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An Evaluation and Assessment of Existing Data and Procedures for Tire Noise Measurement

Applied Acoustics Section
Institute for Basic Standards
National Bureau of Standards
Washington, D. C. 20234

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Final Report

Prepared for
Office of Noise Abatement and Control
U. S. Environmental Protection Agency
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Table of Contents

Medium and heavy trucks were one of the initial major noise sources identified by EPA. Truck noise can be categorized as the noise produced by the propulsion system -- engine, exhaust, intake, cooling fan, etc. -- and by the tire-road interaction. During development of noise emission regulations for new medium and heavy trucks, it became apparent to EPA that regulating total truck noise would not be a very effective means for controlling tire noise. Therefore, EPA decided to regulate trucks and tires separately. It is assumed that this strategy will also apply to other vehicular noise sources, e.g., automobiles.

Tire noise is primarily produced by the interaction of the tire with the roadway. Accordingly, tread design and road texture are the major factors in the production of tire noise. Other parameters which influence the tire-road interaction process, such as tread wear, speed, load, etc., also can have an influence.

The importance of tire noise is emphasized by ongoing demonstration projects, data from which indicate that, utilizing available technology, the overall noise from diesel trucks, due to sources other than tires, can be reduced to levels comparable to passenger cars. When such technology is routinely incorporated into production trucks, as a result of the new medium and heavy duty truck noise emission regulations, tires will be an even more predominant noise source for high speed motor vehicles than they are at present.

This report reviews existing tire noise measurement procedures with regard to their usefulness in the regulation of tire noise as well as the availability, extent and applicability of existing data. On the basis of this review, the following probable or potential measurement difficulties have been identified which could hinder the promulgation and/or enforcement of future EPA regulations to control the noise emission from tires.

- NEED TO DEVELOP A TEST PROCEDURE TO MEASURE THE NOISE LEVEL OF A SINGLE TIRE. The present test procedure specifies that the test tires are to be mounted either singly (for tires used in single installation, i.e., wide base -- two tires) or in dual pairs (for tires used in dual installations -- four tires) on the rear axle of a single-chassis vehicle. Quiet tires are to be mounted on the steering axle. Using this test procedure, an axle of test tires and -- although not of interest -- an axle of steering tires are evaluated. Thus, the noise level for four, or more typically six, tires is measured rather than the noise level for a particular tire. Therefore, there exists the need to develop a test procedure that allows the evaluation of the noise level of a single tire and not an axle of tires.

- NEED TO QUANTITATIVELY CHARACTERIZE PAVEMENT TEXTURE. There exists a need to extend the data base regarding the influence of pavement roughness on tire noise levels. Since the noise generated by tires can vary significantly between different pavements, there exists a need to develop a method of quantitatively characterizing pavement surface texture which can be correlated with tire noise levels. This quantitative measure is necessary to establish a standard test pavement texture (or place bounds on allowable test pavements) for tire testing and to serve as the basis for comparison of tire noise data measured on different surfaces.

- NEED TO INVESTIGATE THE EFFECTS OF TIRE SIZE. An insufficient amount of data exist in the public domain to determine the effect tire size has on the generation of tire noise levels, i.e., the tire size for which maximum noise is produced. Considering the wide range of tire sizes currently available for passenger cars, trucks and other motor vehicles, it is important to determine if all tire sizes must be measured or if a single size can be measured that would represent the maximum noise level for a particular carcass construction/tread design combination.

- NEED TO ESTABLISH APPROPRIATE METER RESPONSE FOR MEASUREMENT OF TIRE NOISE. The existing tire noise measurement standard specifies the use of the "slow" meter response; however, nearly all of the data existing in the public domain were measured using "fast" meter response. Studies of the correlation between the maximum A-weighted sound level (with "slow" response and "fast" response) and human reaction to tire noise do not clearly establish a preferable meter response characteristic. The sound levels measured using "fast" and "slow" meter responses can vary by as much as three decibels; therefore, when existing data are utilized to establish noise limits for tire noise emission regulations, particular attention should be paid to both the noise level and the meter response used for the measurement.

- NEED TO MEASURE TIRE NOISE AT THE STATE OF WEAR THAT PRODUCES MAXIMUM NOISE. 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. The radiated noise from tires, as a function of tread wear, can not be predicted analytically as yet. Therefore, it is necessary to conduct costly and time-consuming noise measurements with in-service worn tires, in order to establish a relationship between tread wear and tire noise.

- NEED TO ACCOUNT FOR ENVIRONMENTAL/SITE EFFECTS. There is a need to systematically investigate the influence of various environmental and test site effects on noise generation, radiation and/or propagation and to develop correction factors so that measurements made under any conditions may be corrected to a single standard set of conditions. If correction factors are not feasible then there is a need for a site calibration procedure or definition of limiting test conditions.

- NEED FOR SIMPLER NOISE MEASUREMENT TEST PROCEDURE. There exists a need to develop a test procedure that is simpler to perform than SAE J57 and is less dependent on weather and test site variables. Correlation should be established between the results -- i.e., the acoustic quantity measured -- obtained utilizing such a test and human response to tire noise.

- NEED TO BETTER SPECIFY TRANSIENT RESPONSE OF INSTRUMENTATION. There exists a need to measure the response of existing instrumentation to actual transient signals, e.g., a vehicle passby, in order to establish the relationships among the various precision instruments, to supply data to strengthen existing standards, and to establish a data base so that the technical community, manufacturers, lawmakers and enforcement agencies will have a common basis for comparison of results obtained using supposedly comparable equipment.

Even though existing understanding of tire noise source mechanisms is at a primitive level, existing tire noise data and test facilities can serve as the foundation for development of an appropriate measurement methodology for the regulation of tire noise emission. Additional data are necessary to determine the tire size (or sizes) that need to be certified and the allowable range of surface textures for a standard test site needs to be defined. In addition, it would be desirable to develop a test procedure for the evaluation of a single tire rather than an axle of tires (plus the two steering axle tires) as is the case in the existing procedure.

The knowledge necessary to design a tire significantly quieter than conventional tires with rib tread designs does not presently exist. A blank tire (full tread depth but no tread pattern) on a smooth surface generates a sound level 2-4 decibels lower than some rib tires currently in use. A major breakthrough in the state-of-the-art of tire carcass design would be necessary to significantly decrease the noise generated by conventional tires.

AN EVALUATION AND ASSESSMENT OF EXISTING DATA AND PROCEDURES FOR TIRE NOISE MEASUREMENT

This report reviews existing tire noise measurement procedures with regard to their usefulness in the regulation of tire noise as well as the availability, extent and applicability of existing noise data. On the basis of this review, probable or potential measurement difficulties are identified that could hinder the promulgation and/or enforcement of future EPA regulations to control the noise emission from tires.

Key Words: Acoustics (sound); measurement methodology; noise emission standard; noise measurement; tires; traffic noise.

1. Introduction and Scope

The U. S. Environmental Protection Agency (EPA) is charged with taking strong comprehensive action to protect public health and welfare from increasing noise. Vehicular traffic noise continues to be a major source of community annoyance; therefore, one of the first major noise sources identified was medium and heavy trucks.

Truck noise can be categorized as the noise produced by the propulsion system [including engine, exhaust, intake, cooling fan, etc.] and by the tire-road interaction. At moderate to high speeds the noise from tires typically dominates, provided the vehicle is equipped with a reasonably good exhaust muffler and is in a good state of repair. The exact speed at which the tire-roadway noise starts to predominate power-plant-associated noise is a 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 the following two alternative approaches to controlling truck noise: (1) regulation of the complete truck, including tires, and (2) 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 speeds[1/] and therefore, would not satisfy the need to protect health and welfare by lowering community noise levels, EPA decided to regulate tires and trucks separately. It is assumed that this strategy will also apply to other vehicular noise sources, e.g., automobiles.

For this reason, EPA identified tires as a candidate major noise source (see Federal Register, Vol. 40, No. 103, Wednesday, May 28, 1975, pp. 23105 -

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[1/] The breakdown of shipments of new truck tires in 1974 which totaled over 34 million indicated 34.6 percent were original equipment, 62.2 percent were for after-market replacement and 3.2 percent 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 (see Table 1). This coupled with the fact that the majority of tires on the market today could meet the noise 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.

23107). In anticipation of the identification of tires as a major noise source, the National Bureau of Standards (NBS) under the sponsorship of the EPA Office of Noise Abatement and Control (ONAC), has attempted to identify probable or potential measurement difficulties that could hinder the promulgation and/or enforcement of future noise regulations to control the noise emissions from tires. A search of the open literature in conjunction with numerous personal contacts established the basis for discussion of the following topics:

1. The basic characteristics of tire design.

2. The tire industry structure.

3. The effect of tire noise on people and the parties affected.

4. The usefulness of existing measurement procedures for regulation of the noise from tires considering the viewpoint of EPA, manufacturers and enforcement personnel.

5. The availability, extent and applicability of existing data that could be utilized by EPA in its efforts to promulgate noise emission regulations for tires.

This report is limited to those factors affecting the measurement of tire noise. EPA/ONAC will independently investigate the technical feasibility and economic implications of tire noise regulation.

2. Tire Design

Before proceeding into a discussion of tire noise, it is important to briefly describe basic tire-performance functions and representative tire designs.

Basic tire functions essential to performance include load carrying, cushioning (more so for automobiles than trucks), transmission of driving and braking torque, and development of cornering and directional-stability forces. To be economical to the operator or user, the tire must resist abrasion, roll freely, and be durable. During the design of a tire these basic functions and properties of tires are related to the basic tire designs, to factors affecting fundamental stress relationships within the tire, to the tire's performance characteristics, and, ultimately, to the criteria for application of the tire in service. The tire structure and materials must be balanced with the anticipated stress environment, while heeding the prerequisites of efficient manufacturing practices at a minimum cost. There are many design alternatives, and considerable latitude exists within each one. However, due to the many conflicting effects of these alternatives, the design process is basically one of determining the operable range of a structure, component, or material and selecting that which offers the optimum balance of characteristics. Wear and traction requirements have a dominant influence over the geometry selected for the tread elements, but factors such as tread stability, manufacturing requirements, and tread noise are also considered.

The structure of the tire defines the type, number, location and dimensions of various components used in its composition. Structural regions and components of a bias-ply tire are shown in Figure 1[1][2/]. The conventional tire comprises three primary structural components: (1) the rubber matrix which contains the air and provides abrasion resistance and road grip, (2) the cords which reinforce the rubber and carry most of the load applied to the tire in service, and (3) the beads which circumferentially connect the tire to the rim. The secondary components, such as chafers, flippers, and breakers, reinforce or protect the primary components from high-stress concentrations by distributing forces over greater areas or through materials capable of withstanding particular stress conditions. These components, with air under pressure, form a thin-walled composite which is both highly flexible and relatively inextensible.

There are three principal types of tires, as shown in Figure 2, in use today -- the bias-ply, bias-belted, and radial-belted tires. In the bias-ply tire, the cords in adjacent plies cross the meridian of the tire at opposite and approximately equal angles. The bias-belted tire consists of a bias-ply carcass with a constraining belt. The ply cords in the radial-belted tire extend radially from the beads and are normal to the meridian of the tire.

The tread is an important consideration for both the user and manufacturer of tires. Tread wear is the most obvious factor of endurance since it is the parameter that undergoes the most obvious physical change and thus is identified directly with economic value.

Tread design is simply the division of a smooth tread into smaller elements. The tread elements are usually arranged within the pattern to give the tread design directional tractive characteristics as well as a specific ratio of net-to-gross contact area. The main purpose of tread design is to allow for water drainage.

Tread patterns can be categorized into three basic types -- rib (continuous or discrete block), cross-bar and pocket (Figure 3). Rib designs are the most common type and possess characteristics that are suitable for all wheel positions. With the major tread elements oriented in the circumferential direction, these tires are noted for their lateral traction and uniform wear characteristics. Rib tires are typically utilized at all four wheel positions of automobiles (except when the winter weather dictates the use of snow tires on the drive axle). Many trucks also utilize rib tires at all wheel positions and nearly all trucks have rib tires mounted on the steering and trailer axles.

Cross-bar tires, with the major tread elements oriented in the lateral direction, are used primarily on the drive axles of both automobiles (snow tires) and trucks. This design gives maximum driving traction in mud and snow conditions and provides a much more rigid tread structure plus added original tread depth.

The pocket-tread pattern is not a design used by major tire manufacturers but represents the work of independent retread companies. This design should

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[2/] Numbers in brackets indicate the literature references at the end of this report.

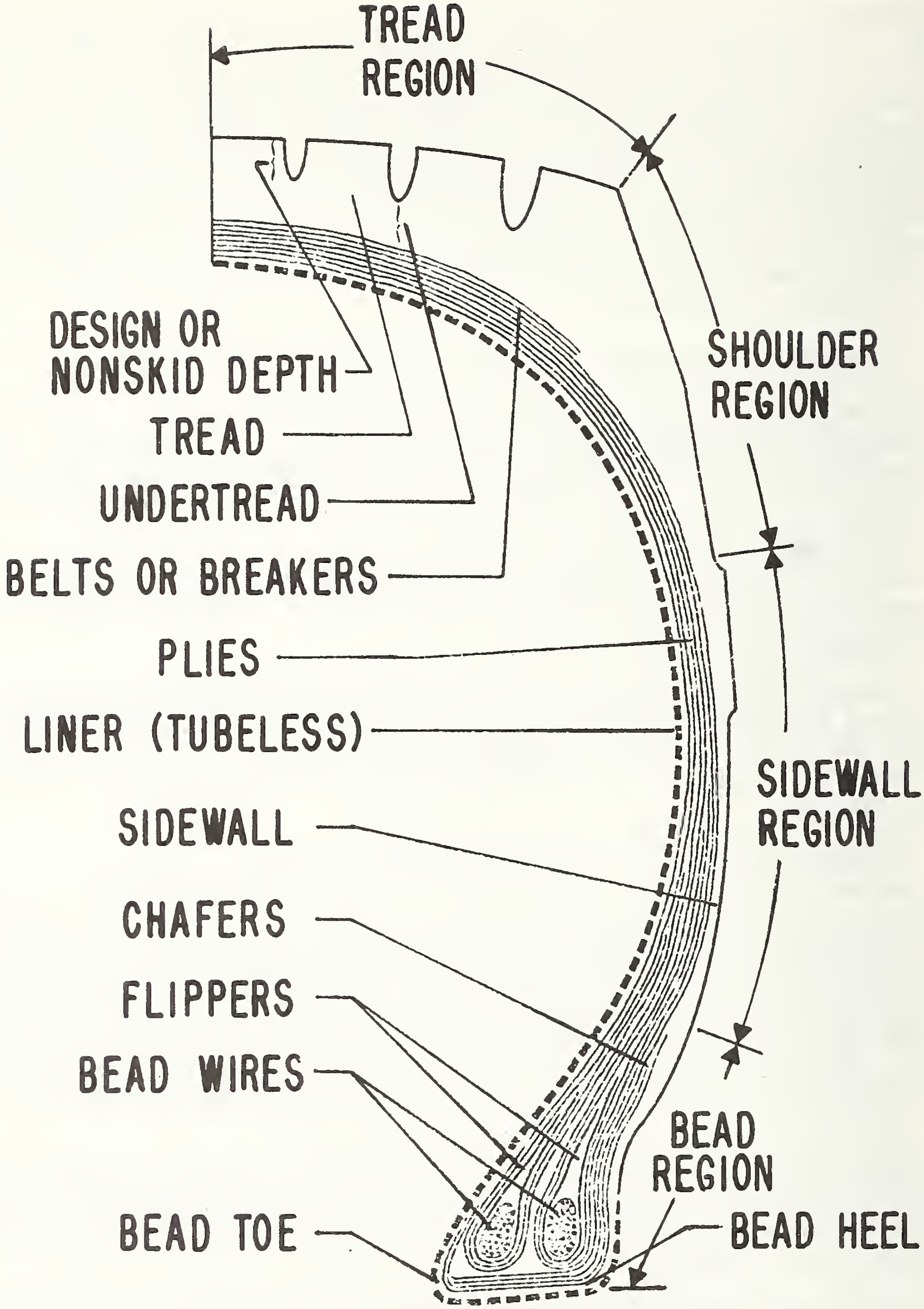
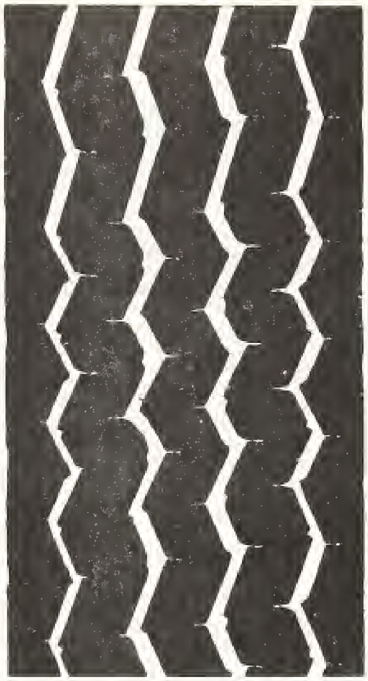
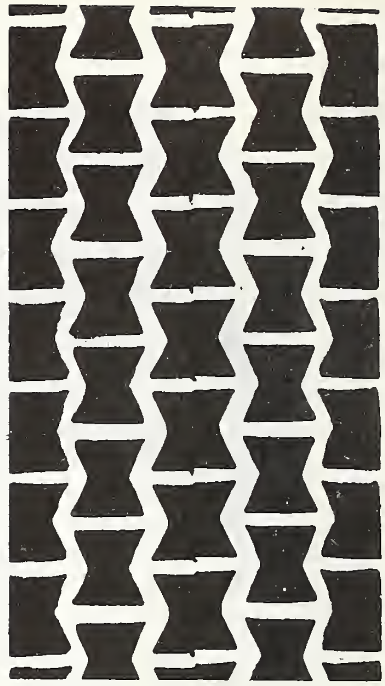


Figure 1. Structural regions and components of a bias-ply tire[1].

Figure 2. Basic tire structures.

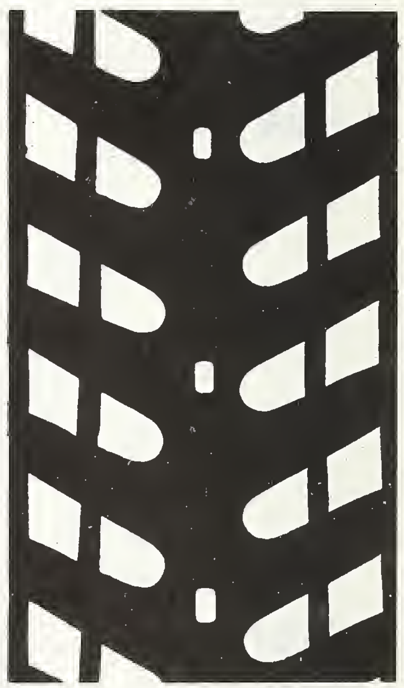


Continuous Rib



Discrete Block

Cross-Bar



Pocket

Figure 3. Basic tread patterns.

not be a factor in the future since it does not conform to the requirements of the U. S. Environmental Protection Agencies Motor Carrier Noise Emission Standard 40 CFR 202.23 which states that: "No motor vehicle should be operated on any tire having a tread pattern composed primarily of cavities in the tread (excluding sipes and local chunking or irregularities of wear) which are not vented by grooves to the tire shoulder or circumferentially to each other around the tire."

3. Industry Structure

The tire industry is, in general, composed of a few major manufacturers and their associated subsidiaries. An accurate breakdown of the total tire market among these manufacturers is, however, difficult, if not impossible, to obtain due to the sizable portion of the tire market that is produced specifically for sale by chain stores and oil companies -- tires which are sold under the brand name of the particular distributor.

The tire market can, however, be separated into three primary categories -- original equipment, after-sale replacement and export. A breakdown of the new passenger car tires and truck tires shipped in 1974 according to these categories and their relative percentages of the total market is given in Table 1[2]. Also presented are the relative percentages of the total market when retread tires are included in the after-sale replacement totals -- approximately 36 million passenger car retreads and 13 million truck retreads.

An estimated breakdown of the original equipment tire market according to manufacturer is given in Table 2[3]. Although similar data for the replacement tire market are not available, a breakdown in terms of brand share of the replacement tire market is presented in Table 3[3]. As previously discussed, this breakdown by brand name does not provide a true picture of the replacement tire market since tires marketed under the trade names of the chain stores and/or oil companies are actually produced by the major manufacturers.

Table 4 presents additional tire market data for various types of passenger car tires categorized by carcass construction -- bias-ply, bias-belted and radial-belted -- in terms of 1974 shipments plus estimates for 1975[3]. The important trend to note from this table is the significant projected increase in the use of radial belted tires for both original equipment and after-sale replacement applications.

4. Effects of Noise and Parties Affected

As noted earlier in this report, for most vehicles the engine structure, intake and exhaust, transmission and differential, brakes and tires are all important contributors, under various conditions, to total vehicle noise. Although the exact speed at which tires become the dominant source is not known, it occurs at moderate to high vehicle speeds for well-maintained

Table 1. Breakdown of new passenger car tires and truck tires shipped in 1974 into original equipment, after-sale replacement and export categories. Also presented are the relative percentages with retreads included in the replacement totals[2].

Tire Category	Passenger Car Tires			Truck Tires		
	Total (1974)	Percentage of Market	Percentage Including Retreads	Total (1974)	Percentage of Market	Percentage Including Retreads
Original Equipment	43,307,000	24.8	20.6	11,848,000	34.6	25.1
After-Sale Replacement	123,460,000	70.8	75.8	21,299,000	62.2	72.6
Export	7,616,000	4.4	3.6	1,103,000	3.2	2.3
Total	174,383,000	100%	100%	34,250,000	100%	100%

Table 2. Estimated breakdown of 1974 original equipment tire market (automobiles and light trucks) according to manufacturer[3].

Manufacturer	Percentage of Original Equipment Market
Goodyear	31.5
Firestone	25
Uniroyal	21.2
General	11.5
Goodrich	9
Michelin	1.8

Table 3. Breakdown of the 1974 replacement tire market according to brand[3].

Goodyear	13.5%
Firestone	10.6%
Sears	10.0%
Wards	4.6%
Atlas	4.5%
B. F. Goodrich	4.4%
Uniroyal	3.6%
Penney's	2.3%
Dayton	2.3%
Michelin	2.2%
General	2.2%
Dunlop	2.2%
Kelly-Springfield	2.2%
Tire & Battery Corp.	1.5%
Armstrong	1.5%
K-Mart	1.5%
Delta	1.5%
Remington	1.3%
Western Auto	1.3%
Gulf	1.2%
Mobil	1.2%
Cooper	0.5%
Seiberling	0.5%
Others	23.4%
TOTAL	100%

Table 4. Passenger car tire market in terms of carcass construction type for 1974 and estimates for 1975. Data are in terms of percentage of the market[3].

Year	Construction	Original Equipment	Replacement
1974	Bias-ply	14.6	40.4
	Bias-belted	45.4	36.2
	Radial Belted	40	23.4
1975 (Estimated)	Bias-ply	8	36
	Bias-belted	29	35
	Radial Belted	63	29

vehicles.

In general, tire noise affects the residents of communities near high-speed highways more than the occupants of the vehicle itself. Although the data base is limited, the "quiet" that is designed into some American automobiles indicates that the noise abatement technology exists for the attenuation of not only tire noise but also noises from aerodynamic, engine, exhaust and other sources.

The interior truck noise problem is, in general, covered under the provisions of the Bureau of Motor Carrier Safety Regulations[4] which establish a maximum allowable interior sound level for commercial trucks and buses operated in interstate commerce. Truck design is such that the engine and exhaust are located much closer to the driver than the tires; therefore, tire noise has less influence on the overall interior noise.

The residents of communities near highways, however, can be affected adversely by tire noise. Although hearing loss is not a potential problem, task interference and annoyance can certainly be a problem. Tire noise can also interfere with speech communication, disrupt sleep, rest and recreation, and cause other possible psychological and/or physiological effects.

To adequately assess tire noise effects on the community, a satisfactory objective acoustic metric is needed which correlates well with human response to tire noise.

Tetlow[5] conducted a study in which two juries of ten people each listened to 36 passby recordings of tire noise. On the basis of the jury evaluations the 36 recordings were numerically ranked with respect to the annoyance they produced. Acoustic metrics evaluated in this study included: perceived noisiness in decibels [PNdB], loudness level in Stevens Mark VI phons and SAE phons (calculated from octave band analysis of the noise) as well as the A-weighted and B-weighted sound levels. A correlation analysis of objective and subjective ratings was performed and the results obtained are given in Table 5 in terms of the resultant correlation coefficients. On the basis of this study, it was apparent that SAE phons and A-weighted sound level were the better objective metrics.

A similar study was performed by the SAE Truck Tire Noise Subcommittee[6] in which a jury of 23 people made subjective assessments of truck tire noise. The tests consisted of exposing the jury to actual passby noise of trucks operating under highway conditions, rather than tape recordings in a laboratory environment. Subjective evaluations were obtained for 85 passbys of various truck and tire combinations in both the coastby and powered passby modes. These subjective evaluations were then correlated with the corresponding A-weighted sound levels which were measured for each test run. The results of this analysis are given in Table 6 in terms of the resultant correlation coefficient. From these data it was concluded that the A-weighted sound level correlated well with subjective ratings of truck tire noise.

Table 5. Results of correlating objectives to subjective ratings for the annoyance of truck tire noise in terms of the correlation coefficient[5].

Objective Rating	Correlation Coefficient
A-weighted sound level, dB	0.957
B-weighted sound level, dB	0.885
SAE Phons	0.965
Stevens Mark VI Phons	0.932
PNdB	0.951

Table 6. Results of correlating A-weighted sound level to subjective rating for the annoyance of truck tire noise in terms of the correlation coefficient[6].

Test Condition	Correlation Coefficient
All coast	0.89
Powered - Rib tires	0.80
Powered - Cross-bar tires	0.69
Powered - All	0.80
All test data	0.93
Extra runs	0.95
All data	0.90

Based on the results of these two studies and the fact that the A-weighted sound level can be obtained directly from field measurements utilizing available instrumentation rather than extended calculations, the A-weighted sound level is probably a suitable objective metric for assessing the effects of tire noise.

5. Existing Measurement Procedures

At present there is only one existing standard which specifies a method of test for tire noise measurements -- Society of Automotive Engineers Recommended Practice J57, Sound Level of Highway Truck Tires[7]. To better facilitate a discussion of this measurement procedure, a table -- Table 7 -- has been developed which outlines the pertinent sections of the test method. The complete text of SAE J57 is reproduced in Appendix B.

This standard establishes a test procedure for measuring the sound level produced by tires intended primarily for highway use on motor trucks, truck tractors, trailers and semi-trailers. Although the procedure was developed for use with truck tires, automobile tire noise has also been measured utilizing the basic procedures outlined in this standard.

The procedure allows one to measure the sound generated by a set of test tires mounted on the rear (drive) axle of a test vehicle -- a single-chassis vehicle -- operated at 50 mph (80.5 km/hr) on a relatively smooth, semipolished, dry Portland concrete surface that is free of extraneous surface material. In addition, the standard provides specifications on the instrumentation, the test site, vehicle operation as well as outlining the basis of the sound levels reported when utilizing this test procedure.

This standard is reviewed in more detail in Section 7 of this report with regard to its usefulness in the regulation of tire noise.

6. Data Base and Correlations

Data from recent studies now establish a fairly consistent picture of tires as a noise source. It is relatively simple to intercompare United States studies since they utilize the same basic test procedure -- a coastby with the vehicle engine shut off -- to measure the maximum A-weighted sound level 50 feet (15.2 m) to the side of the centerline of the lane in which the vehicle travelled. Most Europeans studies measure at 7.5 meters or approximately 25 feet. In addition to A-weighted sound level data, a limited amount of spectral data and directionality data in the form of equal sound level contour plots are also available[11]. Since trucks are generally considered to present a more serious tire noise problem than passenger cars, most of the data available have resulted from measurements of truck tire noise.

One very important fact that should be pointed out is that the majority of the existing data available in the literature were obtained using "fast"

Table 7. Summary of measurement procedures for determining truck tire noise as specified by SAE J57.

Instrumentation	(1) Type 1 sound level meter meeting the requirements of ANS S1.4-1971[3/] (2) Alternative measurement system meeting the requirements of SAE J184[4/]
Test site	Level open space free from reflecting surfaces located within 100 ft (30 m) of either the vehicle path or the microphone.
Measurement area surface	Concrete, asphalt or similar hard material
Vehicle path surface	Smooth, semipolished, dry Portland concrete
Length of vehicle path	100 ft (30 m)
Microphone location	50 ft (15 m) from the centerline of the vehicle path and 4 ft (1.2 m) above the ground plane
Test Vehicle	Motor truck equipped with a nonpowered steering axle and a powered rear axle; and with a body nominally 96 in. (2440 mm) in width, extending a minimum of 36 in. (910 mm) rearward of the powered axle centerline, with a flat, horizontal undersurface providing a minimum tire clearance of 5 ± 1 in. (127 ± 25 mm) when fully loaded.
Test tires	Mounted on rear (drive) axle; and (1) operated at the maximum pressure and load as specified by the Tire and Rim Association[5/] (2) alternatively, operated at the pressure recommended by the Tire and Rim Association for the actual load; quiet tires mounted on the steering axle
Vehicle operation	Coasting or similar operation such that the sound level due to the engine and other mechanical sources is minimized; vehicle speed of 50 mph (80 km/hr)
Quantity measured	Maximum A-weighted sound level, slow response
Reported value	Average of the two highest readings that are within 2 dB of each other

[3/] American Standard Specifications for Sound Level Meters, S1.4-1971, American National Standards Institute, New York, New York (1971)[8].

[4/] SAE Recommended Practice J184, Qualifying a Sound Data Acquisition System, Society of Automotive Engineers, Warrendale, Pennsylvania (1970)[9].

[5/] Tire and Rim Association Year Book, Tire and Rim Association, Inc., Akron, Ohio[10].

meter response characteristics. SAE J57, on the other hand, specifies use of the "slow" response. A study by the National Bureau of Standards[12] has shown that the noise levels can vary by several decibels for measurements of tire noise using "slow" and "fast" meter response. It is important to keep these facts in mind when utilizing existing data to establish the regulated level in tire noise emission regulations.

Based on data currently available in the literature, the noise generated by tires has been determined to be a function of a variety of parameters including tread design, speed, road surface, load, tire inflation pressure and tread wear. Although the effects of these parameters are well documented, only limited knowledge of the tire noise source mechanisms exists (see discussion in Appendix A).

6.1. Effect of Tread Design, Speed and Road Surface

It is difficult to distinguish clearly among the effects of speed, tread design and road surface. Data are typically presented as maximum A-weighted sound level versus speed, with tread design and road surface as parameters.

Existing data[5,13,14,15] indicate that sound levels rise with increasing speed for all tires, but at slightly different rates. Typically, tires are characterized by an increase in A-weighted sound level on the order of 6-18 dB as the vehicle speed increases from 30-70 mph (48.3 - 112.6 km/hr)6/. This corresponds to sound level increasing as the third to fourth power of speed.

In the case of truck tires the results of studies by General Motors (GM)[5] and the National Bureau of Standards (NBS)[13,14]7/ concur in the fact that truck tires fall into three clearly defined categories as noise producers based on tread design. The pocket-tread tire8/ produces noise levels ranging from 2-11 dB above the noisiest cross-bar tire[14]. The difference between the quietest cross-bar tire and the noisiest rib tire is typically 4-8 dB. A further decrease of 1-2 dB below the levels measured for the circumferentially-grooved tread (neutral rib) could be expected for a completely smooth tread[20].

6/ Hillquist and Carpenter[16] and Veres[17] report increases in A-weighted sound level on the order of 8-18 dB for passenger car tires as the speed increases from 40-70 mph (64.4-112.6 km/hr). Leasure, et al[18] report -- for passenger cars -- increases on the order of 5-7 dB for speed changes from 50-70 mph (80.5 - 112.6 km/hr); with the range of data being 3-8 dB. Typically, truck tires are characterized by an increase of 6-12 dB for a doubling of vehicle speed in the range of 30-60 mph (48.3 - 96.5 km/hr)[19].

7/ Work sponsored by the Office of Noise Abatement, U. S. Department of Transportation.

8/ This tread design is being phased out of use because it does not conform to the U. S. Environmental Protection Agency Motor Carrier Noise Emission Standard because of the presence of cavities in the tread which are not vented to the tire shoulder or circumferentially to each other around the tire.

Tread design is not as significant a factor in passenger car noise as it is for trucks since most passenger car tires utilize rib-type tread patterns -- either continuous rib or discrete blocks. Hillquist and Carpenter[16] report that discrete block tread patterns, typical with radial-ply carcasses, tend to be slightly noisier than continuous rib tread patterns. As could be predicted on the basis of truck tire data, the highest noise levels are produced by snow tires, which possess cross-bar type tread patterns.

Road surface conditions can have a strong influence on tire noise levels; however, the road surface does not influence the noise from various tire types in the same way. Normally continuous-rib tread tires tend to produce higher noise levels on rougher road surfaces while cross-bar tread tires tend to produce similar noise levels regardless of the surface.

It does appear, however, that road surface can have a much greater effect on the noise of passenger car tires than on truck tires[18]. This is due to the fact that the texture within the tire-road interaction area is of the same scale as the tread element spacing typical of passenger car tires. The scale of interest, which is thought to be important in at least some tire noise source mechanisms, is pavement macrotexture. The macrotexture scale is that appropriate to the overall dimensions of individual stones in the pavement aggregate -- generally on the order of one or two centimeters and less.

It should be noted that no established method now exists for quantitatively characterizing the surface roughness or texture of pavements typical on today's roads. The American Society for Testing and Materials (ASTM) Committee E-17.23 has investigated approximately 25 methods for characterizing surface roughness for traction purposes[21]. The relative attributes of these methods must be questioned, since results of tests utilizing these methods have not, on the whole, produced consistent or reproducible quantitative results.

Although limited success has been achieved in correlating A-weighted sound level with stereophotograph data[22] and with profile spectral analysis data utilizing an electro-mechanical profile tracer[23], it is obvious that more research is needed in the area of surface texture characterization. Until the surface texture can be physically characterized in a quantitative manner, little can be known about the effect of surface texture on the generation of tire noise.

6.2. Effect of Load

In general, an increase in load results in an increase in the maximum A-weighted sound level. In the case of truck tires, load has been found to significantly affect the noise level generated by tires with cross-bar (snow tread) tread patterns[9/], while noise from tires with rib tread patterns are relatively unaffected by load changes.

[9/] Typical increases on the order of 7 dB are observed when the load per tire increases from 1240 pounds (563 kg) to 4500 pounds (2041 kg)[5].

Hillquist and Carpenter[16] reported data on passenger car tires which showed variations of only about 1 dB in A-weighted sound level for bias-belted and radial-belted automobile tires with continuous rib and discrete block tread patterns over a vehicle weight range of 4700 to 6370 pounds (2132-2889 kg). These weights represented 85-115 percent gross vehicle weight and 75-100 percent of tire load ratings. Later work by Veres[17] also showed changes in sound level to be on the order of 1 dB between minimum (curb weight of the car plus the driver) and maximum (maximum design load as recommended by the Tire and Rim Association) loads.

Although tires may produce higher noise levels on one surface than on another, the increase in sound level between the unloaded and loaded condition remain essentially constant, independent of the pavement surface on which the tires run.

6.3. Effect of Tire Pressure

A change in tire pressure can be intentionally made or it can occur unintentionally in service as a result of poor maintenance or temperature. Temperature increases, which result in increases in tire pressure, principally occur through heat buildup in the tire caused by flexing and friction during extended driving. Hillquist and Carpenter[16] studied the effect of inflation pressure on A-weighted sound levels by making measurements while the tire inflation pressure was varied over the range 12 to 36 psi (82.7×10^3 - 248.0×10^3 Pa) ($\pm$12 psi around a control pressure of 24 psi) in increments of 4 psi. This was felt to be representative of the range of inflation pressures one is likely to encounter in "normal" driving conditions. The results showed that the noise levels tend to increase with increasing pressure and decrease with decreasing pressure; however, the changes were not found to be significant. Until a change of $\pm$8 psi from the control pressure was achieved, differences between the passby noise levels at the control pressure and the test pressure were less than 1 dB. Further pressure changes resulted in little or no additional changes in passby noise levels. Comparable data for truck tires does not exist. The important consideration here is the fact that most tires are used at pressures set within a fairly narrow range.

6.4. Effect of Tread Wear

Tread wear occurs both through natural abrasion under normal operating conditions and through faulty wheel alignment. For truck tires, tread wear was found to be a variable that can greatly affect the sound level generated by tires[5,13,14]. In general, the noise increased then decreased with increasing tire wear. The actual tread depth at which the maximum noise is generated for any given tread design is not known; however, this maximum usually occurs at or near the half-worn state of tire wear. The physical phenomenon responsible for this behavior is unclear; but, work by Tetlow[5] indicates that change in tread curvature is a significant parameter. Tetlow found that when a new tire is ground down artificially to simulate the tread depth of a worn tire but the tread radius kept the same as for a new tire, there is much less increase in sound level than would be expected under conditions of normal wear. In fact, the sound level is scarcely changed at all from that when new (Figure 4). When both the worn tread depth and tread radius have been simulated artificially, the data obtained have varied, with the sound levels measured for these tires sometimes being very close to those measured for normally worn tires. The difficulty is finding a tire worn in actual over-the-road service that can serve as a model for the grinding of the tire to be artificially worn.

These trends, however, do not hold in the case of passenger car tires. Data[18] show that automobile tire noise either slightly increases or slightly decreases 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.

6.5. Miscellaneous Effects

a. Temperature

Tests conducted by General Motors[5] showed tire temperature to be an unimportant parameter. A rib and a cross-bar tire were run on a dynamometer and there were no significant changes in the overall sound level with changes in temperature over the range 25° to 125° F (-4° to 52° C).

b. Number of Plies

Yurkovski, et al[24] report that using two plies rather than four slightly increases the noise level. They speculate that this is due to lower hysteresis losses in the tires as a result of the lower rubber content, and consequently the high-frequency vibrations caused by obstacles in the road are damped by the tires to a lesser extent.

c. Tire Reinforcing Fabric

Weiner[25] tested tires of various construction and observed a remarkable constancy of the tire noise spectrum and level with respect to changes in the fiber material of the tire reinforcing fabric, e.g., nylon, rayon, etc., for a given set of operating conditions.

d. Tire Dimensions

Hillquist and Carpenter[16] investigated two aspects of tire dimensions utilizing automobile tires -- overall size and aspect ratio (tire sectional height/sectional width). No significant differences in A-weighted sound levels were observed for tests utilizing 14 and 15 inch tires with the same tread pattern. However, coastby noise levels increased approximately 2 dB when low aspect ratio (e.g., "wide oval") tires were compared with more conventional tires.

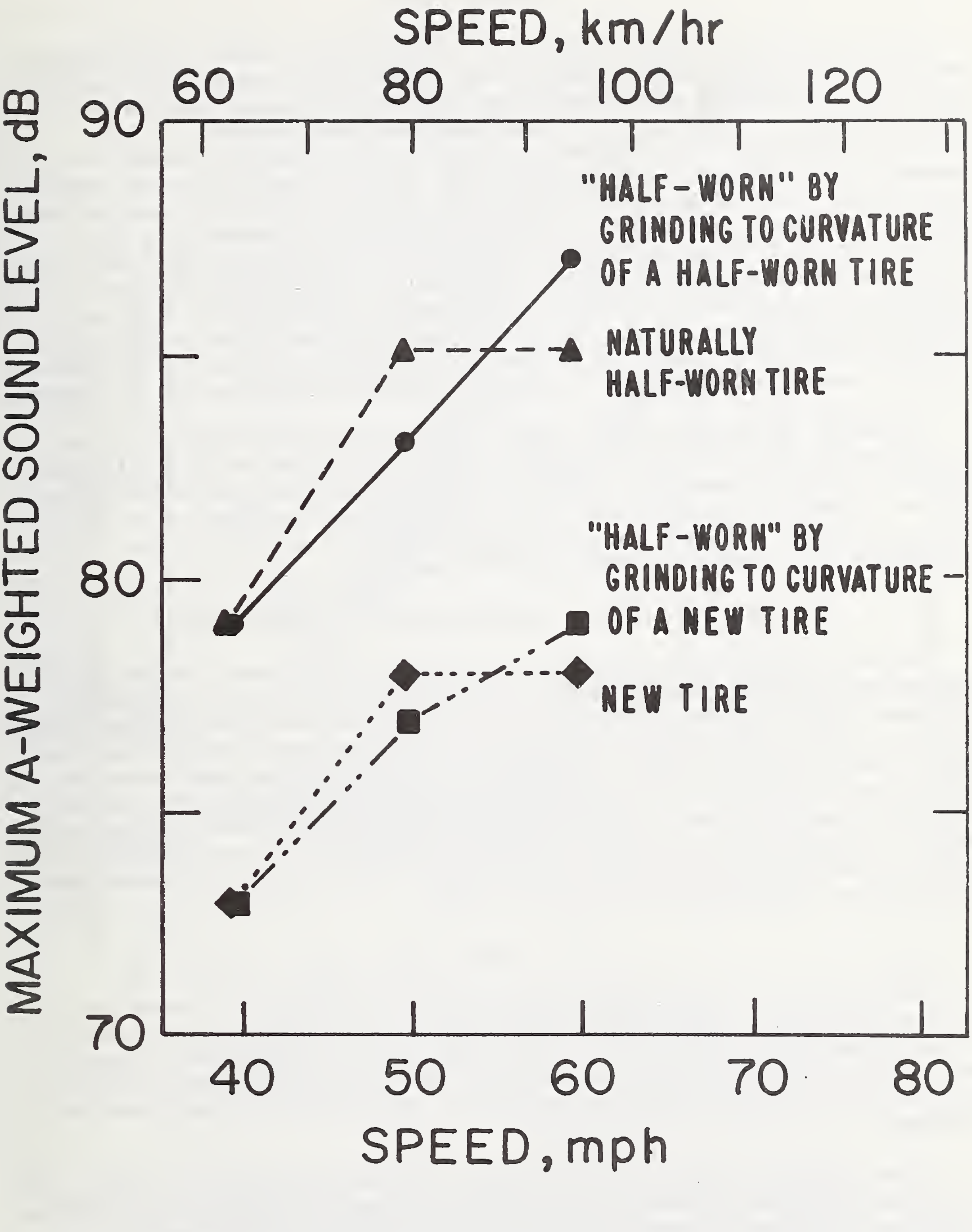


Figure 4. The effect of tread curvature on tire noise for a typical cross-bar tire when (1) new, (2) "half-worn" by grinding to curvature of a half-worn tire, (3) "half-worn" by grinding to curvature of a new tire, and (4) naturally half-worn tire[5].

e. Wet Road Surface

When it rains, a layer of water is present in the contact area between the tire and the road which affects noise generation. Engler[26] reports that higher A-weighted sound levels and different frequency spectra occur on a wet road and are chiefly due to the additional splash noise. Other European work[27,28] show typical increases in the A-weighted sound level for passenger cars equipped with "summer tires" on the order of 6-10 dB between data for wet roads as compared to dry road surfaces. Spectral data on United States truck tires (see Figure 5) show considerable increases in sound pressure level at frequencies above 1000 Hz but little or no increase (0-3 dB) in the A-weighted sound level. A recent U. S. study[22] utilizing automobile tires showed an average difference of approximately 4 dB in A-weighted sound level between wet and dry surface conditions. The range however, was 0-8 dB. Thus, it appears that truck and automobile tires are affected somewhat differently by the environmental conditions of the roadway.

Although at present no more than a superficial understanding of the mechanisms of noise generation by tires exist, an extensive data base does exist for those parameters which influence the tire-road interaction process and the effect that variation of these parameters has on tire noise levels. Thus, it appears that EPA can utilize the existing data base as the foundation of its Notice of Proposed Rule Making.

7. Overview of Tire Noise Measurement Difficulties

In this section, the information discussed in Sections 2 through 6 of this report serves as the basis for an overview of tire noise measurement problems. Utilizing this information in conjunction with the existing tire noise measurement procedure, potential noise measurement problems that could hinder the promulgation and/or enforcement of future noise regulations to control noise emission from tires are identified. Such considerations as test site specifications, instrumentation requirements, operational mode of vehicle, specifications of test tires and vehicles, etc., are reviewed in order to lay the ground work for establishment of an appropriate measurement procedure for determining the noise of tires.

7.1. Test Site

Selection of an appropriate outdoor test site presents a number of problems which have been addressed previously for vehicle noise (as opposed to tire noise) test purposes. In fact, the test site specified in SAE J57 represents a compromise between test sites specified in SAE J366b (Exterior Sound Level for Heavy Trucks and Buses[29]) and SAE J986a (Sound Level for Passenger Cars and Light Trucks[30]).

These standards specify that the test site shall consist of a level open space free of large reflecting surfaces such as parked vehicles, sign boards, buildings or hillsides located within 100 feet (30.5 m) of the vehicle path or the microphone; that the microphone is to be located 50 feet (15.2 m) from and perpendicular to the centerline of the vehicle path and 4 feet (1.2 m)

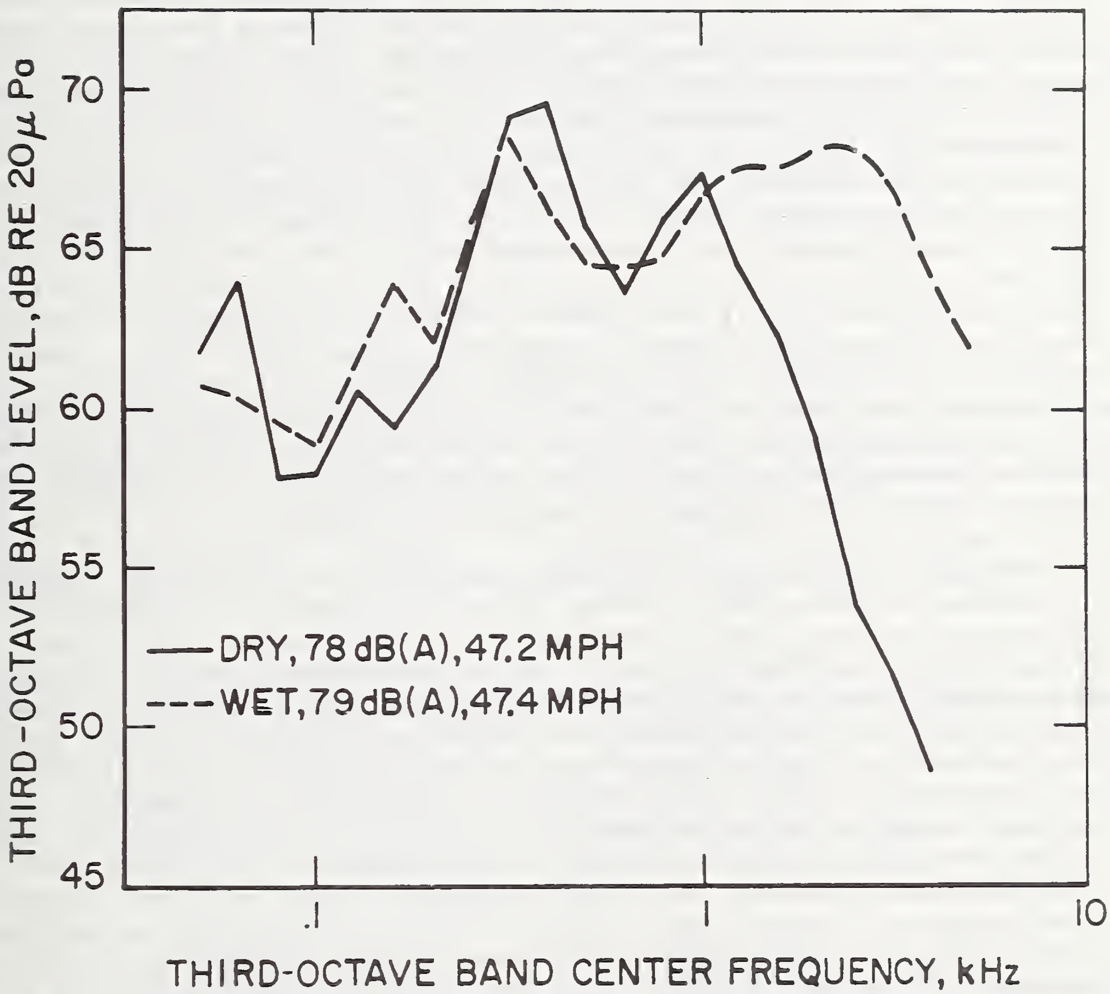


Figure 5. The effect of a wet surface on the frequency spectrum and A-weighted sound level of the noise generated by truck tires as measured at 50 feet (15.2 m). The test truck was a loaded single-chassis vehicle equipped with new neutral rib tires on the steering axle and dual, half-worn-rib tires on the drive axle. The road surface was concrete [14].

above the ground plane; and prescribes the test zone between the microphone and the pertinent portion of the vehicle path which shall be free of extraneous material such as loose soil, ashes, grass and snow. Furthermore, the standards require that the ambient sound level (including wind effects) coming from sources other than the vehicle being tested shall be at least 10 dB lower than the level produced by the test tires.

The important point in tire certification testing is that the vehicle be at the proper speed and that the maximum noise generated by the tire be recorded at the microphone while the vehicle is in the test zone. Directionality data resulting from DOT/NBS tire noise studies[11] provide information pertinent to the establishment of minimum requirements for measurement test sites suitable for tire certification testing. From these data, it has been ascertained that maximum A-weighted (fast response) sound levels generated by tires are typically measured prior to the passage of the drive axle of the truck past the microphone when tires with rib or cross-bar tread patterns are mounted on the vehicle. On the average, such maximum noise levels are recorded 30 to 40 feet (9-12 m) prior to the passage of the drive axle. Thus, it would appear that the minimum vehicle path should be the 100 feet (30.5 m) -- ±50 feet (15.2 m) on either side of the microphone location -- specified in SAE J57, if one hopes to achieve a measurement of maximum tire noise on a 50 mph (80.5 km/hr) coastby of a single drive axle, loaded vehicle utilizing a 50 foot (15.2 m) microphone location. If other vehicle speeds or microphone locations are utilized in the future, the minimum test site requirements stated here may not be valid; therefore, the situation would have to be reevaluated based on the directionality contour characteristics for the chosen vehicle speed and microphone location.

Results from several tire noise studies[5,13,14,16,18,31] indicate that the surface on which the test vehicle travels produces a significant difference in noise levels. The need for a hard reflecting surface is well documented[13] and the SAE truck tire noise subcommittee went a step further in requiring that the test surface be smooth, semi-polished, Portland concrete in order to "maximize tire sounds and provide a surface definition that is known to exhibit least variation according to present knowledge"[32]. The correlation tests on four Portland concrete surfaces showed a range in maximum A-weighted (slow response) sound level of 0.2-2.4 dB for cross-bar tires and 4.0-5.9 dB for rib tires. The subcommittee attributed the differences observed for rib tires to ambient noise level and vehicle noise level problems; however, most probably they were observing the influence of surface texture. For example, in a recent report[22] data are reported for passenger car tires that show a range of 2 dB at 40 mph and 7.6 dB at 60 mph for five different textures on Portland cement concrete surfaces. Thus, there exists a need to develop a method of quantitatively characterizing pavement surface texture which can be correlated with tire noise levels. This quantitative measure is necessary to establish a standard test pavement texture -- or place bounds on allowable test pavements -- for tire testing and to serve as the basis for comparison of tire noise data measured on different surfaces.

7.2. Test Vehicle

The truck tire noise subcommittee was asked to develop a measurement procedure applicable to truck tire noise. Thus, their considerations were based on the nominal tire size -- 10.00-20 -- and vehicle found on the road at the time the recommended practice was developed.

The recommended practice specifies:

"The vehicle shall be a motor truck equipped with two axles (a non-powered steering axle and a powered axle).

The vehicle shall have a platform, rock 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 5 ±1 in. (127 ± 25 mm) minimum clearance with the tires fully loaded. This body shall be nominally 96 in. (2.4 m) in width and extend a minimum of 36 in. (0.9 m) rearward of the rear (powered) axle centerline.

Mud flaps should be removed at the test site, if permissible."

At a minimum, a specification will be needed to establish the nominal vehicle appropriate for passenger car tire testing. Until data are available on the effect of tire size on noise levels, it is not known whether a series of test vehicles to cover the range of tire sizes from sub-compact passenger cars to heavy duty truck-tractors or a single vehicle -- full size automobile, heavy duty truck-tractor -- that can accomodate the largest size tire for a particular class of vehicles are needed. Some general guidelines that should be applied to the selection of a suitable test vehicle follow.

Since tires are the primary noise source of interest, the motor vehicle utilized for tire noise testing should not contribute a significant portion of the sound level measured. Therefore, precautions must be taken to ensure the minimization of engine, chassis, and other running gear generated noise. Testing tires with the vehicle in a coasting mode -- i.e., engine shut off and the transmission in neutral -- is an important first step. Loose and rattling components of the test vehicle must be removed, tightened and/or damped.

The test vehicle should have sufficient load carrying capability to provide for ballasting to near maximum rated load of the test tires. Also the vehicle should be equipped with an engine which provides sufficient power to be able to accelerate to speeds slightly in excess of the test speed within the confines of the test area prior to entering the test zone.

Although the effects of undercarriage geometry and obstruction typically found below the frame of a truck -- such as mud flaps -- have been minimally investigated[33], no information is available on the effect of wheel well geometry in the case of passenger car tires. Since the noise from tires is produced through the interaction of the tire with the roadway, the noise is generated at the tire/road interface and therefore, any vehicle which provides open wheelwells -- i.e., unobstructed view of the tire/road interaction zone -- should be acceptable. The need for a detailed test vehicle specification is primarily for purposes of test data comparability.

7.3. Vehicle Operation

SAE Recommended Practice J57 specifies the following vehicle operational mode:

> "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 50 mph (80 km/hr)."

This wording allows a choice of either coastby or powered passby vehicle operation. However, G. M. Dougherty[32] in discussing the rationale for the decisions made by the subcommittee on truck tire noise during development of J57 states that "A coastby is the only method that has been found suitable for isolating tire noise. A coastby ... is accomplished with the engine at an idle speed and with the gear train in neutral while the truck is within the test zone. It is advisable to disengage the clutch approximately 150 feet (45 m) before the microphone intercept so that the truck sounds do not affect the results."

The test speed of 50 mph (80 km/hr) represents a compromise of several factors. It is obvious that the test speed should be high enough so that sound levels representative of highway operations are generated but low enough to ensure the availability of test sites with sufficient space for acceleration and deceleration of the test vehicle before and after the test zone, respectively. The test speed of 50 mph (80 km/hr) enables utilization of a reasonably sized test site and is consistent with typical truck speeds near residential communities.

7.4. Tires

The test vehicle specified in Section 7.2 typically utilizes six tires -- two on the front (steering) axle, and four on the rear (drive or powered) axle. Wide base tires now coming into more wide spread usage on trucks, may dictate the application of four tires only on a test vehicle. In the case of passenger car tires the suggested mounting configuration is as follows: (1) when continuous rib or discrete block tread patterns are to be tested, test tires will be mounted at all four wheel positions, (2) in the case of snow tires, two test tires will be mounted on the rear axle while the front steering axle should be equipped with the quietest tires available to minimize their contribution to the sound level generated during the coastby. In practice, the noise generated by steering axle tires will influence the measured sound level of the coastby significantly when the quietest tires are tested on the rear axle. The sound level of noisier tires tested will be minimally influenced. According to available data[20], a blank tire should probably be specified as the "quiet" tire.

Test results[5,13,14] have also indicated that the higher the tire loading, the higher the sound level produced. Accordingly, SAE J57 procedures require tires to be loaded to the maximum rated load as specified by the tire manufacturer. The standard further states that "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."

It should be noted that the majority of the tire noise data in the open literature was generated utilizing a vehicle at approximately 75 percent of maximum rated load. In the case of automobiles, 100 percent of tire load ratings results in 115 percent of gross vehicle weight -- i.e., the automobile is overloaded. With trucks the most probable overloading would occur on the front axle. In addition, American Trucking Associations data[34] show that most dry freight operations run at approximately 60 percent of maximum pay load weight.

The data showing the effect of tire loading on generated tire noise levels are too sparse at present to disregard load effects if the inflation pressure is adjusted according to the load (e.g., as per the inflation/load tables provided by the Tire and Rim Association). Thus, it appears that a load of 75 percent maximum rated load is a more realistic loading consistent with state load limits for operating on highways.

7.5. Instrumentation

The instrumentation section of a tire noise regulation should require equipment meeting the Type 1 requirements of American National Standard Specifications for Sound Level Meters, S1.4-1971[8]. In addition, pertinent sections of American National Standard Methods for the Measurement of Sound Pressure Levels, S1.13-1971[35] should be incorporated. For instruments for which standards do not exist, or where existing standards are not sufficient, the regulation should include specific criteria for evaluating the performance of such devices. For example, a critical deficiency in existing standards is that the response of instrumentation to transient signals, e.g., vehicle passbys, is not well understood.

It is important to state clearly in the regulation the allowable tolerances for frequency response, environmental effects, harmonic distortion, etc., which the instruments are required to meet. These specifications should be applied not only to specific components of the system but to the overall system as well. The overall system measurement error should not be degraded below that allowed for direct measurements regardless of the instrumentation configuration.

In addition, overall system calibration should be required at frequent stipulated intervals. The fact that each component of a system appears satisfactory does not ensure that the system performance will be acceptable.

The simplest noise measuring system from which one may obtain sound level data is a sound level meter. These instruments have a switch that provides either a "fast" or "slow" meter response. The choice of which meter ballistic characteristic to use depends on the character of the sound being measured. On steady sounds the reading of the meter will be the same for either "slow" or "fast" response, while on fluctuating sounds the "slow" position provides a time average reading.

The SAE recommended practice for measuring the sound level of highway truck tires specifies the use of the "slow" response. The basis for this recommendation was that the truck tire noise subcommittee felt that the use of "slow" response would "eliminate errors and increase the validity of tire noise measurements by eliminating the quick sporadic meter measurements associated with "fast" response or with subjective impressions of sound"[32]. Also, the "slow" response subjectively correlated better -- correlation coefficient of 0.89 for "slow" response, 0.87 for "fast" response -- with the Lansing jury tests[32].

Based on DOT/NBS data taken during the Pecos truck tire noise tests[12], one would expect that approximately 60 percent of the time the difference between data taken utilizing the "fast" and "slow" meter ballistic characteristics would be on the order of 1.0 -1.5 dB; however, differences as great as 2.5 dB were noted. In general larger differences were observed for cross-bar-type tires but the largest difference was observed for the rib-type tires.

There exists a need to establish the appropriate meter response for measurement of tire noise. The adoption of slow meter response would of necessity result in the adoption of a lower noise level limit. Such a decision must carefully weigh the following factors:

- The small difference between correlation coefficients for human response to slow and fast response to tire noise is not sufficient to allow selection of one over the other.

- Total vehicle noise standards and regulations are based on fast response.

- Maximum hold circuits, which hold the maximum value of the A-weighted sound level, are becoming more prevelant and their use eliminates the possible human error that can occur when an observer attempts to read a maximum meter reading during a vehicle passby situation at moderate to high speeds.

7.6. Summary

The SAE truck tire noise subcommittee formulated a test procedure applicable to highway truck tires which they felt was adequate for their purposes; namely, "qualification of tires for radiated sound level by (tire) manufacturers and recappers". They realized that many issues were not resolved and that further research was necessary to address the remaining issues; however, they also realized that the need for a standard precluded further delay. Therefore, SAE J57 was issued in 1973.

The preceding sections of this report indicate the deficiencies in the existing standard that should be addressed prior to formulation of the Notice of Proposed Rule Making. The major problems include:

- Existing test procedure does not measure the noise level of a single tire.

- Pavement texture is not quantitatively characterized.

- The effects of tire size on the generation of tire noise is not well established.

Once a practical noise certification test for tires has been established which results in the rating of a tire measured according to prescribed procedures, an additional need arises which deserves attention. Namely, such a rating by itself does not allow the prediction of in-service noise levels. For this reason a predictive scheme which allows one to utilize the certification test results to predict in-service noise levels is needed.

Utilizing SAE J57 procedures, DOT/NBS has developed an empirical model to satisfy this need. The basic assumptions and necessary data for application of the model are as follows:

(1) The necessary input data are A-weighted sound level versus time data which can be converted to A-weighted sound level versus distance data.

(2) The basic assumptions are:

-- The data for a given axle can be represented by the certification data assuming the number of tires mounted on the axle, the tread design and state of tread wear of the tires are comparable.

-- For vehicles with numerous axles and axle locations, the certification data representative of each axle can be adjusted to account for load and speed differences (between certification and in-service), can be shifted spatially according to the geometric arrangement of the axles of the particular vehicle of interest and can be added together on an energy basis.

The usefulness and expected accuracy of the predictive model has been shown through a comparison of measured versus predicted maximum A-weighted sound levels for a variety of truck/tire combinations[23].

It is obvious, however, that the model would have to be updated to account for data from a single tire rather than an axle of tires once a test procedure is established which allows measurement of a single tire.

In summary, an extensive data base has been established utilizing test procedures basically identical to those specified in SAE J57. The critical difference is that the data base was established using "fast" meter response while the SAE recommended practice specifies use of "slow" response. However, little or no data are available in the open literature on test procedures for testing a single tire rather than an axle of tires. Also, as pointed out earlier in this report, the problems of tire size and pavement texture -- as they affect tire noise certification -- need to be addressed. Therefore, in order to perform a comprehensive analysis of the economic factors and technical feasibility associated with the given regulation, it appears that EPA will need to address these major questions prior to formulation of the Notice of Proposed Rule Making.

8. Alternative Test Methods

Whether one is attempting to certify and/or label tires as to their noise level or attempting to evaluate the mechanisms by which tire noise is generated, it would be desirable to study a single tire running near maximum load on a typical road surface. As was discussed earlier, the present test procedure (SAE J57) does not satisfy this desire.

A step towards a single tire test procedure was taken by the General Motors Corporation when they designed a single wheel trailer for tire research purposes[36]. GM researchers are utilizing the single wheel trailer to provide insight into the correlation between measurements of a single tire compared to tire noise levels measured according to SAE J57 procedures. It is also felt that the data generated will extend the applicability of indoor testing, e.g., on dynamometer rolls or endurance wheels, presently utilized by some tire manufacturers.

At least four types of measurements come to mind when one considers measurement procedures which will permit adequate assessment of the tire noise problem. To facilitate comparison of the various possible approaches, the following summary is presented.

- SAE J57

  - Does not allow measurement of a single tire
  - No control of external environment -- rain, snow, wind, noise, etc.
  - Requires a large outdoor test site (on the order of 1.5-2 miles for a fully loaded test vehicle).
  - Choice of meter response characteristic, i.e., "fast" or "slow" is important, since one is dealing with a transient signal.

-- Tire loading relatively easy.

-- Need to quiet test vehicle (noises associated with coast mode).

-- Road surface effects need to be quantified.

-- Contact between tire and road is a curved surface on a flat surface.

-- Need different vehicles to accomodate various tire sizes.

■ GM Single Wheel Trailer

-- Allows measurement of a single tire.

-- No control of external environment -- rain, snow, wind, noise, etc.

-- Requires a large outdoor test site (on the order of 1.5-2 miles for a fully loaded test vehicle).

-- Choice of meter response characteristic, i.e., "fast" or "slow" is important, since one is dealing with a transient signal.

-- Tire loading difficult due to stability problems with the trailer.

-- Need to quiet towing vehicle and trailer (noises associated with coast mode).

-- Road surface effects need to be quantified.

-- Contact between tire and road is a curved surface on a flat surface.

-- Need different trailer designed to accomodate various size tires.

■ Near Field, in situ

-- Allows measurement of a single tire.

-- Minor control of external environment -- rain, snow, wind, noise, etc. -- since measurements made close to the tire and microphone somewhat protected by the test vehicle.

-- Test site requirements reduced, can be performed on an existing highway.

-- Steady state signal; therefore, choice of meter response charactersitic not important.

-- Tire loading relatively easy.

-- No vehicle noise control required.

-- Road surface effects need to be quantified.

-- Contact between tire and road is a curved surface on a flat surface.

-- Need different vehicles to accomodate various tire sizes.

■ Near Field, indoors (endurance wheel, dynamometer, etc.)

-- Allows measurement of a single tire.

-- Complete control of environment.

-- Requires a specialized well-controlled acoustic facility, e.g., a semi-anechoic space.

-- Steady state signal; therefore, choice of meter response characteristic not important.

-- Tire loading easy.

-- Drive machinery of endurance wheel, dynamometer, etc., needs to be quiet.

-- Correlation between smooth wheel surface and typical road surfaces needs to be established.

-- Contact between tire and wheel is analogous to a curved surface on a curved surface. As the size of the wheel gets large in comparison to the size of the tire the real world situation -- curved surface on a flat surface -- is approached.

-- May need two different size wheels to accomodate automobile and/or truck tires.

Each of the alternative test procedures have associated with them pros and cons for their adoption as a tire test procedure that could be utilized by both the government and the affected industry. Gaps remain to be filled with each procedure and additional data will have to be acquired.

There is no assurance that indoor test facilities would simulate road conditions with sufficient correlation; however, the concept deserves attention since the potential benefits of such a test are great.

A concentrated effort should be made to develop a simple, repeatable, accurate test procedure that would be independent of weather and site influences and would correlate with what the community hears as "tire" noise.

9. Appendix A. Tire-Noise Source Mechanisms

At least three generic types of tire noise source mechanisms have been posutlated; these may loosely be termed -- aerodynamic, air pumping, and vibration.

Aerodynamic sources refer to unsteady flow over the tire, attributable largely to the whole-body motion of the tire through nearly-stationary air. Air pumping, on the other hand, applies to the vicinity of the tire/roadway interface where air is squeezed out of and flows back into tire-tread and roadway-surface interstices. Vibration of the tire carcass (caused by tire/road interaction) is believed to be a third source of noise. In this section of the report some of the quantitative work conducted thus far to describe the generation of sound by these mechanisms is discussed. The evaluation of tire-noise source mechanisms is a very complex task, still is its infancy.

A. Aerodynamic

Flow over the tire surface will generate noise, but the level has not been firmly established. Based on experimental work by Chanaud[37] with spinning disks,[10/] and data on noise generated by turbulent boundary-layer flow, Hayden[38] concludes that aerodynamic noise per se is inconsequential. For example, Chanaud's results suggest that the sound pressure level varies as the 6th power of tip velocity while experimental data in the literature support the 40 log V relationship between sound pressure level and speed. Siddon[39], on the other hand, speculates that fluctuating pressures from vortices generated at the trailing edge of a tire near the road are sufficient to contribute substantially to roadside noise. While this may be the case for smooth tires operating on smooth roads, it hardly seems likely to be a major source, in view of the overwhelming data demonstrating a dependence of tire noise on road surface texture and tread design.

B. Air Pumping

Air pumping can be a major contributor to tire noise. This mechanism may be visualized with the aid of Figure A-1. As a tire-tread segment contacts the road surface, air may be squeezed or pumped out of small depressions in the road and the tire interstices in sufficient volume to create significant noise. As the tread leaves the surface, air rushes back to fill the voids. This oscillating flow at the leading and trailing parts of the contact area may be modeled to the first order by monopole sources of noise.

Hayden[38] has estimated the sound pressure level radiated by a compact array of these monopoles associated with the forward or rear contact region of a single tire as

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[10/] For an aluminum disk of 12 inch (30.5 cm) radius and 1/4 inch (0.6 cm) thickness, Chanaud never observed sound pressure levels in excess of 38 dB for a tip velocity of ∼100 ft/sec (30.5 m/sec) [at a distance of ∼5.6 disk radii].

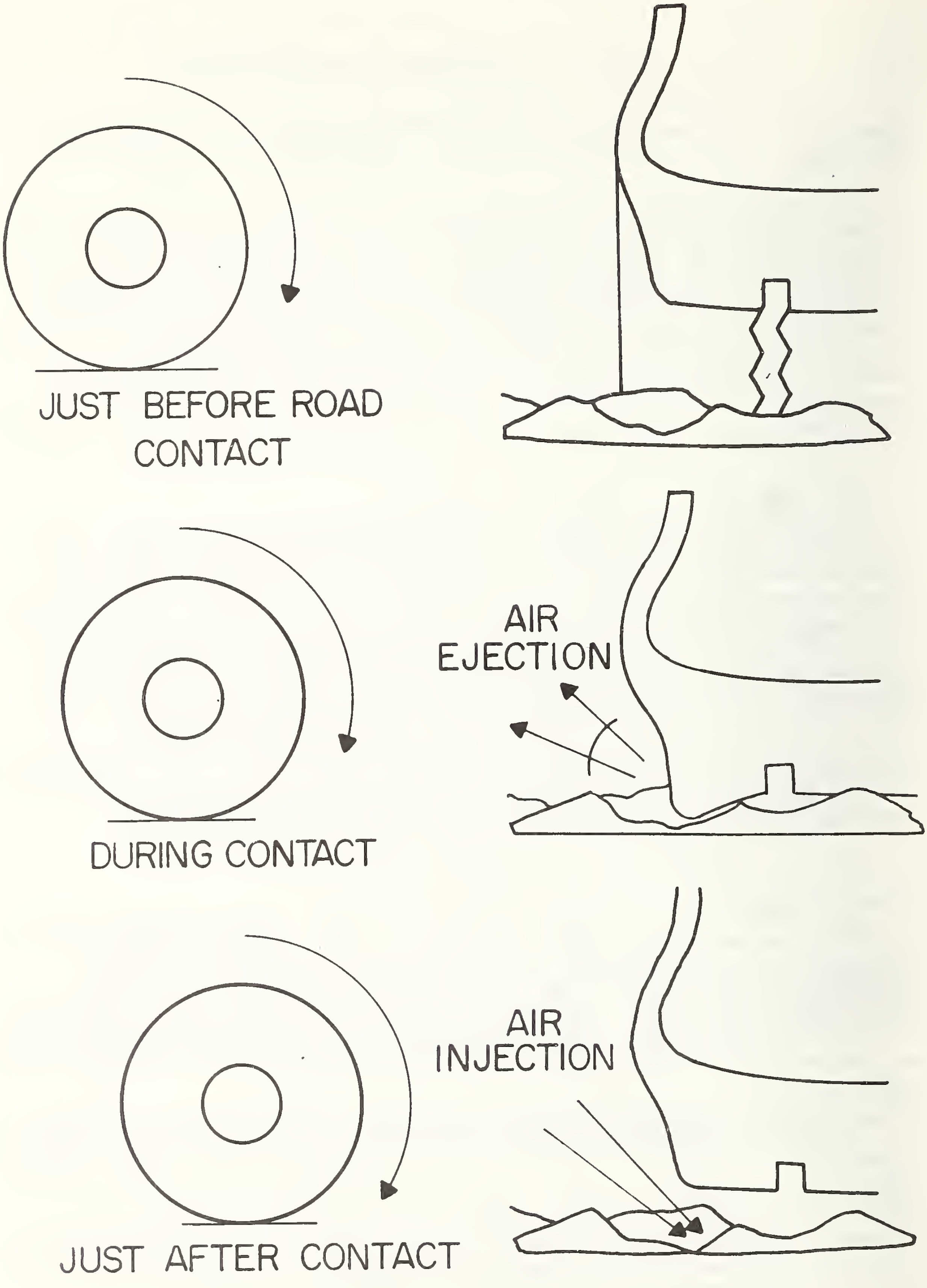


Figure A-1. Air-squeezing mechanism of tire-noise generation.

$$SPL = 68.5 + 20 \log \frac{\delta w}{S} + 40 \log V + 20 \log f + 10 \log m - 20 \log r \quad \text{(A-1)}$$

Where δ is the tread depth, w the width of a single cavity or groove in the tread, S the circumferential distance between tread grooves, V the vehicle velocity, f the fractional change in the cavity volume, m the number of cavities per unit width of tire, and r the distance from the tire to observation point. A similar concept may be applied when one treats the roadway depressions in the same manner as the tread interstices.

In practice, the 40 log V relationship with speed does not always hold true. Probable reasons for this lack of agreement are (1) air pumping is not the only mechanism contributing to the generation of tire noise, and (2) tire noise is directional (see Figure A-2), which is not predicted by the Hayden model in which a simple spherical source is assumed. A further difficulty with this model is that the effect of tire wear, tire load, or differences between tire types (cross-bar or rib) on noise produced is not explained.

C. Vibration

There are various excitation mechanisms, types of tire response, and radiation mechanisms that characterize tire vibration and attendant sound generation.

The primary excitation mechanisms are the periodic deflection of the toroid in the contact patch area (tire-road interaction zone) as the tire rolls along and the interaction of the tread elements with roadway-surface irregularities. Roadway-surface irregularities may be thought of as a continuous process at low frequencies, where the lengths of waves associated with the roadway wavenumber spectrum are long compared with the length of the tire-contact patch (e.g., <100 Hz for automobile tires at highway speeds). At higher frequencies, however, the process becomes discontinuous as segments of the tire impact individual roadway surface asperities.

Another potential excitation mechanism results from tire nonuniformities -- both of the tire itself (not really round or a flaw in construction) and the tread (uneven wear) -- which give rise to force variations in the tire. The fundamental component of this mechanism is related to the tire rotation rate (i.e., a variation of the force each time the nonuniformity impacts the roadway) which would correspond to about 10-20 Hz for automobiles operating at highway speeds.[11] It is unlikely that harmonics of this will be significant in the frequency regime of substantial sound radiation (~300-500 Hz).

11/ The frequency of the force variation and resultant tire vibration due to the impact of the tire nonuniformity with the roadway is approximately equal to the speed divided by the tire circumference. For example, an automobile tire with a circumference of 25 inches (63.5 cm) traveling at 50 mph (80.5 km/hr) corresponds to a frequency of about 11 Hz.

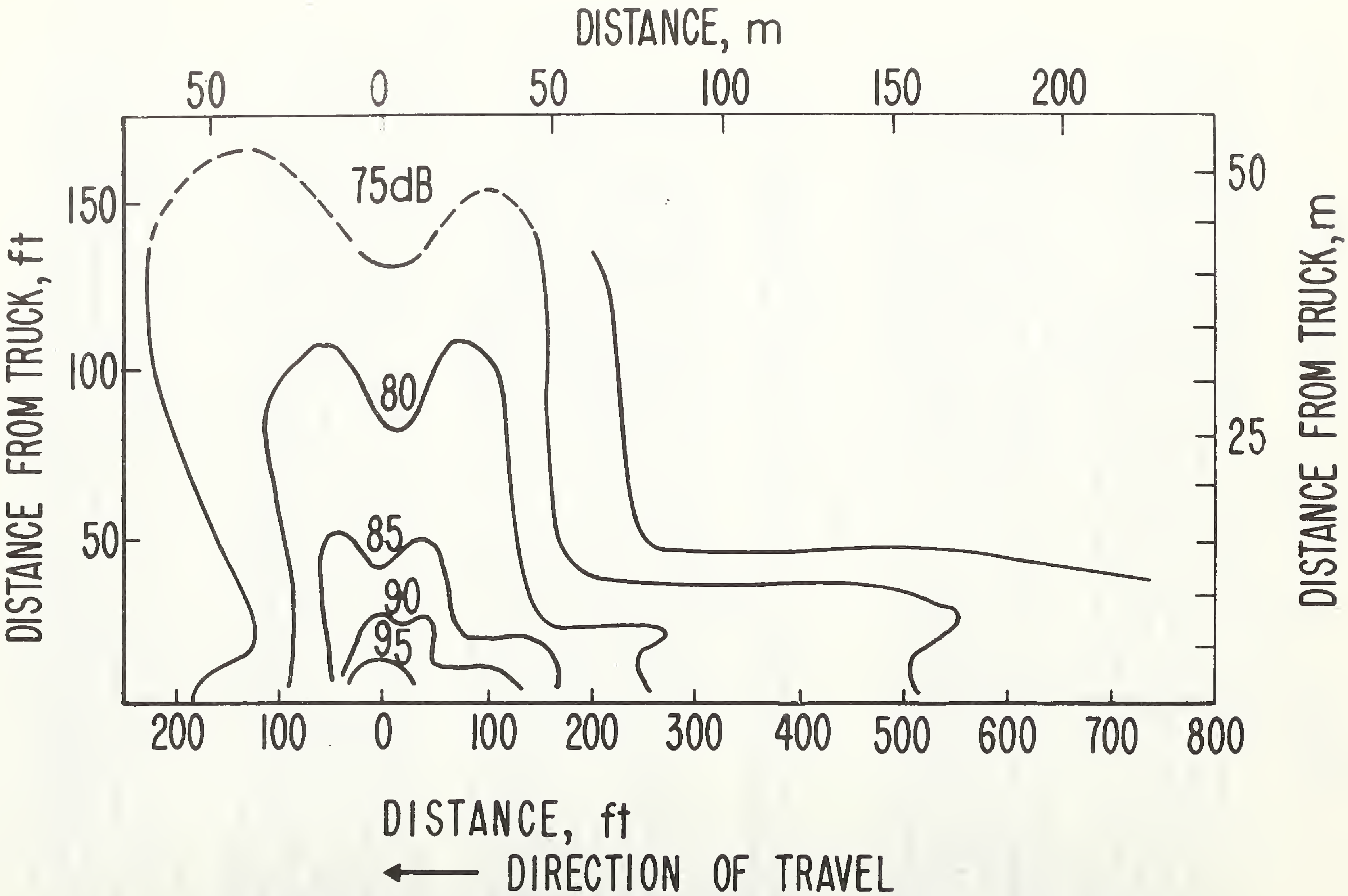


Figure A-2. Equal A-weighted sound level contours (in decibels re 20 µPa) characteristic of a single-chassis vehicle coastby at 45 mph (72.4 km/hr). The test tires were fully-worn pocket treads[19].

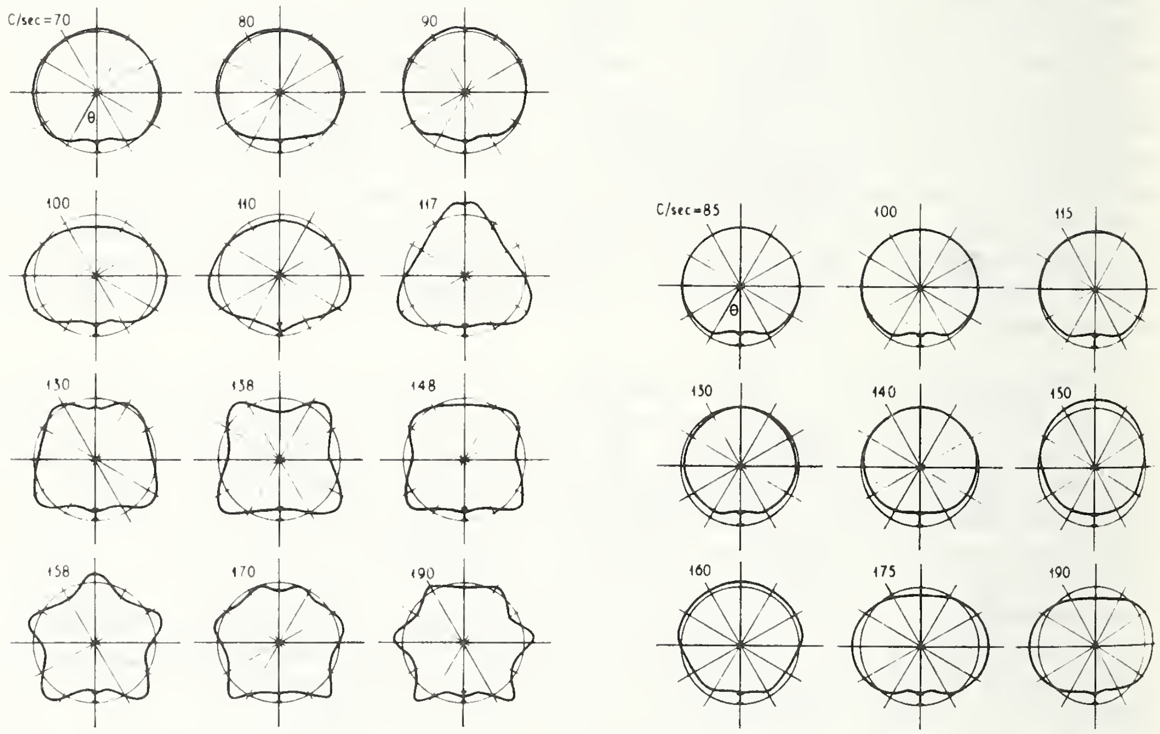
Based on the results of several laboratory studies[40, 41, 42], tire vibrational characteristics and mechanisms of sound generation may be evaluated in three frequency regimes -- low frequency, mid frequency and high frequency.

The low frequency regime covers the range from 20 Hz (below 20 Hz the tire responds approximately as a rigid mass on a spring) to frequencies just below the first carcass mode, which can vary from 80 to 180 Hz depending on the tire size, construction and inflation pressure. In this frequency range the tire responds only in the vicinity of the contact area. This is illustrated in Figure A-3, which shows the deformation lines and their variation with frequency for a stationary, loaded tire (for radial ply and conventional bias ply carcass construction) subjected to vertical oscillations on a vibratory table[41]. Since the tire deforms only in the vicinity of the contact area, sound radiation is likely to be monopole in nature, with an equivalent volume velocity corresponding to the change in tire volume accompanying a fluctuating load. However, because these frequencies are so low and because human hearing is largely insensitive to low-frequency sound, this range of tire vibrations is not likely to be of consequence.

The mid frequency regime extends from the first carcass mode ($\sim$80-180 Hz) to about 400 Hz, again depending upon the size, construction and inflation pressure of the tire. As illustrated in Figure A-3, in this frequency range, the carcass responds in a modal manner. The number of distinguishable modes and the frequency at which they occur is dependent on tire size, tire construction, inflation pressure and tread wear. Referring to Figure A-3, it can be seen that the radial ply automobile tire exhibits four resonances -- 90, 117, 138 and 158 Hz, while the automobile bias ply tire has only a single resonance at 150 Hz. These resonances correspond to a 155-15 size tire at an inflation pressure of 22 psi (1.5×10^5 Pa). These results do not indicate that bias ply tires, in general, have only one major resonance. Reiter[42] found that for a 10.00-22 bias ply truck tire with a cross-bar tread pattern inflated to 100 psi (6.9×10^5 Pa) there were four distinguishable tire resonances.

Chiesa[41] has shown that when either the inflation pressure was increased or the tire size decreased, the tire resonances were shifted towards higher frequencies. These trends were confirmed by Reiter[42] in the previously mentioned study in which he also showed that the resonant frequency increased with tread wear.

The effect of the first mode on sound radiation is illustrated in Figure A-4. As the bottom part of the tire flattens, the top elongates, and vice versa. There will be some volume change associated with each part which causes the tire to behave as a dipole. The efficiency of sound radiation depends on the distance between the contracting and expanding parts of the tire and on the frequency of vibration, or, equivalently, the wavelength of sound λ corresponding to a given frequency. As illustrated in Figure A-5,



Radial Ply Tire

Bias Ply Tire

Figure A-3. Deformation lines obtained at various frequencies at the instant of highest amplitude of disturbance for radial ply and bias ply tires [size; 155-15; inflation pressure 22 psi (1.5 x 10^5 Pa)] [14].

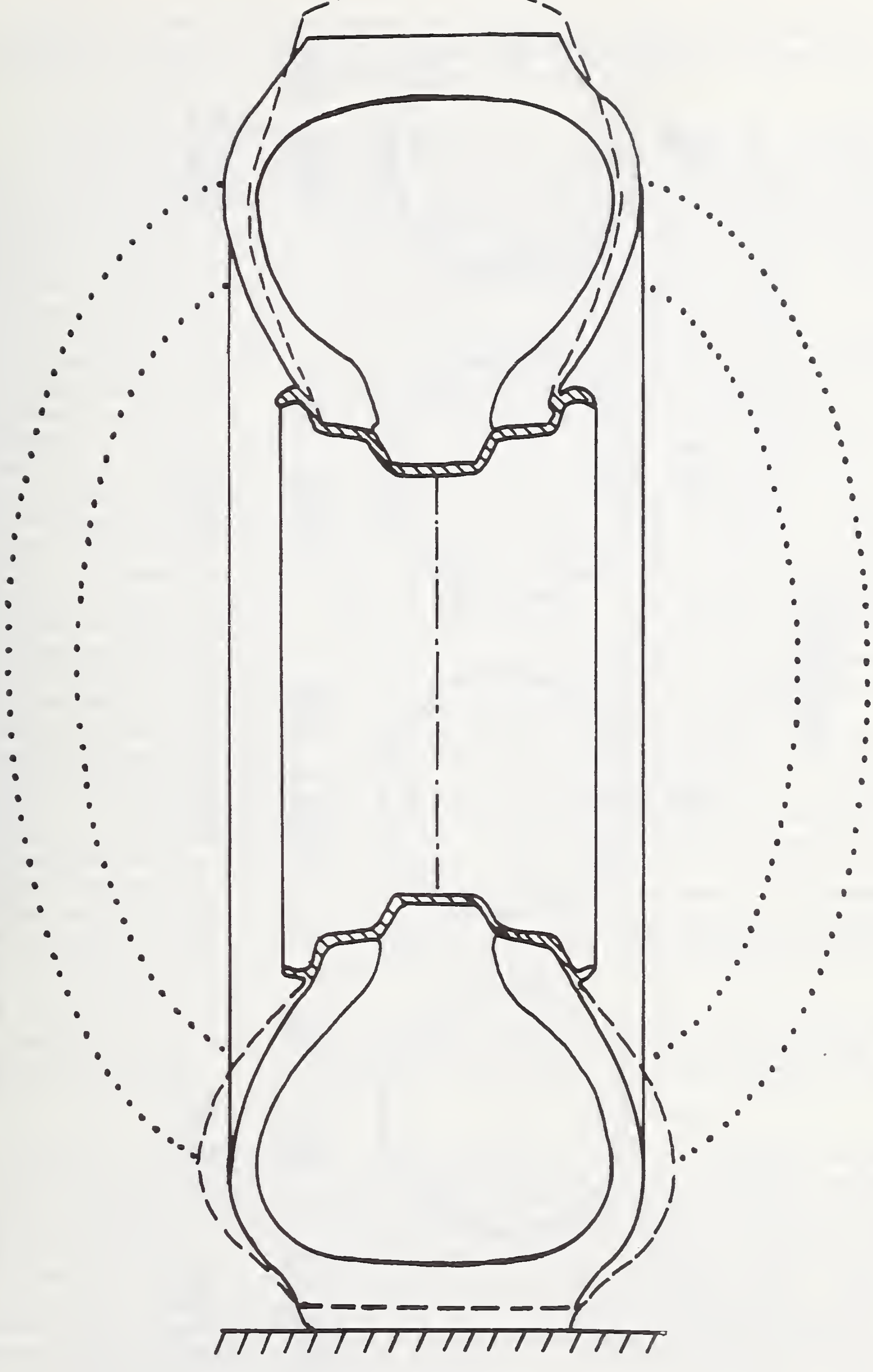


Figure A-4. First mode of tire vibration.

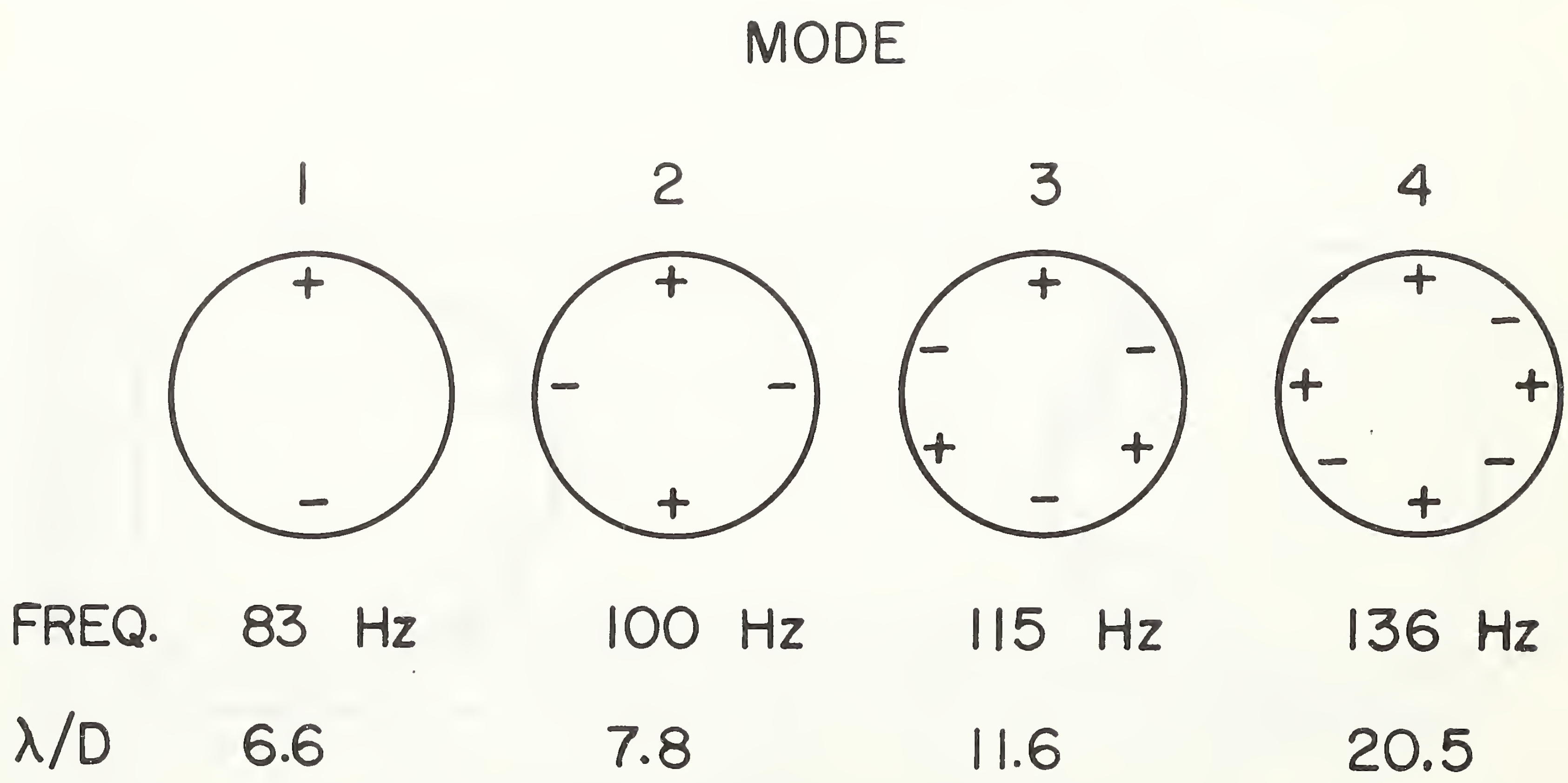


Figure A-5. Modal response of a tire.

$\lambda >> D$ for all modes (these modes correspond to a nonrotating radial-ply automobile tire[40]), illustrating that the tire carcass is indeed an inefficient radiator while responding in a modal manner.

In the high frequency regime (>400 Hz), one can apply the theory of infinite plate radiation[43] (bending waves in plates) to gain some insight into the importance of this regime of tire vibration. As sketched in Figure A-6, for tire vibrations at high frequencies waves in the carcass will be generated at the tire-road interface, however, these waves are expected to attenuate rapidly in the tire with distance from the contact area. The sound radiated by these waves depends on a number of factors, the most important of which is the phase velocity. The propagation speed of a complex wave is frequency dependent, with the high-frequency components travelling with greater velocities than the low-frequency components, thereby altering the shape of the wave. Each frequency component of the complex wave progresses at its own velocity -- the so-called phase velocity of the component. If this velocity is above critical (i.e., above the speed of sound in air) the waves will radiate very efficiently. However, even subcritical waves may radiate significant sound levels owing to low-wavenumber components associated with damping, edge effects, and the structural nearfield associated with the excitation point. In point-excited plates, for example, a nearfield is created (in addition to the free-bending wavefield) whose strength decreases exponentially with increasing distance from the excitation point. Below the critical frequency, the free-bending-wave sound field radiates sound very inefficiently, so that almost the entire sound radiation is produced in the nearfield. The radiated power in this instance is equal to that produced by a rigid piston of radius one-quarter wavelength of the free-bending wave. If this were true for tires, wavelengths greater than a few inches would correspond to source strengths similar to those identified as potentially significant air-pumping sources. This, of course, assumes that amplitudes are similar, which is appropriate since both mechanisms have as their source the deformation of a tire segment at the tire/road interface. The problem here is the fact that neither the damping of the tire nor the wavelength are known. Preliminary accelerometer data[44] indicate that waves are also propagated out from the contact patch along the tread circumference. The waves propagate both to the front (before contact) and to the rear (following contact) of the tire tread.

Since both the vibration and air-pumping mechanisms result from the interaction of the tire with the roadway surface, the tire tread design and the surface texture of the roadway are very important determinants of the noise generated by a given tire.

The tire noise spectrum is composed of two parts: a periodic variation due to the tread pattern and tire nonuniformities and an aperiodic variation due to the road surface features. The periodic component exhibits spectral peaks at discrete frequencies while the aperiodic component exhibits a more continuous spectrum. The frequencies of the spectral peaks are associated with the tire design (tread spacing) and the tire rotational rate. The fundamental frequency can be predicted by calculating the number of tread elements which pass through the footprint per second. If the distance between consecutive tread elements is uniform, the sound produced is nearly a pure tone whose frequency is given by[45]

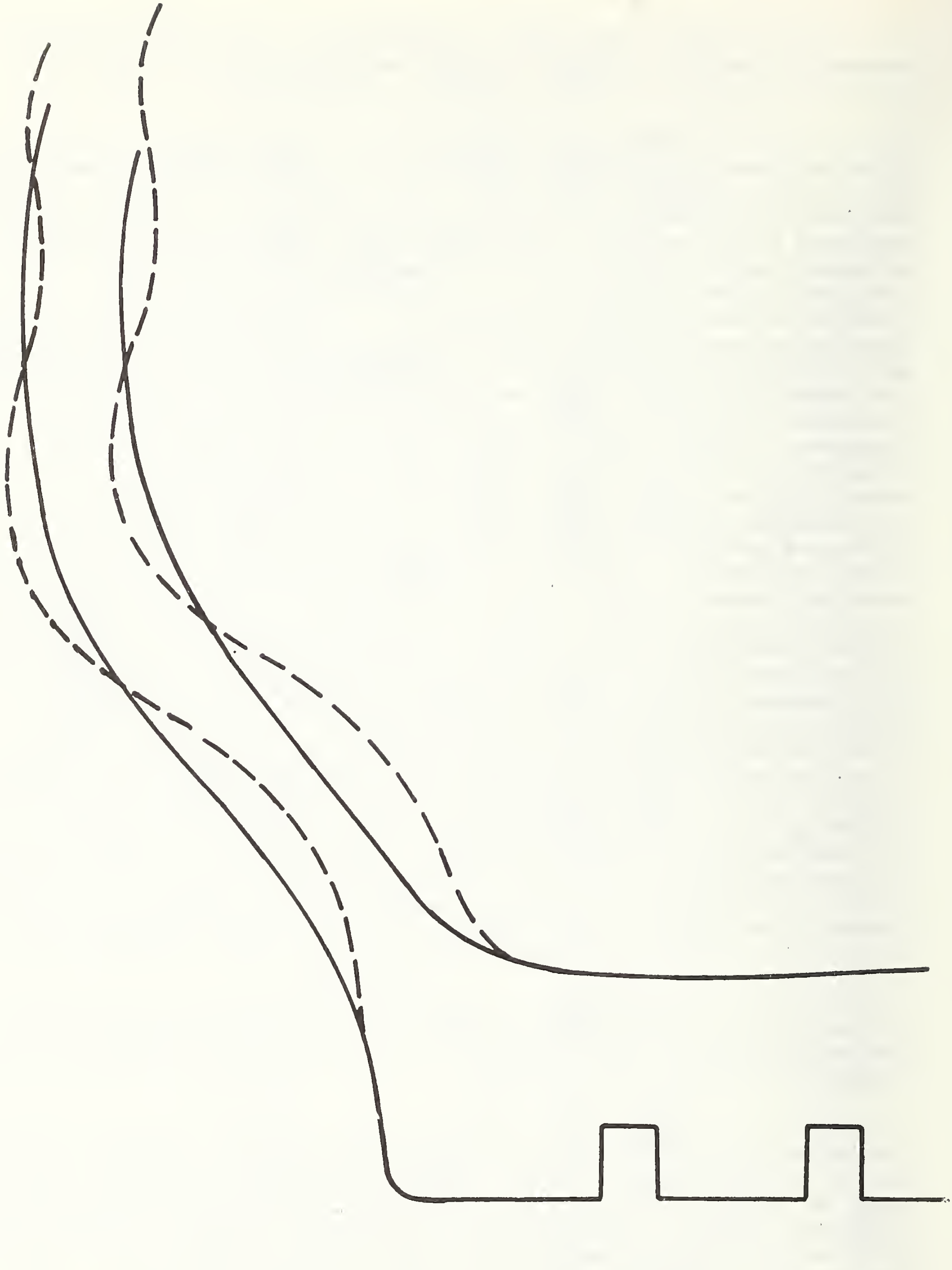


Figure A-6. Tire vibration at high frequencies.

$$f = \frac{27.8V}{a} \tag{A-2}$$

Where, f = fundamental frequency, Hz
V = vehicle speed, km/hr
a = tread spacing, cm

Most tire manufacturers, however, do not utilize a uniform element spacing. The pitch lengths are usually varied in some manner so as to produce a less intrusive sound than a pure tone.

SOUND LEVEL OF HIGHWAY TRUCK TIRES—SAE J57

SAE Recommended Practice

Report of Vehicle Sound Level Committee approved July 1973.

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 50 mph (80 km/h) 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 levels.

Reference to sound levels is 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 ANSI S1.4-1971, Specification for Sound Level Meters.

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 indicating meter, providing the system meets the requirements of SAE J184, with "slow" response specified in place of "fast" as applicable in paragraph 3.6 therein.

2.2 An acoustical calibrator for establishing the calibration of the sound level meter and associated instrumentation.

2.3 An anemometer.

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 100 ft (30 m) of the measurement area.

3.2 The vehicle path shall be relatively smooth, semipolished, dry, Portland concrete which is free of extraneous surface material.

3.3 The microphone shall be located 50 ft (15 m) from the centerline of the vehicle path at a height of 4 ft (1.2 m) 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 50 ft (15 m) 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 powdery snow, grass, loose 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 12 mph (19 km/h).

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 5 ±1 in (127 ±25 mm) minimum clearance with the tire fully loaded. This body shall be nominally 96 in (2410 mm) in width and extend a minimum of 36 in (910 mm) 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 50 mph (80 km/h).

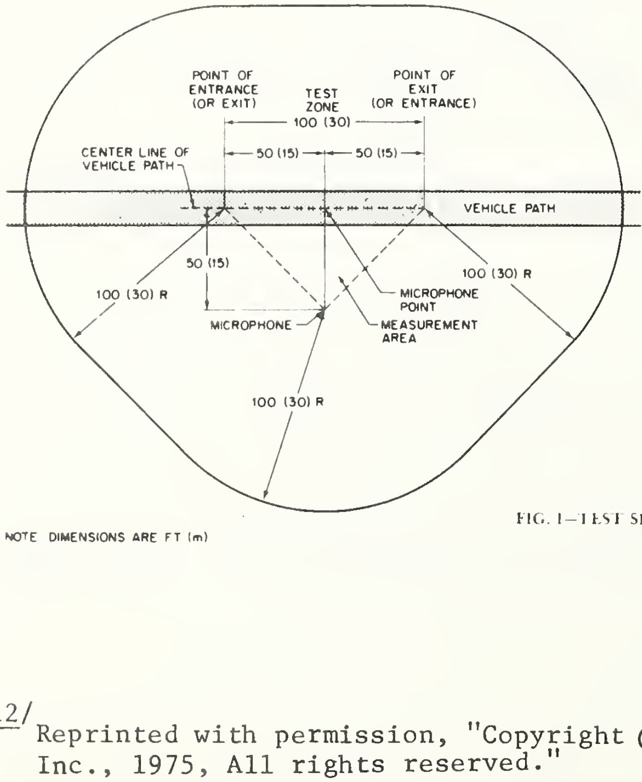
5.2.1 If local load limits will not permit full rated load, the test may be conducted at the local load limit with inflation pressure reduced to provide a tire deflection equal to the maximum load and inflation pressure, provided the load is not less than 75% of the maximum rated load.

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 may not be reported as absolute 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



NOTE DIMENSIONS ARE FT (m)

FIG. 1—TEST SITE (SEE PARAGRAPH 3). (VEHICLE MAY BE RUN IN EITHER DIRECTION)

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sources is minimized throughout the test zone. The vehicle speed at the microphone point shall be 50 mph (80 km/h).

6.2 The sound level meter shall be set for "slow" 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 50 ft (15 m) 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, Acoustical Terminology

8.2 ANSI S1.2-1962, Physical Measurement of Sound

8.3 ANSI S1-4-1971, Specification for Sound Level Meters

8.4 SAE J184, Qualifying a Sound Data Acquisition System

8.5 Tire and Rim Association Yearbook

Applications for copies of the ANSI documents should be addressed to the American National Standards Institute, Inc., 1430 Broadway, New York, New York 10018.

APPENDIX

A1. An A-weighted sound level exceeding 85 dB, determined in accordance with this recommended practice, is not 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 level exhibited by truck tires. The vehicle path surface specified herein is not sufficiently defined to eliminate variations in sound level due to surface (see paragraph 3.2).

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.

Insufficient data are available concerning the measurement of the sound from distant truck tires and the significance of these sounds compared to the sound levels measured with this procedure.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report reviews existing tire noise measurement procedures with regard to their usefulness in the regulation of tire noise as well as the availability, extent and applicability of existing data. On the basis of this review, probable or potential measurement difficulties are identified that could hinder the promulgation and/or enforcement of future EPA regulations to control the noise emission from tires.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*
Acoustics (sound); measurement methodology; noise emission standard; noise measurement; tires.

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