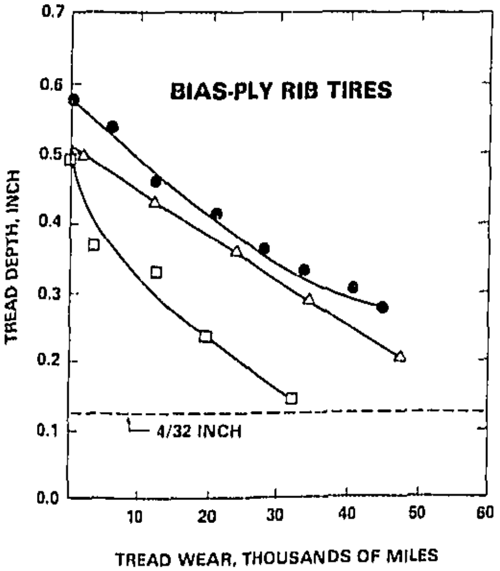

Fig. 8 - The first life tread wear of bias-ply rib tires mounted on the drive axle of a single drive axle tractor (9)

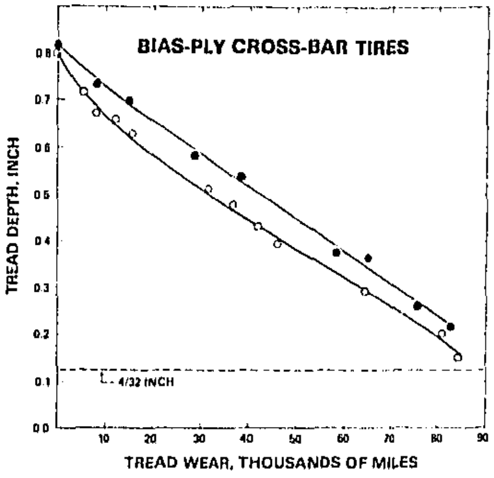

Fig. 9 - The first life tread wear of bias-ply cross-bar tires mounted on the drive axle of a single drive axle tractor (9)

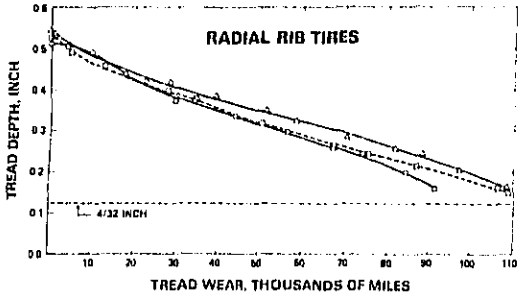

Fig. 10 - The first life tread wear of radial rib tires mounted on the drive axle of a single drive axle tractor (9)

is assumed to cost approximately 8% more than for a bias-ply tire. For these scenarios, the bias-ply rib price is arbitrarily set at $100 with the bias-ply rib cap at $45. These figures should be adjusted by each fleet operator to account for individual purchase prices and tire mileage statistics.

For these calculations, 200,000 revenue miles is utilized as the base with the tread depth at removal of steering and drive axle tires for runout on the trailer dictated by the particular vehicle configuration--that is, for economical operation it is important that the tractor generate the proper number of tires for trailer use. For example, in the case where bias-ply rib tires are utilized on both the steering and drive axles of a single drive axle tractor (scenario number 1) pulling a double axle trailer, if the tires are rotated to the trailer from the steer axle at 9/32 in and from the drive axle at 6/32 in, then the proper number of trailer tires are generated. (Operators of longer combinations, that is, double or triple bottoms, will find that partially worn tires for the trailer positions will not be generated fast enough by the truck tractor. To make up for this, operators will either have to pull tractor tires at earlier stages of wear or will have to purchase new tires for use on the trailer axles - a practice which has not been typical with standard length combinations.) It is further assumed that 60% of the tires coming from the steeing and drive axles can be recapped following runout on the trailer. Although possible, and in many cases probable, no additional recaps are considered. Thus, for this particular case, in order to most economically accomplish 200,000 revenue miles the fleet operator would need 6.25 new bias-ply rib tires for the steering axle at $100 per tire, 16.16 new bias-ply rib tires for the drive axle at $100 per tire and 13.45 bias-ply rib recaps at $45 per tire for a total cost of $2846. Over the 200,000 miles of operation the tire costs would be $.0142 per mile.

Under the given assumptions of tire placement, rotation and initial cost, the scenarios yield the cost comparisons shown in Table 2. These cost comparisons assume a $100 purchase price for bias-ply rib tires as a base and 15% and 20% increases in cost for bias-ply cross-bar and radial rib tires respectively. The base price for the bias-ply rib cap is $45 with an approximate 8% increment for radial caps.

In all cases the scenarios suggest that the radial tire is less costly to operate than the bias-ply tire. The shortcoming of any generalized scenario of this type is, of course, that any given tire type (carcass construction/tread design) is not applicable to every situation and ultimately the average cost per tire mile for any particular fleet and type of operation is governed by the original tire selection and by the tire use and maintenance program. Great perturbations can be expected depending on the controls fleets place on the many factors affecting tire costs such as speed, inflation pressure, loading, etc. For example: 10% under inflation results in 10% loss in expected tire mileage, a 10% overload results in 20% loss in expected tire mileage, and a 15% reduction in tread life results if the average operating speeds increase from 55 to 65 mph (88.5 - 104.6 km/h) (13).

This scenario did not consider the costs associated with tire and wheel maintenance and inventory, running gear maintenance, the effect of roadway or terrain, the added front end alignment maintenance possibly necessary for radials as a result of severe uneven wear observed on some radial rib tires mounted on steer axles, etc. On the other hand, the scenarios were conservative in limiting the bias-ply rib tires to a single recap when

Table 2 - Cost Comparisons

		Vehicle Configuration	
Axle	Tires	4 x 2 DAT	6 x 4 DAT
Steer Drive	bias-ply rib bias-ply rib	$.0142/mile	$.0153/mile
Steer Drive	bias-ply rib bias-ply cross-bar	$.0119/mile	$.0126/mile
Steer Drive	radial rib radial rib	$.0110/mile	$.0125/mile

the likelihood that at least 25% of these tires could be recapped a second time. Radial tires also were limited to a single recap. Radial tires run cooler and are less susceptible to road hazards, therefore, it seems reasonable to assume that the average carcass life for a radial tire should be greater than for a bias-ply tire. Also not factored in are the very significant fuel economy benefits associated with radial tire use due to the 25-30% lower rolling resistance. For actual in-service operations, the power loss would be approximately 12 - 15% less for radial tires than for bias-ply tires once the aerodynamic and driveline losses have been accounted for.

TIRE TRACTION

Much research remains to be accomplished in order to answer the many questions about tire traction. It is not the purpose of this paper to attempt to answer all the questions of tire/road force development, but rather to attempt to briefly summarize the pertinent data that are available in relation to possible noise abatement strategies. Most importantly, the statement that "tires with good traction make more noise" will be critically examined.

A small body of relative traction data (14) was made public by the tire industry. These deceleration data indicated that there can be wide variations in tractive forces produced by different tires, but that one particular tread type is not necessarily advantageous. While these data are limited to a relatively few tires, it is evident that differences among brands are larger than differences among generic tread types.

Data on the traction performance qualities of a sample of twelve truck tires - six bias-ply tires and six radial tires - with characteristic rib and lug tread designs have recently been developed by the Highway Safety Research Institute of the University of Michigan under the sponsorship of the Motor Vehicle Manufacturers Association and the Department of Transportation's Office of Noise Abatement (15, 16). Traction measurements were made on each of the test tires using the HSRI Flat-Bed Tester and the HSRI mobile traction dynamometer. The Flat-Bed Tester is a low speed laboratory dynamometer which was used to obtain precision measurements of the "cornering stiffness" parameter. In its current stage of development the HSRI mobile dynamometer consists of a tractor, semi-trailer vehicle which permits investigation of either longitudinal or lateral traction characteristics of heavy truck tires. The system is designed such that a truck tire specimen can be exposed to a set of operating conditions which cover the full range of possible loads, velocities, longitudinal or angular slip, and pavements such as can be encountered under either normal or emergency situations on the highway. While these devices are not totally unique in their capabilities, they represent the only such hardware which can be used to develop traction data of high statistical quality.

The range of cornering stiffness values as a function of normal load for the twelve test tires categorized by carcass construction and/or generic tread design is shown in Fig. 11. In the case of bias-ply tires, the data clearly discriminate between the rib-type and lug-type tread patterns with the rib tires characterized by cornering stiffness values 20% higher than the lug tires tested. Data on radial tires do not allow discrimination between "rib" and "traction" tread designs. At all except the low end of the load range, the radial tires exhibit characteristically higher cornering stiffness values than the bias-ply tires.

Some insight into the meaning of these data can be obtained by analyzing vehicle response to braking in a curved path and the sensitivity of the understeer behavior of a cornering vehicle in the absence of braking.

One must first consider that a vehicle employing tires with lower cornering stiffness characteristics will experience greater excursions in longi-

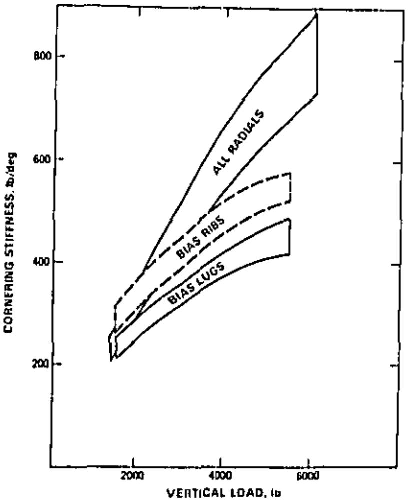

Fig. 11 - Cornering stiffness as influenced by vertical load. All tires were tested at their rated cold inflation pressure - bias-ply (10.00-20, load range F), 85 psi (5.87×10^5 Pa); radial (10.00R-20 load range G), 105 psi (7.25×10^5 Pa)

tudinal slip to effect the same deceleration levels as a comparable vehicle equipped with higher cornering stiffness tires. As longitudinal slip increases, the tire's ability to generate lateral forces decrease; thus, there exists a mechanism by which the longitudinal properties of tires can influence the cornering response of vehicles to braking inputs. Therefore, as a vehicle is negotiating a turn, at a given level of lateral acceleration it will experience a perturbation in centripetal force and/or yaw moment as a consequence of a braking input. The tire with a lower cornering stiffness value will, for a given braking input, suffer a large instantaneous change in side force and thus will serve to more severely disturb the vehicle's curvilinear motion. The common usage of the more traction capable rib tires on the steer axle and least traction capable cross-bar (lug) tires on the drive axles, enhances the potential for yaw moment disturbances deriving from braking applications. Since heavy trucks typically "overbrake" their rear axles in favor of "underbraking" the steering axle, the cited yaw moment influence of rear-mounted lug tires is further aggravated. Thus, with the possibility of wheel lockup and jack-knife accidents enhanced, one must conclude that the increased noise level characterizing cross-bar tires is not offset by beneficial influences on the path curvature response characteristics of vehicles.

In addition, a typical cross-bar tire installation on a drive axle employing a dual set of tires would yield an understeer level - a property which is generally regarded as pertinent to vehicle control - which is lower than that for the corresponding installation of typical rib tires.

With regard to limit braking capability, the pertinent values are the peak value of longitudinal force and the value under the locked wheel condition (that is 100% wheel slip).

The ranges of peak normalized longitudinal force/normal load) data for the tires tested are shown in Figs. 12 and 13 for dry and wet road surfaces respectively. These data show, in general, a reduced peak traction capability among the lug tires in comparison to the radial (rib and lug) and bias-ply rib tires. It is interesting to note that while the peak value of longitudinal force for the average cross-bar is 13% below that of the average rib tire on dry pavement, on wet pavement the difference increases to 23%. Typical slide values show the same behavior with the difference being 6% for dry and 15% for wet pavements. Cross-bar and rib tires of bias-ply construction are, therefore, clearly differentiable in both the elastic and friction-limited regimes of their longitudinal traction behavior. As was the case with cornering stiffness, the radial rib and lug tires are not discernible. The differentials in both regimes render the rib tire more beneficial. Therefore, trucks equipped with rib tires (radial or bias-ply) can start at higher loads and/or stop quicker.

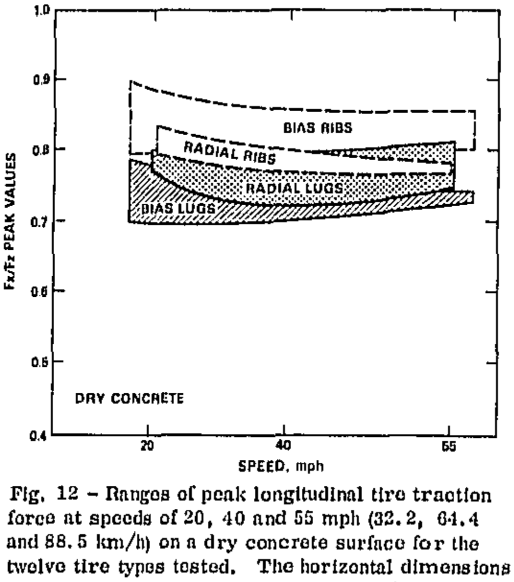

Fig. 12 - Ranges of peak longitudinal tire traction force at speeds of 20, 40 and 55 mph (32.2, 64.4 and 88.5 km/h) on a dry concrete surface for the twelve tire types tested. The horizontal dimensions are purposely distorted in the interest of graphical clarity

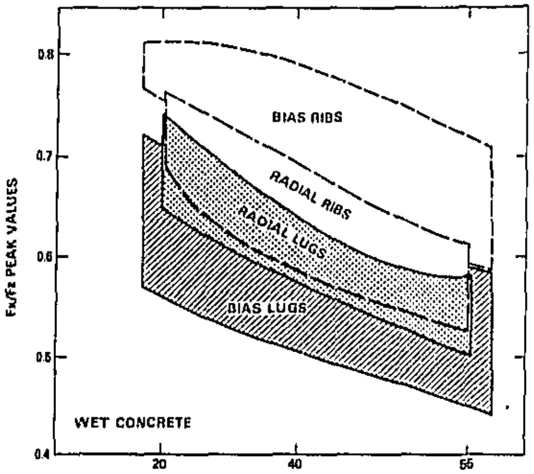

Fig. 13 - Ranges of peak longitudinal tire traction force at speeds of 20, 40 and 55 mph (32.2, 64.4 and 88.5 km/h) on a wet concrete surface for the twelve tire types tested. The horizontal dimensions are purposely distorted in the interest of graphical clarity

These data show that for both wet and dry conditions tires exhibiting improved traction performance are generally those whose tread patterns yield lower noise output. Regarding both lateral and longitudinal traction properties, the common usage of cross-bar tires on rear driving axles (with rib tires on steering axle) results in a typically disadvantageous arrangement, from a vehicle control point of view.

Although these data provide significant insight into tire traction from a safety viewpoint, that is, vehicle controllability in the context of highway steering and braking maneuvers, another dimension of tire traction behavior - namely the tractive effort which can be sustained by tires operating on deformable surfaces such as mud and snow - remains undefined.

TIRE/VEHICLE NOISE AND THE COMMUNITY

Operational noise emission standards are presently in effect for interstate motor carriers (6). The present limit for high speed highway operations (speeds above 35 mph (56.3 km/h)) is 90 dB - a limit which is expected to be revised downward in the near future as the new truck noise emission standard begins to have an effect. The EPA point-of-sale noise emission standard for medium and heavy duty trucks (17), which becomes effective January 1, 1978, specifies an A-weighted sound level limit of 83 dB under low speed, high engine acceleration operation. The limit is to be decreased to 80 dB by January 1, 1982.

In order to develop an understanding of what level of tire noise is necessary to meet the interstate motor carrier noise emission standards, one must translate the SAE J57a (fast response) certification levels into actual in-service truck noise levels. Table 3 illustrates the values and ranges of sound levels that would be generated realizing the myriad of tire combinations that are possible on today's trucks. These predictions were made utilizing an experimentally validated empirical model developed by DOT/NBS (18). The model utilizes the A-weighted time histories from SAE J57a-like coastby measurements (fast response), shifts the time histories in time to represent the distance between the axles of the configuration of interest, and logarithmically sums the time histories. Speed and load corrections are applied and an omnidirectional 86 dB engine noise source is added to the predicted tire noise levels to arrive at the total vehicle noise levels shown in Table 3.

The left hand column - A-weighted certification level - represents the maximum sound level for a 50 mph (80.5 km/h) coastby of a loaded 4 x 2 truck equipped with the noisiest tires (on the drive axle) assumed in the particular scenario. The levels across the Table represent the in-service noise levels for the seven different truck configurations (at the gross vehicle weights indicated) operating at 55 mph (88.5 km/h) or nominally smooth roads. The certification tires are mounted on the drive axle and half-worn rib tires are mounted at all other axles.

Considering the 90 dB limit of the Federal Interstate Motor Carrier Noise Emission Regulation, these data indicate that, in general, certification level tires of 82 dB or less should be applied to the vehicles in order to be in compliance.

Numerous scenarios may be postulated for examining the future of motor vehicle noise. To analyze the benefits deriving from the various possible control strategies, a population setting exposed to high speed highway traffic is investigated (19). Traffic is assumed to be composed of 7% trucks (1% straight trucks, 6% combination vehicles) and 93% automobiles. Traffic flow is assumed to be 7200 vehicles per hour.

Increases in truck population of 12%, 9%, 5% and 10% are assumed between 1975 - 1980, 1980 - 1985, 1985 - 1990, and 1990 - 2000, respectively. It is further assumed that such vehicle population increases translate into identical vehicle mile percentage increases. Finally, it is assumed that automobile traffic grows by the same proportions, and that no significant change occurs in the automobile fleet noise levels over this period of time. (The latter assumption is based upon the fact that at highway speeds automobile noise is dominated by tire noise, with little improvement foreseen in the reduction of passenger car tire noise.)

Table 3 - Effects of tire noise certification levels at 50 feet (15.2 m) on passby sound levels at 50 ft (15.2 m) assuming an engine noise level of 86 dB.

Vehicle Configuration	4 x 2 Straight	6 x 4 Straight	4 x 2 Single Axle Trailer	4 x 2 Double Axle Trailer	4 x 2 Double Bottom	6 x 4 Double Axle Trailer	4 x 2 Triple Bottom
Total Gross Vehicle Weight, Pounds (kg)	27000 (12247)	43000 (19505)	47000 (21319)	62000 (28123)	80000 (36288)	80000 (36288)	105000 (47628)
A-Weighted Certification Noise Level Measured at 50 feet (15.2 m) and 50 mph (80.5 km/h), dB	Predicted In-service Maximum A-weighted Sound Level at 50 feet (15.2 m) and 55 mph (88.5 km/h), dB						
78	87	87	87	87	88	88	88
80	87	88	88	88	88	89	88
82	88	89	89	89	89	90	89
84	89	90	89	90	90	91	89
86	90	92	92	92	92	93	92
90	92	95	93	94	93	96	93
95	97	100	98	98	97	100	97

For the purposes of this paper, the energy mean equivalent traffic noise level is evaluated for:

1. The "do-nothing" case,
2. Engine noise only regulations, (The engine regulation option is based on the EPA promulgated levels and time schedules applicable to new medium and heavy duty trucks.)
3. Tire noise only regulations, (The base case for tires is current use practice (that is, rib tires on steering and trailing axles and cross-bar tires on drive axles). The tire noise regulation option assumes a limit of 82 dB which effectively eliminates tires noisier than current bias-ply rib tires or radial rib tires, but which allows a full latitude for such tires.) and,
4. Engine and tire noise regulations.

Fig. 14 portrays the disbenefits of the "do nothing" scenario resulting from increased traffic and the benefits, if any, of the various noise control strategies. In the highway situation, where tire noise equals or exceeds engine noise in the "do nothing" case, the benefits of engine noise controls or tire noise controls alone are slight - the uncontrolled source holding the resultant level nearly at the totally uncontrolled level. Only when engine noise and tire noise are controlled simultaneously, are significant benefits possible.

CONCLUSIONS

Significant reductions in community noise levels near highways can be achieved by simultaneously controlling vehicle engine noise and tire noise. Although at present no more than a superficial understanding of the mechanisms of tire noise generation exists, truck tire noise reductions can be accomplished utilizing current tire technology without adversely impacting tire manufacturers (if adequate change-over lead time is provided) or fleet operators. The data presented in this paper show that from both a cost and safety point of view, the use of quieter tires provides at least equal, and, in general, advantageous performance when compared to current tire use practices.

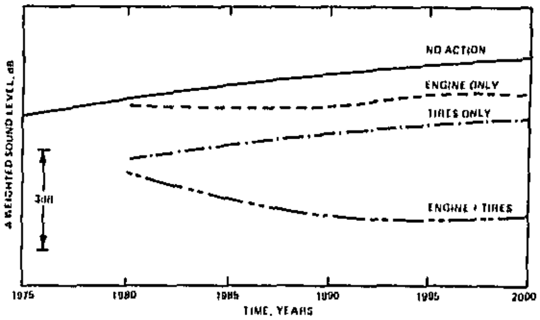

Fig. 14 - Effect of various control strategies - (a) no action, (b) 83 dB and 80 dB engine only regulation, (c) 82 dB tire only regulation, and (d) engine plus tire noise regulations - for a suburban or rural location principally exposed to high speed highway noise

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APPENDIX A
TIRE WEAR/NOISE STUDY

Currently the Department of Transportation and the American Trucking Associations in cooperation with Consolidated Freightways, Firestone, Goodyear, Michelin, and the National Bureau of Standards are conducting a study to generate data from in-fleet service which can be used to compare both the wear rates and noise levels of bias-ply rib, bias-ply cross-bar and radial rib tires.

Since the purpose of this test is the development of data for comparing wear rates among tire types, it is imperative that controls be established to assure that the test vehicles experience similar service.

The Consolidated Freightways trailer shuttle operation was selected for this test not because it was "typical" of nationwide fleet activities but rather because it afforded a degree of control over several variables which could not be achieved in more normal service. Aside from safety and operational constraints, operating procedures were established to obtain the best performance from each tire, not to make this test more "typical" of general fleet practices.

Consolidated Freightways uses twin trailer combination vehicles (double bottoms) for the majority of its operations. That combination consists of a tractor, lead semitrailer, converter dolly, and second semitrailer. While such equipment is permitted to operate in Ohio and on the New York Thruway, they are prohibited in Pennsylvania. The CF shuttle service is used to carry the second semitrailer and converter dolly of a twin trailer either eastbound or westbound across that portion of Interstate 90 in Pennsylvania between Conneaut, Ohio, and Ripley, New York.

The shuttle utilizes 4x2 tractors fitted with pintle hooks to draw its trailer set and have large concrete ballast blocks over the drive axle to provide traction. The average load on the drive axle tires for the seven tractors utilized in this test program is 15650 lb (7099 kg). Since the shuttle tractor pulls what is essentially a full trailer (a trailer which carries all of its own weight plus that of its cargo on its own tires) its weight does not vary regardless of the payload being handled. It must be noted, however, that while drive axle load does not change with payload for this vehicle, the tractive effort required of the drive axle tires does. This is an uncontrolled variable, the effects of which are minimized since the tractors pull a large variety of trailers.

The test has been underway for two years. All tires have been worn from their original new tread depth to 4/32 in 0.32 cm) (which was the arbitrary) pull depth for capping) and presently the first recap life is being monitored. Because of the loss of test control on the tires, no trailer runout was attempted.

APPENDIX B
SIX TIRE USE/COST SCENARIOS

Scenario 1 - bias-ply rib tires at all axle positions on a single drive axle tractor

Vehicle: 4x2 tractor with double axle trailer
Tires: Steer axle - bias-ply rib (17/32 in)
Drive axle - bias-ply rib (17/32 in)

Assumptions: Wear Rates
steer axle - 8000 miles/32nd
drive axle - 4500 miles/32nd
trailer axles - 5680 miles/32nd

Pull Depths
steer axle - 9/32 in
drive axle - 6/32 in
trailer axles - 2/32 in

Recappability - 60% of all carcasses are recapped at least once.

On the basis of these assumptions, and using 200,000 revenue miles as a base, the number of steer axle and drive axle tires and the trailer runout mileages need to be determined and an inventory assessment - that is an evaluation of the number of tires generated by the tractor for trailer use, needs to be carried out.

1. To determine the number of steer axle tires needed, the number of steer axle tire positions multiplied by the base tire mileage is divided by the product of the steer axle wear rate (miles/32nd) and the difference in 32nd of an inch between the new tread depth and the tread depth at which the tires on the steer axle are pulled and rotated to the trailer.

Steer axle tires: (2) (200,000)/(8000) (8) =
6.25 tires

2. To determine the number of drive axle tires needed, the number of drive axle tire positions multiplied by the base tire mileage is divided by the product of the drive axle wear rate (miles/32nd) and the difference in 32nd of an inch between the new tread depth and the tread depth at which the tires on the drive axle are pulled and rotated to the trailer.

Drive axle tires: (4)(200,000)/(4500)(11) =
16.16 tires

3. To determine the trailer runout mileages:

- The number of steer axle tires multiplied by the trailer axle wear rate and by the difference in 32nd of an inch between the tread depth at which the tires on the steer axle are pulled and rotated to the trailer and the legal limit (2/32) in).

(6.25)(5680)(7) = 248,500 miles

- The number of drive axle tires multiplied by the trailer axle wear rate and by the difference in 32nd of an inch between the tread depth at which the tires on the drive axle are pulled and rotated to the trailer and the legal limit (2/32 in)

(16.16)(5680)(4) = 367,155 miles

- The number of drive axle plus the number of steer axle tires multiplied by the percentage assumed to be recappable by the trailer axle wear rate and by the difference in 32nd of an inch between the new recap tread depth and the legal limit (2/32 in).

(22.41)(.6)(5680)(15) = 1,145,599 miles

4. The addition of the trailer runout mileages divided by the number of trailer tires needed (for example, 8 for a double axle trailer) provided an indication of the available trailer tires.

1,761,254/8 = 220,156

This value should be roughly equivalent to the base tire mileage to ensure that the tractor generates the proper number of tires for trailer use.

Cost: 22.41 new bias-ply rib tires at $100/tire = $2241
13.45 bias-ply rib recaps at $45/tire = 605
$2846

$2846/200,000 = $.0142/mile

Scenario 2 - Bias-ply rib tires on the steering axle, bias-ply cross-bar tires on the drive axle on a single drive axle tractor

Vehicle: 4x2 tractor with double axle trailer
Tires: steer axle - bias-ply rib (17/32 in)
drive axle - bias-ply cross-bar (27/32 in)

Assumptions: Wear Rates
steer axle - 8000 miles/32nd
drive axle - 4200 miles/32nd
trailer axles - 5680 miles/32nd

Pull Depths
steer axle - 9/32 in
drive axle - 10/32 in
trailer axles - 2/32 in

Recappability - 60% of all carcasses are recapped at least once.

Using 200,000 as a base
steer axle: 200,000/(8)(8000) = 3.125
2 tires (3.125) = 6.25 tires
drive axle: 200,000/(17)(4200) = 2.8
4 tires (2.8) = 11.2 tires

(6.25) (7)(5680) = 248,500
(11.2) (8)(5680) = 508,928
(.6)(17.45)(15)(5680) = 892,044
1,649,472

1,649,472/8 = 206,184

Cost: 6.25 new bias-ply rib tires at $100/tire = $ 625
11.2 new bias-ply cross-bar tires at $115/tire = 1288
10.47 bias-ply rib recaps at $45/tire = 471
$2384

$2384/200,000 = $.0119 mile

Scenario 3 - radial rib tires at all axle positions on a single drive axle tractor.

Vehicle: 4x2 tractor with double axle trailer
Tires: steer axle - radial rib (17/32 in)
drive axle - radial rib (17/32 in)

Assumptions: Wear Rates
steer axle - 8000 miles/32nd
drive axle - 8600 miles/32nd
trailer axles - 8520 miles/32nd

Pull Depths
steer axle - 9/32 in
drive axle - 6/32 in
trailer axles - 2/32 in

Recappability - 60% of all carcasses are recapped at least once.

Using 200,000 miles as a base
steer axle: 200,000/(8)(8000) = 3.125
2 tires (3.125) = 6.25 tires
drive axle: 200,000/(11)(8600) = 2.114
4 tires (2.114) = 8.46 tires

(6.25) (7)(8520) = 372,750
(8.46) (4)(8520) = 288,327
(.6)(14.71)(15)(8520) = 1,127,963
1,789,030

1,789,030/8 = 223,629

Cost: 14.71 new radial rib tires
8.83 at $120/tire = $1765
8.83 radial recaps at $50/tire = 442
$2207

$2207/200,000 = $.0110/mile

Scenario 4 - Bias-ply rib tires at all axle positions on a dual drive axle tractor

Vehicle: 6x4 tractor with double axle trailer
Tires: steer axle - bias-ply rib (17/32 in)
drive axle - bias-ply rib (17/32 in)

Assumptions: Wear Rates
steer axle - 8000 miles/32nd
drive axles - 12900 miles/32nd
trailer axles - 5680 miles/32nd

Pull Depths
steer axle = 12/32 in
drive axles = 11/32 in
trailer axles = 2/32 in

Using 200,000 miles as a base
Steer axle: 200,000/(5)(8000) = 5
2 tires (5) = 10 tires
Drive axle: 200,000/(6)(12900) = 2.58
8 tires (2.58) = 20.67 tires

(10)(10)(5680) = 568,000
(20.67)(9)(5680) = 1,056,650
1,624,650

1,624,650/8 = 203,081

Cost: 30.67 new bias-ply rib tires at $100/tire = $3067

$3067/200,000 = $.0153

Scenario 5 - Bias-ply rib tires on the steering axle, bias-ply cross-bar tires on the drive axles of a dual drive axle tractor.

Vehicle: 6x4 tractor with double axle trailer
Tires: steer axle - bias-ply rib (17/32 in)
drive axle - bias-ply cross-bar (27/32 in)

Assumptions: Wear Rates
steer axle - 8000 miles/32nd
drive axles - 12040 miles/32nd
trailer axles - 5680 miles/32nd

Pull Depths
steer axle - 12/32 in
drive axles - 17/32 in
trailer axles - 2/32 in

Using 200,000 miles as a base
Steer axle: 200,000/(5)(8000) = 5
2 tires (5) = 10 tires
Drive axle: 200,000/(10)(12040) = 1.66
8 tires (1.66) = 13.29 tires

(10)(10)(5680) = 568,000
(13.29)(15)(5680) = 1,132,308
1,700,308

1,700,308/8 = 212,539

Cost: 10 new bias-ply rib
tires at \$100/tire = \$1000
13.29 new bias-ply cross-
bar tires at \$115/tire = 1528
2528

\$2528/200,000 = \$.0126/mile

Scenario 6 - Radial rib tires at all axle
positions on a dual drive axle tractor

Vehicle: 6x4 tractor with double axle trailer
steer axle - radial rib (17/32 in)
drive axle - radial rib (17/32 in)

Assumptions: Wear Rates

steer axle - 8000 miles/32nd
drive axles - 24653 miles/32nd
trailer axles - 8520 miles/32nd

Pull Depths
steer axle - 12/32 in
drive axles - 11/32 in
trailer axles - 2/32 in

Using 200,000 miles as a base
steer axle: 200,000/(5)(8000) = 5
2 tires (5) = 10 tires
drive axle: 200,000/(6)(24653) = 1.35
8 tires (1.35) = 10.82 tires

(10)(10)(8520) = 853,000
(10.82)(9)(8520) = 829,678
1,681,678

1,681,678/8 = 210,210

Cost: 20.82 new radial rib
tires at \$120/tire = \$2498

\$2498/200,000 = \$.0125

DISCUSSION

MR. THRASHER: Mr. Leasure, one of the most fascinating problems, as you have pointed out, is the increase in noise level with tire wear. Past studies, as you and I both well know, show that the noise level does increase significantly with wear. I noticed in your presentation that data from your latest study show a less drastic increase in the noise level during the wear cycle. Have you had a chance to analyze the data, and do you know why, by looking at the tires, this has happened?

MR. LEASURE: I think what we are seeing is simply the ranges that we can anticipate. The noise level increase with wear depends as much, or more, on the particular operation as it does on the tires that you begin with.

MR. THRASHER: So you are actually observing the lower end of expected noise level increases during the wear cycle in this particular test?

MR. LEASURE: The noise level increases with wear that I talked about today ranged from the low to the high end of what we have seen thus far. The numbers resulting from the cooperative tire wear/noise test tend to show noise level increases with wear more or less in the 3 - 5 dB range. In this particular test we haven't seen any increases that would even approach the 8 dB observed in other tests.

MR. THRASHER: There is one other point, Mr. Leasure, I would like to make. I think you well understand this point. Considerable reduction has been made in terms of the engine-related vehicle noise, and is a difficult problem to reduce vehicle noise. It is also a very difficult problem to reduce tire noise. We both know this, and I think everybody present knows this. However, there is a difference between these two problems. Vehicle noise can be reduced by off-the-shelf hardware items that are available such as mufflers, dampening materials, modified fans, etc. Unfortunately, with tires I don't think that there is any available off-the-shelf technology to solve the problem. There is nothing that we can just pick up and place on a tire and say, "It is done." I think it is important throughout this Sumposium to keep these thoughts in mind. It would be wonderful if we could find something to pick up and place on a tire and say, "It is going to be quiet."

MR. LEASURE: To put your comment in perspective, what we have tried to do here today is look at what can be done within the latitude of what we have available today.

MR. THRASHER: That's right.

MR. LEASURE: The point you are making is what do we do as a next step?

MR. THRASHER: That's correct.

MR. SWING: You itemized in your economic analysis some things that you didn't include in the considerations, and I didn't ascertain whether or not you included a factor for labor associated with the fact that certain types of tires will have to be changed more often than others. This would appear to give radials some advantage because of less labor involved in tire changes and maintenance.

MR. LEASURE: In this limited scenario we only examined the initial cost. We have underway now, or very shortly will have underway, a contract which will examine tire life cycle costing. In this study we will start examining past initial cost to the costs involved with maintenance, with changing tires, with inventorying tires, etc. We will also examine the changeover costs in going from one given type of tire to another. It is an important question which has to be addressed. What we have shown here today was simply a limited cost analysis based on the original tire cost. It was developed to give us a feeling of alternatives which were economically feasible. There is a tremendous variety of costs which have to be addressed. It is difficult to address these costs in a general manner, because they totally depend on the attitude and practices of the individual fleets. It is a difficult area to generalize.

MR. SWING: Further question, Mr. Leasure: You mentioned that sufficient time needs to be allotted before, for example, the changeover to a new type of tire design might be required to achieve lower tire noise limits. Will your life cycle cost study attempt to define this time period?

MR. LEASURE: As we get into the study, I am sure that some data pertinent to that question will become available, however, that isn't one of the primary objectives.

MR. DAVIS: I had a related question. I would like to hear your figure again on the miles per 32nd wear rate for bias crossbar and radial tires. I believe you said 8000 miles per 32nd for bias tires. Is that correct?

MR. LEASURE: That is correct for bias-ply rib tires mounted on the steering axle.

MR. DAVIS: Then that would give roughly 96,000 miles tread life. Is that correct?

MR. LEASURE: That is approximately correct if you consider original tread life only.

MR. HINDIN: Is there any contribution of tubeless versus tube-type tires in your noise and economic considerations?

MR. LEASURE: In our tire noise investigations we have been looking almost totally at tubeless tires. I don't think any of the data involved tube-type tires.

MR. HINDIN: That's in spite of the fact that 80% of the tires on the ground today are tube-type.

MR. LEASURE: From a noise standpoint we haven't seen any difference between tubeless and tube-type tires. However, it certainly would be a factor in an economic analysis where you have to account for the extra expense for the tubes themselves, and the differences in maintenance.

MR. ANDERSON: I was very interested in your comments in regard to safety which were based on traction data on dry and wet concrete. I am also very interested in the safety factor on snow, especially operations over the high mountain passes in this country, and also the safety factor associated with chains having to be applied. Chains tear up considerably faster than tires and distribute a great deal of metal around the road for everyone to run over. As a result, we have considerably more slippage inside those chains. The tire has a tendency to chew itself through, and thus cause the loss of radial ply tires considerably faster. I feel much of your testing when you deal with safety should be conducted with conditions other than just wet and dry cement.

MR. LEASURE: I think you have raised a good point. There are so little available data in this area that we only taken a first step. We have compared, in a controlled situation, the difference between the various types of tires under highway conditions of wet and dry pavement. As I pointed out, the whole area of operation on either snow or mud certainly needs to be looked at.

MR. CROWELL: You estimated in your cost analysis that the retreadability of radial tires would be 60%. Can you tell me the source of the information which led you to that estimate?

MR. LEASURE: For this scenario, we assumed that no matter what tire you began with on the steering and drive axles, that you will have 60% of those available for recapping. The basis for the 60% figure is the Western Highway Institute cost study of four or five years ago and our discussions with a selective group of fleet operators. Obviously, there is a lack of experience at this stage with what the number should be for radial tires.

MR. CLENDENEN: I would like clarification on the next-to-the-last slide where you were drawing a comparison of the engine plus tire noise reduction. If I read the slide correctly you were talking about a 3 dB change, yet the appearance of the curve indicated there was a change as far as the year 2000 of about 1.5 dB. Did I read that correctly?

MR. LEASURE: The 1.5 dB represents the approximate reduction in traffic noise levels if tires only were regulated. A 3 dB reduction can only be attained if both tire and engine noise are regulated. A 3 dB change in a community noise level is pretty significant. You are talking about all of the vehicles on the road, and the assumption was that there wouldn't be any great change in the noise levels of automobiles, and of course automobiles represented 93% of the vehicles on the road. The reduction in community noise might not be as large as you would suppose, but you have to look carefully at the assumptions and the fact that we are talking about an L_{eq} traffic noise level.

MR. COULTER: On the cost scenarios, if I understood correctly, are those list prices?

MR. LEASURE: No, the prices are somewhat fictitious.

MR. COULTER: Alright, this is what the manufacturer publishes.

MR. LEASURE: No, it is not even that. It is one step removed from that. We had much discussion on how to represent tire prices. In this case what we did was review all of the published costs, however, you have to realize that nobody pays these costs. We found percentage differences to be on the order of a 15% increment for bias-ply crossbars over bias-ply ribs, and a 20 percent increment for the radials. We set a base of $100 - an arbitrary base.

MR. COULTER: So we are looking at the difference?

MR. LEASURE: You are looking at the relative differences.

MR. COULTER: Is it safe to assume that the crossbar tires and the rib tires are discounted equally by the manufacturers? I would suspect so, but perhaps it will come up later.

MR. LEASURE: I don't feel competent to answer that question; maybe someone else could. I just don't know.

MR. SHERARD: This isn't a question, but for everybody's information, WHI is planning a field test next February in Utah. We will test the radials versus the lugs and crossbars for traction on a six % grade. Information should be available shortly after our tests. It will be made in cooperation with the Utah State Highway Department.

MR. LEASURE: We have thrown a great deal of numbers (noise levels, wear rates, prices, etc.) around today. They may seem in the ballpark to some of you and out of the ballpark to others. During the remainder of the program, we are going to be obtaining additional input which will allow us to evaluate these numbers in light of everybody's experience.

762034

Test Procedures for Future Tire Noise Regulations

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THE U. S. ENVIRONMENTAL PROTECTION AGENCY (EPA) recently promulgated "point-of-sale" noise emission standards for new medium and heavy trucks. In the development of these regulations, the EPA considered proposing a standard for high speed noise but recognized that such a standard would, to a substantial degree, largely be a standard on tire noise (1)*. As a consequence, EPA decided to address tire noise in a separate rulemaking and to place a ". . . high priority on reducing the noise from tires . . ."(1).

Tire noise is treated in part by the EPA interstate motor carrier noise emission standard which sets a level of 90 dB at 50 ft (15.2 m) for speeds greater than 35 mph (56.3 km/hr) as the noise limit for vehicles operated in interstate commerce. As further indication of the intent of EPA to regulate tire noise, tires were identified as a candidate for major noise source in May 1975 (2). On the state level, the California state legislature enacted a law in 1971 which requires the establishment of noise standards for tires sold in the state (3). One year after the establishment of these tire noise standards, the sale or use of tires not complying is prohibited. Thus it appears that some form of regulation on tire noise, either Federal or state, is imminent.

Before promulgating noise standards for tires, regulators must consider a variety of economic and technical problems. In the development of these regulations it will be necessary to specify a measurement procedure for determining the noise emission of tires and a formal procedure for establishing required compliance testing. Since the only existing standardized procedure for the measurement of tire noise is SAE Recommended Practice J57a - Sound Level of Highway Truck Tires (4), it seems probable that SAE J57a (or some adaptation of it) will be used as the basis for the development of noise emission measurement procedures in these regulations. With this premise, the remainder of this paper addresses two questions relevant to the development of noise emission standards for tires:

1. Are the SAE J57a recommendations for adjusting load and/or inflation pressure appropriate?
2. For tires with similar carcass construction and tread design, will it be necessary to establish

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*Numbers in parentheses designate References at end of paper.

ABSTRACT

Based on the actions of the U.S. Environmental Protection Agency and the State of California, it appears that Federal and/or state regulations on tire noise are imminent. Basic questions involving the measurement procedure and other technical problems are likely to arise in the development of such tire noise regulations. This paper treads two specific questions, the first dealing with the load/tire inflation pressure adjustments recommended in SAE J57a and the second with the effect of tire size on tire noise. Based on the limited set of data presented, it appears that either the load/tire inflation pressure recommendations of SAE J57a or the more convenient alternative of maintaining the tire inflation pressure constant at the maximum rated value with reduced loading can be used provided the loads are greater than 70— 75% of the maximum rated tire load. It also appears that compliance testing using a single tire size is feasible since sound level variations with size for tires with similar carcass construction and tread design are small.

compliance for all tire sizes or can a single tire size be tested?

Data obtained in two National Bureau of Standards (NBS) field test programs sponsored by the U. S. Dept. of Transportation (DOT) are presented to provide a basis for discussion of these questions.

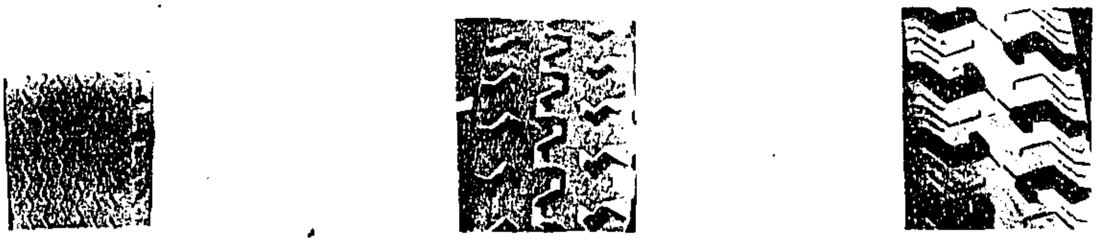
EFFECT OF LOADING ON TIRE NOISE

Data presented in the literature show that in general tire noise increases with load and that the magnitude of the increase is dependent upon, among other parameters, tire tread design (5 - 9). Because of this dependence on load, SAE J57a specifies standard vehicle/tire loading conditions to be used in the test. SAE J57a recommends that the ". . . test tires be inflated to the maximum pressure and loaded to the maximum load specified by the Tire and Rim Association (T&RA) for continuous operation at highway speeds exceeding 50 mph (80 km/h)." SAE J57a allows an exception to this requirement if the local load limits will not permit full rated load. In this case, ". . . the test may be conducted at the local limit with inflation pressure reduced to provide a tire deflection equal to the maximum load and inflation pressure, provided the load is not less than 75% of the maximum rated load." The standard suggests as another alternative that the tire inflation pressure may be adjusted to correspond to the actual load following the appropriate load/pressure tables in the T&RA Yearbook. Thus, three possible procedures for adjusting the load/inflation pressure are permitted by SAE J57a:

1. Maximum rated load and inflation pressure as specified by the T&RA
2. Adjustment of inflation pressure to maintain constant tire deflection with reduced loading, that is, constant axle height and,
3. Adjustment of inflation pressure to correspond to the actual load following T&RA recommendations.

Whether the sound levels corresponding to these alternate load/inflation pressure conditions are similar is an important question. Data for these alternate conditions were obtained by NBS for a set of bias ply rib and a set of bias ply crossbar truck tires. The characteristic tread patterns of these tires (rib-1 and crossbar-1) are shown in Fig. 1. These tires were mounted on the drive axle of a 4 x 2 single-chassis truck. (The nomenclature 4 x 2 relates to the number of wheel positions - four, and the number of driven positions - two, but has no relationship to the number of tires - six. Thus, a 6 x 4 would have 10 tires mounted at six wheel positions, four of which are driven.) The resulting data consisted of the maximum A-weighted sound level measured at 50 ft (15.2 m) for coastbys at 50 mph (80.5 km/h) using "fast" meter response. In this test program both the vehicle path and measurement area were sealed asphalt. The measurement procedures used in this test program are similar to those used in previous NBS studies and are described in Reference 10.

These data (averaged for two test runs) are presented in Fig. 2 as a function of tire load in terms of percent maximum rated tire load. As seen in Fig. 2, the results obtained following the T&RA recommendations are quite similar to those obtained by maintaining constant tire deflection. For the rib tire, the test results at the alternate load/inflation pressure conditions are approximately within ± 0.5 dB of the sound level at maximum rated load and inflation pressure for loads greater than 75%, indicating little sensitivity to load or inflation pressure. For the crossbar tire



RIB-1 **CROSSBAR-1** **CROSSBAR-2**

Fig. 1 - Characteristic tread element patterns of truck tires used in the study of load/deflection effects on tire noise

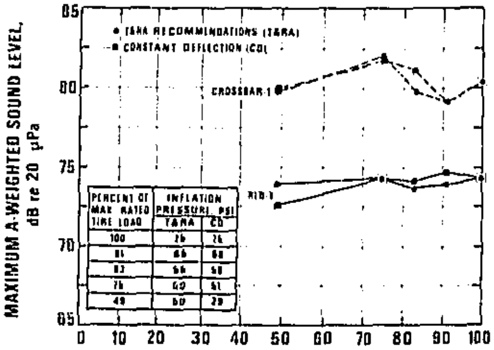


Fig. 2 - Maximum A-weighted sound levels, as measured at 50 ft (15.2 m), versus tire load for various inflation pressures. These data correspond to vehicle coastbys at 50 mph (80.5 km/h) on an asphalt surface

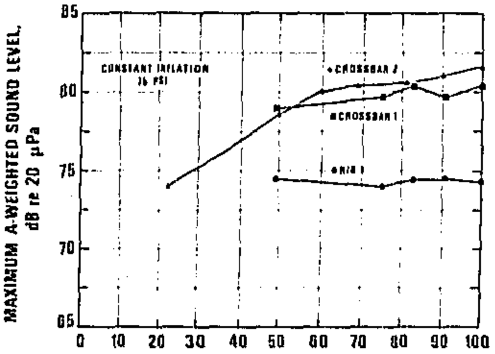


Fig. 3 - Maximum A-weighted sound levels, as measured at 50 ft (15.2 m), versus tire load for constant inflation pressure. These data correspond to vehicle coastbys at 50 mph (80.5 km/h) on an asphalt surface

the data are within approximately ±1.5 dB of the sound level at maximum rated load and inflation pressure. Depending upon how future tire noise regulations are structured, this variation may be within acceptable tolerances, thus permitting testing to be performed at other than maximum rated load and inflation pressure.

As an alternative to adjusting the inflation pressure to correspond to either T&RA recommendations or constant tire deflection, data for constant inflation pressure and varying load were also obtained and are plotted in Fig. 3. In addition to rib-1 and crossbar-1, data for crossbar-2 (see Fig. 1) obtained in a later field test program are also shown. The variations of the sound levels from the values at the maximum rated load and inflation pressure are (+0.2 to -0.3 dB) for rib-1, (0 to -0.7 dB) for crossbar-1 and (-0.6 to -1.3 dB) for crossbar-2 for loads greater than 70 - 75%. These variations are less than those observed for similar loading when the inflation pressures were adjusted. Thus it appears that based on this limited set of data, if reduced loading is necessary to comply with local load limits, testing can be performed using the maximum inflation pressure without encountering serious errors, provided that the loads are greater than 70 - 75% of the maximum rated tire load. This would be more convenient particularly if road-side enforcement were required since this essentially represents the actual in-service case where the load varies between trips but the tire inflation pressure is maintained at a constant value.

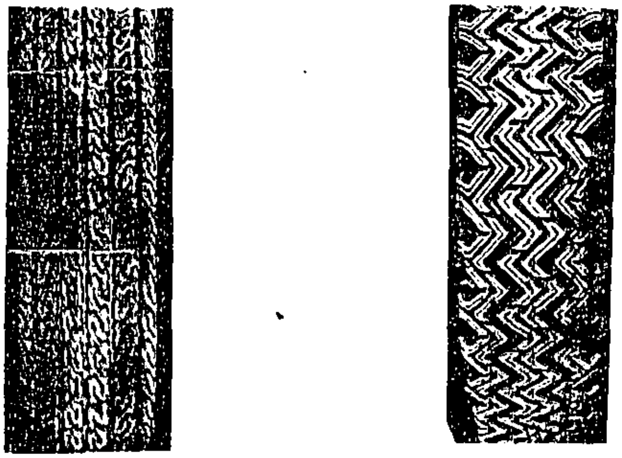
EFFECT OF TIRE SIZE ON TIRE NOISE

In the event that tire noise regulations are established which require some form of noise certification testing for new tires, it would be desirable, especially from considerations of the cost of testing, to be able to test a single tire size to establish compliance. For this to be feasible the dependence upon tire size of the noise levels generated by tires with similar carcass construction and tread design must be better understood.

An extensive field test program was conducted by NBS in which the effect of tire size on both automobile and truck tire noise was investigated. Data were obtained for six sizes of bias ply rib and snow automobile tires and four sizes of bias ply rib and crossbar truck tires. The tires in each of these four groups had the same carcass construction and tread design. The characteristic tread patterns are shown in Fig. 4 and a list of tire sizes is given in Table 1.

For the automobile tire tests three cars - a compact, intermediate and full-size - were used as test vehicles. In each case, rib tires were always mounted on the steering axle and either rib or snow tires on the drive axle with a loading equivalent to 100% of the maximum rated tire load. For the truck tire tests a 4 x 2 single-chassis truck was used as the test vehicle. Blank tires (full tread depth but no tread pattern) were always mounted on the steering axle and the test tires mounted on the drive axle with a loading equivalent to 75% of the maximum rated tire load.

These data (averaged for three test runs) are presented in Fig. 5. The variations of sound level with size between the maximum and mini-



AUTO RIB

AUTO SNOW

TRUCK RIB

TRUCK CROSSBAR

Fig. 4 - Characteristic tread element patterns of tires used in the study of tire size effects on tire noise

mum values for the automobile tires are 1.3 dB for the rib tires and 2.6 dB for the snow tires. Similarly for the truck tires, the variations are 0.6 dB for the rib tires and 0.5 dB for the crossbar tires. Based on these data, noise compliance testing utilizing a single tire size appears to be plausible for truck tires since the sound level variations with size were quite small. The variation of sound level with size is slightly larger for automobile tires, but still within a reasonable range for the rib tires and also for the snow tires if the L78 is excluded. Excluding the L78, the variation is 1.2 dB for the snow tires from size A to H. Further data are needed to determine if this is a general trend for the L78 snow tire or if these levels are characteristic only of the particular set of tires used in this study. Thus, a testing procedure for both auto and truck tires based on measuring the noise generated by any size tire of a particular type would appear to be a valid check for compliance with the appropriate tire noise regulation for all other size tires with similar carcass construction and tread design.

Table 1 - Tire sizes tested to determine the influence of tire size on tire noise.

Automobile Tires	Truck Tires
A78-13	9.00-22.5
B78-13	10.00-22.5
C78-14	11.00-22.5
E78-14	11.00-24.5
H78-15	
L78-15	

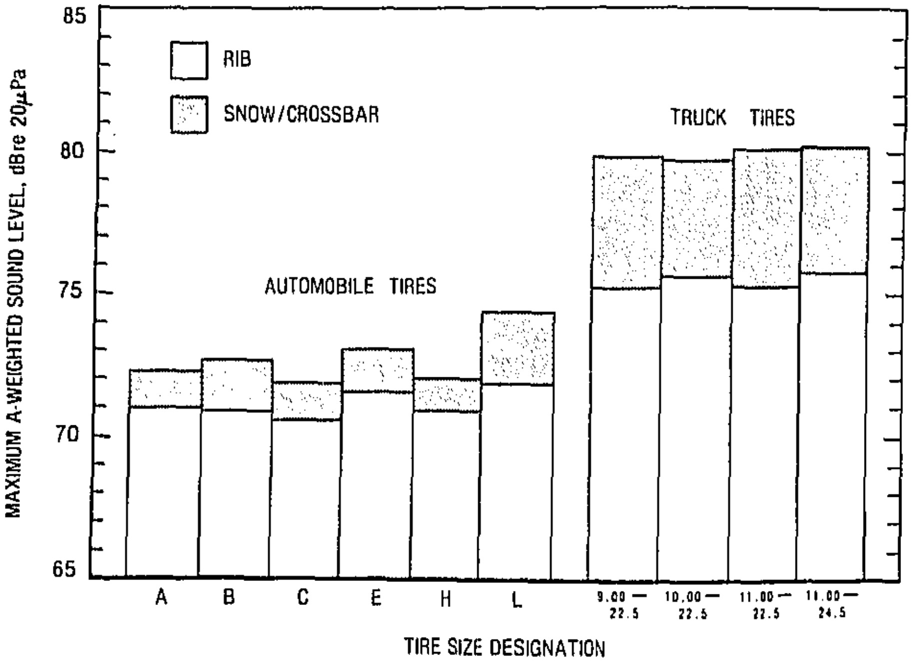


Fig. 5 - Maximum A-weighted sound levels, as measured at 50 ft (15.2 m), versus tire size for automobile and truck tires. These data correspond to vehicle coastbys at 50 mph (80.5 km/h) on an asphalt surface

SUMMARY

Based on the data presented in this paper the following conclusions can be made:

1. The load/inflation pressure adjustments recommended by SAE J57a induced variations in the resulting sound level from those at the maximum rated load and inflation pressure on the order of ±0.5 dB for the rib and ±1.5 dB for the crossbar truck tires utilized in this study.

2. For tire loads greater than 70 - 75% of the maximum rated loads, smaller variations of the measured sound level were observed when maintaining constant inflation pressure than when adjusting the inflation pressure to correspond to either T&RA recommendations or constant tire deflection.

3. The variation of sound level with tire size was approximately 1.3 dB or less (excluding the L78 snow) for the four groups of tires tested. Thus, it appears that compliance testing utilizing a single tire size might be feasible.

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The Environmental, Commercial and Regulatory Implications of SAE Recommended Practice J 57a for Truck Tire Sound Levels

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THE VERY NATURE of the standardized test procedure for evaluating truck tire noise has implications well beyond that of providing an objective measure. The procedure in considerable part determines the attainable goals for the public's protection from tire noise, the practicality of regulatory actions, the process by which improvements will take place, the cost to the nation, the balance between noise and functional properties of tires, economic burdens on tire manufacturers, and the time table for improvements.

The procedure that has been in use since the initial efforts of the mid-1960s is formalized in SAE's J57a Recommended Practice. It is now relevant to review some of the concepts that underlie its formation. This review should emphasize three areas:

1. The objectives - what they were and how well are they met by the procedure,
2. The limitations and undesirable side effects, and
3. The alternatives that might be better suited to the objectives.

THE UNDERLYING CONSIDERATIONS OF THE APPROACH

Since the first collective efforts of industry and government to assess the community impact of noise emanating from truck tires, there has been the question of how to measure the tire sounds in a manner that supports certain practical goals of the community and of manufacturers. The primary objectives that were generally agreed upon were to:

1. Provide a measure that could be used to compare tire designs for reductions in community annoyance.
2. Assure that a well defined procedure existed so that new tires could be developed against a fixed target.
3. Establish a consistent standard that would produce the same rating for all test establishments - competitive manufacturers and regulatory agencies.
4. Maintain the lowest practical level of cost and technological complexity so as to avoid excluding the agencies and tire manufacturers who could not participate with elaborate testing facilities.

ABSTRACT

There can be no control over environmental pollution without methods for measuring how the environment is being affected by mankind. Consequently, when traffic noise was identified in 1964 by communities as an important form of pollution, it became necessary to measure the amounts of noise present and to assign relative importances to various sources in vehicular traffic.

Truck tires were identified as being significant contributors and engineers from the tire and truck manufacturing industries acting under the auspices of the SAE set about to develop a test procedure that satisfied the immediate need - to initiate control over truck tire noise.

This paper is a review of the outcome of that effort by one who participated in the earlier work on the testing standard. How well the method works, and how well it serves to meet the objectives now on the horizon are the preliminary topics of this discussion. The paper contains a discussion of the accumulated experience in testing tire noise and the current indications for a meaningful test procedure.

To the uninitiated, perhaps this problem of how to measure tire sound seems trivial, but it soon became obvious to those engaged in the investigations that there were both critical functions and background information to be determined. All aspects of tire noise are not equally important to the community and the choices among measurement procedures requires a decision concerning which aspects are paramount and which are secondary. For example, should tire noise be measured in accordance with the way it affects communities surrounding high-speed throughways, or as lower speed noise in the manner it is sometimes detected by occupants of other vehicles on the highway, as an intrusion on the natural beauty of wild terrain or for still other kinds of circumstances? Certainly frequency weighting and treatment of modulations will differ, depending on the target.

Another central task was to identify what properties of tire sounds are the major contributors to annoyance. Among the candidates for consideration were the many existing measures of sound level, the occasional tonal character, modulations in level and tone (pulsating noises), and the tendency of some tire sounds to persist over inordinately long distances of vehicle travel.

The Truck Tire Noise Subcommittee of SAE conducted a detailed study of the issues and acquired as large a base of information for supporting its judgments as circumstances permitted. In October 1972 the findings were reported in the SAE publication Truck Tire Noise, SP-373.

The testing scheme arrived at implied that truck tire noise was probably most important to communities located alongside high-speed highways. Truck tires become noisier as the speed increases and the sound levels at speeds under 30 mph are negligible when compared with those at 50 mph and above. Furthermore, it appeared probable from what was known about the behavior of tires at the time, that if the high speed noise was reduced, on the average, there would be a corresponding reduction in other manifestations of community disturbance.

The only means of measuring tires for radiated sound then prevalent was by mounting the tires on a truck and driving or coasting the truck past a microphone. In addition, it was essential for economic reasons that the measurement procedure not involve excessive speeds and consequently not require test tracks with long approach roads for accelerating heavy trucks. For these reasons the test speed was set at 50 mph. With these minimal stipulations, the decisions thereby dictated a test procedure that nevertheless requires an expensive special test track. A track of this nature could be acquired by most potential participants or could be rented for their use and therefore was considered practical. In addition, there was also a need to isolate the test from extraneous noise sources, that is, traffic, machinery, engines, and exhausts, and to maintain a sound field between the tires and the microphone that is free of acoustic reflectors and absorbers. This further restricts the characteristics of suitable test sites and leads to a highly specialized facility. Economics requires that this test track also be an outdoor installation.

With these stipulations, the procedure must contend with interferences which arise fundamentally from its character. There are, or should be, restrictions on climatic conditions (wind, rain, snow, temperature, sound reflecting thermal layers in the air) and there are sound affecting properties of the road surface to be considered.

Climatic effects are controllable by excluding certain conditions from validated test runs. The surface must be free of contaminants, the wind speed must be less than certain values, etc. However, one result of such exclusions is to limit the testing capacity of an outdoor facility.

Experience has shown that because of weather conditions, the needs of industry for product development and product certification is very difficult to satisfy, even with test tracks in advantageously endowed parts of the country. Furthermore, no account has been made thus far for interferences resulting from the refraction of sound due to wind currents, or to thermal layering of the air. It was hoped, however, that such phenomena would have only a minor influence if the distance between the microphone and the truck is held to 50 ft. This refraction effect is known to occur over distances of hundreds of feet - but has not been explored for smaller path lengths, such as 50 ft.

The road surface defied an exact and meaningful description for purposes of noise testing. There was information showing that the generation of truck tire noise results from a surface-tire interaction, and therefore will vary with the test surface. SAE's J57a Recommended Practice attempts to minimize this source of variability by calling for longitudinally brushed concrete. However, this stipulation is not entirely effective since the detailed requirements elude description.

Thus, the SAE Committee was aware that many uncontrollable factors would influence the test results when it proposed the procedure to initiate work on quieter tires. It realized the imperfections of the method, but acted to accommodate an immediate need. It was expected that the procedure would lead to some inconsistencies. Relative noise ratings for various kinds of tires could be assigned and these would not necessarily order the sounds in the same way as for different speeds of travel or locations of the listener. However, the committee anticipated, that on the average, an improvement in rating of tires by the proposed method would lead to a generally quieter environment across the nation.

The SAE committee introduced precautions and practices into the procedure in order to improve the sensitivity and reproducibility. These items had no specific objective or effect of simulating the conditions with which the public experiences truck tire noise. For instance, the point of detection was chosen to be 50 ft from the centerline of the vehicle in order to reduce the errors that might result from extraneous sound sources if the microphone were further away. The 50 ft microphone placement is also the same as is used in the total truck sound measurements. The 50 ft distance in that instance, was chosen so that sounds originating at various locations on the truck (from the front to the rear) would have a reasonable chance of integrating into a single maximum pass-by level. Here consistency among SAE standards was the objective.

Although the sound level, the frequency distributions, the rise and fall of the sounds and their spectral components were known to vary with distance, no technology had been developed either to measure tire sounds accurately at more representative distances, nor to evaluate the annoyance at such locations.

The SAE committee investigated the reactions of a jury to a range of truck tire sounds and compared the jury ratings with physical measures of the sound. Both the jury and the microphone were located 50 ft from the centerline of the highway in accordance with the objectives noted earlier. The best correlation obtained was with the peak-value of the A-weighted sound level. Other less significant factors also are indicated as being present but to this date have not been isolated and assigned relative weightings.

At this moment the A-weighted peak level at 50 ft is the only positive correlation we have to annoyance, but the correlation is for a jury also at 50 ft under unnatural environmental circumstances. We are not aware of how the A-weighted peak or other measures would correlate with more representative intrusions on the community's peace and quiet. For instance, does the 50 ft A-weighted peak level account for the irritation with a long persistent modulated whine heard from a considerable distance?

In any event, the committee decided that some measure of loudness must be important, even if not all inclusive, and loudness in the community, depending on radiation patterns, frequency selectivity, etc. might more often correspond to the 50 ft peak A-weighted rating than disagree with it.

Summarizing from the points already presented, it is evident that even though experience has shown that SAE's J57a Recommended Practice has served to identify some of the goals for reducing tire noise and has assisted manufacturers in eliminating noisier tires, it nevertheless has practical limitations and is an arbitrary and expensive test method. This state of affairs opens the door to other standard procedures that may be better adapted to the needs but which have only to satisfy the same kind of statistical relationship to the general reduction of the noise environment of the country.

A further issue not touched on in the previous section that deserves further elaboration is the precision of the measurements. The extent to which the sound level is accurately defined, is the extent to which detailed sound levels can be guaranteed. That is the subject to be considered next.

EXPERIENCE WITH THE PROCEDURE

Ever since the early proposals leading to the J57a test procedure, tests employing the essential features have been run extensively. The experience gained has uncovered some lack of reproducibility of the measured values both in repeats over long periods with the same test course and equipment, and among different facilities.

The degree of reproducibility is important in the control of tire sounds since it limits the accuracy required to classify tires into meaningful groups. As an example, let us consider a hypothetical situation where the minimum noise level consistent with the best tire noise reducing technology is 70 dB and the highest level consistent with other desirable operational tire features were 76 dB. Then commercial tires would be classified over a 6 dB range. However, if the test procedure contained an irreducible "error" band of 3 dB, then there could only be two separable categories of tires in the range. Regulations and efforts at the redesign of tires for noise reduction would have little practical meaning unless the objectives were 3+dB (that is, 5 dB) changes in level and a required 3+dB drop might well frustrate normal evolutionary development programs.

Thus it is apparent that if, as already indicated, regulatory agencies wish to promote improvements in a series of reasonable steps, and if tire designers are to be allowed to participate in an evolutionary process, then it is important to have a test procedure that is reproducible and has a satisfactory resolving power.

The Rubber Manufacturer's Association (RMA) has conducted a program in which eight differing sets of truck tires have been tested for noise on five separate commercial proving grounds. Each of these tests was performed in accordance with SAE's J57a Recommended Practice. The tire types involved represent the design range of current and anticipated commercial truck tires. This series of tests is intended to serve as an indicator of the reproducibility and resolving power of the procedure.

Most of the proving grounds participating in the program ran six individual tests for each set of tires in one direction of travel along the site. Some

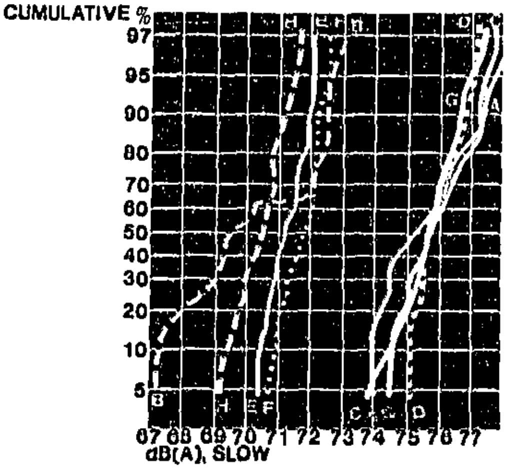


Fig. 1 - 1976 RMA Round Robin Test - all individual runs

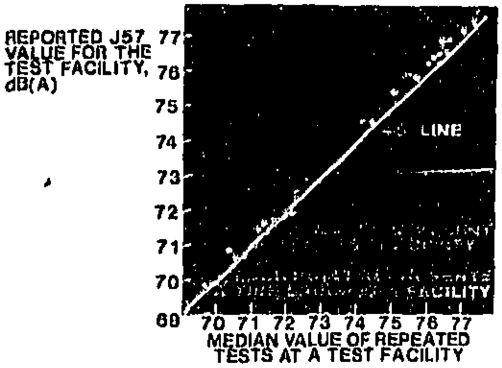


Fig. 2 - Reproducibility of J57a ratings at each facility

also reversed the direction and procured an additional set of readings. All of the individual peak sound levels, A-weighted and for slow response are combined to form the cumulative distribution curves of Fig. 1. A considerable spread in measurement is evident (over 5 dB in one case).

In order to minimize the spread at any one test facility, the J57a practice requires that the reported values from a series of repeat tests at a site "shall be the average of the two highest readings which are within 2 dB of each other".

The effectiveness of this rule in achieving its objective is indicated by comparing the J57a reported levels for each tire at a test facility with the median value obtained during the test at that site and then with the median value obtained on all tests at all sites. The median values represent the most probable level that occurs during actual testing experience. Fig. 2 indicates that the median value for each test facility agrees quite well with the value reported in accordance with J57a. An examination of the values of repeated runs demonstrates that the short term internal consistency of ratings at any one test facility is adequate. Neither observation anticipates the larger discrepancies among the measurements of the various test facilities. Fig. 3 shows a considerable scatter of ratings for each particular tire over the five separately reported evaluations by the J57a. Table 1 summarizes the range of scatter for the eight different groups of tires.

It is apparent that a regulatory agency or a manufacturer obtaining a measurement of tire noise cannot know, a priori, where in the possible range of measurements, his particular value resides. If it is at the low end, it is possible that some other test facility could rate the sound level from 1.2 - 5.3 dB(A) higher. This condition is further confounded by the fact, that the different brands and types of tires do not even order according to sound level in the same way at all of the test facilities. There is no known general calibration for the sensitivity of a test facility.

Table 2 shows that the median values of the ratings for the five tire sets at each of the test facilities are identical within 1.3 dB(A) and thereby indicate approximately equal average sensitivity for all five test grounds. Nevertheless, certain mixes of tire, test track, equipment and technique promote significantly higher or lower sound levels as determined by the details of the operation.

THE OUTLOOK FOR AN IMPROVED TESTING TECHNIQUE

Those working on the control of truck tire noise are faced with the question of whether or not SAE's J57a Recommended Practice can be improved so as to consistently separate meaningful gradations of

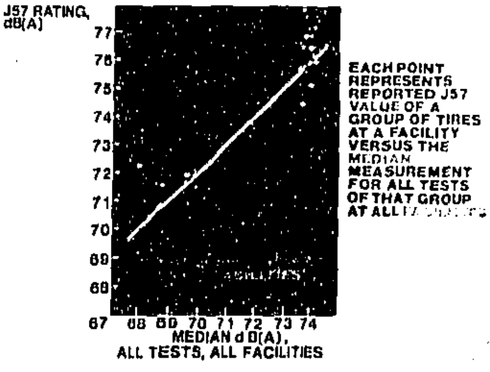


Fig. 3 - Reproducibility of J57a ratings among facilities

Table 1 - Summary of Range of Scatter for Eight Groups of Tires

Tire Set	Median Value, dB(A)	Range, dB(A)
B	70.0	5.3
H	70.8	1.6
E	71.6	1.2
F	71.9	1.2
A	75.7	3.4
C	75.8	3.4
G	76.0	1.7
D	76.1	1.3

Table 2 - Median Values of Ratings

	All Tests, All Tire Groups	
Test Facility	Median Value, dB(A)	Range dB(A)
L	74.0	6.9
M	73.5	4.4
N	72.7	7.0
P	73.8	5.3
Q	74.0	8.4

noise levels among tires. An additional question is whether consideration should be given to a substitute for the J57a Recommended Practice. A first step in answering these questions is an exploration of the causes underlying the lack of reproducibility among various test sites.

There are a number of areas that are likely to differ among test facilities and therefore stand out as likely sources for the variations in test results. These are:

1. Sound inducing tire vibrations excited by the minor irregularities of the road surface.

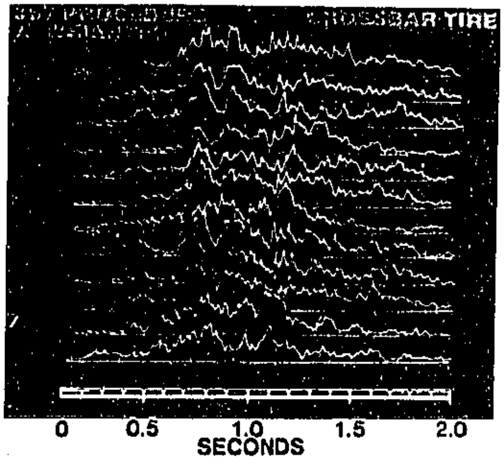


Fig. 4 - Signal amplitudes for 12 repeated passbys

2. Friction properties of the tire-road interface which affect the sound generating stick-slip vibrations of a rolling tire and the influence of texture, composition, humidity, contamination, and temperature on the friction.

3. Air turbulence due to the vehicle's motion interacting with thermal gradients in the air causing sound refraction and distortion of the radiation patterns of the tires.

4. Details of the vehicle's acceleration along with minor variations in road profile, causing vehicle bounce, which in turn modulates tire sounds and interacts with the dynamic response of the sound measuring system.

5. The different radiation patterns of the many types of tires leading to peculiarities in the rise and fall of sound level and this too interacting with the dynamic responses of commercial sound level measuring devices.

6. The fact that different models of sound level meters or sound level measuring systems may have identical steady-state sensitivities but exhibit significant distinctions in dynamic responses.

7. Absorption properties of the road surface or variations in acoustical impedance of the road affecting the transmission of the ground wave.

8. Accuracy of speed at passby.

9. Thermal effects within the tire.

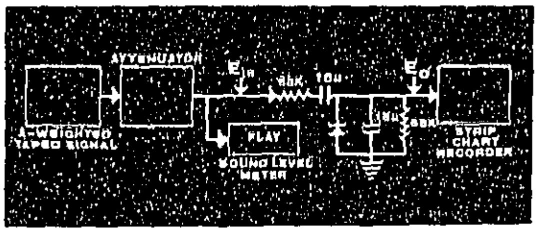
10. Variability in techniques for reading the peak level.

There is considerable evidence for the influence of road profiles and the details of vehicle acceleration on bounce, and then, because of changes in tire load, on fluctuations in sound level. This effect can be detected audibly at test sites and also appears on tape recordings of the tests. Fig. 4 illustrates the point. Twelve consecutive runs of the same tire set on the same vehicle passed the same microphone and the A-weighted signal enters the same recording equipment. The recordings are subsequently analyzed as in Fig. 5 for short term changes in amplitude of the sound signal (measured at the standard microphone location for the J57a test). These changes are recognized as sounding similar to those which visually are found to correspond to vehicle pitch and bounce. The traces of the twelve tests are not identical showing inconsistencies in the levels and rates of rise of the first and second peaks. In the case of this group of tests at a single facility, the variation in recorded level was about 0.8 dB. However, in view of the fact that the road was considered to be extremely smooth, and the acceleration and control of the truck quite even, one would expect that much larger differences would occur among test facilities where the pavement contour, the trucks, the instruments and the test operators are not the same.

The influence of interface friction on stick-slip vibrations and of road texture on vibratory excitation require an elaborate exposition for separation from other phenomena, and is out of place in this paper. However, the combined influence can be demonstrated by a series of tests of the same tire set on a variety of surfaces, once again employing the same personnel and equipment.

Fig. 6 contains both the spectra and the dB(A) ratings for a J57a passby of a cross lug tire on each of six road surfaces. Not only do the spectra differ significantly but the A-weighted levels range from 77.5 - 83 dB. Furthermore, we do not believe that these surfaces exhibit the practical extremes over which the road texture can influence the ratings.

In addition, it has been reported from two test facilities participating in the RMA Round Robin experiment that when the test pad is traversed in one direction, the mean sound level may vary as much as 2 dB from traversal in the opposite direction. This observation is consistent with our background on the stick-slip vibrations of tires. The friction properties of the tire-road interface is directional and depends on the manner in which the concrete was surfaced. This should affect the sound generating process and cause a reversal in direction of travel to yield a change in sound level.



$$E_o(t)=\frac{1}{(.01)}\int_0^t e^{-2\frac{(t-\tau)}{(.01)}}E_{in}(\tau)d\tau \qquad t=\text{SECONDS}$$

Fig. 5 - Typical instantaneous sound amplitudes of passbys - all attenuated to yield peak 86.5 ± 0.5 dB(A) slow (from UniRoyal portion of Round Robin)

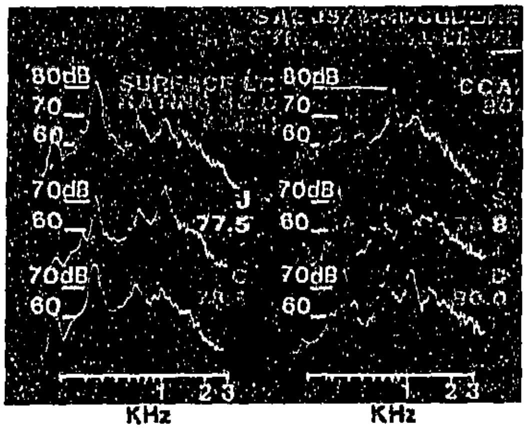


Fig. 6 - A-weighted spectra of a lug tire on six different road surfaces

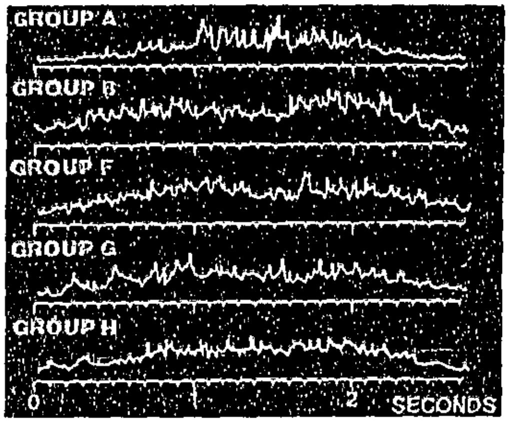


Fig. 7 - Typical instantaneous sound amplitudes of passbys - all attenuated to yield peak of 86.5 ± 0.5 dB(A) slow (from UniRoyal portion of Round Robin)

The only data which is in our possession concerning air turbulence and refraction is a statistical difference in sound levels of about 1 - 2 dB for repeated tire sets which occurred when the model of test truck was changed. This did not appear to be due to the mechanical sounds of the truck, the operating technique or the instrumentation. In our judgment, this point is not substantiated, but needs further exploration if SAE's J57a Recommended

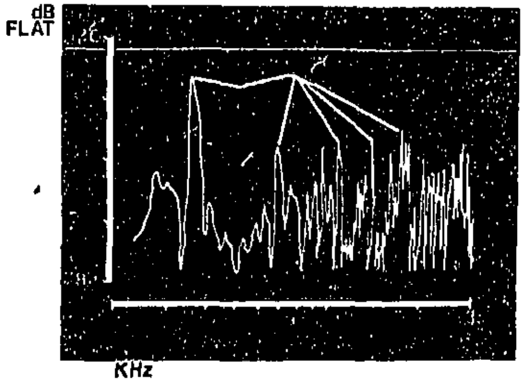


Fig. 8 - Spectrum at exit of contact patch

Practice is to be applied extensively. We probably experience less of this effect because our tests are performed at night when the thermal layering is at a minimum.

Fig. 6 represents the detailed variations in sound level during each run for repeated tests on a single set of tires. In contrast, Fig. 7 indicates the variations in general character of the fluctuations in sound amplitude for different kinds of tires tested by the same facility with the same equipment and personnel. In this group of traces, the gain of the play back has been set so that the same peak dB(A) level at slow response occurs for all runs. This kind of comparison, therefore, emphasizes the differences in character of level variation and obscures differences due to absolute level. Here once more, we find numerous characteristics of rise and fall of level related to the tire design. These characteristics react with the dynamics of the measuring equipment, so that the reading derives from the particulars of the rise and fall of sound at the 50 ft location. We also observe that the 86.5 dB(A) reading corresponds to various peak amplitudes.

Figs. 8 and 9 illustrate the interactive nature of the reported J57a rating. Fig. 8 shows that the near field sound radiated on a test machine from a typical tire at 50 mph contains dominant harmonics of the tread element spacing. Fig. 9 features the effect of speed on the sound levels at various harmonic frequencies of the element spacing. It will be observed that the magnitudes of the harmonics generally trend to higher values with increasing speed. However, in addition there is the emphasis or de-emphasis of these harmonics at various speeds. This emphasis of levels is determined by whether the particular harmonic at a particular speed coincides with some resonance of the tire structure. The corresponding resonance study is not presented here but has been examined in detail. Similar information concerning interactions of tread spacings and resonances is also available from road tests but are not as clear cut. Here then is one phase of the interactive process of sound generation that affects the ratings obtained with the Recommended Practice.

In addition, the sound level at any instant not only depends on the coincidence of the average (that is, Fourier series) value of a harmonic and on the resonances, but also on what part of the tire's circumference is actually in contact with the road. This fact is difficult to capture for presentation in a paper but can be seen by observing the screen of a free-running real-time spectral analyzer. This phenomenon takes place because the resonant systems of the tire are low in Q and because the spacing between consecutive crossbars (or other tread elements) varies about the tire. Therefore, the instantaneous spacing of the tread sequence, not the average Fourier transformed value has a major effect at the moment the peak sound level is recorded.

Beyond these interacting influences, there are the position dependent irregularities in pavement texture, vehicle bounce and interface friction. Along with the foregoing items, the measured maximum peak level is a statistically rare value that reflects the accumulation of all these interacting effects.

More important, however, is the fact that these interactions are not defined by the test procedure and consequently lead to variations in test results.

What then may one conclude from these various observations? Fig. 1 shows that any testing facility could only be certain of rating modern commercial tires within two categories. One category is for J57a levels between 74 dB and higher, and the other

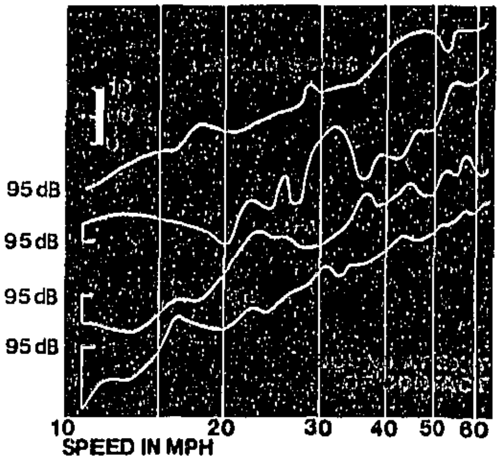


Fig. 9 - Harmonics of average lug spacing, for a cross bar tire on a 10 ft road wheel

is for levels between 73 dB and lower. This rough separation into ranges is an artifact of past commercial objectives. It does not represent the conditions that will prevail when efforts at tire noise reduction have been in existence for an appreciable time. We anticipate a more gradual distribution of median values for tires now being developed to improve noise. Therefore, it is important to determine from these statistical indications whether or not the J57a procedure is suitable for promoting one of its major objectives - a testing standard for the continued development of tires for reduced noise.

New tire developments are brought into existence by a procedure involving great caution. The risks concerning safety, economics, and relative acceptance of brands by vehicle operators requires that the complex compromises of operational properties, durability and price-performance trade-offs be well-founded before there is a massive distribution of any one new kind of tire.

As a result, tire modifications are generally moderate in nature and require extensive evaluations. Limited commercial service provides the evaluation since most of the unusual circumstances of usage are likely to be encountered.

The approach to noise improvement consistent with tire development techniques requires that the progression of changes be discernible by the means used for noise evaluation. It is evident to tire engineers that the uncertainty of a J57a test value (a probable band of indiscrimination of 2 - 4 dB) is excessive for practical tire developments.

Now in light of the foregoing discussion, let us review the four primary objectives of SAE's J57a Recommended Practice which were listed at the beginning of this presentation.

1. Provide a measure that could be used to compare tire designs for reduction in community annoyance.

The procedure yields a rough measure that is not yet tied to community annoyance. The discrimination of the method is not suitable.

2. Assure that a well defined procedure existed so that new tires could be developed against a fixed target.

Although the statement of the procedure is precise, too many uncontrolled variables such as road surface excitation, etc., preclude the usefulness of the method as a "fixed target". Climatic conditions greatly reduce the use of SAE J57a for new tire development.

3. Establish a consistent standard that would produce the same rating for all test establishments - competitive manufacturers and regulating agencies.

This function does not appear to be practically obtainable because of factors such as the road surface texture, the details of road profile, transient vehicle bounce, motor dynamics, air refraction, etc.

4. Maintain the lowest practical level of cost and technological complexity so as to avoid excluding the agencies and tire manufacturers who could not participate with elaborate testing facilities.

The passby procedure is within the scope of the larger manufacturing firms, others rent or share facilities. However, the investments and operating costs are considerable.

All factors considered, it appears that a new testing procedure is needed for the emerging requirements of the nation.

BROAD OUTLINE FOR A NEW TESTING PROCEDURE

What are the lessons we may draw from experience with the J57a procedure that will assist us creating a new and more useful method for evaluating truck tire sound levels?

Transient testing of tire noise as in passby procedures appears to create much of the variability in measurements from the many test tracks. As indicated earlier, transient testing emphasizes the random interactions between the variations in friction and profile of the road, the acceleration of the vehicle, the bounce and pitch dynamics of the truck and the accidental location of the tread spacing sequence at the peak of sound and tire resonances.

Transient testing embodies the additional feature that the manner in which the sound amplitude increases with the passage of time, along with the amplitudes achieved, determine the peak rating. It is fair to question what this composite rating signifies in terms of noise pollution. In addition, the rating also depends on a property not standardized in currently available sound level measuring equipment - the dynamic response of the measuring system. All of these factors emphasize the desirability of techniques in which tire sounds are averaged over periods of time at steady-state, not evaluated in the state of rapid change.

The sensitivity of the test procedure to the road surface has several implications. One is that consideration should be given to developing rating procedures for separating "internally" excited tire noise from that of external excitations. There is a serious question of whether or not the tire's design should carry the burden of the contribution from the road surface. Certainly, it seems desirable to test tires in such a manner that the properties designed into them determine the rating.

Climatic interferences have been a major impediment in the use of the passby test for new tire development. A new test procedure, therefore, should be capable of being conducted indoors.

Although no direct connection has been established between J57a ratings and community annoyance, we still have reason to support the original premise that improvements in level for some reasonable standardized test procedure will ultimately yield reductions in annoyance. For this reason, the new test procedure should demonstrate some statistical conformity with the J57a results. On the other hand, because of the arbitrary emphasis of the J57a test, it is not relevant to have the ratings of the new procedure correlate precisely with J57a results. Precise correlation is also thwarted by the variability of the J57a ratings among facilities.

The new test procedure should also be capable of reproducible ratings (to within ±0.5 dB) from one test facility to another. This will greatly enhance its value for tire development and qualification.

A companion paper (1)* at this session considers these factors and offers a testing method that appears to meet the new objectives.

REFERENCES

1. S. A. Lippmann and K. A. Reid, "A Laboratory Procedure for Measuring the Sound Level of Truck Tires." Published in P-70, "Highway Tire Noise," Warrendale: Society of Automotive Engineers, Inc., 1977, Paper 762015.

DISCUSSION

MR. SWAYNE: My question concerns the difference in tire noise ratings where they are using fast or slow response on the sound level meter. The previous paper talked about fast response, and Mr. Leasure's work refers to slow response, as does the SAE J 57a procedure. I wonder, have controlled tests determined the differences at 50 ft or 100 ft? I would expect the difference between fast and slow varies with road surface, and the tire tread design, too.

MR. LIPPMANN: There is a paper coming up that covers that.

MR. THURMAN: Mr. Leasure's data is all at fast response.

MR. CLOSE: I was a little confused regarding your figure where you said that the procedure would only allow you to distinquish between something that was below 73 dB(A) and something that was above 74 db(A). Could you elaborate on what it was on that figure that we were looking at, the different letters, the different line codes, and the significance of the statement that you could only separate below 73 and 74 above? What are all the numbers and letters?

MR. LIPPMANN: It varies. The letters refer to different tire groups.

MR. CLOSE: Different in tread types or carcass types?

MR. LIPPMANN: They are different tires, and they do involve such things as the radial ply tire and the bias ply, rib and lug designs.

MR. CLOSE: Each line is a type of tire?

MR. LIPPMANN: That's correct. They represent the gamut from "ribbiness" to "lugginess."

MR. CLOSE: The variations we see, cumulative percentage, are they the values arrived at, at one facility for one type tire?

MR. LIPPMANN: All facilities for all tests conducted on that tire. There were six tests conducted generally at a facility on each type of tire, and there are five types.

MR. CLOSE: I still don't understand how you reach the point of saying that this procedure would only allow a distinction of 73 and below, and 74 and above.

MR. LIPPMANN: I am looking for a range in which you could say that there is no overlap. A range where you could make a distinction and say, "All tires have to be below such and such a level," or conversely, "This tire is going to be above such and such a level no matter who tests it," and you see that there is a clear region between 71 dB and approximately 73 dB in which you could make that distinction.

MR. CLOSE: Couldn't one say that tire H is 70.5 ± 1 or 1.5 dB, and that tire E was 71 ± 1, and tire F was 72 ± 1?

MR. LIPPMANN: You could say that if the same distribution curve of your own test facility occurred at every one of the test facilities. But the distribution is broader over everybody's test facility, and the individual distributions are not the same. At a particular test facility, you are dealing with a much more restricted range, but you don't know where you are in the entire population of distributions that occur. That's the reason for the inability to make a decision. You will see this later in the other papers.

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*Numbers in parentheses designate References at end of paper.

762036

Noise Regulations-Impacts and Restraints

Leo M. Cyr
Rubber Manufacturers Association

THE INTENT OF THIS PAPER, which represents the collective voice of the Rubber Manufacturers Association (RMA) is to provide the reader with an overview of noise regulation and its potential impact on the tire industry.

The present discussion of tire noise is highly complex even when reduced to layman's language. How do you define tire noise and what factors affect the quality of this noise? Who is to determine what sound level is unacceptable and will that judgment be applicable in all environments - urban, residential, and rural? What methods are to be used to evaluate or to test sound sources? The list of possible questions has no end.

A tire makes no sound sitting or spinning in the air. If it rolls down a hill like a hoop, it would make little more sound than it does in a stationary position. Obviously, a tire is not intended to be used in this fashion. It is designed to carry a load.

THE CAUSE OF TIRE SOUNDS

A medium sized passenger tire normally carries a load of about 1,000 lb. This load causes the tire to deflect, or squat down on the road surface. It is inherent in the behavior of tires that when rolling while deflected, vibrations are created in the tire. Through the interactions of these vibrations with the air surrounding the tire, sound is emitted.

Increases in the deflection of the tire generally promote the formation of vibrations and noise and lead to greater sound levels. Furthermore, the generation of vibrations occurs in such a manner that as speed is increased and the tire rolls faster, more sound energy is produced.

Tread design is directly involved in certain aspects of sound production. The grooved designs, which are more suitable for traction on wet surfaces or for winter conditions, are usually noisier than a tire without a tread design. However, it is to be noted that a tire with no tread design whatever will still not be noiseless. Such a tire has proven quieter than rib patterns on smooth textured pavement. However, in recent tests conducted by the rubber industy, some rib patterns proved to be less noisy than totally smooth tires on highly textured pavements.

This contradiction is partly due to the character of the road surface on which the loaded tire was rolling. Different road surfaces do have a profound effect on the sounds emitted by tires. In point of fact, variations in the character of similarly constructed real life road surfaces can produce wide variations in the noise - differences of as much as 13 dB(A) have been observed. To appreciate how substantial the difference is, one must realize that a drop of a mere 3 dB(A) halves sound power; or conversely, that an increase of 3 dB(A) doubles sound power.

The level of tire sound depends on the interaction of the tire and the road, and even subtle differences among road surfaces are apt to cause much larger changes in tire sounds than those caused by design differences in the tires. This, of course, introduces grave problems in

ABSTRACT

The paper provides the reader with an overview of noise regulation and its potential impact on the tire industry.

The author investigates existing techniques for measuring the sound levels of tires. They do not accurately do this because they do not give meaningful and repeatable data.

Tire noise regulations should be deferred until suitable test procedures are developed. Also regulations should be national not local, the author states and the cost of such regulations to both consumer and manufacturer must be balanced against the benefits.

the in-use measurement of tire sound. How does any enforcer of noise regulations insure he has duplicated the situation upon which the sound level of the regulation is based?

Another area warranting attention is the quality of sound involved; that is, objectionable versus non-objectionable. Acousticians define noise as unwanted or objectionable sound. However, noise is a social phenomenon which can have as many definitions as society has people. For purposes of regulation, noise can have only a statistical or a consensus meaning. For special conditions, such as hospital or school zones, states and localities should consider traffic re-routing, speed constraints, barrier construction, or other solutions before setting unrealistic maximum sound levels on vehicles/tires.

In our passenger car illustration we spoke of an average 1000 lb load placed upon each of four, medium sized tires. What happens when one graduates to highway truck tires where load carrying expectations are greater and the number of tires used per vehicle is increased?

Instead of a 1000 lb load, the highway truck tire sustains a load of 5000 lb. Moreover, truck tires are on vehicles which employ many more tires in close proximity. Obviously the truck at highway speeds is a much more intense source of noise than a passenger car.

Compared to a truck, a single passenger car is a much less important problem as a noise source. Cars can be conceived to be a noise problem only when viewed from the standpoint of sheer numbers of passenger vehicles operating in close proximity in an urban area.

REGULATION OF TIRE NOISE

It becomes evident with research that the presently used methods for measurement of truck tire pavement interaction noise are of questionable adequacy. These methods are also unsatisfactory for measuring the sound levels of passenger cars or even light trucks.

Regulation of tire/pavement interaction noise should be based upon a complete and accurate data base if constructive purposes are to be served. The RMA believes, to date, the art of noise evaluation has not been sufficiently advanced to permit "tire noise" regulation.

The state of California has already authorized the Commissioner of the California Highway Patrol to set noise standards for pneumatic tires. One qualifying provision in Section 27503 of the California Vehicle Code has a direct bearing on current research into tire "Noise".

The proposed California "standards are to be set at the lowest level of noise consistent with economic and technological feasibility, and with public safety". Collective information and research provide current state-of-the-art of several phases of tire noise technology and define a valuable foundation for further work. One can also see that there are many unresolved questions which must be answered before regulation is practical.

RMA is well aware of the highly complex nature of tire noise technology and, while we do not presume to interpret the intentions of the California legislature, this body's reference to noise levels "consistent with economic and technological feasibility" does indicate a similar appreciation of the complexity of the issue. A former National Highway Traffic Administrator touched upon the many expectations we have of the pneumatic tire when he testified before the U. S. House Appropriations Committee in 1970. He stated:

> "The pneumatic tire is probably the most complex component of an automobile. The tire is principally composed of textile fibers and various rubber compounds with several other chemical additives, extenders and modifiers. When inflated with air, the tire must support the vehicle and transmit all steering, driving and stopping forces from the vehicle to the roadway, while providing a comfortable ride to passengers and durability at a reasonable cost to the consumer."

It was recognized by Congress in passing the Noise Control Act of 1972 that although "primary responsibility for control of noise rests with state and local governments, Federal action is essential to deal with major noises in commerce, control of which require national uniformity of treatment. To acheive these goals, Congress designated the Federal EPA as the coordinating and promulgating agency.

In Section 18 of the Noise Act dealing with noise emission standards for in-use motor carriers engaged in interstate commerce, Congress directed that, "no State or political subdivision thereof may adopt or enforce any standard applicable to the same operation of such motor carrier unless such standard is identical to" the standards promulgated under authority of this Section at the Federal level.

The RMA supports Congress' statement in Section 2/a/3 of the Noise Control Act, "national uniformity of treatment" is necessary if uncertainty and confusion on the part of regulators and manufacturers are to be avoided.

A wide array of topical papers are available on the progress tire manufacturers have made in advancing the body of knowledge on the sounds emitted through tire pavement interaction. We expect the industry to be much further along during 1977, but we also recognize the industry's responsibility to bring you abreast of what has been accomplished to date.

The RMA would stress that our findings to date are not a definitive or final study. This distinction should not be overlooked by those who are entrusted by the public with regulatory responsibilities. The drawing of conclusions based upon incomplete data could be particularly dangerous when dealing with a product as complex as the National Highway Traffic Safety Association (NHTSA) and others recognize the pneumatic tire to be.

Mr. Lyle F. Verges, Contributing Editor of "Sound and Vibration" Magazine added a further word of caution in the June 1976 issue when he referred to present sound measurement techniques:

"Our penchant for performing brain surgery with a remarkably dull axe is neither professional nor scientific. It's arrogant and foolish; and it only delays our work and confuses everyone."

Considerable reference has already been made to the Federal Noise Control Act of 1972. It is now time to place that Act in perspective.

Section 6 of the Noise Control Act gives the Federal EPA the authority to establish emission standards for new products "distributed in commerce" which are identified as a "major source of noise."

Heavy and medium duty trucks have been so identified and a regulation has been promulgated which sets an initial requirement of 83 dB(A). This regulation becomes effective January 1, 1978. Further, by 1982, the dB(A) level for heavy and medium duty trucks must be reduced another 3 dB(A), or to a maximum emission level of 80 dB(A). A reduction of a mere 3 dB(A) may seem inconsequential at first glance. However, as we have already noted nothing could be further from the truth. The drop from 83 dB(A) to 80 dB(A) represents cutting the sound power in half. In fact, due to its logarithmic characteristics every increase of 3 dB(A) doubles sound power and, conversely, every decrease of 3 dB(A) halves sound power.

Buses and motorcycles have also been identified as major sources of noise by EPA under Section 5 of the Noise Control Act. Regulations covering those vehicles have not been issued as of the writing of this paper.

Tires, automobiles, and light trucks have not been identified as major sources of noise. They are currently under study by Federal EPA for possible identification and regulation at a later date. Dr. William E. Roper of EPA conducted a meeting on July 16, 1976 for the purpose of receiving information on measurement methodology for automobile and light truck noise. Dr. Roper stated at that meeting that EPA was in the early stages of their study and was anxious to obtain as much information on the subject as possible.

It can be said then that current Federal noise regulations focus on the sound levels of the vehicle. There are no specific "new product" regulations for tires. The only possible exception may be the reference to "closed cavity" truck tire tread design in the Interstate Motor Carrier Noise Emission Standard.

Despite the existence of strict preemptive provisions in the Noise Control Act which apply to EPA regulation of noise emissions from new products (Section 6 (e)) and the operation of interstate motor carriers (Section 18 (c)), there is the potential for some involvement of the 50 states and hundreds of local subdivisions which is not conducive to our stated goal of uniformity of treatment.

STATE AND LOCAL REGULATIONS

In practice, state and local government may affect the market for a new product even though the manufacturer has satisfied federal standards on the new product. This situation could be disruptive and costly to consumers and manufacturers alike since tires are mass produced at relatively few locations for general distribution.

Today, even without EPA identification or regulation of automobiles or tires as major sources of environmental noise, many states and localities have already enacted regulations setting maximum sound emission levels and testing procedures for vehicles. The variations in permissible sound emission levels would go beyond forseeable manufacturing and distribution capabilities. The lack of uniformity in the test procedures prescribed would make compliance very complicated, if indeed possible at all.

There are presently 16 States (Appendix A) which have legislation in effect to regulate the noise levels of vehicles in use and 10 of these regulate the noise levels of new vehicles for sale. If, as may be expected, there are variations from state to state in such important measurement parameters as character of the roadway, environmental conditions, measurement distance, measurement site characteristics and others; the measured sound levels will be different and not be necessarily relatable to one another.

Even when states and localities establish the same dB(A) level as a maximum sound emission standard, their measurement procedures will be governed by local conditions and the results will not be the same. Intuitively, you think you are measuring the same vehicle under what appear to be the same conditions. However, uncontrollable changes in any of the previously mentioned measurement parameters will distort the results. Thrasher, Miller and Bauman in

SAE paper 762011, "Effect of Pavement Texture on Tire/Pavement Interaction Noise" discuss how substantially this particular variable can affect measured sounds.

For the moment, suffice it to say that the manner in which a tire interacts with the pavement to produce sound and the many factors which influence this interaction further complicates a complex situation. Sufficient information has been published to enable us to identify some of the variables that are generally applicable to the tire/pavement interaction which causes noise. They are:

1. Driving Conditions
   Wet Roads - Sound levels increase with wetness, but by different amounts for different tires.
   Vehicle Load - Sound levels increase as load increases.
   Vehicle Speed - Sound levels increase as speed increases.
   Vehicle Configuration - The greater the number of axles the greater the sound level due to the involvement of more tires.
   Tire Inflation - Sound levels decrease as pressure increases.
2. Special Applications
   Traction Aids - State and local regulations requiring traction aids such as snow tires or chains.
   Studs - In winter tires.
3. Roadway
   Pavement Characteristics - Differences in pavement texture caused greater difference in sound generation than existed between the best and the worst of a large selection of tires, including a mud and snow tire on one pavement.
   Federal Highway Department Programs - to texture and/or groove highways to give better traction.
4. Tire Characteristics
   Tire Wear - Normally, as a tire wears it will become noisier during the earlier stages of wear, then quieter as it approaches the minimum legal groove depth of 2/32 in.
   Tread design - Generally more aggressive tread patterns are noisier.
5. Measurement Methodology
   Present Techniques - do not permit fine distinctions among sound levels of various kinds of tires or separate out the contribution of the vehicle and aerodynamic noise.

This list covers many of the variables the federal, state, or local regulator must be aware of when approaching the subject of sounds originating in tire/pavement interaction.

ECOLOGY

In recent years, the regulator has assumed the added burden of society's pressure for rapid ecological improvement. Noise reduction is certainly a part of that movement. The tire industry recognizes that noise reduction is in the public interest and we are supportive of efforts to improve the environment. The industry's concern is that tire regulation not require sacrifices in other important tire characteristics where the public has high expectations for performance, reliability, and safety. We expect this concern to be shared by regulatory bodies as well. They must also live within the constraints of what is economically and technically feasible today.

It should also be recognized that the consumer is not likely to reduce his performance and economic demands of the product. As the sound of the vehicle, or the sound of the tire pavement interactions are lowered by regulation, it may be difficult for consumers to understand why some properties of the tire were sacrificed to achieve satisfactory values for the new noise requirements. Socially motivated demands for environmental improvement will have resulted in tire design changes which may affect such consumer expectations as traction and braking capabilities, ride comfort, durability and wear resistance, etc.

The immediate threat of noise regulation is to the cross lug tire which has proved very valuable to the American truckers, both for traction and for treadwear. Because of treadwear forfeited to noise control, displacement of these tires from the market place will inevitably add many millions of dollars to the tire bills of the nation's truckers, which must be passed on to the consumer.

A further question must be posed. How will noise regulations interact with existing standards which cover tire characteristics other than noise?

Currently there are a number of standards regulating tire safety and performance characteristics. Tire design must involve highway safety as a prerequisite. DOT has specified such requirement for passenger tires in FMVSS 109. At the present time, with regard to truck tires, there are three DOT regulations that come into play: FMVSS 119; 120; and 121.

For example FMVSS 121 establishes minimum stopping distances for trucks, and tires were included as part of the system. The aspects of tire construction and tire design that most strongly influence wet skid resistance are the same aspects which determine the tire's contribution to sound.

There are sometimes, but not always conflicting requirements for good wet skid resistance and low sound levels. However, historically, tread patterns that are best for skid resistance tend to be poorer for noise. L. T. Dorsch in SAE Paper 762032, "Predicting Tire Sound and Performance Interactions," discusses some performance sacrifices that may be required to achieve reductions in the sound levels.

Finally, the question of an adequate test procedure remains unsolved. For trucks, the test procedure generally used for measuring the sound levels of truck tire/pavement interaction (as opposed to total vehicle sound) is SAE J57a or some modification thereof. The experience of the tire industry is reported in SAE paper 762013 "Round Robin Testing with SAE J57a." The feasibility of using the SAE J57a to measure tire/pavement noise levels on the road is very questionable. Mr. Seymour A. Lippmann speaks to this issue in SAE Paper 762035 "The Environmental, Commercial, and Regulatory Implications of the SAE J57a Recommended Practice for Truck Tire Sound Levels" Problems of accuracy and repeatability of the J57a method have not been solved. Even if these problems were resolved, the method is only applicable to the loudest of truck tires and cannot be used for passenger car tires at all.

As limits for vehicle sound levels are lowered, the absence of suitable measuring techniques becomes an increasing concern. There is a need for the development of a laboratory test that would provide repeatable results in the measurement of sound emission levels of new tires. Tire engineers are currently working toward such a goal.

Not only is there concern for the limitations of existing measurement techniques but also for the feasibility of achieving significantly lower sound levels for tires. We are working near the bounds of known engineering principles.

CONCLUSIONS

The passby techniques for measuring the sound levels of tires accurately and independently as a separate entity are not sufficiently developed to give meaningful and repeatable data.

A laboratory method to measure this property free from the complicating influences of road surface, tire wear, speed, weather, etc. is desirable if the test can be made to correlate with highway experience. There are laboratory tests under development that we hope will provide the meaningful, repeatable results desired in the near future.

Tire noise regulations should be deferred until suitable test procedures are developed. Such regulations must be uniform throughout the country. It must be recognized that it is impossible for a mass produced product to comply with differing local regulations each of which has its own diverse regulatory requirements.

Existing safety and performance regulations must be considered when promulgating new noise regulations. Such consideration must take standards such as FMVSS 105, 109, 110, 119, 120, 121 under advisement. Above all, consumer safety must not be sacrificed.

The cost of a regulation to the manufacturer and the consumer must be weighed against the benefits.

This paper has endeavored to set a framework and guidelines against which the papers and panel discussions to come can be assessed. We urge that this framework be kept in mind as the days go on so that each paper and discussion can be viewed in the overall context of this very complicated subject of noise resulting from the tire/pavement interaction.

APPENDIX

The following states currently have in effect decibel emission limitations for motor vehicles by law:

Vehicles in Operation (16)	New Vehicles (10)
California	California
Colorado	Colorado
Connecticut	Florida
Florida	Maryland
Hawaii	Minnesota
Idaho	Nebraska
Indiana	Nevada
Maryland	Oregon
Minnesota	Pennsylvania
Montana	Washington
Nebraska	
Nevada	
New York	
Oregon	
Pennsylvania	
Washington	

\+ Rhode Island passed a statute in 1976 to become effective July 1, 1977.

DISCUSSION

MR. NILSSON: You say that the sound level increased when the tire inflation pressure was decreased. Over what speed range?

MR. CYR: Mr. Englebürger, could you help me with that question?

MR. EAGLEBURGER: The sound level decreases as pressure increases.

MR. HERSHEY: Do you notice that you have had any more trouble meeting the DOT safety standards with radial rib tires as opposed to other types?

MR. CYR: I don't know that this is a question that RMA could very conveniently answer. It would depend on the experience of the various manufacturers. Any one of them may well wish to address themselves to your question.

MR. HILLQUIST: Some of these specific topics will be coming up later in the program. It is a rather broad question to answer.

MR. FULLER: I believe you mentioned that regulation of lug tires out of existence would result in some significant cost increase being passed on to the consumer, but, at the same time, don't you think it is very realistic to also consider that the increased mileage through the use of the radial tire would also be passed on to the consumer through the potential decrease in the average cost per mile?

MR. CYR: I think possibly, Mr. Fuller, that you are just taking my words and turning them around a little bit. We are certainly not against radial tires in any way, shape or form. Possibly you stated it differently than I did. I didn't mean to connote that impression. We do recognize that there is, in certain instances, increased mileage.

MR. LAWTHER: In citing the wide variation in noise as a function of the pavement texture, were you suggesting that the variation was dependent or independent of the ranking of the various treads? In other words, independent of the pavement on which the tires run?

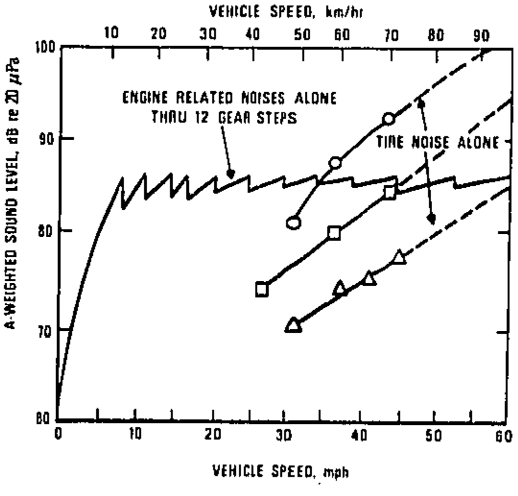
MR. CYR: I think I indicated during the course of the presentation that this meant to simply be an overview of the entire industry position. We are going to go into greater detail on that subject during presentations which will deal specifically with your question.

MR. LIPPMANN: I think that question deserves a direct answer. The ranking does change.

762037

Empirical Model for Predicting In-Service Truck Tire Noise Levels

D. M. Corley
National Bureau of Standards
U. S. Dept. of Commerce



TIRE NOISE

	STEERING AXLE	DRIVE AXLE	TRAILER AXLE
○	NEW RIBS	½ WORN X-BARS	NEW POCKET RETREAD
□	NEW RIBS	NEW X-BARS	NEW RIB RETREAD
△	NEW RIBS	NEW RIBS	NEW RIB RETREAD

Fig. 1 - Engine-related and tire noise for an 18-wheel tractor-trailer as measured 50 ft (15.2 m) from the centerline of the path of travel of the vehicle (6)

FEDERAL INTERSTATE MOTOR CARRIER REGULATIONS (1)* limit the total vehicle noise of interstate carriers in high speed operations. As is evident in Fig. 1, the predominant contributors to this total noise at high speeds are the tires. The question addressed here is: Can the noise level of a combination of tractor and trailer (which represent a complex array of tire noise sources) be confidently predicted by adding together simpler arrays of noise sources (namely tires as measured and specified in a certification measurement such as SAE J57a standard measurement technique (2) plus a simple source representing the engine noise of the truck?

The results of an in-depth study of this question are presented here. Only those details are presented which are necessary to understand the basic process. For further details of the measurement site and measurement techniques as well as specifications of the tires, trucks, trailers and electronic equipment the reader is referred to Ref. 3.

BASIC PROGRAM

The program is best described with reference to Fig. 2. This is a schematic representation of all the tractor-trailer combinations used in the

ABSTRACT

SAE Recommended Practice J57a - Sound Level of Highway Truck Tires - specifies a simple, practical noise certification test procedure for tires which results in a single-number rating - maximum A-weighted sound level - of the coastby sound level measured according to prescribed procedures. Such a rating by itself, however, does not allow prediction of in-service noise levels. This report discusses the basic assumptions and necessary input data for a DOT/NBS developed empirical model which utilizes the certification test results to predict in-service noise levels. The usefulness and expected accuracy of the predictive model are shown through a comparison of measured versus predicted maximum A-weighted sound levels for a variety of truck/tire combinations.

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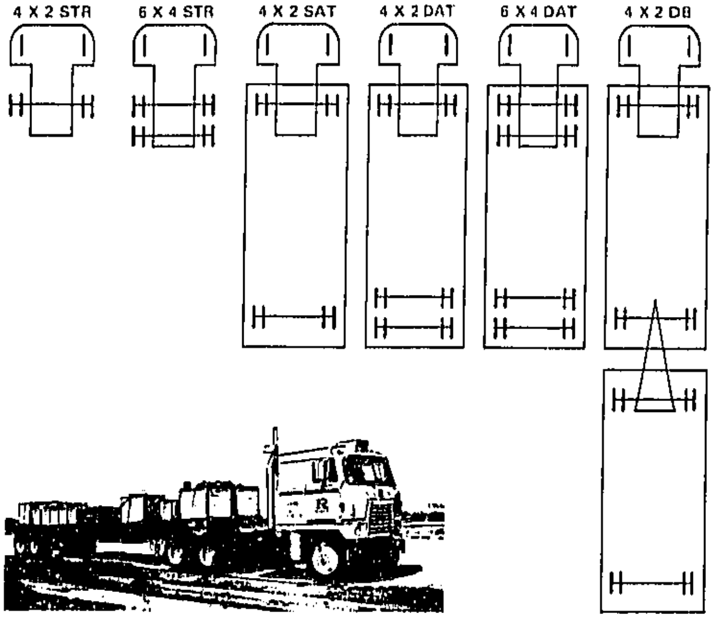
*Numbers in parentheses designate References at end of paper.



6 X 4 TRACTOR WITH DOUBLE-AXLE TRAILER (6 X 4 DAT)

Fig. 2 - Schematic diagram of the combinations of tractors and trailers showing the wheel locations.

tests. The terms 4 x 2 STR and 6 x 4 STR refer to the tractors alone while the designations SAT, DAT, DB are shorthand for single-axle trailer, double-axle trailer and double bottom respectively. A photograph of one of these is given in Fig. 2. This is the 6 x 4 DAT which the reader will recognize as the familiar "18 wheeler".

In all that follows noise generated due to the front (steering) axle is ignored. (In the actual tests the front axle was equipped with the quietest rib tires available). This reduces all the data to combinations of four tire axles. The complex arrays are predicted by adding together the contribution from each axle taking into account differences in load, speed, and spatial separation.

The basic program proceeds as follows:

The input data to the model are obtained from the certification measurements. These data consist of measured A-weighted sound levels versus time. The microphone of the sound level meter was located 50 ft (15.2 m) from the centerline of the path of travel of the 4 x 2 STR at nominally 50 mph (80.5 km/h). These are converted to sound level versus distance data by making use of the measured speed of the vehicles. These data are adjusted for speed to exactly 50 mph (80.5 km/h); they are adjusted for differences between loads and finally added together on an energy basis after appropriate spatial shifting to simulate the geometry of the complex array. The maximum level and the shape of the A-weighted sound level versus distance data can then be compared to measured values. This entire procedure is summarized in Fig. 3.

In this Figure the truck is imagined to be at rest at the center with the zero at the first drive axle.

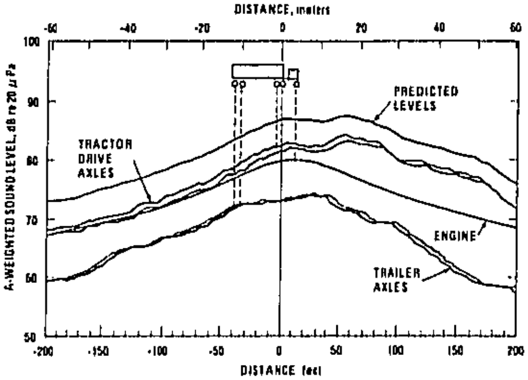
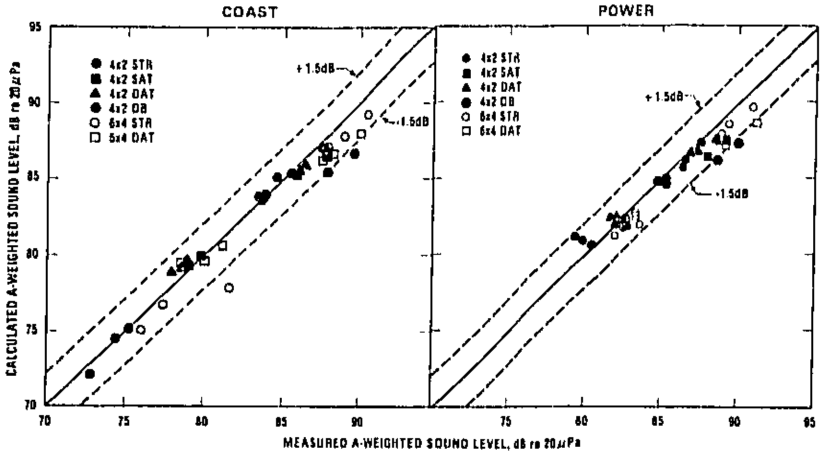


Fig. 3 - Predicted A-weighted sound level versus distance data at 50 ft (15.2 m) for the passby of the 6 x 4 tractor with double-axle trailer at 55 mph (88.5 km/h) in the power mode



	COAST	POWER
AVERAGE DEVIATION (dB)	-.50	-.66
ABS. AVERAGE DEVIATION (dB)	.86	.94
STANDARD DEVIATION (dB)	.90	.99

Fig. 4 - Comparison of calculated and measured A-weighted sound levels for runs at 55 mph (88.5 km/h) in the coast and power modes using linear dependence of sound level on tire load shown in Fig. 5 (dotted line)

Positive distances correspond to positions in front of the truck and represent (in the actual passby) the truck approaching the stationary microphone and vice versa for negative distances. There are four important details of this procedure to discuss.

1. The speed corrections are made assuming a 40 log V dependence of the noise. Three speed corrections are made, first the certification measurements are adjusted exactly to 50 mph (80.5 km/h) because SAE J57a measurement technique calls for this speed, second, after the certification tires are added together to simulate the complex arrays, 1.65 dB (40 log 55/50) is added to raise the effective speed from 50 - 55 mph (80.5 to 88.5 km/h), and finally, the measured complex arrays are corrected to 55 mph (88.5 km/h) because of the 55 mph speed limit on interstate highways. These corrections allow comparability of the simulation of the complex arrays with the measured data at exactly 55 mph (88.5 km/h).

2. All measurements are repeated until the maximum A-weighted sound level of two runs agree to within 2 dB. These two runs are then averaged.

3. The tractors and trailers are loaded to approximately the maximum load permitted by Federal laws. The Federal-Aid Highway Act of 1974 revised Section 127 of Title 23 of the United States Code to permit commercial vehicles to carry a maximum of 20,000 lb (9,072 kg) on a single axle, 34,000 lb (15,422 kg) on tandem axles and 80,000 lb (36,288 kg) total gross combination weight. These limits affect the interstate highway system but provide that any state which allowed higher limits previous to July 1956 may continue those limits in effect on the interstate system.

Since the load on each axle in the actual measured passby can differ from that in the certification passby, sometimes by as much as 3000 lb (1360 kg), adjustments must be made to the sound levels. For this procedure load information is scarce. Measurements are available (4, 5) in only two cases, for approximately 18,000 lb and 6000 lb (8160 and 2720 kg) per axle load. The assumption is made that the variation of sound level with load is linear.

4. Finally, to simulate powered runs, the engine is assumed to be a point source with a sound level of 80 dB at 50 ft (15.2 m) located above the steering axle. This value is obtained from a comparison of the measured powered and unpowered runs.

RESULTS

The results are summarized in Fig. 4. On the left are presented the unpowered measurements (that is, unpowered runs of the complex arrays at 55 mph (88.5 km/h) predicted by the certification measurements at 50 mph (80.5 km/h)) with statis-

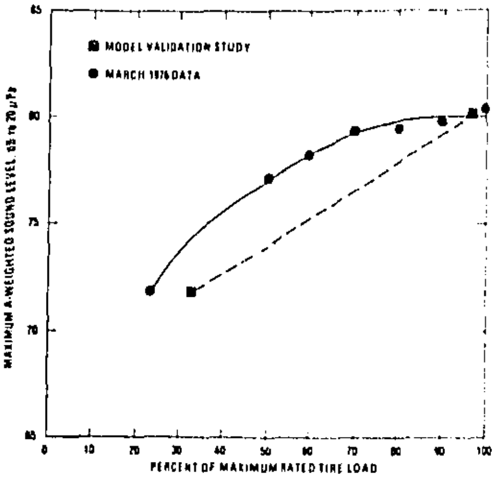


Fig. 5 - Comparison of load data obtained during a March 1976 field test program with the linear relationship used in the model validation study. These data are for coastbys of a 4 x 2 single-chassis vehicle with cross-bar tires mounted on the drive axle operated at 50 mph (80.5 km/h) over an asphalt surface

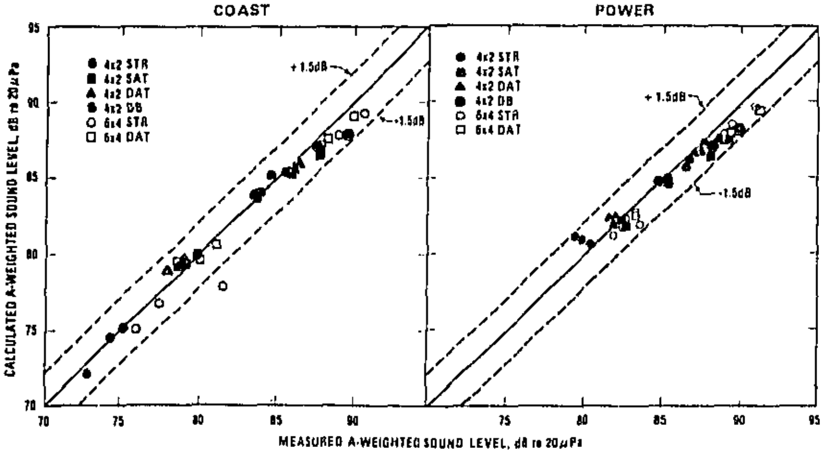
tics below. On the right are presented the powered measurements (that is, powered runs of the complex arrays at 55 mph (88.5 km/h) predicted by the certification measurements at 50 mph (80.5 km/h) plus an 80 dB engine source) with statistics below.

The agreement between the measured and the calculated values is quite good considering the simplicity of the model. There is a slight (but pronounced) tendency for the calculated values to be low at the upper ends of the curves. A major part of this is thought to be due to the linear load corrections which are applied. Recent data (3) suggest a non-linear dependence of noise level on load (see Fig. 5). If this non-linear dependence on load is used, five of the worst data points are markedly improved resulting in the graphs and statistics of Fig. 6.

Since both the average deviation and the standard deviation are less than 1 dB, it is concluded that the model gives accurate estimates of the maximum A-weighted sound level of complex arrays. Before further refinements can be made, more information on the effect of load is required.

APPLICATION

The predictive model can be used to estimate the range of noise level expected in-service from the certification data for tires as is shown in Fig. 7.



	COAST	POWER
AVERAGE DEVIATION (dB)	-.35	-.53
ABS. AVERAGE DEVIATION (dB)	.64	.86
STANDARD DEVIATION (dB)	.68	.81

Fig. 6 - Comparison of calculated and measured A-weighted sound levels for runs at 55 mph (88.5 km/h) in the coast and power modes using the non-linear dependence of sound level on tire load shown in Fig. 5 (solid line).

VEHICLE CONFIGURATION	4 X 2 STR	6 X 4 STR	4 X 2 SAT	4 X 2 DAT	4 X 2 DB	6 X 4 DAT	4 X 2 TB
TOTAL GROSS VEHICLE WEIGHT, POUNDS (kg)	27000 (12247)	43000 (19505)	47000 (21319)	62000 (28123)	80000 (36288)	80000 (36288)	105000 (47628)
A-WEIGHTED CERTIFICATION NOISE LEVEL, MEASURED AT 50 FEET (15.2m) AND 50 mph (80.5 km/hr), dB re 20 μPa	IN-SERVICE MAXIMUM A-WEIGHTED SOUND LEVEL AT 50 FEET (15.2m) AND 55 mph (88.5 km/hr), dB re 20 μPa						
78	85	86	85	86	86	86	86
80	85	86	86	86	87	87	87
82	86	88	87	88	87	88	88
84	88	89	88	89	88	90	88
86	89	91	90	90	90	91	89
90	92	95	92	93	92	95	92
95	97	99	97	98	97	99	96

Fig. 7 - Truck tire noise criteria chart for predicting in-service noise levels at 50 ft (15.2 m) and 55 mph (88.5 km/h) from tire certification noise levels. The tires for which the certification level applies are mounted on the drive axle(s), quiet rib tires on the steering axle and half-worn rib tires on the trailer axles. The engine noise level is assumed to be 83 dB at 50 ft (15.2 m)

Certification levels from 78 - 95 dB representing the span of noise levels from the quietest rib tires through cross-bar types and including the levels of pocket-tread tires are used on the drive axle(s). For the purposes of this demonstration only, half-worn rib tires are used on all trailer axles. The certification levels are taken from actual measurement data adjusted to give the appropriate maximum A-weighted level. The engine is assumed to be an 83 dB (at 50 ft) point source located over the steering axle. This is the maximum allowable engine noise level as specified in the EPA standard for new trucks (effective January 1, 1978). The results are shown in Fig. 7 which includes load data as well as the designation 4 x 2 triple bottom (4 x 2 TB) which is the same as a 4 x 2 DB with an extra dolly and single axle trailer.

As an example of one use of a Table of this sort, one can predict what certification level tires could be used on the drive axles of different combinations and still have the total noise less than 90 dB (the limit of the Federal Interstate Motor Carrier Regulations). This level is shown in Fig. 7 as the bold line running through the Table. A 4 x 2 tractor with double-axle trailer, for instance, should be equipped with tires on the drive axle whose certification level is 84 dB or less in order to meet the 90 dB total vehicle noise limit.

There are at least three variables which have to be considered when utilizing this Table. First, the sound level generated by truck tires is dependent on the state of tread wear and generally increases with wear, in certain cases, as much as 4 - 5 dB (5, 6). Second, the predicted in-service noise levels are dependent on the engine noise level. If this level is greater or less than 83 dB, adjustments have to be made. Third, the noise levels are sensitive to the type of surface on which the tires are run. If enough information about the effects of load, wear and surface on tire noise is obtained, it should be possible to make an accurate prediction of the total noise of a specific vehicle from the knowledge of the tires used along with the load and state of wear.

REFERENCES

1. U. S. Environmental Protection Agency Final Noise Emission Standards, Motor Carriers Engaged in Interstate Commerce, Title 40, Code of Federal Regulations Chapter I, Part 202, U. S. Federal Register Vol. 39 (209), (October 29, 1974), pp. 38208 - 38216.

2. SAE Recommended Practice - Sound Level of Highway Truck Tires - J57a SAE Handbook.

3. R. D. Kilmer, et al., "Empirical Model for Predicting In-Service Truck Tire Noise Level." National Bureau of Standards, U. S. Department of Transportation Report DOT-TST-76T-6, 1976.

4. "Truck Noise-I, Peak A-Weighted Sound

Levels Due to Truck Tires." National Bureau of Standards, U. S. Department of Transportation Report OST-ONA-71-9, 1970.

5. W. A. Leasure, Jr., D. M. Corley, D. R. Flynn, and J. S. Forrer, "Addendum to Truck Noise-I, Peak A-Weighted Sound Levels Due to Truck Tires." National Bureau of Standards, U. S. Department of Transportation Report OST/TST-72-1, 1974.

6. W. A. Leasure, Jr., and T. L. Quindry, "Methodology and Supporting Documentation for the Measurement of Noise from Medium and Heavy Trucks." National Bureau of Standards, NBSIR 74-517, June 1974.

DISCUSSION

MR. CAMPBELL: I don't know whether or not you said it. I don't understand it, but what is the mechanism for adding together noise sources spread out over a 60 ft length to predict a dB reading at a microphone 50 ft away from the path of the truck? How do you handle the geometry problem?

MR. CORLEY: We can go back to that slide we have. I suppose it was the third or the fourth slide. We have the passby data, A-weight versus time, which turns out to be A-weight versus distance for the 4 x 2 truck, so we know in this case how it varies with distance away from the truck. We take, therefore, each of those individual four axles and we shift them spatially by the proper amount and the proper footage, so the maximum lines up the red are fairly close, and the yellow are obviously shifted.

MR. CAMPBELL: What you are saying, then, is that you took a lengthy recording of the dB reading of the tested tires from approach to "S" and you obtain the spatial thing from the lengthy recording?

MR. CORLEY: Correct.

MR. HODGES: On the passby, how would you classify the road surface?

MR. CORLEY: All of this data was taken on asphalt surface.

MR. HODGES: Do you know if it was Federal Highway specification asphalt?

MR. CORLEY: I don't know. Mr. Leasure might be able to answer that.

MR. LEASURE: I would like to answer Mr. Hodges' question. I don't think it is. It was a special high surface strength asphalt test surface at the test ground, and it's important in the sense of levels, but in this sense it is all relative, a single surface.

MR. LAWTHER: To what extent does your prediction model require omnidirectionality of the individual axle sources?

MR. CORLEY: Well, to the extent that you can see in the figure. The agreement is so good that it really doesn't depend on that, at all. In fact, if I understand what you mean by "omnidirectionality", the truck tire noise from the individual axle is very directional. In fact, most of the noise goes out from the back of the truck, and very little of it goes out the side, so that I think, since we obtain good agreement with it, we are looking at the size loads which I think implies that it doesn't depend on that at all.

MR. LANDERS: When testing some of those larger configurations for our customers, in some cases we found that we couldn't just add sources, and that apparently there was some cancellation or some other phenomenon going on.

MR. CORLEY: In one case we found that out here; that one point.

MR. LANDERS: Then you did see that?

MR. CORLEY: We don't know how to explain the one point that occurred. As I remarked, we took special pains to do double runs to make sure we weren't obtaining any wild runs. One of the things that happens when you perform truck passbys is that you obtain data that varies 5 dB(A) off the rest of the data. We still have a mystery point that we can't explain. I don't know why it falls so far away.

CONTRIBUTED COMMENT
R. F. Miller

The concept of synthesizing the passby noise level of a tractor-trailer combination from simple tire and engine noise measurements would appear to be desirable and useful. However, such a procedure can be quite misleading considering the variables in the measurements. The following are some of the major problems which are not discussed in the paper.

Pavement texture is an extremely important contributor to the so-called "tire noise". (1) If the initial SAE J57a levels for rib tires are obtained on low texture pavement and the tractor-trailer combination is run on a high texture pavement, the level contributed by the tire/pavement interaction can exceed its prediction by 8 dB. (See Fig. 12, Ref. 1). This is under conditions requiring none of the uncertain adjustments for load, speed, and engine noise.

The basis for choosing the initial data can lead to another problem. "Measurements are repeated until the maximum A-weighted sound level of two runs agree to within 2 dB. These two runs are then averaged."

Fig. 5 of Ref. 2 shows that by such means we could obtain an average of +2.2 or -1.2 dB different from overall average of the first set of tires. In other words, the initial data used to calculate the composite could vary by at least 3.4 dB.

An idealized passby sound level temporal shape was shown. However, the passby peak takes on many different shapes. Often the main peak is double pronged, with one prong before and one after the microphone line. The higher level varies between them from run to run. The intervening valley is as much as 4 dB below the lower prong. The spacing of these prongs of the major peak is as much as 80 ft of truck travel. This would appear to make the geometry of the calculation extremely uncertain.

Ignoring the tires on the front axle on the basis of using "the quietest rib tires available" is a dangerous procedure. Furthermore, it betrays a lack of understanding of the very basis of tire/pavement interaction noise. The tractor-trailer combination may be used on a pavement texture which causes "the quietest rib tires available" to be as noisy as lug tires.

Another point that was not discussed is that the SAE Recommended Practice J57a specifies slow response for the sound level meter, while regulations require the use of fast response which gives variably higher readings. This would appear to require yet another uncertain adjustment.

This technique of synthesizing the noise level of a tractor-trailer combination seems to be a precarious procedure at this time.

REFERENCES:

1. D. B. Thrasher, R. F. Miller, and R. G. Bauman, "Effect of Pavement Texture on Tire/Pavement Interaction Noise." P-70, Highway Tire Noise, November, 1976. Paper 762011.
2. R. F. Miller and D. B. Thrasher, "Passby Tire/Pavement Interaction Noise Measurement Problems." P-70, Highway Tire Noise, November, 1976. Paper 762012.

APPENDIX I

SOUND LEVEL OF HIGHWAY TRUCK TIRES—SAE J57a

SAE Recommended Practice

Report of Vehicle Sound Level Committee approved July 1973 and last revised June 1976. Approved by American National Standards Institute November 1976. Rationale Statement available.

1. Introduction—This SAE Recommended Practice establishes a test procedure for measuring the sound level produced by tires intended primarily for highway use on motor trucks, truck tractors, trailers and semitrailers, and buses. The procedure provides for the measurement of the sound generated by a set of test tires, mounted on the rear axle operated at 80 km/h (50 mph) and at maximum rated tire load.

Specifications for the instrumentation, the test site, and the operation of the test vehicle are set forth to minimize the effects of extraneous sound sources and to define the basis of reported sound levels.

Factors influencing sound level measurement and reference to sound levels are given in the Appendix.

2. Instrumentation—The following instrumentation shall be used for the measurements as required:

2.1 A sound level meter which satisfies the Type 1 requirements of American National Standard Specification for Sound Level Meters, S1.4-1971.

2.1.1 As an alternative to making direct measurements using a sound level meter, a microphone or sound level meter may be used with a magnetic tape recorder and/or a graphic level recorder or other indicating instrument, providing the system meets the requirements of SAE J184, Qualifying a Sound Data Acquisition System, with slow response specified in place of fast response as applicable to paragraph 3.6 therein.

ϕ 2.2 An acoustical calibrator, having an accuracy of ±0.5 dB, for establishing the calibration of the sound level meter and associated instrumentation.

ϕ 2.3 An anemometer having an accuracy of ±10% at 19 km/h (12 mph).

3. Test Site

3.1 The test site shall be located on a flat area which is free of reflecting surfaces (other than the ground), such as parked vehicles, trees, or buildings within 30 m (100 ft) of the measurement area.

3.2 The vehicle path shall be relatively smooth, semipolished, dry, Portland cement concrete which is free of extraneous surface material.

3.3 The microphone shall be located 15 m (50 ft) from the centerline of the vehicle path at a height of 1.2 m (4 ft) above the ground plane. The normal to the vehicle path from the microphone shall establish the microphone point on the vehicle path. See Fig. 1.

3.4 The test zone extends 15 m (50 ft) on either side of the microphone point along the vehicle path. The measurement area is the triangular area formed by the point of entrance into the test zone, point of exit from the test zone, and the microphone.

3.5 The measurement area should be surfaced with concrete, asphalt, or similar hard material and, in any event, shall be free of snow, grass, soil, ashes, or other sound-absorbing materials.

3.6 The ambient sound level (including wind effects) at the test site shall be at least 10 dB below the level of the test vehicle operated in accordance with the test procedure.

3.7 The wind speed in the measurement area shall be less than 19 km/h (12 mph).

4. Test Vehicle

4.1 The vehicle shall be a motor truck equipped with two axles (a nonpowered steering axle and a powered axle).

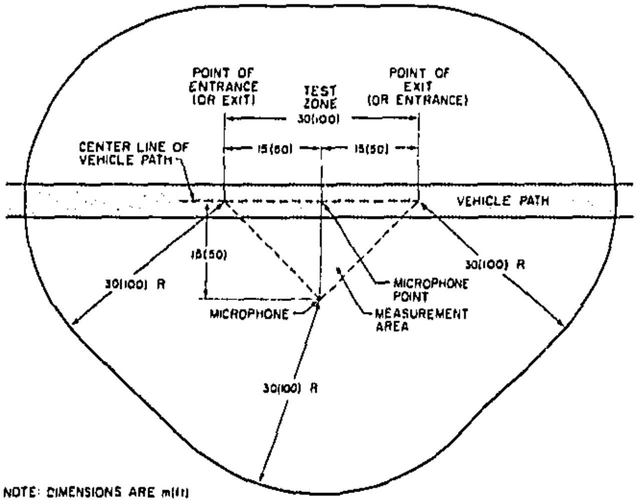
4.2 The vehicle shall have a platform, rack, or van body capable of retaining the loading or ballast. This body shall have an essentially flat and horizontal undersurface, and be mounted such that this surface has a 230 ± 100 mm (9 ± 4 in) clearance with the tire fully loaded. This body shall be nominally 2440 mm (96 in) in width and extend a minimum of 910 mm (36 in) rearward of the rear (powered) axle centerline.

4.3 Mud flaps should be removed at the test site, if permissible.

5. Tires

5.1 Tires used for dual installations shall be dual mounted (four tires) on the rear axle for testing. Tires used in single installations (wide base) shall be mounted singly. A tire used as both duals and singles may require test at both dual and single mounting. The sound level reported must be identified as to type of mounting.

5.2 The tires shall be inflated to the maximum pressure and loaded to the maximum load specified by the Tire and Rim Association for continuous operation at highway speeds exceeding 80 km/h (50 mph).



NOTE: DIMENSIONS ARE m(ft)

FIG. 1—TEST SITE (SEE PARAGRAPH 3) (VEHICLE MAY BE RUN IN EITHER DIRECTION)

5.2.1 If local load limits will not permit full rated load, the test may be conducted at the local load limit with inflation pressure reduced to provide a tire deflection equal to the maximum load and inflation pressure, provided the load is not less than 75% of the maximum rated load.

As an alternative, the pressure in the tires can be adjusted to correspond to the actual load following the appropriate load/pressure tables in the Tire and Rim Association Yearbook. Because the choice of procedure may cause small differences in level, such levels shall not be reported unless they are identified with the percent load used.

5.3 Quiet tires are recommended for use on the front axle.

6. Procedure

6.1 The test vehicle shall be operated in such a manner (such as coasting) that the sound level due to the engine and other mechanical sources is minimized throughout the test zone. The vehicle speed at the microphone point shall be 80 km/h (50 mph).

6.2 The sound level meter shall be set for slow dynamic response and the A-weighting network. The observer shall record the highest level attained during each pass of the test vehicle, excluding readings where known acoustical interferences have occurred.

6.2.1 Alternatively, each pass of the test vehicle may be recorded on magnetic tape and subsequently analyzed with a sound level meter and/or graphic level recorder.

6.3 There shall be at least three measurements. The number of measurements shall equal or exceed the range in decibels of the levels obtained.

6.4 The sound level reported shall be the average of the two highest readings which are within 2 dB of each other.

7. General Comments

7.1 It is recommended that technically competent personnel select the equipment to be used for the test measurements and that these tests be conducted only by persons familiar with the current techniques of sound measurement.

7.2 All instrumentation should be operated according to the practices recommended in the operating manuals or other literature provided by the manufacturer. All stated precautions should be observed. Some specific items for consideration are:

7.2.1 Specifications for orientation of the microphone relative to the ground plane and the source of sound should be adhered to. (Assume that the sound source is located at the microphone point.)

7.2.2 Proper signal levels, terminating impedances, and cable lengths should be maintained on all multi-instrument measurement systems.

7.2.3 The effect of extension cables and other components should be taken into account in the calibration procedure.

7.2.4 The position of the observer relative to the microphone should be as recommended.

7.3 Instrument manufacturer's recommended calibration procedure and schedule for individual instruments should be employed. Field calibrations should be made immediately before and after testing each set of tires.

7.4 Not more than one person, other than the observer reading the meter, shall be within 15 m (50 ft) of the vehicle path or the microphone, and that person shall be directly behind the observer reading the meter, on a line through the microphone and the observer.

7.5 The sound level of the tires being tested is valid only when the sound level of the vehicle equipped with quiet tires is at least 10 dB below that of the vehicle equipped with test tires. The sound levels obtained with this procedure may be used for a relative ranking of the test tires, if the sound level of the vehicle equipped with the quietest tires available is 3–10 dB lower than when equipped with the tires being tested.

8. Reference Material—Suggested reference material is as follows:

8.1 ANSI S1.1-1960 (R1971), Acoustical Terminology

8.2 ANSI S1.2-1962 (R1971), Physical Measurement of Sound

8.3 ANSI S1.4-1971, Specification for Sound Level Meters

8.4 SAE Recommended Practice J184, Qualifying a Sound Data Acquisition System

8.5 Tire and Rim Association Yearbook

8.6 SAE Publication SP-373, Truck Tire Noise

8.7 G. R. Thurman, "Effect of Road Surface and Bed Clearance on Truck Tire Noise." Paper 740607 presented at SAE West Coast Meeting, Anaheim, California, August 1974.

The ANSI documents are available from the American National Standards Institute, Inc., 1430 Broadway, New York, New York 10018.

APPENDIX

A1. An A-weighted sound level not exceeding 85 dB, determined in accordance with this recommended practice, is consistent with present best current practice for cross ribbed tires in normal states of wear. It is general experience that the sound level of unworn tires is significantly less than that of worn tires.

A2. Road surfaces are known to significantly affect the sound levels generated by highway truck tires. Rib type tires generally produce lower sound levels on smooth surfaces than on surfaces having a textured finish such as that brushed in during construction. Differences as great as 5 dB have been observed between sound levels obtained on very smooth and coarse concrete surfaces for tires producing relatively low levels of sound. For cross-ribbed tires, however, generated sound levels have been found to not differ by more than approximately 1 dB for given tire types on a variety of Portland cement concrete surfaces judged to be relatively smooth. For these reasons, the vehicle path description in paragraph 3.2 is sufficient to provide for reproducible sound levels for cross-ribbed tires, within the expected accuracy of such measurements (±1 dB), and to provide surface-dependent relative sound levels for rib type tires.

A3. Persistence of tire sounds after the passage of the vehicle and the tonal components of these sounds are properties of certain types of tires which tend to occur concurrently. Both are factors that direct attention to the sound, and are important determinants of the acceptability of the sound.

APPENDIX II

ATTENDEES - HIGHWAY TIRE NOISE SYMPOSIUM

1.	ABDOO, Dennis A.	Mohawk Rubber Co.
2.	ALLEN, J.	Battelle Columbus Labs
3.	ANDERSEN, Alan J.	Owner Tire & Rubber Co.
4.	ANDERSON, Richard	Garrett Freightlines, Inc.
5.	APPLEGATE, Lohren	California Trucking Assn.
6.	BEMELL, Paul	Bandag, Inc.
7.	BRESETTE, Anne Marie	Michelin Americas R & D Corp.
8.	BRETAG, Gerald D.	Consolidated Freightways
9.	BURROUGHS, Courtney B.	Bolt Beranek & Newman
10.	CANTWELL, William C.	Department of Mechanical Engineering
11.	CARANO, Jim	Mohawk Rubber Co.
12.	CLARK, Samuel K.	University of Michigan
13.	CLENDENEN, Don	Firestone Tire & Rubber Co.
14.	COULTER, John E.	Ontario Ministry of Environment
15.	CROWELL, Larry W.	Firestone Tire & Rubber Co.
16.	DAMIAN, John U.	Ford Motor Co.
17.	DAVIS, George F.	B. F. Goodrich Co.
18.	DENCKLAU, Roy	Toyo Tire (U.S.A.) Corp.
19.	DIMAGGIO, A. J.	Firestone Tire & Rubber Co.
20.	DYE, Edward R.	The General Tire & Rubber Co.
21.	FOXWORTH, Marvin	Automotive Research Assn. Inc.
22.	FREUND, Adam A.	Standards Testing Laboratories, Inc.
23.	FULLER, Bill	Wyle Laboratories
24.	GALE, John B.	Armstrong Rubber Co.
25.	GIBSON, Gary E.	B. F. Goodrich Tire Co.
26.	GRAFMILLER, G. B.	Yellow Freight System
27.	GRAY, Damon C.	U.S. Environmental Protection Agency
28.	GRIMALDI, Frank	Michelin Tire Corp.
29.	HATANO, Mas	California Department of Trans.
30.	HAUGH, Rooney E.	Rubber Manufacturers Assn.
31.	HEATH, Warren	California Highway Patrol
32.	HERSHEY, Dr. Robert L.	Booz Allen Applied Research
33.	HILL, Gene	Consolidated Freightways
34.	HINDIN, H. B.	H. B. Hindin Associates
35.	HOLT, Bob	Bandag, Inc.
36.	HOWELL, Thomas M.	Ford Motor
37.	HUTCHINSON, Joe F.	Goodyear Tire & Rubber
38.	JENSEN, Jim	Peterbilt Motors Co.
39.	KEELER, W. G.	Mansfield Tire & Rubber Co.
40.	KING, Michael J.	Oliver Tire & Rubber Co.
41.	KLINGMANN, Horst	Michelin Tire Corp.
42.	KRIVONEN, Arvo	Consolidated Freightways
43.	KURTZ, Don	Jet Propulsion Laboratory
44.	LACIS, Andris	UniRoyal Tire Co.
45.	LAWTHER, James M.	Penn State University
46.	LEE, Robert F.	Kelly Springfield Tire Co.
47.	LEONG, Robert K.	Transport Canada
48.	MACDONALD, Ken	Commercial Car Journal
49.	MCCOLLAR, Dave	Bandag, Inc.
50.	MILLER, Nicholas A.	International Harvester Co.
51.	MIZOGUCHI, Max T.	California Highway Patrol
52.	MOLLOY, Dr. Charles T.	U.S. Environmental Protection Agency
53.	MOON, Charles L.	White Motor Corporation

54.	MURPHY, Kerry J.	N. D. T. R. A. - Murphy's Inc.
55.	MURPHY, Ray W.	Freightliner Corp.
56.	OBERT, Lt. M. J.	Washington State Patrol
57.	OSBORNE, J. R.	Dunlop Tire & Rubber Corp.
58.	PENN, Gary R.	Noise & Vibration Laboratory
59.	RAABE, Ralph	Bandag, Inc.
60.	RATERING, Edwin G.	G. M. Technical Center
61.	RIPLEY, J. E.	Goodyear Tire
62.	SANKEY, J. R.	Cooper Tire Co.
63.	SCARTON, Maynard	McCreary Tire & Rubber Co.
64.	SEARS, W. James	Rubber Manufacturers Assn. Inc.
65.	SEKULA, Paul J.	Firestone Tire & Rubber Co.
66.	SCHWALL, Chester F. Jr.	The Armstrong Rubber Company
67.	SCHWERDTFEGER, Henry	Michelin Tire Corporation
68.	SHEPHARD, Sterling	Michelin Tire Corporation
69.	SMITH, Derek	Peterbilt Motors Co.
70.	SMITH, Harry R.	General Tire & Rubber Co.
71.	SMITH, William A.	Kelly Springfield Tire Co.
72.	SWING, Jack W.	California Office of Noise Control
73.	TALIN, George	Talin Tire Inc.
74.	TREE, David R.	Purdue University - Herrick Labs
75.	VOKE, Frances S.	B. F. Goodrich Co.
76.	WALSH, James A.	The Armstrong Rubber Co.
77.	WILLIAMS, T. M.	Yellow Freight System
78.	WILLS, Jim	Tri-Texas Inc.
79.	WIREMAN, Jack	A. M. F.
80.	WOODWORTH, Robert G.	Pacific Intermountain Express
81.	WOOTTEN, E. J.	B & K Instruments
82.	ZUZACK, William A.	McCreary Tire

APPENDIX III

RELATED SAE PAPERS

There have been many papers presented at SAE meetings in the past that form a foundation for the papers and discussions at the Highway Tire Noise Symposium. The following listing contains those papers published over the last ten years which are pertinent to the theme and objective of the Symposium.

Note: Copies of these papers can be purchased from SAE. For information contact Publications Division, Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, Pennsylvania 15096.

660375 Performance Requirements for Passenger Car Tires. J. J. Goudie, Jr., Firestone Tire and Rubber Co.

660377 Improvement in Materials in Passenger Car Tires. J. A. Davisson, Goodyear Tire and Rubber Co.
SAE Trans., Vol. 75

660378 Performance Comparison - 2-Ply versus 4-Ply Passenger Car Tires. R. F. Bogan and W. J. Dobie, United States Rubber Tire Co.
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