268

National Cooperative Highway Research Program

NCHRP Synthesis 268

Relationship Between Pavement Surface Texture and Highway Traffic Noise

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

TRANSPORTATION RESEARCH BOARD EXECUTIVE COMMITTEE 199

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Synthesis of Highway Practice 268

Relationship Between Pavement Surface Texture and Highway Traffic Noise

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Highway and Facility Design and Pavement Design, Managment, and Performance

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration of the U.S. Department of Transportation.

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis report will be of interest to state DOT pavement engineers, environmental specialists, and noise analysts. The relationship between pavement surface texture and highway traffic noise is discussed. Information for the synthesis was collected by surveying state transportation agencies and by conducting a literature search of both domestic and foreign publications.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This report of the Transportation Research Board provides detailed information on acoustical definitions and concepts, the theory of tire/pavement noise generation and current mitigation practice, measurement techniques, interior vehicle noise, reported noise emission results for pavement type and texture, effects of pavement wear, and surface friction and safety considerations.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the research in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

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Roger L. Wayson, P.h.D., P.E., Associate Professor, University of Central Florida, collected the data and prepared the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of Robert E. Armstrong, Noise Team Leader, Federal Highway Administration; James D. Chalupnik, Ph.D., P.E., Professor (retired), Department of Mechanical Engineering, University of Washington; D.W. (Bill) Dearasaugh, Jr., Engineer of Design, Transportation Research Board; James (Jim) Grove, Portland Cement Concrete Engineer, Office of Materials, Iowa Department of Transportation; Rudolf W. Hendriks, Associate Transportation Engineer, California Department of Transportation; Howard Jongedyk, Research Hydraulic Engineer, Federal Highway Administration; Roger M. Larson, Development Group Leader, Federal Highway Administration; Rebecca McDaniel, Technical Director, North Central Superpave Center; and Kenneth Polcak, Environmental Specialist, Office of Environmental Design, Maryland State Highway Administration.

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Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance are appreciated.

RELATIONSHIP BETWEEN PAVEMENT SURFACE TEXTURE AND HIGHWAY TRAFFIC NOISE

SUMMARY

Pavement/tire noise has been studied for well over 30 years and several large databases have been compiled in the last decade. This synthesis is a summary of the research findings on this extensively studied topic. Summaries of selected sample sets are included to allow comparisons of the various results and reports. Because the reporting is extremely voluminous, care was taken to include up-to-date reports and those that summarize ideas from groups of individuals.

The synthesis first discusses basic acoustic fundamentals and then presents comprehensive details on pavement/tire noise generation and propagation. This permits individuals with various interests in the topic to better assimilate the information.

A survey was conducted to help guide the synthesis. The important findings included:

- About half of the respondents had investigated noise effects from pavement surfaces.
- States specify standard pavement types by a factor of three to one.
- Most states would consider changing pavement types for noise abatement.
- The majority of road surfaces are asphalt, PCC pavement is a distant second, followed by open-graded asphalt.
- The three areas that respondents considered most important for noise abatement are texture, speed, and tire tread design.

A summary of sound and pavement measuring techniques is also presented to help the reader better understand the reported results. Of note is that the two most used noise tests, the close proximity method and the passby method, do not seem to correlate. This is probably due to the fact that the close proximity or trailer method is a measure of noise generated at the tire while passby measurements include propagation effects of the pavement as well.

Measurement data, trends, and findings are discussed from many states, Europe, Africa, Japan, and Australia. Certain trends seem clear. In general, portland cement concrete (PCC) pavements have the advantage of durability and superior surface friction when compared to most dense-graded asphalt. However, data collected to date generally show PCC pavements to create more noise along the highway than asphaltic surfaces. Transverse tining is reported to cause the greatest sideline (roadside) noise levels and also may lead to irritating, pure tone noise. Randomized spacing and changing the tine width have been found to reduce the pure tone that is generated and reduce overall noise levels. Texture depth of the tining also seems to play an important role in sideline noise levels, although exact impact on noise generation has not been proven. Reports vary on the magnitude and impact of using various depths. Longitudinal tining was found to reduce the overall noise levels, but at a cost of reduced surface friction.

Recent research has shown some new concrete pavement textures to be worth further examination. Exposed aggregate (PCC) surfaces appear to provide better noise quality

characteristics as well as good frictional characteristics and durability. Porous PCC pavements also would seem to offer an alternative in the future to reduce sideline noise levels. However, new problems, such as appropriate maintenance and cleaning, must be solved for all porous pavement types.

In general, when dense-graded asphalt and PCC pavement were compared, the dense-graded asphalt was quieter by 2 to 3 dB(A). Even more benefit is shown for dense-graded asphalt when compared to transversely tined PCC pavements. Unfortunately, the dense-graded asphalt usually does not have the strong frictional characteristics of PCC pavements nor the durability.

Open-graded asphalt generally shows the greatest potential for noise reduction of sideline noise and reductions when compared to dense-graded asphalt. Reported reductions ranged from 1 to 9 dB(A). However, the noise reductions seem to decline with surface age and in approximately 5 to 7 years much of the noise benefit has diminished, although the surface is still usually quieter than PCC pavements. Also, porous asphalt suffers from problems such as plugging and deterioration due to freeze/thaw cycles. Other asphaltic surfaces, such as stone mastic and rubberized asphalt, also hold promise, but do not appear to give the noise reductions of open-graded asphalt although most are equal to or better than dense-graded asphalt.

Construction quality is an important consideration in the final overall noise generation no matter which pavement type or texture is selected. Also, safety must always be considered and, unfortunately, some surfaces that produce low sideline noise also have low friction numbers. It is the official policy of the Federal Highway Administration (FHWA), and the opinion of the American Association of State Highway and Transportation Officials (AASHTO) that a small amount of noise reduction is not worth sacrificing safety and durability. This means that the practicing highway design engineer must try to find a "happy medium" between noise control and maintaining a high level of safety.

The maintenance and safety considerations are also reviewed, as are interior noise levels. Of interest is that passby and interior noise levels do not seem to be correlated.

This report provides a comprehensive review, with extensive referencing, to help interested parties expand their explorations. The report provides a good starting point for the topic review, locating needed data, or continuing research.

CHAPTER ONE

INTRODUCTION

Traffic noise is often an annoyance for nearby highway neighbors. Pavement/tire noise is a large component of the overall traffic noise level and has been extensively reviewed. Variance in measurement techniques, conflicts of findings, and the consideration of wear and safety have led to indefinite conclusions on the specification of pavement type and textures for noise abatement. The Federal Highway Administration (FHWA) echoes this thought in the June 12, 1995 Memorandum, "Highway Traffic Noise Guidance and Policies and Written Noise Policies." A document included in this transmittal (*1*) states:

> Pavement is sometimes mentioned as a factor in traffic noise. While it is true that noise levels do vary with changes in pavements and tires, it is not clear that these variations are substantial when compared to the noise from exhausts and engines, especially when there are a large number of trucks on the highway. Additional research is needed to determine to what extent different types of pavements and tires contribute to traffic noise.
>
> It is very difficult to forecast pavement surface condition into the future. Unless definite knowledge is available on the pavement type and conditions and its noise generating characteristics, *no adjustments should be made* for pavement type in the prediction of highway traffic noise levels. Studies have shown open-graded asphalt pavement can initially produce a benefit of 2–4 dBA reduction in noise levels. However, within a short time period (approximately 6–12 months), any noise reduction benefit is lost when the voids fill up and the aggregate becomes polished. The use of specific pavement types or surface textures *must not be considered as a noise abatement measure.*

Because FHWA is the federal agency charged with the responsibility of developing policies and guidelines for the national highway system, this policy applies to all federally funded projects. As such, due to the present uncertainties and safety issues related to pavement/tire noise, abatement due to pavement types ". . . must not be considered as a noise abatement measure." This restricts the potential noise reduction policies available for evaluation by the noise analyst and the highway planner. It is important to continue research on abatement of pavement/tire noise to provide new options to noise analysts in the future. Of course, this must be done without sacrificing safety.

The literature includes a very large number of published and unpublished documents on pavement/tire noise, especially if friction effects of surface variations are considered. While it was not possible to review or include all published documents, this report presents the important considerations from the published literature to provide a starting point for further study by interested parties. Care was taken to include recent reports and those believed to include valuable information.

STUDY APPROACH

The development of this synthesis was accomplished by two discrete work elements: a mail-out survey and an intensive literature review. The mail-out survey results provided direction to the literature research and helped to identify ongoing research. The literature search included Transportation Research Information Services, information provided during the mail-out survey, results of personal communications with experts from four continents, references included in identified sources, and personal knowledge. These reports were reviewed and included as relevant to the various topics discussed in this synthesis.

SURVEY

A mail-out survey was conducted and followed by telephone calls to determine the issues considered to be important for pavement/tire noise research and future applications. Fifty-five responses, representing 41 states, were tabulated and reported.

These responses indicated a strong need for noise control strategies involving pavement surface type and texture. Survey respondents generally agreed that use of different pavement types and textures was the best method for reducing noise from the pavement/tire interactions. However, the need for safety is always a prime consideration and must be included in the selection of pavement type.

REPORT PURPOSE AND FORMAT

This report provides a comprehensive synopsis of pavement/tire noise research as it relates to roadways. It is hoped that this will be an informational text for interested parties and a starting point for researchers. Major topics in the report include results of the survey, acoustical definitions and concepts, a discussion of the theory of pavement/tire noise generation, measurement techniques, interior vehicle noise, reported results for pavement type and texture, effects of pavement wear, surface friction, and safety factors.

Chapter 1 introduces the topic. In chapter 2, responses to the mail-out survey are discussed. Chapter 3 discusses some fundamental acoustics and includes the generally accepted theory of tire/pavement noise generation. Chapter 4 provides an overview of measurement techniques. Chapter 5 is more comprehensive and covers the substance of the topic; reported noise impacts from various locations for different types of concrete and asphaltic surfaces. Chapters 6 and 7 provide information on the important maintenance and safety considerations. Chapter 8 discusses interior noise of the highway vehicles. Chapter 9 provides overall conclusions to the synthesis. Finally, two appendixes show the survey form (Appendix A) and provide acoustic terminology and a bibliography of other information (Appendix B).

CHAPTER TWO

SURVEY RESPONSES

This chapter discusses the responses to questions asked by a mail-out survey conducted for this synthesis. The survey was sent to transportation agencies and consulting engineers worldwide. A special emphasis was placed on the responses of agencies in the United States. A sample survey is included in Appendix A.

A total of 55 surveys were completed and returned. Deleting duplicated responses, a total of 51 surveys were analyzed. Table 1 lists the survey participants. The U.S. Department of Transportation (USDOT) and 41 state DOTs responded, returning 44 surveys. In addition to the federal and state responses, highway agencies for the District of Columbia and three Canadian provinces returned five responses. Completing the list of survey respondents were three research labs and consulting groups.

Table 2 contains a summary of the yes/no questions asked by the survey. About half of the organizations surveyed have conducted some sort of study or investigation of pavement type or surface and how it relates to traffic noise. Due to the nature of the responding organizations and individuals, few conducted research on the effect of tire tread on noise emissions from vehicles (96 percent have not). Noise effects of vehicle speed on different pavement types were studied by about one-fourth of the respondents.

Most of the respondents (70 percent) report that their state, territory, country, or region used standard practices when specifying pavement types. About one-half of the respondents also used standard practices when specifying pavement texture (55 percent).

A majority of those surveyed responded that they would consider different pavement types and surfaces if it could be shown that the new surfaces would reduce vehicle noise (74 and 71 percent, respectively). Of the respondents who would consider different pavement types for noise abatement, open-graded asphalt was the pavement type most often mentioned. Many of those responding positively to the use of various pavement characteristics for noise control added that the pavement/surface alternatives would have to be cost-effective and demonstrate comparable durability. Of the acceptable surface changes considered, the responses included open-graded friction course, random spacing of the transverse tining, and modified, tone-filled sheet asphalt. Also mentioned were rubberized concrete and other asphaltic concrete mixtures.

When asked about pavement texturing used by the states and provinces, almost all responded that transverse tining is used for concrete pavements and friction course and chip seal were used for asphalt pavements.

TABLE 1

SURVEY RESPONDENTS

Alabama Department of Transportation	Maryland State Highway Administration
Alaska Department of Transportation	Massachusetts Highway Department
Arizona Department of Transportation	Michigan Department of Transportation
Arkansas State Highway and Transportation Department	Minnesota Department of Transportation
California Caltrans	Mississippi Department of Transportation
Canada	Missouri Transportation and Highway Department
Newfoundland Department of Works, Service and Transportation	Nebraska Department of Roads
Prince Edward Island Department of Transportation Works	Nevada Department of Transportation
Victoria British Columbia Ministry of Transportation	New Hampshire Department of Transportation
Colorado Department of Transportation	New Jersey Department of Transportation
Connecticut Department of Transportation	New Mexico
Washington, D.C. Department of Public Works	North Carolina Department of Transportation
Delaware Department of Transportation	New York Department of Transportation
Durisol Ltd.	Oregon Department of Transportation (3 responses)
Florida Department of Transportation	Rhode Island Department of Transportation
Hawaii Department of Transportation	South Carolina Department of Transportation
Idaho Transportation Department	Tennessee Department of Transportation
Illinois Department of Transportation	Texas Department of Transportation
Indiana Department of Transportation	U.S. Department of Transportation
France Inrets	Utah Department of Transportation
Iowa Department of Transportation	Vanasse, Hangen, Brustlin, Inc.
Kansas Department of Transportation, Materials and Research Center	Vermont Agency of Transportation
Kuwait University	West Virginia Department of Transportation
Louis Berger and Associates	Washington Department of Transportation
Louisiana Transportation Research Center	Wisconsin Department of Transportation
Maine Department of Transportation	Wyoming Department of Transportation

TABLE 2

SUMMARY OF SURVEY RESPONSES

Question	Yes	No
Has the organization ever investigated noise effects from pavement/surfaces?	26	25
Has the organization ever studied speed effects on noise from various pavements/surfaces?	11	40
Has the organization ever studied tire tread effects on noise?	2	49
Has the organization ever studied effects of pavements/surfaces on vehicle interior noise?	13	38
Does the state, country, etc. use standard practices in specifying pavement types?	36	12
Would the organization consider use of different pavement types for noise abatement?	26	19
Has the organization conducted long-term studies in regard to pavement wear?	16	30
Does the state, country, etc. use standard practices in specifying pavement texture?	21	17
Would the organization consider use of different pavement textures for noise abatement?	29	12
Has the organization conducted long-term studies in regard to pavement wear with different surface textures?	11	36
Has the organization conducted studies on the effects of different pavement types or surface textures on surface friction?	22	26
Has the organization conducted studies on the effects of different pavement types or surface textures on drainage or comfort of ride?	5	44

The respondents provided percentages of pavement types used in their state or province. These percentages were averaged to produce Table 3. Dense-graded asphalt is clearly used more than other pavements in the responding states and provinces. Concrete surfaces are a distant second, comprising only 10 percent of the roadway surfaces in states and provinces that responded. Open-graded asphalt comprised the rest of the surfaces reported. The reported national averages for Federal-aid highway projects (*2*), are 18.8 percent rigid pavements, while 56.6 percent were listed as flexible pavements. In addition, composite surfaces make up 21.8 percent of the total.

TABLE 3

PERCENT OF PAVEMENTS USED BY STATES AND PROVINCES

Pavement Type	Percent of Roads
Dense-graded asphalt	84
Open-graded asphalt	6
Concrete	10

Many pavement parameters were thought to be important in tire/pavement noise control; responses are listed by frequency of occurrence in Table 4. Roadway texture was the number one response. Vehicle speed and tire tread design rounded out the top three items respondents thought were important contributors to tire/roadway noise. Pavement type and type of surface were also mentioned by multiple respondents. Single responses covered several topics and included:

1. Tone or pitch might be considered instead of L_{eq} (equivalent sound pressure level) when evaluating annoyance due to traffic noise.

TABLE 4

RANKING OF RESPONSES OF MOST IMPORTANT PARAMETERS FROM SURVEY

Item	Responses (%)
Texture	22
Speed	18
Tire tread	16
Surface	9
Pavement type	9
Pavement age	4
Vehicle weight	4
Porosity	2
Frequency content	2
Tire age	2
Tining depth	2
Vehicle type	2
Pavement/moisture content	2
Pavement/air temperature	2
Distance to receivers	2
Pavement joints/irregularities	2
Pavement friction	2

2. Work needs to be done to support the position that safety benefits of transverse grooving of road surfaces outweigh the increase in traffic noise.
3. Changes in traffic noise improvement qualities over the lifetime of surfaces need to be considered.
4. Transverse tining was thought to be objectionable because of the increased traffic noise effects.

Traffic noise due to the interaction of the vehicle tires, pavement types, and surface texture is clearly a topic of interest to the states and provinces that participated in this survey. The results of this survey were carefully reviewed and helped define the literature search for the remainder of this work.

CHAPTER THREE

ACOUSTIC CONCEPTS

FUNDAMENTAL CONCEPTS OF SOUND

Any noise source, whether it is a pure tone from a tuning fork or the complicated spectra from traffic noise, initiates an amazing process. The human ear can hear a large range of pressure variations (perceived as loudness) and frequencies (perceived as pitch). These differences in sound permit us to identify the source and its relative importance. Unwanted sound is subjectively considered by individuals to be noise.

Loudness

The intensity of the sound or noise is directly related to the amplitude of the pressure fluctuations transmitted through air and arriving at the ear. Loudness is the subjective determination we make as individuals. These small pressure fluctuations around barometric pressure travel as waves in the medium of air and flex the ear drum, creating the sensation of sound. The tire-to-surface interaction and vehicle vibrations all create pressure fluctuations easily detectable by the human ear. The healthy ear can sense pressure fluctuations as low as 2×10^{-5} Newtons/m^2 (the threshold of hearing) and greater fluctuations until physical pain begins (the threshold of pain is considered to be about 63 Newtons/m^2). This large range of values is difficult to manipulate. In addition, the human auditory response is not linear. An internationally derived unit used to describe sound pressure fluctuations, perceived as loudness, is the decibel. The decibel is logarithmic in nature, usually abbreviated by using the nomenclature dB and indicates the sound pressure level (*SPL*). The decibel is computed mathematically by:

$$SPL\ (\text{dB}) = 10 \log_{10}(p^2/p_o^2) \quad (1)$$

where

p = the ambient root-mean-square sound pressure, and
p_o = the reference pressure (2×10^{-5} Newtons/m^2).

The use of the logarithm not only reduces the large range of values we must deal with (see Figure 1), but also corresponds more closely to the way our ears perceive sound. The derived range now becomes 0 dB (threshold of hearing) to about 130 dB (threshold of pain). The reader should note the big difference between *SPL* and sound pressure.

Decibels do not add linearly, but in a logarithmic fashion. This means that an increase in source strength by a factor of two (twice as much sound energy) would only result in an increase of 3 dB. Put another way, if we had two traffic sources, each at 60 dB, the sum of the two would be 63 dB. This can be easily shown mathematically. The resulting equation to add multiple sources would be:

$$SPL_{total} = 10 \log_{10} \Sigma\, 10^{SPL(i)/10} \quad (2)$$

where *SPL*(i) refers to individual sources.

Under laboratory conditions, a normal healthy ear can determine a change in loudness with a corresponding *SPL* change of about 3 dB. In outdoor situations, a perceived change of loudness is usually greater than 3 dB and 5 dB is typical. A change of 10 dB (10 times the pressure fluctuations) is generally judged to be a doubling or halving of the sound level. This means that a significant change in traffic characteristics must occur for individuals to objectively determine a change in noise levels.

Frequency

The ear also detects a large range in frequency. The healthy ear can determine sound pressure fluctuations occurring from about 20 times each second to 20,000 times each second. These occurrences per second or cycles per second, have the unit of hertz (Hz). As such, the normal, healthy human ear can hear from 20 Hz to 20 kilo-hertz (kHz). It is the frequency component of sound that provides the tonal quality. A passenger car has a much different frequency spectrum than a semi-truck and the human ear is adept enough to easily tell the difference.

The frequency of a sound is inversely proportional to the wavelength. The wavelength, or spacing of the acoustic pressure fluctuations, is mathematically related to frequency as:

$$\lambda = c/f \quad (3)$$

where

λ = wavelength,
c = speed of sound, and
f = frequency.

Since the speed of sound is a relative constant in ambient conditions, the wavelength for any given frequency is also relatively constant. A sound is not perceived or described just by loudness (intensity), but by the frequency spectrum as well.

Again, as a protective mechanism, our ears do not hear all frequencies equally well. The human ear does not respond very well to low frequencies (less than 250 Hz) or to higher

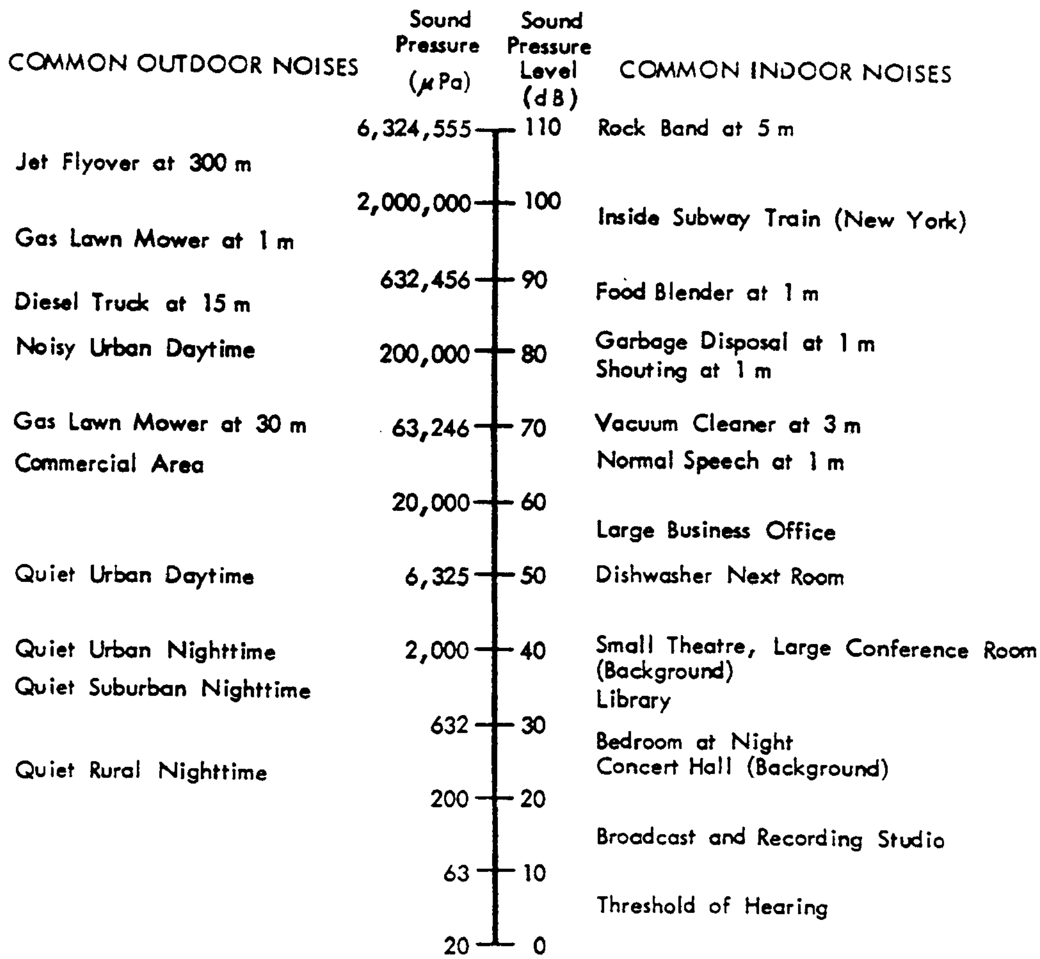


FIGURE 1 Common indoor and outdoor noises *(3)*.

frequencies (greater than 10,000 Hz). Rather than specify the intensity of each frequency to completely describe the noise, we generally use ranges of frequencies or overall weighting schemes for the entire range of frequencies. The overall weighting schemes generally approximate more closely the way we hear sound considering all audible frequencies.

When ranges of frequencies are reported, octave bands are commonly used. In music, a tone that is one octave above another has a frequency twice the first. Using this same idea, the upper octave band frequency is twice the lower limit. As such, the range of frequencies in the octave band is also equal to the lower frequency of the band. Octave bands are designated by the geometric mean of the frequency range, called the center frequency. Each successive octave band center frequency is twice the last. One-third octave bands divide the octave bands to even more narrow frequency ranges and are also commonly used, especially for research. The standard center frequencies are included in Appendix B for octave and third-octave bands in the definition of each term. In some cases, even more narrow frequency ranges may be needed, based on either smaller octave band ranges (i.e., one-ninth or one-twelfth octave bands) or predefined narrow band analysis.

Regulations and typical survey measurements in outdoor situations more typically use a single decibel value, based on the summation of energy in the overall hearing spectrum. This overall weighting, using appropriate factors by frequency band, approximates the way the human ear perceives sound. Three basic scales have been developed and are internationally recognized. Figure 2 shows the A, B, and C weighting scales. The A scale is the way our ears respond to moderate sounds, the B scale is the response curve for more intense sound, and the C scale is the way our ears would respond to very loud sounds. The A scale is most often used. Correct reporting of *SPLs* weighted with the A-scale should be: ##dB (A), where ## represents a numeric value.

SPL Descriptors

A firecracker may be loud, but lasts only a fraction of a second. Traffic noise may not be as intense, but is continual. To account for the duration of the sound and allow for the effective description of how sound level varies with time, various descriptors are used. Some of the more important descriptors with regard to pavement/tire noise research are: L_{max}, L_{xx}, and L_{eq}. In each of these descriptors the capital letter L represents that each is a sound pressure level, and not sound pressure. Accordingly, we know the units to be dB.

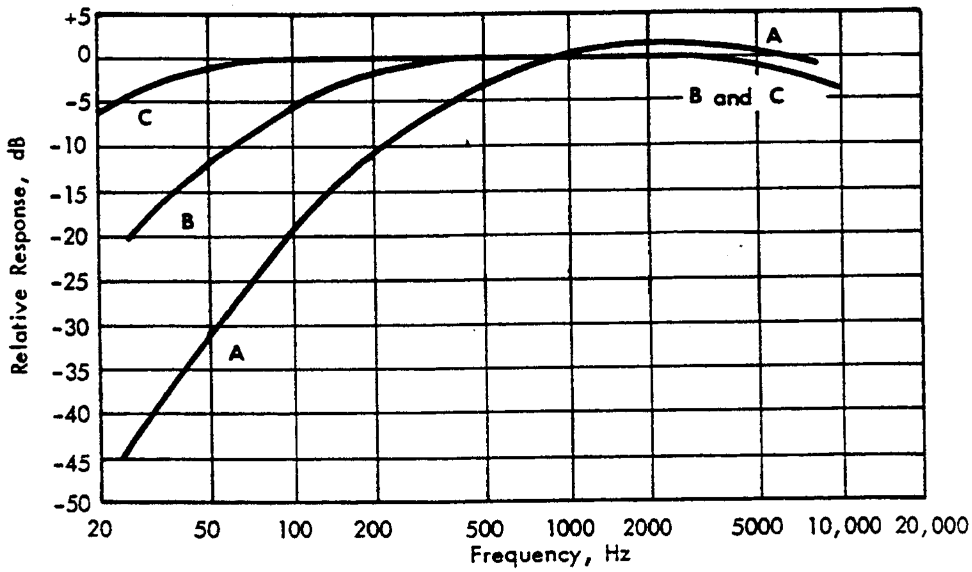


FIGURE 2 Frequency responses for sound level meter weighting characteristics *(3)*.

L_{max} represents the maximum noise level that occurs for a small persistence period during a defined time interval. Accordingly, L_{max} (1 hr) would be a descriptor that defined the maximum noise intensity that occurred for a short time period during one hour.

L_{xx} represents a statistical descriptor for sound pressure level, where the subscript xx represents the percentage of time that the level is exceeded. For instance, a reported sound level of 60 dB (A); L_{10} (1 hr), would mean that a sound pressure level of 60 dB on an A-weighted scale was exceeded 10 percent of the time in a one-hour time period. The numeric value may be any percentage, but L_{10}, L_{50}, L_{90} and L_{99} are most commonly used. L_{90} is the sound pressure level exceeded 90 percent of the time and is commonly used as the background level near major traffic sources.

L_{eq} is the equivalent sound pressure level. L_{eq} is a single number metric that represents the level of a nonvarying tone over a defined time period that contains the same acoustic energy as a varying tone. One might think of L_{eq} as an average acoustic energy descriptor. It should be noted that the average energy is not an algebraic average of SPL over the time period, but a logarithmic average, because of the logarithmic nature of the dB.

Highway Traffic Noise Standards

Standards are difficult to determine in practice because of the subjectiveness of noise. A pleasant sound to one individual is a noise to another. In addition, controversy exists on which descriptor is most accurate for different sounds and situations. In the United States, noise regulations included in 23 CFR 772 define highway noise standards. Among the standards are the Noise Abatement Criteria (NAC). These criteria define levels of sound at which noise abatement must be considered. The criteria are promulgated and reporting monitored by the FHWA. The defined NAC for residential areas is when the traffic noise levels approach or exceed 67 dB(A); L_{eq} or 70 dB(A); L_{10}. Either descriptor may be chosen. It should be noted that the criteria are not design standards or absolute values, only levels where noise mitigation must be considered. If abatement is considered infeasible or unreasonable, then abatement measures may not be implemented even though the criteria are exceeded. This leads to the need for each project to be carefully documented and considered individually.

Traffic Noise Modeling Basics

The following discussion introduces the basic concepts used in traffic noise modeling. At the "heart" of the traffic noise prediction modeling process is the *reference energy mean emission level* (REMELs). REMELs are averages of noise levels and frequency spectra that occur from defined vehicle types at specified distances. A REMEL usually represents the maximum passby level of a single vehicle. REMELs are specific by vehicle type. In the United States, a distance of 15 m (50 ft) from the center of the vehicle track, perpendicular to the direction of travel has been established. In Europe, 7.5 m (25 ft) is more typical. Defined vehicle types are generally automobiles and trucks with subcategories of trucks also used. The FHWA uses the categories of cars, medium trucks, and heavy trucks in the present model and will expand the categories to include buses and motorcycles in a model soon to be released called the Traffic Noise Model (TNM).

It is important to note that pavement/tire noise is an important subsource of the overall vehicle noise and is included in the overall REMEL. Reduction of this subsource would be one possible mitigation measure. Also it is important to note that the pavement/tire noise could be measured at the tire or along the side of the roadway. At the tire, a trailer is commonly used. The method along the roadway is called the passby method. The measurement details and the overall impact of the pavement/tire subsource are discussed in more detail later in this report.

Using the reference level (REMEL: A-weighted; specified distance) the FHWA methodology uses a proven series of adjustments to allow calculation of noise levels for defined situations. The adjustments account for variables that occur in the typical highway situations. Among these are geometric spreading (effects of distance), traffic flow adjustments, adjustments for the geometric design of the highway, adjustments for ground effects, and adjustments for meteorology. Pavement types are not considered.

The FHWA methodology has been incorporated into a computer program called STAMINA. The latest release is STAMINA 2.0. A sister program named OPTIMA is also used for noise barrier design.

Mitigation

Mitigation of traffic noise effects on highway neighbors may occur at the source, in the propagation path, or at the receiver. Typical highway noise abatement measures include:

Source	*Path*	*Receiver*
Engine shielding	Surface (pavement and surroundings)	Insulation of structures
Mufflers for exhaust	Greenbelts	Noise masking
Tire design	Barriers	
Pavement texture	Reflection	
Aerodynamic streamlining of vehicle	Absorption	
Limiting of speed		
Control vehicle types		

Each abatement measure has benefits and deficiencies. It should be noted that pavement/tire noise reduction offers a reduction method for the source and affects propagation characteristics.

PAVEMENT CONSIDERATIONS

The noise generated by motor vehicles comes from several subsources, including the power train, exhaust system, aerodynamic noise, and tire noise. Figure 3 shows the relative contribution of various vehicle sources (*3*). It is common to divide these subsources into two broad groups: power train noise (engine, exhaust, cooling system); and coast-by noise (tire/pavement interaction, aerodynamic noise, vehicle vibrations). The combination of power train and coast-by noise after allowing for propagation effects (absorption, distance, surface) results in the overall passby noise level for a sideline (along the road) receiver. For even low speeds, the tire noise component is a significant portion of the passby noise for automobiles. Work in Minnesota indicated that for speeds of 80 kph (50 mph) or greater, the pavement/tire noise strongly dominates (*4*). Sandberg believes that this very important interaction begins at very low speeds (*5*) and reported that even at speeds of 40 to 50 kph (25 to 31 mph) the tire noise dominates

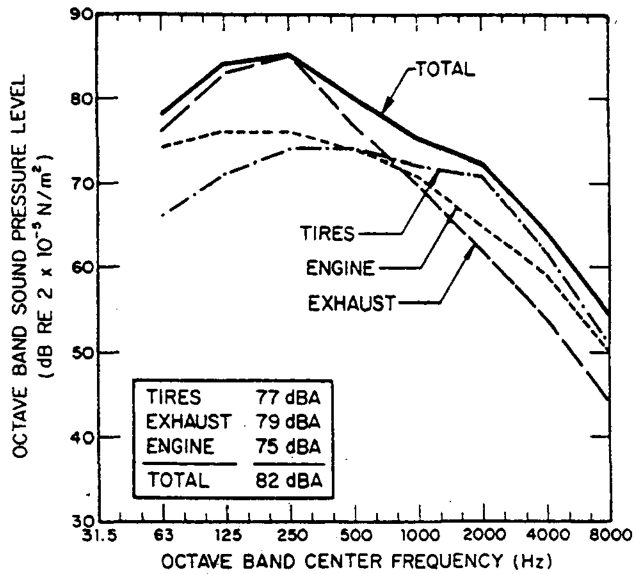


FIGURE 3 Hypothetical mixture of the three principal sources of truck noise. Noise levels will vary for different components in different trucks (*3*).

for most modern European passenger cars. Nilsson also confirms that tire/road noise is the dominant noise source for automobiles (*6*). For trucks, the tire noise typically becomes dominant at higher speeds, overcoming engine and exhaust noise that is greater when compared to automobiles. Of course, the exhaust height of trucks is also a significant factor affecting propagation. Exhaust releases by trucks in the United States tend to be from stacks 10 to 12 ft high (3 to 3.7 meters). In Europe, axle-height release of exhausts from trucks is more common.

The generation mechanism for tire noise has been well researched. A state-of-the-art report published in 1994 (*7*) described three discrete mechanisms of tire/road noise production: tire vibrations, air resonance, and accelerated water droplets.

Tire vibration can be broken into two categories: radial and tangential vibrations. The radial vibrations are caused by the impact of the tire tread pattern, the impact of the road surface textures, and adhesion of the "stick-release" from contact of the tire and pavement surface. Tangential vibrations are caused by frictional forces and "stick-slip" motions. Air resonance is caused by the pipe resonance (dihedral formed by the tire/pavement contact geometry), Helmholz resonance, and tire pocket air pumping. When water is present, water noise of the accelerated droplets becomes important. Most noise research and measurements are done on dry surfaces.

Figure 4 displays some of the important mechanism concepts (*7*). The vibration of the tire and air resonance of the tread results in noise generation in different frequency ranges. Air resonance, due to the geometry of tire tread patterns, is in the higher frequency ranges. To better understand these phenomena, the mechanism must be explored.

Sandberg (*5*) discussed the important generation mechanisms for tire noise on dry pavement:

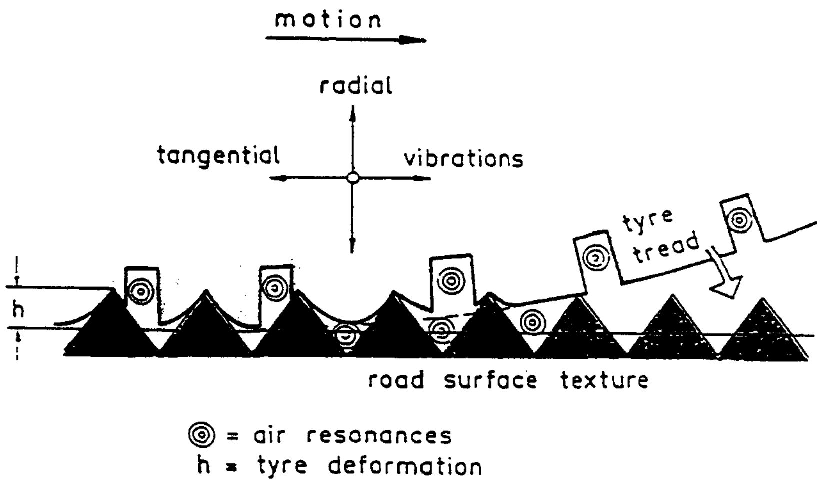


FIGURE 4 Mechanisms of tyre/road noise production *(7)*.

- Tire radial vibrations,
- Tire tangential vibrations, and
- Air pumping.

The tire radial vibrations are excitations in the radial direction caused by the tire tread element impacts on the road or the road surface deforming the tire. Unevenness in the road surface will increase these radial vibrations. The tire tangential vibrations occur due to the stick/slip or sliding motion in the patch forming the tire/road interface. Finally, air pumping is the compression of air and rapid expansion as the air is forced out between the road and the tire tread. It is obvious then that both the road surface and the tire are important when considering sound created by the tire/road interaction.

Bergmann (*8*) discussed the generating mechanisms for the vibration of tires in more detail. The tire vibrations when plotted have a complex shape in the radial, tangential, and axial directions. The vibrations are primarily radiated near the contact patch because of the high dampening of the tire material. The important phases during the rolling process, as pointed out by Bergmann, are the moments when a tread element enters and leaves the contact patch. The tire tread element experiences a large acceleration as it enters the contact patch and a deceleration as it leaves. This leads to strong tire vibrations and sound generation. The point is made by Bergmann that the contact patch varies both by tire and by pavement surface.

The major components, tire vibration and air resonance, then cause different frequencies to be generated. Nilsson (*6*) described the frequency characteristics in two broad categories—low and high frequencies. Measurements made by Nilsson and his colleagues suggest that the limiting frequency between the two frequency regions, high and low, depend on the type of tire and road surface. This boundary region is a range of about 800 to 1,000 Hz for passenger car tires on an asphalt road of "normal" roughness. Low frequency tire noise is generated when the tire/road roughness excites the tire structure mechanically as it rolls over the surface. The excitation occurs mostly in the radial direction but at frequencies below 200 Hz. Coriolis accelerations could also cause coupling and vibrations in the both the radial and tangential directions. At speeds over 70 kph (44 mph) centripetal acceleration also becomes important. Of interest was the point that below about 300 Hz, the wavelength equaled or exceeded the dimensions of the contact patch. The contact patch dimensions then become a good approximation for low frequency noise generation. But the higher frequencies (shorter wavelengths) are smaller than the contact patch, making it important to consider the leading and trailing edges separately.

The results suggested that, in the high frequency region, two main subtypes of mechanisms were responsible, each dependent on the trailing or leading contact edge. For the trailing contact edge the tire/road adhesive bonds excite the tire treads and generate radial and tangential vibrations during the release process. The tangential vibrations excite air resonance that radiates the sound efficiently to the surroundings. For the leading contact edge it was hypothesized that the impulsive deceleration creates a shock wave. This high frequency contact peaks in the outermost level of the tread block. The tread block tends to filter these high frequencies before they reach the tire carcass. Air is expelled between the road surface and the outermost layer of the block, resulting in a time-varying volume being expelled that radiates sound. At the same time, the rigid body radiation process propagates acoustic energy. It was pointed out that this leading edge noise generation is very significant when considering rolling noise and surface type. The indicated noise mechanism as discussed by Nilsson is shown graphically by Donovan's work (*9*). A sample of these graphical representations is shown as Figure 5. In this figure, there are two basic frequency regimes as defined by Nilsson. The sidewall vibration that is texture induced leads to frequencies under 1 kHz. Accordingly, a rough-textured pavement generates more low frequency noise. Fortunately, humans do not hear low frequencies well. At the leading and trailing edge of the contact patch, higher frequencies are generated (> 1 kHz). The tire "slip" and air pumping cause significant noise generation in the frequency range best heard by highway neighbors. Scrubbing, friction effects caused by the tire slippage over the pavement surface, increases as pavement texture increases. This occurs at the leading and trailing edge of the tire patch and causes sound in the higher frequency

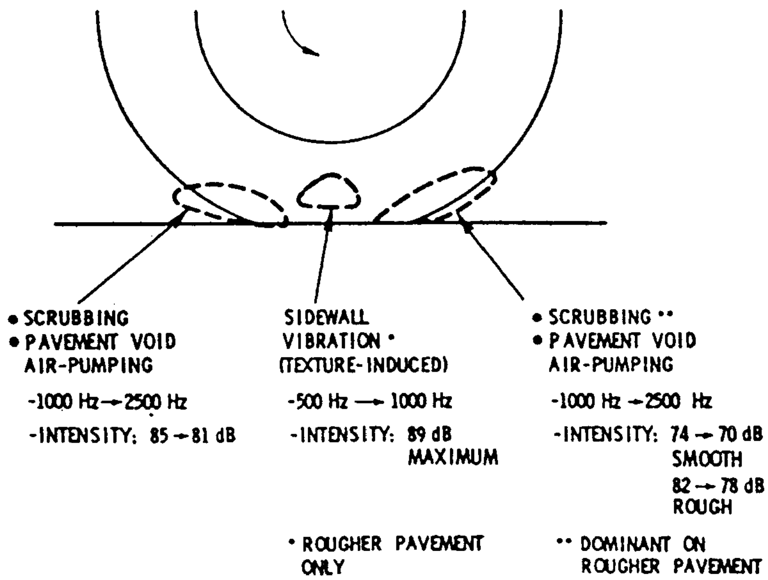


FIGURE 5 Indicated noise mechanisms for blank tread truck tires *(9)*.

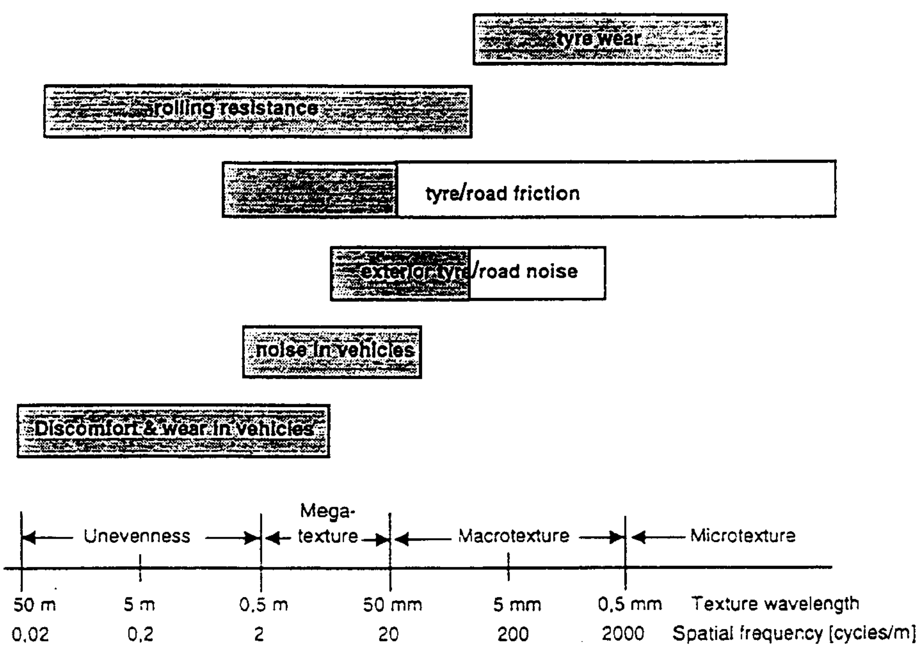


FIGURE 6 Ranges of texture and uneveness and their most significant anticipated results. A lighter shade means a favorable effect of texture over this range, while a darker shade means an unfavorable effect *(10)*.

ranges, as shown in Figure 5. However, the sound due to air pumping increases on smoother pavements. As such, overall noise levels are functions of the surface texture and contain various components or subsources from the tire/pavement interaction. The question becomes, how can this texture and associated noise effects be better identified and perhaps used as an abatement consideration.

The World Road Association's Permanent International Association of Road Congresses (PIARC) Technical Committee on Surface Characteristics has defined the various wavelengths of surface irregularities as:

< 0.5 mm (0.02 in.)	microtexture
0.5–50 mm (0.02–2.0 in.)	macrotexture
50–500 mm (2–200 in.)	megatexture
0.5–50 m (1.6–164 ft)	roughness

A good comparison of the relative importance of each of these ranges of texture on various service parameters was reported by an International Standards Organization (ISO) working group (*10*) and is presented in Figure 6. As can be seen from Figure 6, microtexture is important for safety but does not have a significant impact on noise generation.

Macrotexture and megatexture play significant roles in noise generation and safety.

Sandberg also emphasized the importance of a "cross-over frequency" (*11*). This "cross-over frequency" is a region in which the dominant noise generation mechanism changes. As described by Sandberg, sound pressure levels at low frequencies increase with increasing texture in the wavelength range of 10–500 mm. (0.4–20 in.). The sound pressure levels at high frequencies decrease with increasing texture amplitude in the wavelength range of 0.5–10 mm. These conflicting effects and the resulting exterior noise levels depend on how the texture is composed. The cross-over frequency was reported to be about 1,000 Hz for automobiles and 500 Hz for trucks. The reason given for these different frequencies was that the tire tread pattern elements for trucks are about twice the size of those for automobiles. These findings indicate that there is no simple, general relationship between overall noise levels and pavement texture. Indeed, optimization with respect to automobiles would be different than for trucks.

The recent European state-of-the-art report (*7*) is in agreement that low frequency noise is caused by the tire vibrations and is a function of the large wavelengths of the surface texture (megatexture). Medium frequencies were reported and thought to be mainly controlled by the pattern of the tire tread. Changes in macrotexture and megatextures can lead to significant differences in noise generation but also require various construction techniques. However, it is reported that the overall sideline noise level decreases with increasing amplitude of the texture. Also, the microtexture amplitude has a decisive influence on surface friction that must be maintained, which makes implementation more difficult.

Surface texturing of the paved surface creates macrotexture and allows for water removal but causes radial excitation of the tires. There are many types of texture treatments, and the types of surface treatment vary by pavement type and local conditions. Surface treatments for portland cement concrete surfaces include: tining (longitudinal, transverse, diagonal); dragging, (Hessian or burlap); exposed aggregate; applied aggregate; use of porous textures; and combinations of these methods. Asphaltic pavement surface types include: dense-graded, open-graded (often called drainage, porous, or popcorn asphalt), and stone mastic. Other local surfaces, such as block, have also been evaluated for noise impacts.

The Third International Symposium on Pavement Surface Characteristics was held in New Zealand in late 1996 (*12*). The proceedings of this symposium showed that developments and standardization are occurring in measurement of surface friction and surface characteristics, optimization of pavement friction, as well as traffic noise reductions. Some of the results of this conference are discussed later in this report.

Tire noise is directly related to speed. This was proven by a large data collection effort by Rickley that was reported in 1978 (*13*) and reconfirmed by another large national study completed in 1995 by Fleming (*14*). Sandberg (*15*) showed that as speed increases, tire noise increases at nonlinear rates. The overall energy in the frequency bands also has a tendency to shift toward the higher frequency ranges as speed increases. The lower frequencies tend to increase at a much slower rate. So not only does the overall amplitude of the sound level increase with speed but the overall frequency components increase as well, with a trend toward the higher frequencies. This is shown graphically in Figure 7. These higher frequencies contribute more to the overall sound level when A-weighting is used. This shift toward higher frequencies as speed increases was also demonstrated for U.S. highways (*16*).

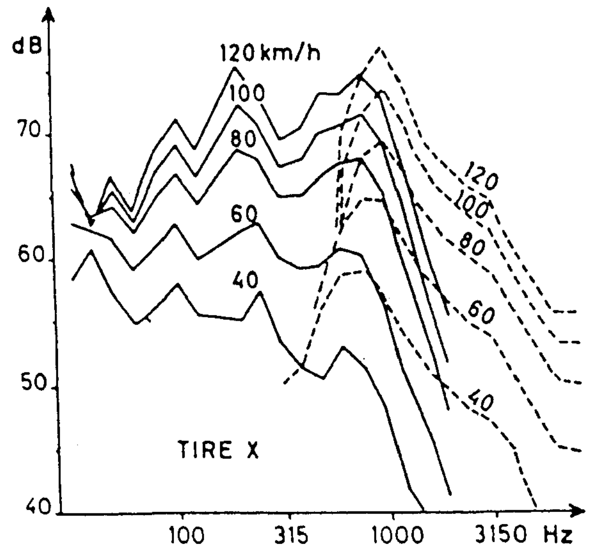


FIGURE 7 Tire X at different speeds showing differentiation of noise spectra into low frequency and high frequency components (*15*).

The Organization for Economic Cooperation and Development (OECD) released a publication that summarizes the tire/road mechanism (*17*). As before, the tire/road noise generation is broken into general categories. These categories are radial vibration, air resonance, and adhesion mechanism.

The radial vibration is described as being caused by the impact between the tire and road as before. The road factors responsible for noise generation are listed as: the surface texture (mega-, macro-, and micro); aggregates (shape, dimensions and physical properties); and temperature. The tire and vehicle factors responsible for noise generation were listed as: tire characteristics (type, temperature, and speed); vehicle types; speed of the vehicle; and driving conditions. These general characteristics are interrelated and impact both the overall sound level and frequency components.

Nilsson is in agreement with the OECD report. Irregularities in the rolling surfaces are said to produce wavelengths close to the mean radius of the contact zone. The megatexture of the pavement (listed as 50–100 mm) is then responsible for these radial vibrations. It is the road megatexture that also causes the resonance phenomena inside the vehicle. The adhesion mechanism is reported to cause tangential vibrations of the tire, as previously reported. The frequencies caused by this mechanism are in both low and high frequency ranges.

Air resonance, caused by pocket air-pumping, is a complex phenomenon described as causing "medium and high frequencies." Smoother surfaces generate more noise in this manner because air is more easily trapped. Porous surfaces reduce the air trapping and resultant noise.

One interesting observation reported is the "horn" effect. This is the reflection of the sound waves from the walls of the dihedral formed by the surfaces of the tire and road. The horn effect causes an amplification of the generated noise. The pavement surface has a dramatic impact on the horn effect. Porous surfaces cause a reduction of the horn effect due to absorption and scattering of the sound.

Based on these physical phenomena and the necessity for safety, three general ways to generate low noise-producing pavement were described by Vollpracht in 1994 (*18*). These are:

- Porous surfaces,
- Texturing of the surface, and,
- Special tining methods.

The use of tining or dragging methods for noise abatement when dense concrete is used can be listed in three major categories (*7*). These categories, related to the main direction of the surface texture structure are longitudinal, transverse, and random. Longitudinal and transverse structuring can be accomplished using tools such as brushes, burlap, and combs on the fresh mortar or by sawing grooves in the concrete. Random structuring can be accomplished by not applying any special surface treatment, various demortaring techniques to expose the aggregate, or gluing small chippings onto the existing surface. The influence of longitudinal or transverse tining on noise production is significant. In general, it was reported that longitudinal and random transverse structuring is less noisy than transversely structured surfaces. The degree to which this occurs is also directly related to the macro- and megatexture grain size and the placement technique used. Microtexture surface friction is obtained in concrete pavements by the natural sand in the mortar.

The microtexture and macrotexture cause deformations in the tread of the tire and lead to the tire vibrations previously discussed. The roughness of the roadway produces deformation of the suspension system but only minimal tire deformation. Roughness is avoided because of the poor vehicle ride. The megatexture wavelength is in the right range to maximize tire deformation beyond the contact profile produced by a flat surface. These effects on tire deformation are shown in Figure 8. The critical wavelength then becomes one-half of the tire footprint length, which is generally between 50 and 100 mm (2 and 4 in.) for both cars and trucks. The megatexture can also have a significant effect on tire noise, vehicle vibration, and rolling resistance (*19*). Figure 9 shows the various wavelengths and the important considerations of each. In regard to surface noise generation, increases in irregularities with wavelengths near 80 mm (3.15 in.) (megatexture) cause the tire noise to increase, primarily in the low frequency range (< 1 kHz.). When macrotexture wavelengths increase [listed as approximately 3 mm (0.12 in.)] tire noise decreases, primarily in the high frequency range (> 1 kHz). This is thought to be associated with air pumping as previously discussed. This

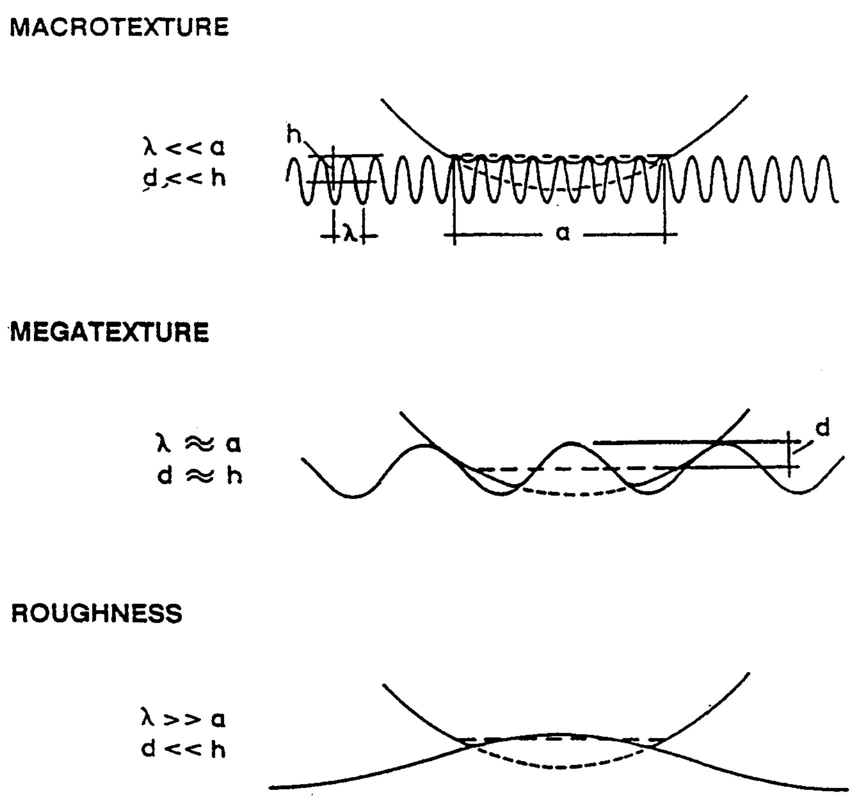


FIGURE 8 Effect of surface profile on tyre deformation *(19)*.

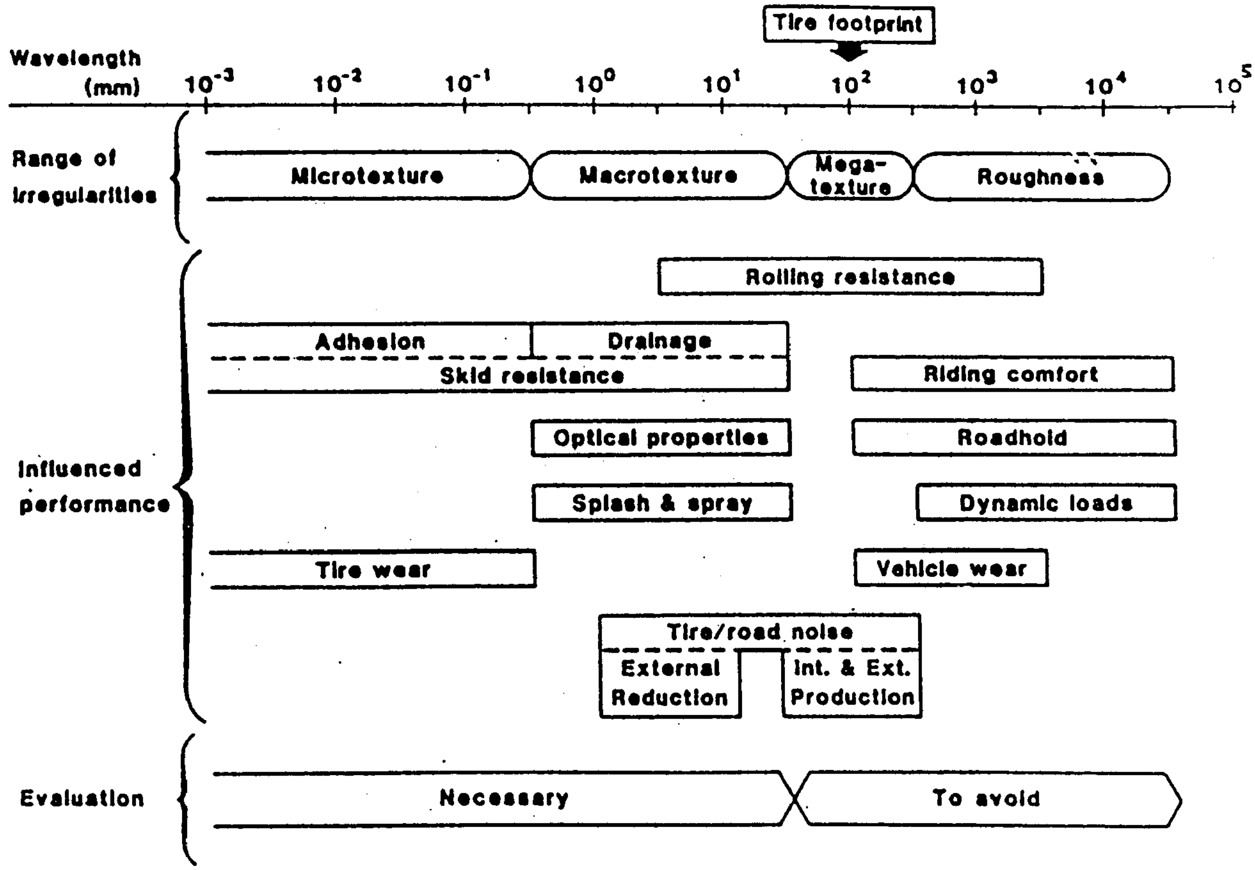


FIGURE 9 Influence of surface profile on measurable driving conditions *(19)*.

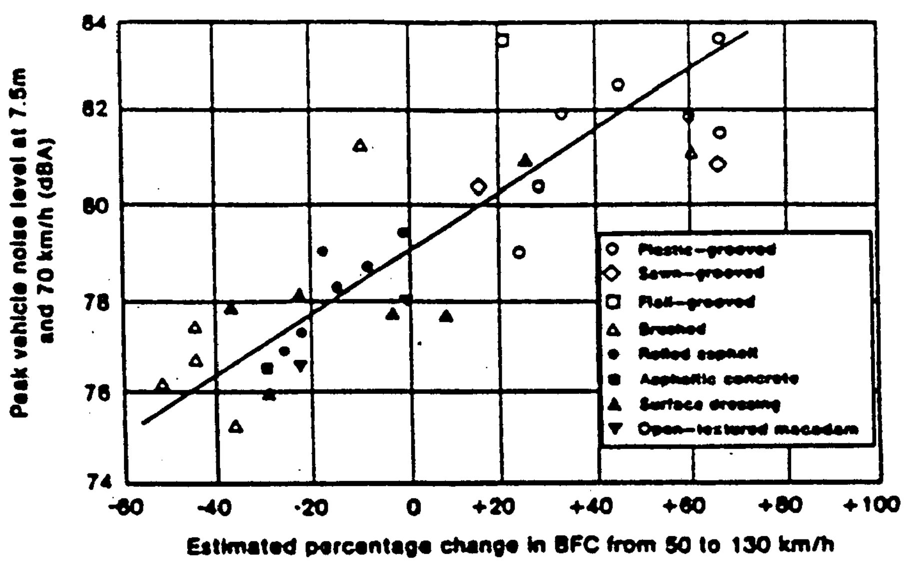


FIGURE 10 Relationship between estimated percentage change in BFC high to low speed and noise, from light vehicles *(19)*.

means that very smooth surfaces may be noisier along the roadway than those with a fine macrotexture or with open-graded surfaces.

Safety is of utmost importance and microtexture is the critical component for surface friction as shown in Figure 9. Macrotexture is the primary concern for moving water to maintain tire contact with the surface. There is then a direct relationship between safety and noise control. Testing by Salt (*20*) showed a direct relationship between the braking-force coefficient (BFC) and road noise. Figure 10 shows this reported

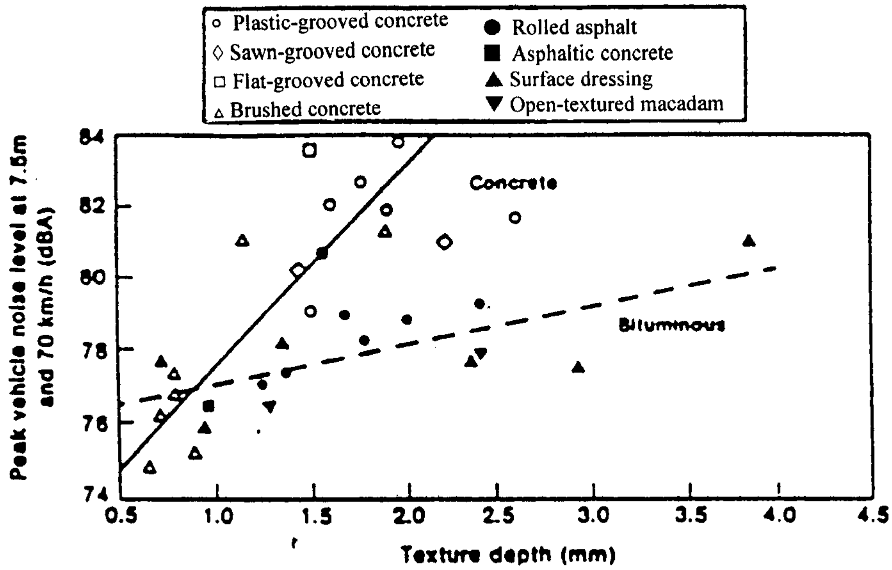


FIGURE 11 Relationships between texture depth and noise from light vehicles for various bituminous and concrete surfaces *(19)*.

linear trend. The depth of the pavement texture is also important for safety in removing water and is also directly related to traffic noise as shown in Figure 11. The information in Figures 10 and 11 was acquired using the statistical passby method discussed in this report. Of note is the different slope or relationship when comparing texture depth and noise levels for PCC pavement compared to asphaltic pavements.

It can be seen that the pavement surface characteristics are a key variable in noise generation. The tire, vehicle type, and propagation characteristics must also be considered. Sandberg *(21)* reports that other variables may also play important roles in the noise generation mechanisms. These included stiffness of the road surface or mechanical impedance, ambient temperature, and even pavement color. The stiffness is directly related to the binder and is thought to have a small effect on noise generation. Temperature is directly related to this stiffness, especially for asphaltic surfaces. The color may cause up to a 10°C change in temperature of the pavement. Also, Sandberg reported that motorists perceive that a black surface is less noisy. In Denmark, a black seal coat was used on a new PCC surface for this reason. Sandberg termed this the "placebo effect."

TIRE CONSIDERATIONS

As noted, the tread pattern and depth also significantly affect noise generation. This variable in relation to the overall sound generation has been found to be small when compared to the pavement surface, but is still important. The important tire air pumping mechanism depends on the tread pattern, wear of the tire, and the macrotexture of the pavement. The sidewall flexibility determines the impact noise from the tire contact patch as discussed previously in this report. A brief discussion is presented here of these phenomena.

The National Bureau of Standards conducted a comprehensive study on the impacts from various truck tire types *(22)*. While the absolute level is greater for trucks, the same principles apply for automobiles and are discussed here for informational purposes. Figure 12 shows the footprint of nine tire tread designs listed from A-I. Using the passby method of measurement, 50 ft (15 m) from the vehicle track, several noise measurements were made in a speed range of 30–60 mph (48–97 kph). The truck engines were off during the tests, so that only rolling noise could be measured. Two road surfaces were used during the tests, "textured" asphalt and smooth PCC pavement. Table 5 shows the results of these measurements again, listing tread types with the letter designations A-I (see Figure 12).

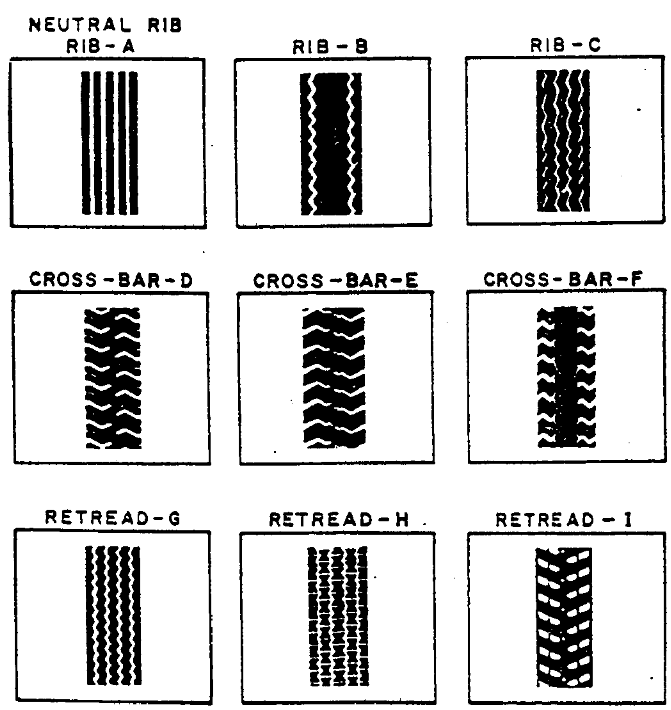


FIGURE 12 Tire tread footprints *(22)*.

TABLE 5

SOUND LEVELS DUE TO TIRE TREAD DESIGN *(22)*

Tread Type	Road Surface	New Tread	Half Worn	Fully Worn
A	Concrete	73		
	Asphalt	75		
B	Concrete	77	81	
	Asphalt	77	79	
C	Concrete	76		
	Asphalt	77		
D	Concrete	84	91	87
	Asphalt	83	86	85
E	Concrete	84		
	Asphalt	82		
F	Concrete	81	88	
	Asphalt	81	86	
G	Concrete	73		
	Asphalt	75		
H	Concrete	81	86	86
	Asphalt	82		
I	Concrete	96	94	
	Asphalt	88	90	

It is obvious from these tests that the rib tire design is the quietest. The most noise was caused by the tires with a "pocket" design on smooth concrete such as D or I. It was surmised that, in general, a quiet tread design is one in which the air inside the tread grooves is allowed to escape as the tread comes into contact with the pavement surface. Noisy tires are those in which the air pocket noise is dramatically increased when the air cannot escape easily. As the tires wear, the air cannot escape as easily due to decreased tread height and the noise generally increases.

During roll-by tests (no engine noise), speed was constantly monitored to allow noise levels and speed to be correlated. Figure 13 shows the results of these measurements again listed by the letters A-I. As expected, overall noise levels increase with speed due to the greater impact of the tire on the road surface and the greater degree of air pumping. The same general trends for tire design occur as previously discussed.

Safety is still of utmost importance. The tire tread must move water on wet pavement to allow good tire/pavement contact. Tire tread designs move water either to the side or along the tire. Recent advances in all-weather tires that move water to the side are closer to the "pocket" design shown above and create more noise. This increase in automobile generated noise is verified when the Fleming (*14*) and Rickley (*13*) data bases are compared. The advanced tire design results in shorter stopping distances but is the suspected reason that the sideline noise levels for passenger cars have generally increased over the last decade (*23*). Tire noise generation will continue to be an area of research for manufacturers as noise regulations continue to become more stringent. Research has also shown that the type of tire and pavement surface result in different noise levels for different combinations. That is, different tread designs provide different results depending on the pavement type and the noisiest tire on one surface may not be on another (*24*).

A good indication of noise variation depending on tire type and pavement type match is presented in Figures 14 and 15.

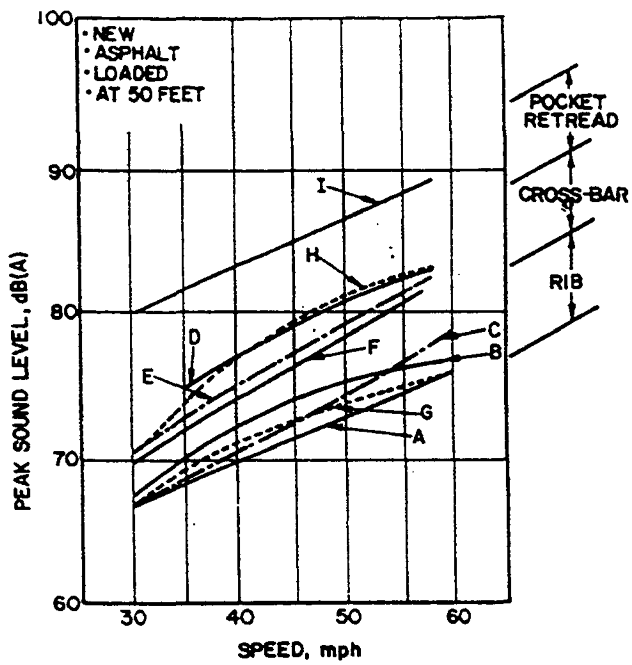


FIGURE 13 Sound levels produced by various tire treads and speeds *(22)*.

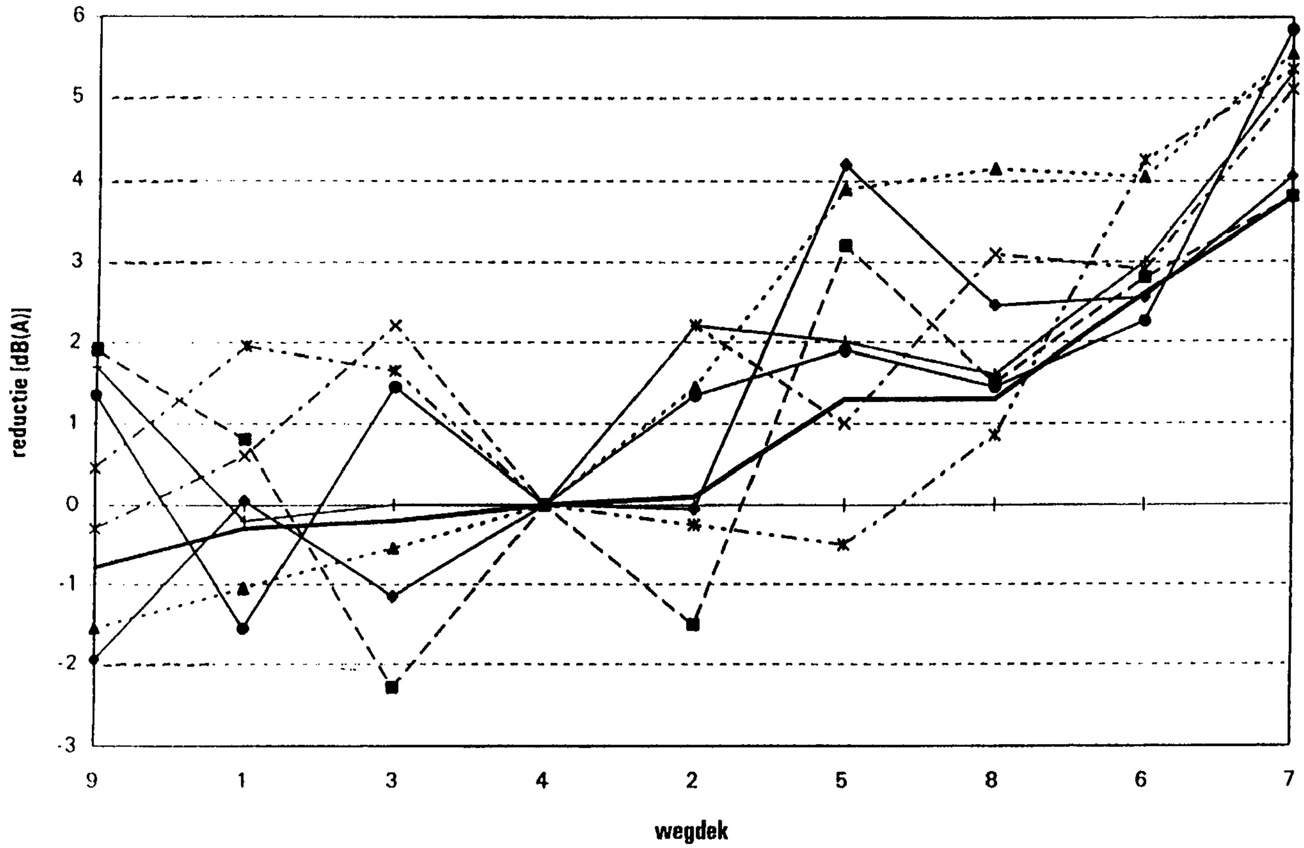
These tests were done by Dr. G.J. van Blokland using the coast-by method and reported during the ISO meeting in Orlando in 1997. Figure 14 is at 60 kph while Figure 15 is at 120 kph. In these figures the following asphaltic pavement types were tested:

Number	*Type*
1, 2, 3	Porous asphalt
4, 5	Dense asphalt
6	Porous, 6 cm thick
7	Porous, 8 cm thick
8	Porous, 4 cm thick, 4–8 mm chipping
9	Porous, 4 cm thick, 16 mm chipping

All tests were normalized to dense-graded asphalt (type 4) and seven multiple tread patterns were tested. It can be seen that large variations occurred both by pavement type and tire type. Of the seven tire types tested and compared to various pavements, no clear trends were present. This leads to the conclusion that multiple variables must be considered together, along with the tire type and pavement surface being considered concurrently.

Eberhardt reported results done over a decade ago had found this same multi-variable relationship for the tire/pavement noise interaction (*25*). Eberhardt's report shows that even the change from a cross-ribbed radial-ply tire to a cross-ribbed bias-ply tire resulted in different overall sound levels and changes in the sound levels by one-third octave bands. Again, the change did not appear to follow any trend when various pavement types were tested. Of course, changes in sound level were quite evident with different trend designs.

Eberhardt did report some important correlations. The pavement texture power spectra and sound power spectra



— ♦ —Slick 155; — ■ — Slick 175; . . . ▲ . . . Rib 175; - - x - - MX 155; – ✱ – MXL 175; — • —MXT 155; —+— MXV2 175; and —— fleet-test.

FIGURE 14 Comparison of normalized reductions (reductie) due to roadsurfaces (wegdek) for various tire types at 20 degrees centrigrade and 60 kph (37 mph). *(Courtesy of G.J. Van Blokland)*

show a definite relationship. At low frequencies, less than 1,000 Hz, texture and sound seem to be correlated. At high frequencies, greater than 1,000 Hz, texture and sound were negatively correlated. Also, pavement texture power spectra were highly correlated with surface friction numbers, but sound power spectra were not.

It is obvious that some definite trends exist but there is some disagreement by researchers based on individual findings. Much work is still needed for determination of how tread designs affect overall noise levels. Until that time, averaged levels for multiple tire types may be the only solution. The ISO working group is now considering definition of a "standard" tire or tires for use in noise evaluations.

PROPAGATION

Starting with the horn effect previously described, the pavement surface plays an important role in the propagation of sound from the tire/pavement contact area to sideline receiver locations (*26*). Pavement type and surface texture both play important roles, but the noise absorption capacity of the pavement surface is extremely important. The noise absorption capacity depends on several properties: accessible porosity, specific flow resistance, configuration factor of the pores, and layer thickness (*7*). The mechanical impedance of the road surface material and the microtexture are thought to be only of minor importance in noise generation. However, microtexture has a decisive influence on pavement friction and cannot be neglected.

The sound is influenced by the surface absorption and diffusion during propagation. Absorption reduces the horn effect and reduces sound at the side of the roadway because the sound energy is not as efficiently reflected. This includes sound reflected by the undercarriage of the vehicle as well. Increased macrotexture also results in greater diffusion of the reflected wave. The overall result is that, while surfaces with high macrotexture create more noise at the tire because of radial vibrations, the effects on propagation may result in lower noise levels along the roadway.

The propagation of the tire generated noise not only depends on the pavement surface but the surface along the road as well. This change in surface impedance must be considered in predictive models. This impedance discontinuity of the surface is also called "fall-off" rate, alluding to the dB reduction that occurs with distance from the roadway. The current FHWA noise methodology (*27*) uses an approach of approximating the overall pavement and ground effects on propagation by using an exponential function. The equation, shown below, includes the exponent $1 + \alpha$. The α term is used for

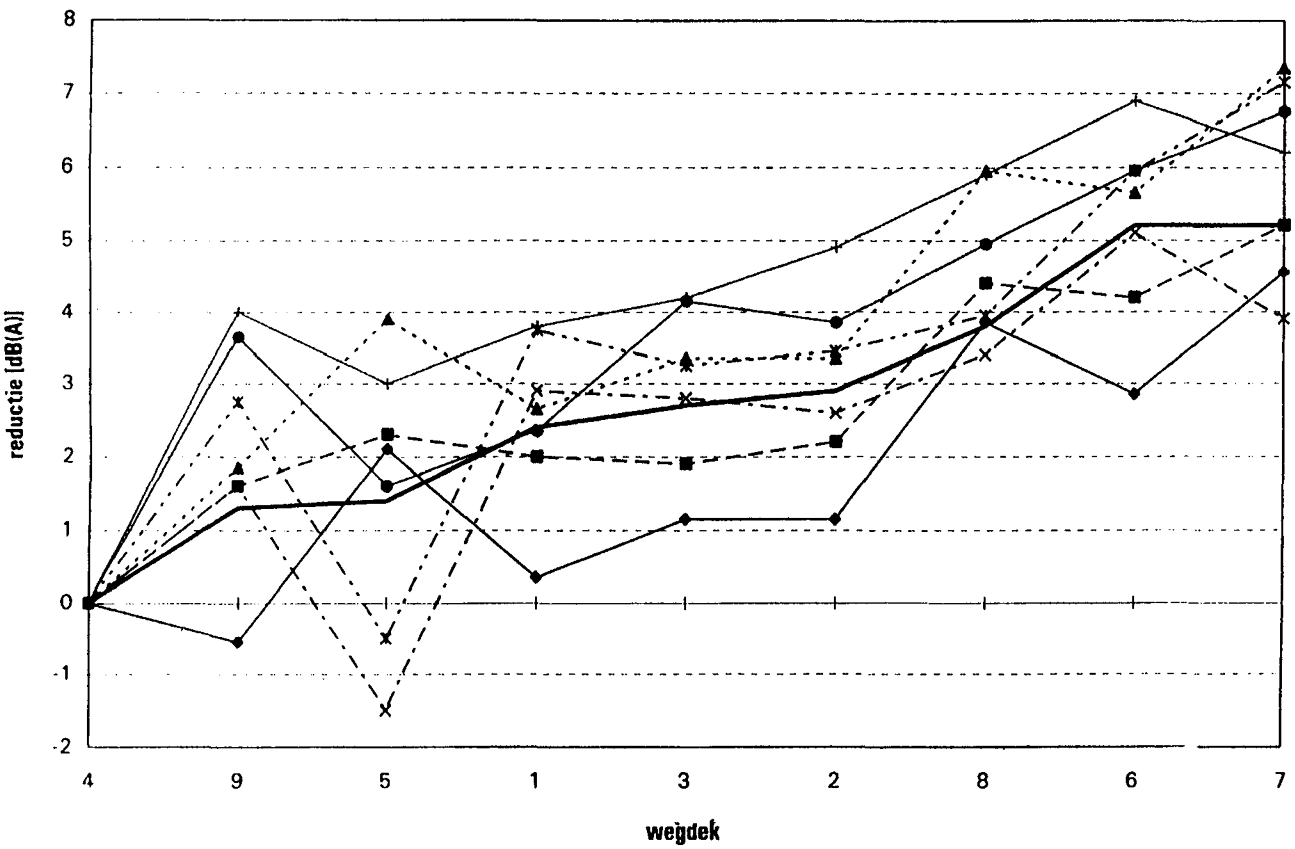


FIGURE 15 Comparison of normalized reductions (reductie) due to roadsurfaces (wegdek) for various tire types at 20 degrees centrigrade and 120 kph (74 mph). *(Courtesy of G.J. Van Blokland)*

determination of the surface effects, with a value of 0.0 used for acoustically "hard" sites and 0.5 used for acoustically "soft" sites.

$$\text{Distance Adjustments dB(A)} = 10 \log_{10} (d_2/d_1)^{1+\alpha} \quad (4)$$

where

α = 0.0 (hard ground),
0.5 (soft ground), and
d_1, d_2 = distance from roadway centerline.

This approximation has adequately served it's purpose but as computing capabilities expand, much more sophisticated methods, for example, that by Chessel (*28*), are being implemented in the next generation of traffic noise models such as the Traffic Noise Model (TNM) soon to be released by the FHWA (*29*).

Two important changes have occurred in the later methods for surface effects. First, the change of impedance at the pavement edge can be included in modeling. Second, specific ground impedance can be included for various soils, pavements and other surfaces rather than just using the two categories of "hard" and "soft."

In addition, meteorological variables such as temperature, barometric pressure, wind speed, and wind direction can be quite important to propagation. Wind speed and temperature profiles can cause refraction of the propagating wave and can have a significant effect on sideline noise levels. Ambient temperature effects also may cause refraction in the sound path as well as affect the tire and road surface deformation as previously discussed. The sound level along the highway then becomes a complex combination of all of these variables.

CHAPTER FOUR

MEASUREMENT METHODOLOGIES

SOUND MEASUREMENTS

The most often used methods for measuring tire/pavement noise include the close proximity method (often called the trailer method) and the passby method (*30*). Another testing method, a rolling drum, has also been used but is not discussed here. The close proximity or trailer method employs microphones mounted near the tire/pavement contact patch. The tire is mounted on a trailer or other special vehicle. The passby method uses microphones set up at a defined distance from the vehicle path at the side of the roadway. Unfortunately, the measurements taken by these two techniques (passby vs. trailer) have not been shown to be comparable. The trailer method measures the tire noise source whereas the passby method includes all noise sources of the vehicle as well as the propagation effects. The International Standards Organization (ISO) Technical Committee 43 has assembled data from both the statistical passby and trailer method for various pavements. The data, collected by Steven in Germany and reported to the ISO working group in early 1997, show wide variations when the two methods are compared. Figure 16 shows this comparison and is from the working documents of this ISO working group. No trend is evident.

Many variations in microphone placement and trailer design are used for the trailer method. Table 6 shows many of the trailers in use as compiled by the ISO working group who also met in early 1997. The ISO Working Group 33 has developed draft standards for the close-proximity method (*31*). A detailed procedure is presented that includes consideration of equipment (sound and vehicles), tires, data analysis, road surfaces, and meteorology. Figure 17 shows the recommended microphone placement included in these draft standards.

The passby method can be further subdivided into two categories: statistical passby and controlled passby. ISO Working Group 33 has also developed draft standards for this method (*32*). The most common distances used for the passby measurements are 7.5 or 15 m (25 or 50 ft) from the vehicle track and a height of between 1.2 and 1.5 meters (4 to 5 ft.). In the statistical passby method, random vehicles are sampled and statistical averaging is used to determine the overall sideline

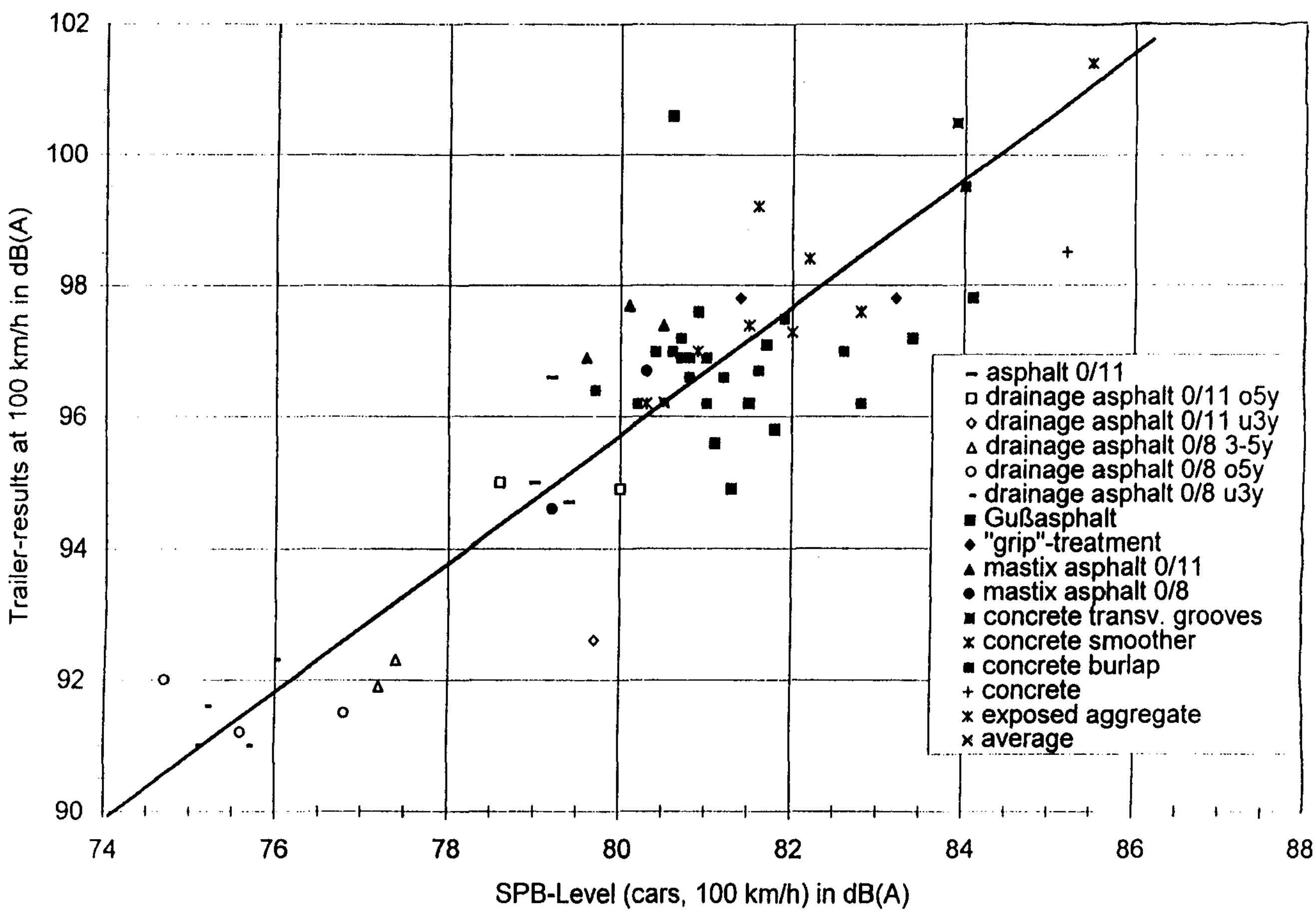


FIGURE 16 Comparison of the trailer and passby methods. *(Courtesy of G.J. Van Blokland)*

TABLE 6

EXISTING TRAILERS USEFUL FOR NOISE COMPARISON OF ROAD SURFACES *(32)*

Trailer Identification (name, institution, country, etc.)	Type of Test Tyre(s)	Number of Test Tyres	Enclosure? (and poss. absorbing lining)	Type of Tow or Power in Vehicle	Microphone Positions (vert. plane)	Microphone Positions (horiz. plane)	Physical Dimensions (see note)	Special Analysis Procedures?	Other Special Features (e.g., special tyre loads)	Notes
"FIGE Trailer", FIGE GmbH, Herzogenrath, Germany	4 car tyres according to GEStrO	4 (but 2 run simultaneously	Enclosure w. absorb lining	Van ??	100-150 mm adjustable (normally 150 mm)	4 micr 1.0 m rel. sidewall. Two of them at 49° rel travel direct., the other at 131° rel travel direction	OW = 2.? m OL = 5.7 m EW = 2.? m EL = m	Two tyres are always measured simultaneously (noise from them not separable)	Tyre loads–340 kg IR thermometer measures road temp. Contactless speedom	IR light barrier available for precise triggering at road site
Trailer at the BASt, Cologne, Germany (same as FIGE)							OW = m OL = m EW = m EL = m			This is similar to the FIGE trailer
"Tiresonic Mk2", Techn Univ. of Gdansk, Poland	Any 135R12–225/70R 16	1	Enclosure w. absorb lining	Ford Sierra	100 mm (adjustable)	200 mm rel. sidewall 135° rel. travel direction Micr. sometimes also on opposite side	OW = 1.5 m OL = 3.8 m EW = m EL = m	Noise correction if measured speeds deviate from nominal ones	Small and easy to handle Problem with high speeds in curves	For road surface comparison, usually 5 tyres are used
"TS1", Techn Univ. of Gdansk, Poland	Any 135R12–195/70R 15	1	Enclosure w. absorb lining	Ford Sierra	100 mm (adjustable)	200 mm rel. sidewall 135° rel. travel direction Micr. sometimes also on opposite side	OW = 1.7 m OL = 5.5 m EW = m EL = m		Adjustable tyre slip from -20% to +20%	Under construction
Austrian one-wheel trailer, ?? Austria	PIARC rib 165R15	1	Enclosure w. absorb lining	?	1. 100 mm 2. 150 mm	1. 400 mm behind centre of tyre/road contact area 2. 220 mm outside centre of tyre/road contact area	OW = 1. 2 m OL = 3.9 m EW = 1.0 m EL = 2.5? m	Sometimes used in conjunction with sound absorption measurements		An Austrian Guideline requires this type of trailer
Trailer (1) at the Moscow Bauman State Techn. Univ., Moscow		1	None	?	?	?	OW = 1.0 m OL = 4.7 m EW = m EL = m			
Trailer (2) at the Moscow Bauman State Techn. Univ., Moscow		1	Enclosure w. absorb lining	?	?	?	OW = 1.6 m OL = 4.8 m EW = 1.0?m EL = 1.0?m			

noise value. FHWA has promulgated a method for statistical passby testing (*33,34*). The FHWA method has been adopted for use by the American Association of State Highway and Transportation Officials (AASHTO). In the controlled passby method, dedicated test vehicles are used, often with prescribed tire types. Other vehicle operating parameters may be defined as well, such as gear selection. For certification testing, the ISO 362 Standard is the most used and specifies vehicle parameters and measurement techniques in great detail. However, problems with this testing method are being examined by ISO working groups. Sandberg suggests several changes in a recent Inter-Noise paper (*35*). These changes include driving condition, load on vehicle, microphone arrays, weather specifications, test surface, and tires.

Measurement techniques have been described in detail for highway measurements (*36, 34*). Instrumentation, recording, data analysis, weather considerations, and traffic parameters are covered in detail. The text by Lee provides an entire chapter devoted to passby testing. Key details of this U.S. methodology include that measurements are made:

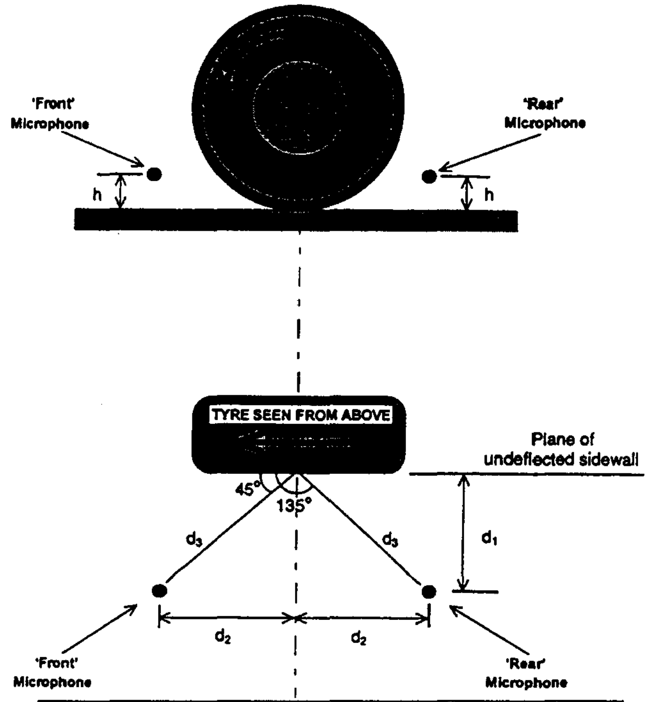
- At a height of 1.5 m (5 ft) above the plane of the pavement,
- 15 m (50 ft) from the center of the near travel lane,
- Flat, open location free of large reflecting surfaces,
- Line-of-sight from the microphone to the roadway is unobscured within an arc of 150 degrees,
- Low ambient levels due to a source other than traffic,
- A fast instrument response, and
- Weather should be considered.

Both passby methods use similar measurement techniques, the major difference being the vehicle(s) used. A detailed method has been prescribed by ISO Working Group 33 (ISO/TC 43/SC 1/WG 33) for the statistical passby method. The Draft International Standard (*37*) describes the methodology in detail. Figure 18 shows graphically the typical measurement configurations and microphone positions. The microphone on each side of the road permits a comparison. Microphones on each side have not been the typical measurement procedure in the United States.

The measurement procedure primarily used in Europe can be summarized as:

Step 1 Calibration and Instrument Selection
Step 2 Selection and Preparation of Test Site
Step 3 Classification of Traffic Conditions
Step 4 Measuring Procedure:

1. Microphone position—typical distance from the microphone position to the center of the lane in which the vehicles are to be measured is 7.5 m (25 ft.).
2. Sound level measurement—During each vehicle passby the maximum A-weighted sound level shall be measured using time weighting "F."
3. Frequency spectrum measurements are recommended during the sound level measurement.



Microphone Position	h (mm)	d_1 (mm)	d_2 (mm)	$d_3 = d1\sqrt{2})$ (mm)
1. "Outer"	200	400	400	566
2. "Inner"	100	200	200	283

FIGURE 17 Microphone positions for the measurements. Values of the microphone positions h, d_1, d_2 and d_3, are shown above.

4. Air temperature measurements are mandatory and road surface temperature measurements are recommended.

Step 5 Normalization of Data
Step 6 Reference Road Surface
Step 7 Meteorological Conditions
Step 8 Background Noise Determination
Step 9 Presentation of Reported Data
Step 10 Calibration of the Vehicle Noise Emission.

The U.S. method and international method show close agreement for most parameters, with the notable exception being the microphone distance to the side of the vehicle track.

For further clarity in measurements, other important variables have also been characterized by the ISO method. Three road speed categories have been defined: low (45–65 kph; 28–40 mph), medium (65–99 kph; 40–62 mph), and high speed (>100 kph; 62 mph). The three speed ranges were generally selected to represent urban, suburban, and motorway (expressway) traffic speeds. Vehicle types have also been defined and include: cars and heavy vehicles. Heavy vehicles are further subdivided into dual-axle vehicles and multi-axle vehicles. Of interest is that the present FHWA traffic noise prediction method supports three vehicle types: cars, and medium

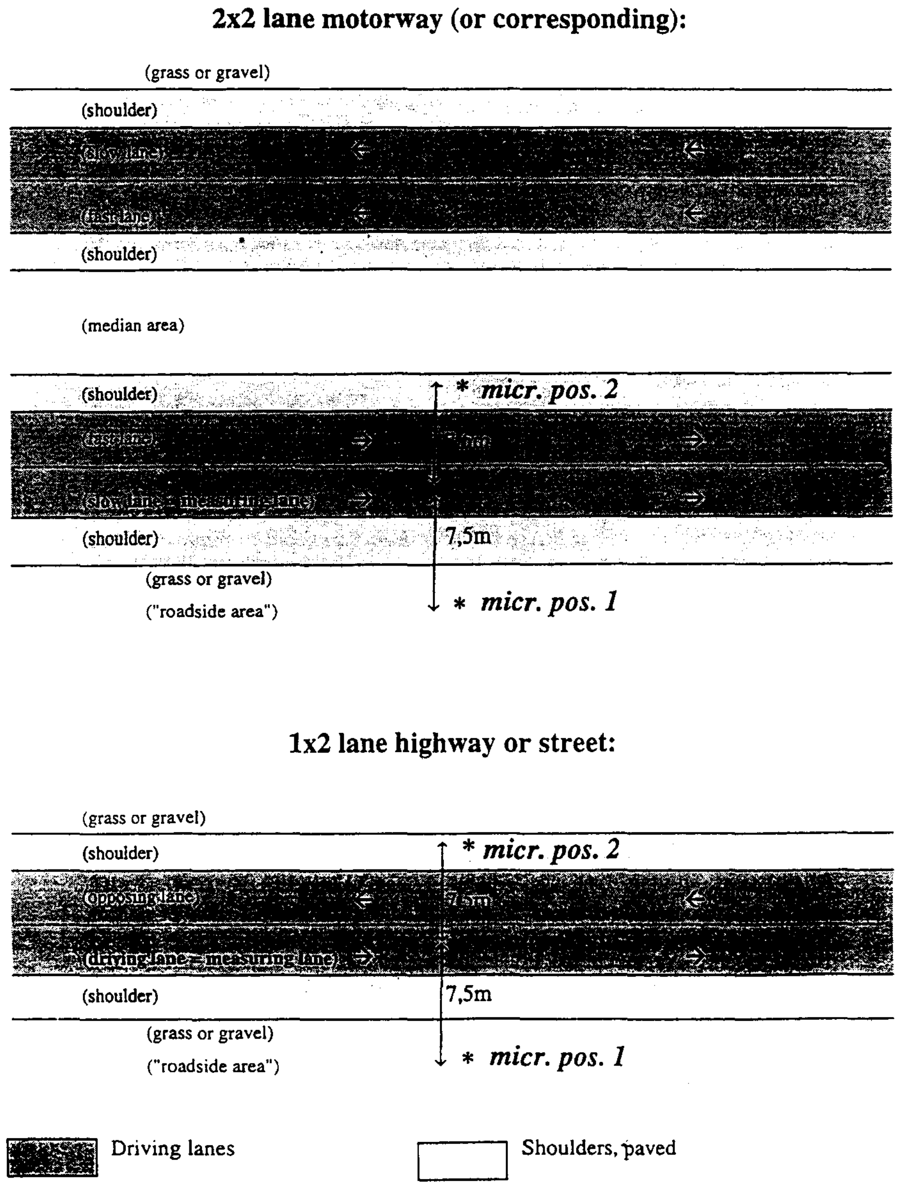


FIGURE 18 Typical road configurations and microphone positions for statistical passby draft standard method *(37)*.

and heavy trucks. A new model, soon to be released by FHWA (*29*) includes two additional vehicle types; buses and motorcycles. The three FHWA categories now supported consider the basic vehicle (car) and trucks as dual-axle or multi-axle just as the ISO standard. The importance of tire noise is quite evident in each of these categories because of the axle considerations. The measurements are usually maximum levels, must be unaffected by background sounds, and are A-weighted. Type 1 sound level analyzers are required. A Type 1 analyzer, based on the American National Standards Institute (ANSI) criteria, is accurate to within one dB from 100 to 4,000 Hz. Type 2 analyzers, allowed in the FHWA testing, are not as accurate in the higher frequency ranges. Frequency analysis of the measured sound using third-octave bands is recommended but not mandatory (50–10,000 Hz; using filters that conform to IEC 225). Allowable weather conditions and vehicle speed parameters are also specified. Methods for correction to reference speeds and ambient temperatures are provided.

The reference roadway surface is very important and designations have been accomplished by the ISO committee (*38*). Of interest is that the close proximity measurements are done with a user-defined surface (reference surface) and other measurements are compared to this surface, making its selection quite important. The following options regarding reference surfaces apply:

1. *General Case*—The reference surface is a dense, smooth-textured, asphaltic concrete surface with a maximum chipping size of 11–16 mm (0.43–0.63 in.). From the acoustical point of view, this is approximately equivalent to a split-mastic asphalt surface with the same maximum chipping sizes. The surface shall have been trafficked for a least one year when used as a reference. Macrotexture depth as measured according to ISO 10844 or ISO/CD 13473 shall be within 0.50 and 1.00 mm. (0.02 and 0.04 in.). To ascertain that the surface is acoustically nonabsorbing, air voids content

or the sound absorption coefficient shall meet the requirements specified in ISO 10844.

2. *Normalized Reference Case*—The reference surface is a fictitious surface of which the levels (L_{veh}) for each vehicle category are defined by convention. This can, for instance, be based on the average results of a great number of statistical passby measurements on asphaltic concrete surfaces as specified under point 1 above. The "Normalized Reference Case" shall be the normally used case when testing potential "low noise surfaces."

3. *Equivalent Age Case*—This reference surface type is the same as the General Case, but the age of the reference surface is always the same as that of the surface under consideration. This means that when a new surface is measured, the reference surface shall also be new. This case may be used when the purpose is to compare surfaces as a function of their age.

4. *Arbitrary Reference Case*—The reference surface is any arbitrary surface, other than above, that the testing organization selects. In this case, measurements are useful only for comparisons between the particular, selected surfaces.

ISO Working Group 33 is developing similar reference surface guidelines for controlled passby testing, which is of extreme importance to vehicle manufacturers.

Other differences and needs in measurement techniques also exist. Equipment and descriptors used are an area of debate. Most measurements are done for the overall noise level using an A-weighted spectrum. However, results from Minnesota (*39*) and Wisconsin (*40*) seem to indicate that the frequency components are important as well. The pure tone generated from transverse tining can be a greater source of annoyance than the overall noise level and A-weighted values do not adequately report this effect. Considering this problem, it may not be enough to measure the A-weighted spectrum but octave-band, one-third octave band, or narrow band analysis may be needed to determine the frequency contributions and frequency shift due to various pavement types. This requires very different equipment than has been typically used. More typical equipment have been sound level analyzers that report levels as an overall value using a weighting scheme, most often A-weighting. It is not possible to recreate the spectral data from A-weighted data unless assumptions are made about the spectra shape. Accordingly, data may need to be collected with equipment that records spectrum frequency data. This equipment is much more costly, more difficult to use, and may not be readily available to all state agencies. Wisconsin (*40*) has used a real-time analyzer, providing octave band data, and their work could provide guidance for other states. It should be noted that other test parameters may need to change if octave band data are taken, but the most important change is the equipment that must be used.

Detailed research must use the more expensive equipment to adequately measure important acoustic parameters.

PAVEMENT TEXTURE AND FRICTION MEASUREMENTS

The surface texture depth, porosity, and surface friction become key parameters in both noise reduction and safety. Methods to test these parameters are briefly discussed here.

Surface Friction

Surface friction is measured typically by pulling a trailer that has a locked wheel friction tester (*41*). In a test, which is normally made at 64 kph (40 mph), water is applied to dry pavement, just ahead of the lockable wheel (*42*). The brake is applied and pertinent forces are measured over a short distance of about 100 ft (30 m). The pertinent forces include vertical force or wheel load (W) and horizontal force or tire/pavement interface friction (F). Various types of tires are used, including smooth and ribbed. A friction number for a smooth tire (SN) or coefficient of friction is then defined as:

$$SN = (F/W)\,100 \qquad (5)$$

If speeds other than 64 kph (40 mph) are used, a suffix to SN is used to designate the speed. If ribbed tires are used, the term RN is used instead of SN. The friction number is directly related to the micro- and macrotexture of the pavement surface. Efforts are underway to establish international standards.

In the United States, the ASTM E-274 towed friction trailer is most often used and friction numbers are developed using the ASTM E-501 method with a ribbed tire. The method defines all test parameters, such as wheel load, tire pressure, waterfilm thickness, etc.

Alternative measurement techniques using different equipment have also been developed. Examples include the Side Force Measurement (SFM) using the SCRIM, the mu-meter, as well as the locked-wheel skid tester, spin-up tester, and video or laser images of pavement texture. The British Sideways Coefficient Routine Investigation Machine (SCRIM) is a truck-mounted machine that has two smooth wheels with a load cell in the axle box. The wheels, mounted at a 20-degree angle allows the side force, or cornering force, to be measured. The mu-meter is a trailer where two wheels are lowered. Each wheel is angled inward and side forces are measured.

The surface texture makes a large difference in the sound generation and propagation. Also, since surface texture and surface friction are integrally related, texture can be used to indirectly determine surface friction.

Texture Depth

A simple, manual test is the volumetric patch method, commonly called the sandpatch method. The sandpatch method (ASTM Standard E-965; ISO 10844) involves careful spreading of a defined amount of sand or glass beads onto the surface in a circular pattern and the spread radius is measured. This allows measurement of the surface texture depth using a volumetric method. Volume of the sand or glass beads is known, as is the spread radius, permitting measurement of the surface depth or texture.

Another manual method is the outflow meter. This indirect measuring device allows water to escape between the pavement surface and a cylinder with a rubber seal. The time for the water to escape is measured and correlated to various surface textures. A smoother surface results in a greater time for the cylinder to empty.

Greater ease of measurement and accuracy through automation are still being sought. In November 1996, ASTM Standard E1845, "Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth" was approved. This standard concerns measuring macrotexture based on the pavement profile and uses a linear transform for estimated texture depth.

ISO Working Group 39 has developed draft measurement procedures, Part 3 of which describes four principles of operation: lasers, light sectioning, stylus, and ultrasonic (*43*). A laser method used in the United States is called ROSAN. In Spain, a Swedish opto-electronic laser device has been used. Similarly, a method has been used in Germany called the Laser Texture Meter. Laser measurements have been used to measure macrotexture in the Netherlands (*44*). The mean texture depth can be determined quite rapidly in this way.

The laser profilometers use an electro-optic sensor to measure a reflected laser beam from the pavement, a method that has been proven in Germany (*45*). In January 1997, FHWA presented such a system using the laser method called $ROSAN_v$ (ROad Surface ANalyzer). The subscript v stands for vehicle mounted. $ROSAN_v$ is a portable, automated system for the measurement of pavement texture at highway speeds along a linear path. This method, already implemented in several states, would serve as a replacement of the manual sand-patch method in the United States.

The light-sectioning profilometer utilizes a narrow or extended light beam creating a thin illuminated line on the pavement. The profile is determined from the transition between the sharp line edges and the background.

A stylus profilometer uses a stylus or needle that touches the pavement and is mechanically connected to a displacement transducer. An electro-acoustic sensor is used by the ultrasonic profilometer. Reflected ultrasonic sound from the pavement is analyzed. Using the data from these tests, profile curves, mean profile depth, profile amplitude, and texture spectrum may be determined.

The texture beam method uses two texture sensors, one a mechanical stylus and the other a laser stylus. The sensors are used to measure the vertical motion. The resulting texture traces are then processed to determine texture and a texture spectrum.

Impedance Tube

An acoustic measurement that provides important noise characteristics of the pavement surface texture as well as indirect analysis of texture depth and surface porosity is the impedance tube method. The impedance tube or Kundt tube may be used to measure the acoustic absorption ability (absorption coefficient) of the pavement. The absorption coefficient is frequency dependent and equal to the fraction of noise absorbed. The testing is done by mounting a loudspeaker at the end of a rigid tube. The open end is placed on the pavement. A long probe microphone is used to measure sound along the length of the tube. By varying frequency, standing waves are created in the tube. The form of the standing wave is measured by the microphone probe. The amplitude of the maximums and minimums that occur along the tube due to the interaction of the direct and reflected wave allow calculation of the absorption coefficient, which is the ratio of absorbed acoustic energy to received energy. This frequency-dependent absorption coefficient may then be calculated as (*46*):

$$\alpha_n = (n\text{-}1/n\text{+}1)^2 \tag{6}$$

where

α_n = normal absorption coefficient, and
n = ratio of maximum sound pressure to its adjacent minimum.

Standardized test methods have been established for using impedance tubes. ASTM E 1050-90 is an example (*47*). But these tests are usually for normal impedance, not the grazing angles that would really occur. Unfortunately, the normal incidence impedance, measured with this method, is usually less than the random incidence value. Also, the seal at the pavement surface is a problem. Even so, researchers are using this method in South Africa with good success, as reported at the 1997 ISO, Working Group 33 meeting in Orlando. Researchers in the United States, such as in Wisconsin and Minnesota, have also made use of this method. The method has also been used in Europe, where modifications to the tube have overcome some inherent problems (*48*).

Other forms of testing may also be used but are not covered here. The interested reader should refer to other reports, such as the *Transportation Research Record 622*, for additional information.

CHAPTER FIVE

MEASURED PAVEMENT AND SURFACE TREATMENT IMPACTS ON NOISE EMISSIONS

Two broad categories of pavement are generally used for highway construction. These are portland cement concrete (PCC) pavement and asphaltic cement concrete pavement. This discussion is primarily divided into these two broad categories, although comparisons of the two pavements are often made and are discussed in each section. The sections are then broken into subcategories that discuss the various surface textures. It is also tempting to combine results of various studies. However, differences in traffic, methods, and measurement geometries must all be considered. Assumptions would have to be made to allow the data to be combined. For this reason, results are shown as originally reported by the authors.

PORTLAND CEMENT CONCRETE (PCC) PAVEMENT

The use of PCC pavement is often desirable because of its long service life when compared to asphaltic pavements. As such, considerable interest exists in PCC surface treatment techniques that would lead to reduced noise levels for highway neighbors. Research and in-situ measurements have been performed. Various geographical area results are reported in the order that facilitates the discussion and no emphasis should be placed on relative location in the text.

Surface Texturing: Dragging and Tining

In the United States, the two least expensive, proven construction methods for texturing PCC pavements are dragging and transverse tining. These proven methods have been used extensively on a global scale as well.

Australia

Tests have been conducted in Australia by Samuels et al. (*49*). Nine pavement surfaces were measured using the controlled passby method. Light and coarse Hessian drags, along with no drag, were compared to transverse tining. The tining was varied in depth, 2 or 3 mm (0.08 or 0.12 in.) and width spacing, 13 or 26 mm (0.5 or 1 in.). The summarized data are shown in Table 7, as reported by Nichols (*50*). The researchers concluded that the quietest surface was the light drag with light transverse tining, but no clear-cut choice of surface texture was demonstrated in terms of noise control. The small change in tining depth had only a small effect on the noise levels, which suggests that greater depths may result in more substantial reductions. Also of interest was that the increased tine spacing seemed to reduce car noise but not truck noise. This is most likely due to the variance in tire size and tread pattern of the two vehicle types.

Samuels also continued his investigation for 24 pavement sections from 1992 to 1994. Comprehensive data were collected using the controlled passby method. Test vehicles used were a car and a moderately sized heavy truck. The same vehicles were used at all sites, but were different each year. All surfaces exhibited good frictional characteristics. In his studies, tined and dragged PCC surfaces were generally more noisy than asphaltic surfaces. Only a 14-mm (0.55 in.) chip seal was more noisy than the PCC pavements. Samuels concluded, "Tyned PCC surfaces, without longitudinal drags were found to be at the upper end of the range while asphalts were at the lower end."

Colorado

In Colorado, a section of I-70 was tested that contained nine pavement types (*51*). These types included:

Section	*Description*
1	Transverse tining, uniform 26-mm (1.02 in.) spacing (state standard)
2	Transverse astroturf drag
3	Transverse random tining (16 mm-22 mm-19 mm [0.63 in.-0.87 in.-0.75 in.)]*
4	Transverse tining, uniform 13-mm (0.5 in.) spacing*
5	Transverse random sawing (16 mm-22 mm-19 mm [0.63 in.-0.87 in.-0.75 in.)]*
6	Transverse tining, uniform 26-mm (0.75 in.) spacing*
7	Longitudinal sawing, 19-mm spacing*
8	Longitudinal astroturf drag
9	Longitudinal tining, 19-mm (0.75 in.) spacing*

*Preceded by longitudinal astroturf drag.

All sections first received a longitudinal burlap drag. Sections were planned to be 3 mm (0.12 in.) deep and 3 mm wide (as-constructed measurements were not recorded).

The variable transverse tining had the highest friction numbers, but it was the longitudinal astroturf drag and longitudinally tined surfaces that had the lowest noise levels. These

TABLE 7

FRICTION AND NOISE PROPERTIES OF TESTED SURFACES *(50)*

	Concrete								Asphalt
	Light Hessian Drag				Coarse Hessian Drag			No Drag	(Open graded)
Surface Texture No.	2	8	7	9	1	6	5	3	4
Transverse tining									
Depth	nil	L	L	M	nil	L	L	M	
Width (mm)		2	3	3		3	3	3	
Nominal spacing (mm)		13	13	13		13	26	13	
Friction—Sideways Force Coefficient (SCRIM)									
50 km/h									
Minimum	0.50	0.62	0.69	0.69	0.64	0.69	0.69	0.69	–
Standard deviation	0.050	0.040	0.028	0.012	0.035	0.034	0.022	0.018	–
Mean	0.64	0.75	0.77	0.89	0.77	0.84	0.84	0.84	–
80 km/h									
Minimum	0.46	0.55	0.69	–	0.64	0.69	0.69	0.69	–
Standard deviation	0.059	0.079	0.017	–	0.034	0.020	0.020	0.035	–
Mean	0.56	0.68	0.74	–	0.72	0.84	0.77	0.79	–
Average Noise Levels [dB(A)]—Two Instruments									
50 km/h									
Car	72.7	73.4	–	75.2	–	76.9	74.7	75.0	73.2
	73.5	–	73.0	75.1	74.6	76.2	–	74.8	73.0
Truck	88.6	89.6	–	86.6	–	86.2	88.2	89.7	87.4
	88.4	–	89.3	86.2	87.3	86.4	–	89.2	86.7
65 km/h									
Car	77.2	76.2	–	78.1	–	78.4	77.8	77.7	73.9
	77.3	–	75.7	78.2	77.6	–	77.2	73.3	–
Truck	90.0	88.8	–	89.2	–	88.1	88.4	90.2	87.1
	89.9	–	89.3	88.4	89.5	87.6	–	89.3	86.2
80 km/h									
Car	80.1	79.6	–	80.7	–	82.0	80.5	80.4	77.1
	80.0	–	79.0	80.0	81.1	81.0	–	79.3	75.9
Truck	92.4	91.4	–	90.5	–	90.9	90.5	91.2	88.7
	92.3	–	89.9	89.9	90.4	90.9	–	90.3	88.4

results are shown in Table 8. Surface friction was a problem for both the transverse and longitudinal astroturf drag, but were very good on just the longitudinally tined sections. A comparison of variable transverse tining (plastic concrete) to variable transverse diamond-sawed grooves in the hardened concrete resulted in the tined sections being a little better for surface friction but louder by up to 4 dB(A). It was postulated that the greater average texture of variable transverse diamond grinding resulted in the improved noise reduction.

Missouri

Work in Missouri also showed interesting results for transversely tined PCC pavement (*52*). Passby noise measurements showed that the noise level generally increased or was considered more objectionable as the wire comb spacing increased. When a burlap drag was used ahead of the wire comb, noise levels decreased in many cases. Table 9 shows the measurement results. The annoyance from the surface was not only related to the overall level, but to the frequency components as well. With the comb alone, no respondents found the noise "highly objectionable." However, when the comb and burlap drag were used in conjunction, "highly objectionable" opinions occurred and increased as tine spacing increased. In general, more respondents objected to the comb and drag method when compared to the comb only. Also, as the tine spacing increased for each pavement surface, annoyance seemed to increase based on this subjective testing. The tonal qualities of the pavement surface would seem to play a major role in annoyance. This tonal characteristic has been long noted. While not from Missouri, in 1971 Maynard and Lane recommended that transverse grooving should be arranged so that the frequency would vary in a random manner (*53*).

Kentucky

Testing in Kentucky was also being done in the 1970s and is reported by Agent and Zeeger (*54*). The authors concluded

TABLE 8

COLORADO TEST SECTION: I-70 AT DEERTRAIL *(51)*

	Test Results: Noise [dB(A)] at 105 km/hr					
	Inside Vehicle		7.5 m from Road		Wheel Well	
Pvt. Section	1994	1995	1994	1995	1994	1995
1	68	67	89	87	104	107
2	67	66	87	83	102	104
3	68	68	90	88	103	106
4	68	68	87	86	102	105
5	66	67	88	86	103	106
6	67	67	87	86	102	105
7	66	66	85	82	99	103
8	66	65	84	82	99	101
9	68	67	88	84	101	104

Test vehicle was a 1994 Oldsmobile Cutlass station wagon.

	Test Results: Friction (ASTM Method E 274)					
	64 km/h		80 km/h		96 km/h	
Pvt. Section	1994	1995	1994	1995	1994	1995
1	56/54*	56/43	58/48	50/41	52/45	46/35
2	68/48	52/22	68/40	45/18	52/35	40/14
3	69/67	59/52	68/58	52/50	58/52	51/45
4	68/62	59/55	68/58	56/55	58/55	57/49
5	60/59	52/50	60/52	50/45	49/45	46/41
6	60/55	56/42	59/49	50/39	51/43	49/35
7	54/55	50/48	52/49	48/46	44/41	39/32
8	52/30	49/20	48/21	39/16	39/19	33/11
9	65/57	55/50	61/52	52/49	51/44	42/36

*Ribbed tire/Smooth tire

TABLE 9

SOUND LEVEL [dB(A)] MEASUREMENTS *(52)*

		Wire Comb Tine Spacing (inches)		
Speed (mph)	Texturing Method	1/2	3/4	1
30	Comb alone	62.0	62.0	62.0
		62.5	62.0	63.5
			64.0	
	Comb with burlap drag	61.0	62.0	62.5
		62.0	62.0	62.0
				65.0
40	Comb alone	64.0	64.0	65.0
		64.5	64.5	65.0
			65.0	
	Comb with burlap drag	63.0	64.0	64.5
		64.0	64.0	64.0
				66.0
50	Comb alone	66.5	67.0	68.5
		67.5	67.5	68.0
			68.0	67.0
	Comb with burlap drag	67.0	66.5	68.0
		66.5	67.0	67.0
			68.0	69.0

Typical tine depths are 0.09 in., 0.18 in., and 0.12 in., for the tine spacings of 1/2 in., 3/4 in., and 1 in. respectively.

that grooved PCC pavements were 4 dB(A) more noisy than "normal" pavements, which included non-grooved PCC pavement. When compared to sand asphalt and "Kentucky Rock Asphalt" the grooved PCC pavement was reported to be 7 dB(A) greater.

New Jersey

Results from New Jersey verified public annoyance by the tonal emissions created by transversely tined PCC pavement sections *(55)*. The results of this study using octave band analyzers not only found that the transverse tining created the annoying "whine," present near a frequency of 1 kHz, but that the overall levels were 4.9 to 6.7 dB(A) greater than asphalt pavement.

Wisconsin

Kuemmel et al. *(56)* also conducted frequency band measurements from transverse tining. Their results tend to indicate that the dominant frequency remains in the mid-frequency ranges for different spacing, while the overall A-weighted levels are affected. Peaks or spikes are apparent in their spectral data, especially inside the vehicle. Levels inside the vehicle are discussed later in this synthesis. These results are shown in Figure 19. Testing at various speeds also indicated

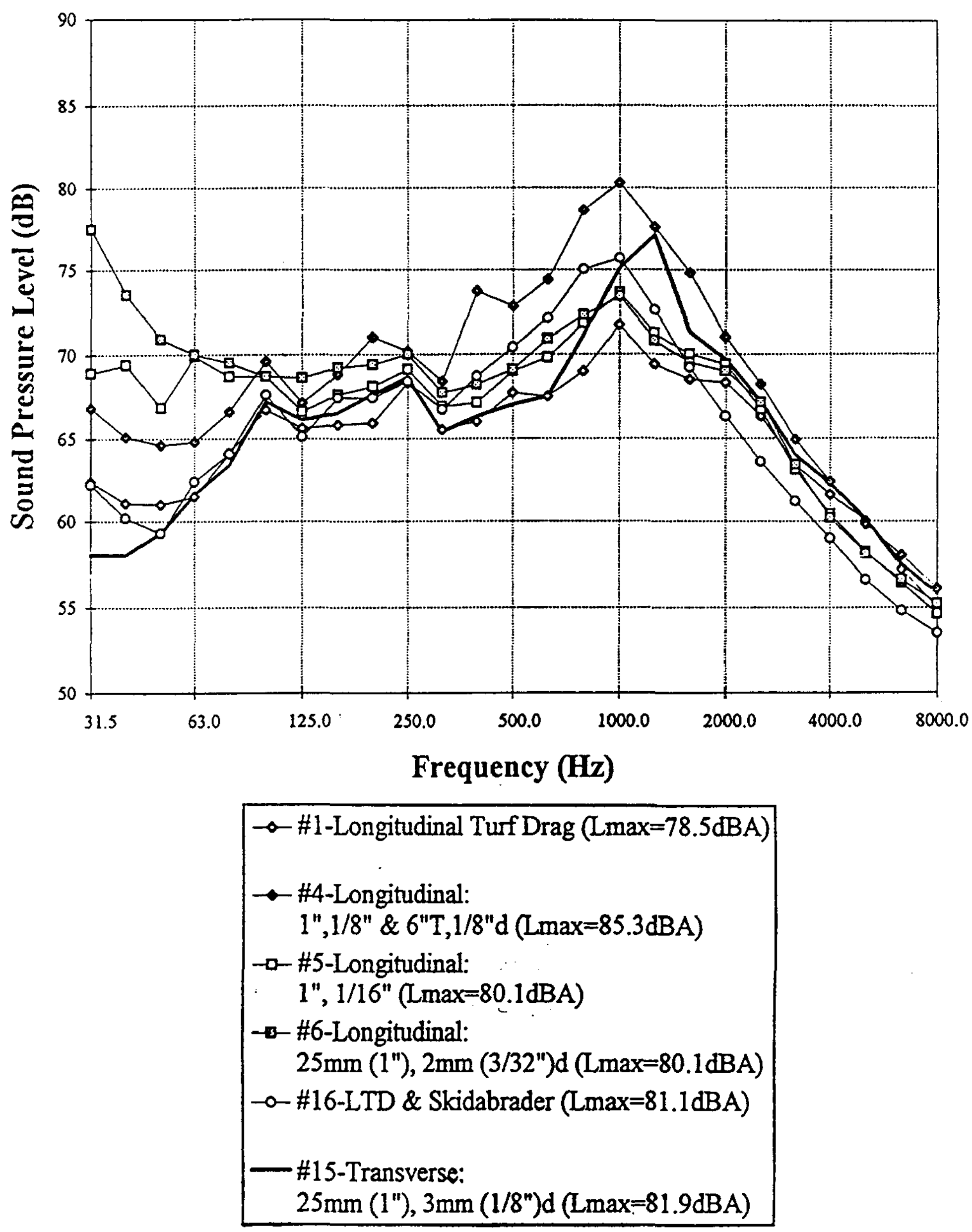


FIGURE 19 Exterior noise spectra for longitudinal and special PCCP compared to WISDOT standard for car at 96 kph (60 mph) *(72)*.

TABLE 10
WISCONSIN TEST SECTION: STH 29 CLARK COUNTY*(4)*

Pvt. Section	FN 40R**	Texture (mm) ASTM E 965	Exterior Noise Car (km/h) 96	105	112	Exterior Noise Truck (km/h) 96	105	112
1	41	0.22	79.4*	80.0	81.6	90.9	93.2	–
2	–	–	–	–	–	–	–	–
3	51	0.22	83.8	84.8	88.7	92.7	93.9	–
4	49	0.36	85.3	87.2	88.8	93.2	95.0	95.6
5	40	0.40	80.1	81.0	83.0	92.3	92.6	94.5
6	45	0.45	80.1	84.8	82.6	91.1	93.0	94.5
7	–	–	–	–	–	–	–	–
8	41	0.46	80.4	82.9	83.3	92.1	91.7	–
9	47	0.46	78.0	79.3	79.5	90.8	92.0	92.3
10	46	0.47	79.2	80.2	81.5	90.2	91.0	92.8
11	43	0.55	80.8	81.7	83.9	91.6	93.5	93.3
12	42	0.59	77.2	78.8	80.0	91.5	93.1	93.9
13	–	–	–	–	–	–	–	–
14	41	0.60	80.2	81.3	82.5	91.5	92.5	93.0
15	46	0.60	81.9	82.7	84.2	92.5	94.0	93.7
16	52	0.65	81.1	82.1	83.1	90.5	91.6	92.4

*All noise measurements in dB(A).
**Friction tests performed in early 1995 (ASTM Method E 274 Skid Trailer with ribbed tire-E 501).

overall noise level increases proportional to increasing tine spacing and speeds. It was determined that the whine produced by PCC pavements was the "most publicly objectionable and intrusive noise produced by highway traffic on PCC pavements." However, it was reported that the whine could be eliminated by the use of randomly spaced transverse tining, without compromising friction. The random pattern that produced the best results had spacing that varied from 10 to 40 mm (3/8 to 1-5/8 in.) with 50 percent of the spacing less than 25 mm (1 in.).

This major research project in Wisconsin using the controlled passby technique (same vehicles for all tests) also allowed a more in-depth analysis. The tests were for high-speed events ranging from 60 to 70 mph (97 to 112 kph). The pavement surfaces included:

Section	*Description (as planned*) and Texture*
1	Longitudinal turf drag, 0.22 mm
2	Transverse tining, 26 mm spacing, 3 mm deep
3	Transverse tining, 39 mm spacing, 3 mm deep, 0.22 mm
4	Long., 26 mm spaced/Trans., 156 mm spacing, 0.36 mm
5	Long, tining, 26 mm spacing, 1.5 mm deep, 0.40 mm
6	Longitudinal tining, 26 mm spacing, 3 mm deep, 0.45 mm
7	Transverse tining, 26 mm spacing, 3 mm deep
8	Skewed (1:6), 26 mm spacing, 3 mm deep, 0.46 mm
9	Transverse tining, 13 mm spacing, 3 mm deep, 0.46 mm
10	Transverse tining, 19 mm spacing, 3 mm deep, 0.47 mm
11	Transverse tining, random spacing, 3 mm deep, 0.55 mm
12	Transverse plastic broom, 1.5 mm deep, 0.59 mm
13	Transverse tining, 26 mm spacing, 3 mm deep
14	Transverse tining, 26 mm spacing, 1.5 mm deep, 0.60 mm
15	Transverse tining, 26 mm spacing, 3 mm deep, 0.60 mm
16	Longitudinal turf drag and Skidabrader, 0.65 mm

*Actual spacing, width, and depth were not measured.

The measured noise levels are listed in Table 10. Trends are difficult to determine as surface textures change. For example, longitudinal tining and longitudinal turf drag had very different surface depths but produced similar results. Also, rates of increase in noise levels due to increased speed were different for the various surface types. One interesting note is that a combination of longitudinal and transverse tining resulted in the greatest passby noise levels.

Figure 20 shows how the frequency spectra change due to the use of transverse tining for automobiles. The dominant frequency is clearly evident by the peak in Figure 20 for the transverse tining. This tone is easily detected by the ear and often reported when transverse tining is used. The dominant frequency does vary somewhat and is dependent on the vehicle speed and the tine groove width. For a constant speed, the dominant frequency will decrease with increased spacing. This is a function of the timing of the wheel impacts and can be calculated. As Kuemmel points out (*56*), this is about 704 Hz for 38-mm (1-1/2 in.) tine spacing at 60 mph (97 kph) and the frequency would increase to 2112 Hz for a 13-mm (1/2 in.) spacing. The measured results of Figure 20 generally follow this trend. Of note is that the quietest pavements were the 13- and 18-mm (0.5 and 0.71 in.) transverse tine spacing for automobiles. From a review of the presented spectra, this can be seen as a result of reduced peaks for the (dominant) frequency and an energy shift to higher frequencies. It was later discovered that the depth of tining was less than reported in the figures. Later tests also showed that the sound pressure level at the sideline was about 2 dB higher and similar to the other tining. However, the overall trends remain worth noting. The dominant frequency effect was also very evident for trucks, as shown in Figure 21. For this testing the depth of spacing also had a greater impact on the sideline noise levels than results reported by Samuels, even though the depths were reported to be the same in both measurement samples. As such, both width and depth should be considered along with other characteristics.

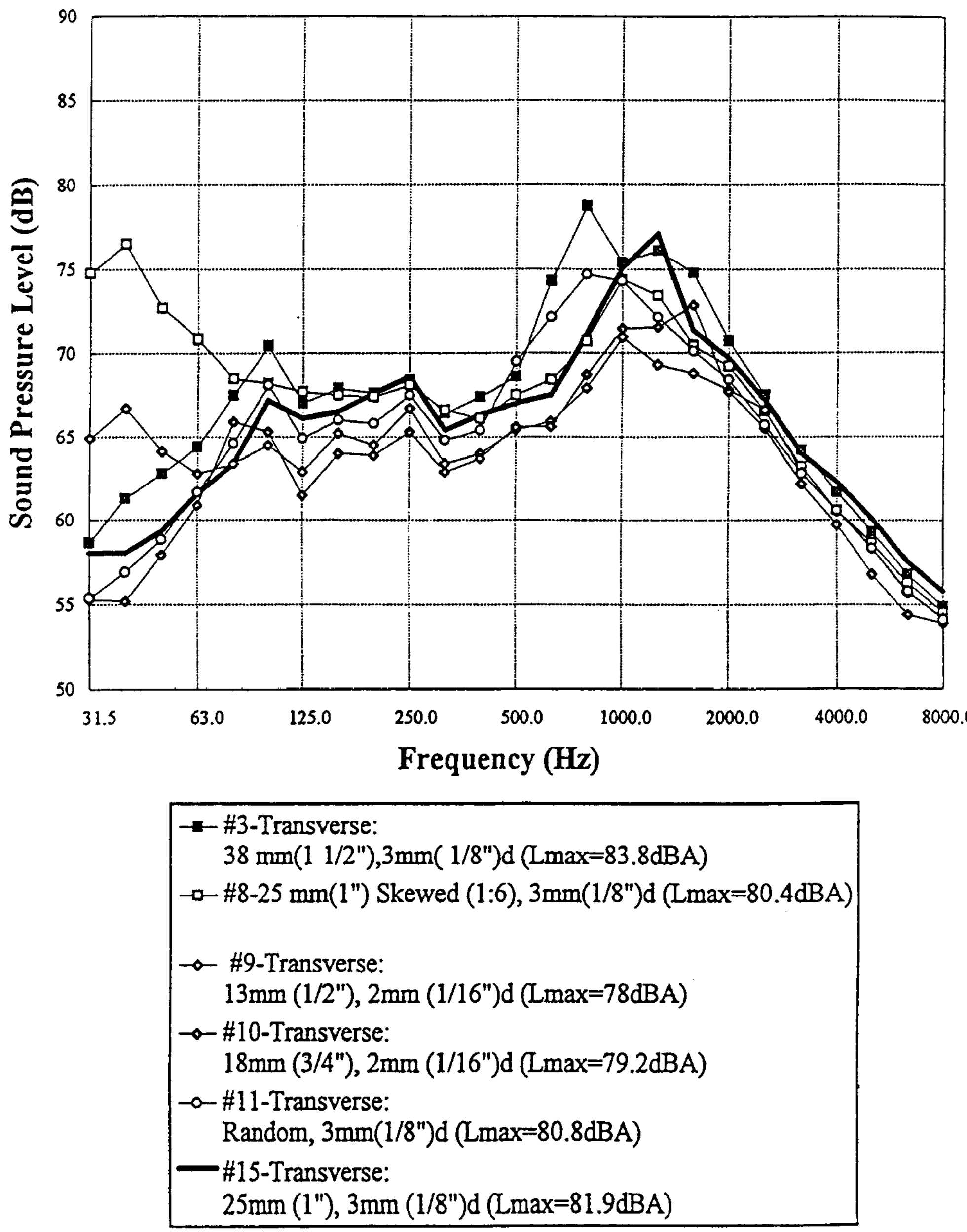


FIGURE 20 Exterior noise spectra for transverse-tined PCCP with car at 96 kph (60 mph) *(72)*. Passby method and all PCC pavement sections less than two years old.

Minnesota

In 1979, Minnesota released results of a measurement study comparing six different textures applied to PCC pavement and three bituminous pavements *(57)*. In-situ sideline measurements (45 ft from vehicle track) were conducted and compared to a test section measured at the same time, resulting in matched pairs. Since all test sections were on the same highway, it was assumed that vehicle noise generation would be similar for the two sections and the differences in the measured noise levels could then be attributed to tire/pavement differences. The ranking of pavements, where number one is the quietest pavement was reported as:

1 (tie) MN specification 2371 open-graded bituminous pavement,
1 (tie) MN specification 2361E open-graded bituminous pavement,
3 MN specification 2361W dense-graded bituminous pavement,
4 PCC pavement with 1-in. tining spacing,
5 PCC pavement with 3-in. tining spacing,
5 PCC pavement with random tining spacing,
6 PCC pavement with 1¾-in. tining spacing,
7 PCC pavement with 2-in. tining spacing, and
8 PCC pavement with 2½-in. tining spacing

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* All PCC pavement used primarily longitudinal Astrograss drag.

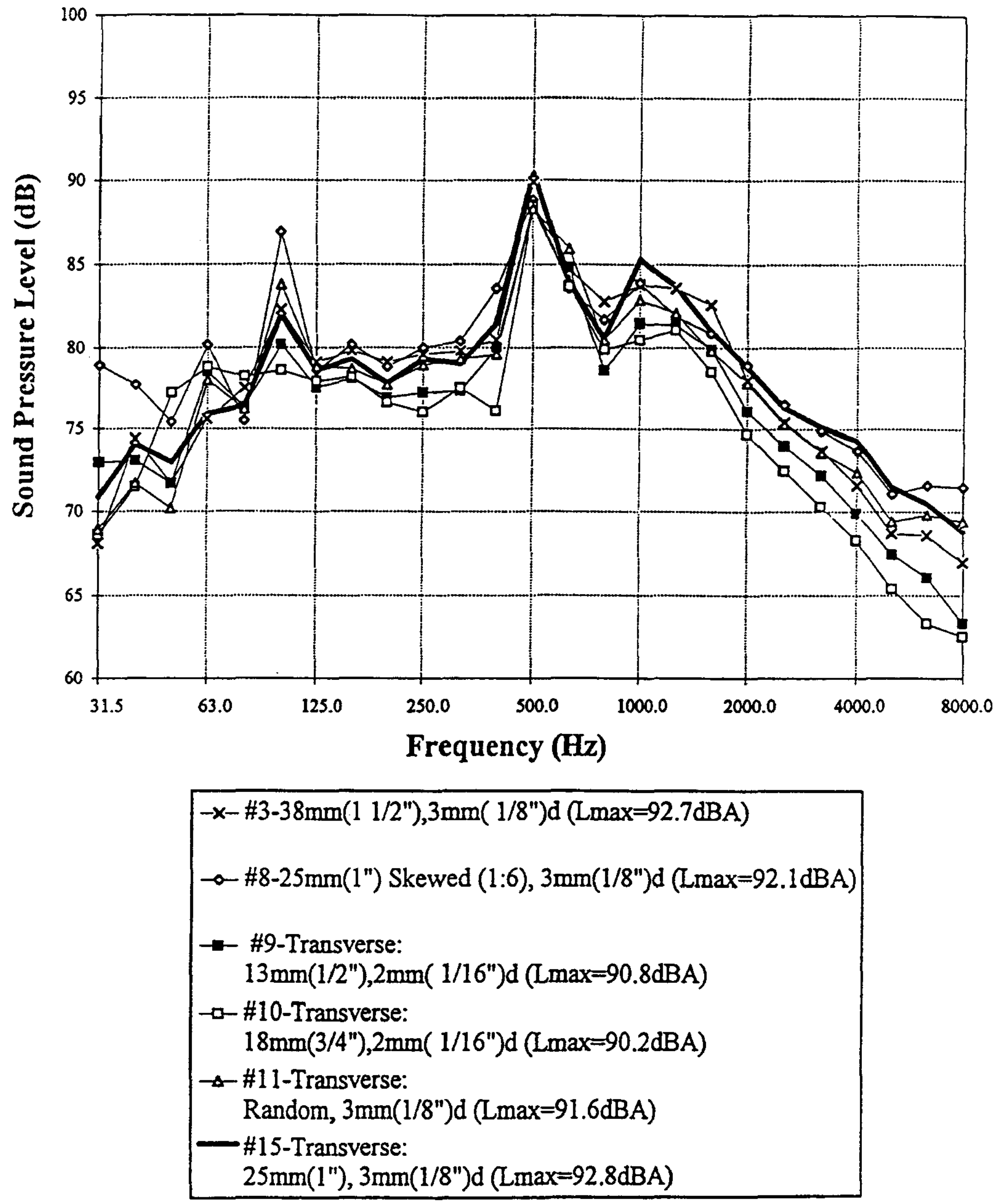


FIGURE 21 Noise spectra for transverse-tined PCCP with truck at 96 kph (60 mph) *(72)*. Passby method and all PCC pavement sections less than two years old.

Texture and tining depths were not reported. All asphalt surfaces had less than average texture depth but were quieter than any of the PCC pavements. The increase in noise levels for the 1¾ -, 2-, and 2-½-in. (44, 51, 64 mm) spaced tining was primarily in the 800 to 1,250 Hz range.

No apparent trend developed with tine spacing, again suggesting that other surface characteristics interact to produce the final overall sideline noise. The authors also reported that when vehicles with low mechanical noise were compared to vehicles with high mechanical noise (trucks and motorcycles), the largest change occurs in noise levels when going from surface to surface for the vehicles with high mechanical noise. This suggests an overall source/pavement relationship. Also, the amount of sideline noise increase, when compared to speed, had both the greatest and lowest slope (regression coefficient) for asphalt surfaces giving somewhat conflicting results. Overall, sideline noise was reported to have a 12 dB(A) difference for all test sections when going from 35 to 72 mph (56–116 kph).

Follow-up measurements on the test sections were repeated in 1980, 1981, and 1982 *(58–60)*. Rankings remained the same, except the Minnesota specification 2371 open-graded asphalt became the quietest pavement. In the 1982 work, the 2-in. and 1¾-in. tining reversed in the overall rankings. One major change in testing occurred when the same test car could not be used in the 1982 study.

Research has continued in Minnesota; studies on the same surfaces were conducted in 1987 and 1995 *(39, 61)*. Seven

TABLE 11
MINNESOTA TEST SECTION: STA 12 AT WILLMAR *(4)*

	Ext. Avg. Car (88 km/h)		Ext. Control Car (88 km/h)		Int. Control Car
Pvt. Section	1987	1995	1987	1995	1987
26, 39, 52, 65 mm repeated	78.5*	78.7	79.5	78.2	71.4
Astroturf	74.0	75.0	73.5	74.5	67.8
26 mm	76.0	76.5	75.5	76.1?	68.1
45 mm	80.5	82.0	80.5	81.1	71.1
52 mm	80.0	80.6	81.0	79.9	71.9
65 mm	80.5	81.6	82.0	81.9	72.0
78 mm	77.5	79.1	78.5	79.1	72.1
Bituminous	70.2**	72.5	68.8**	72.4	65.1

*All noise measurements in dB(A).
**Average of three bituminous pavements.
All PCC sections transversely tined. The astroturf section is the control section.

tined PCC pavements were compared to an asphalt surface. These surfaces included:

Pavement Sections	*Texture Depth (mm)*
Transverse Variable (26,39,52, 65 mm)	0.41
Transverse (78 mm space)	0.61
Transverse (65 mm space)	0.61
Transverse (52 mm space)	0.68
Transverse (45 mm space)	0.57
Transverse (26 mm space)	0.75
Asphalt Concrete	0.28
Astroturf Drag (Long.)	0.26

The trend of the earlier research continued as the quietest pavement was the asphalt surface. However, the poor megatexture of the asphalt concrete and longitudinal astroturf drag probably affected these test results. The longitudinal astroturf drag, with the 26 mm (1 in.) transversely tined section was next. Measurement results are shown in Table 11. Although not reflected in the table, it was concluded that the noise spectra could differ greatly without the overall noise levels (dB(A)) changing considerably. Of interest is that the surface with the greatest surface texture depth (0.75 mm (0.03 in.)) and 26-mm (1 in.) tine spacing was the third quietest pavement with results close to the astroturf results. The next pavement in order of sideline noise was the section with widest tining (78 mm (3.1 in.)) but still fairly deep texture depth (0.61 mm (0.024 in.)). Tining spacing within this range of values caused greater sideline noise levels. Friction test data were not available on these sections. It was noted, however, that splash and spray were noticeably less during rainfall events for transverse tined PCC sections compared to dense-graded asphalt.

Iowa

Results reported previously tend to indicate that use of longitudinal tining as opposed to transverse tining is better for noise control. However, longitudinal tining has lower surface friction. Accordingly, it would be desirable to have a surface texture with high friction characteristics and low noise levels. Safety must always be considered. In October of 1985, Iowa conducted a study of how sideline noise levels would be affected if transverse tining were modified by longitudinal surface grinding (*62*). A total of 44 15-minute samples were taken before the grinding and 32 after. The results were time averaged (L_{EQ}), A-weighted levels. In addition, 27 third-octave frequency bands were recorded at one location. The measured values are somewhat deceiving because they were measured at different time periods with different vehicle mixes and volume. The researchers did conclude that ". . . the modification of transverse groove pavement surface texture by longitudinal grinding has lowered traffic noise levels by reducing a high frequency component of the total traffic noise spectrum." However, this comes at a cost in safety. The pavement friction of longitudinal tining is less than transverse tining and is discussed in the next chapter.

Spain

The same concerns extend outside the United States. Spain has reported successful use of a combined texture of a longitudinal burlap drag followed by a plastic brush to provide high friction characteristics while minimizing tire/pavement noise (*7*). A minimum of 30 percent siliceous sand was required to assure satisfactory microtexture for pavement friction. Noise levels are reported to be similar to porous asphalt with an average noise level 0-2 dB(A) higher. In 90 to 95 kph (56 to 59 mph) tests, friction numbers of 0.29 and 0.21 were measured with the ASTM skid trailer test.

Other interesting results on longitudinal texture patterns were reported by Jofre (*63*). As shown in Figures 22 and 23, five texture patterns were measured using the close proximity (trailer) method (Rolling Noise Analyzer). It should be noted that the results represent a measure of noise generation without propagation effects. The texture developed using a plastic-bristled brush gave the best results when both noise generation and pavement friction were considered. It was concluded that transverse textured surfaces tend to be noisier than longitudinal texturing with similar texture depths. However, longitudinal

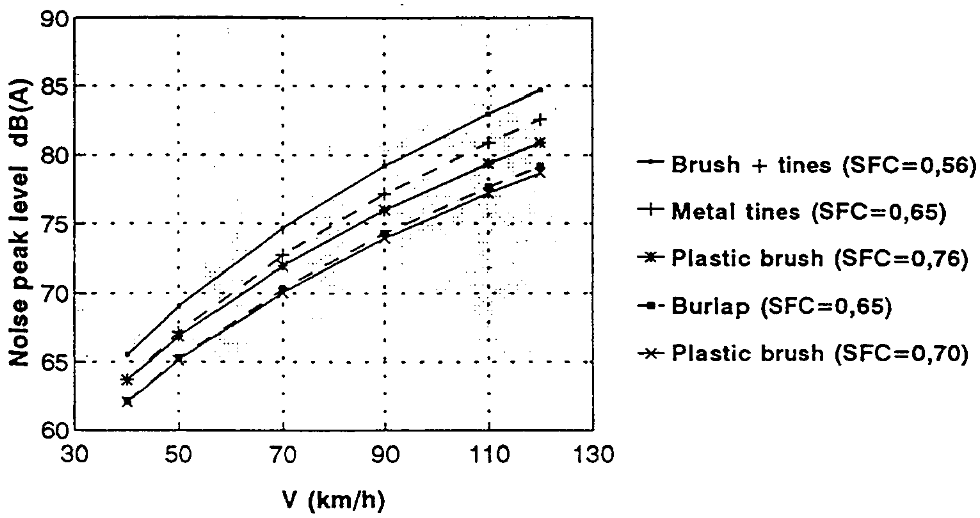


FIGURE 22 Longitudinal finishes—relationships between noise and speed *(63)*.

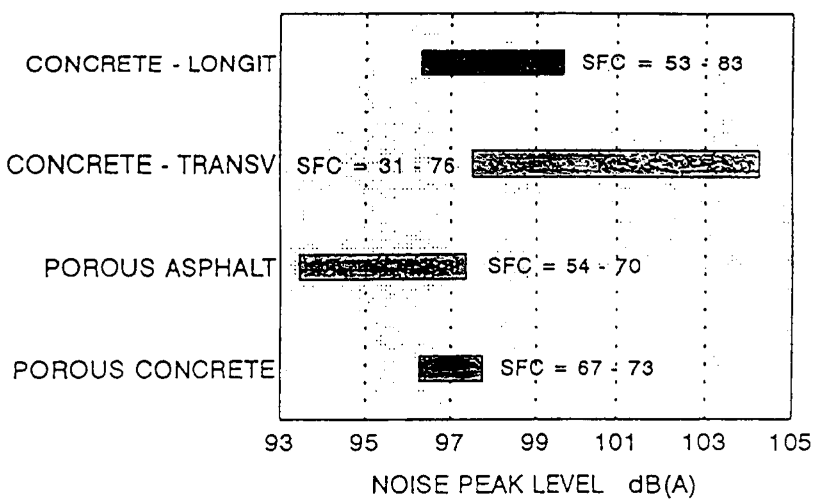


FIGURE 23 Rolling noise levels on several types of surfaces *(63)*. Tests were done using a PIARC tire and 100 kph (62 mph).

textured PCC pavements still generated more noise than porous asphaltic surfaces.

The general trends reported by Jofre are shown in Figure 23. Transversely tined PCC pavement was clearly the greatest sound generator and porous asphalt was the least noisy. Longitudinal tining produced less sound than transverse tining. One interesting result reported was for porous concrete as shown in Figure 23. Results show porous concrete to be similar to the high end of porous asphalt.

North Dakota

Exterior and interior noise levels were measured in North Dakota for nine test textures on I-94 *(64)*. Four test vehicles were used in controlled passby measurements. The pavement types included:

Pavement Section	*Texture Depth (mm) ASTM E 965*
Transverse (26-mm skew)	0.60
Transverse (19-mm spacing)	0.82
Transverse (52-mm spacing)	0.69
Transverse (78-mm spacing)	0.49
Transverse (104-mm spacing)	0.53
Transverse (Variable) (26-, 52-, 78-, and 104-mm)	0.43
Transverse (13-mm spacing)	1.17
Longitudinal (19-mm spacing)	0.37
Transverse (control: 26-mm spacing)	0.76

Test results are shown in Table 12. Results to date indicate that the skewed tining and variable spaced tining produce the lowest sideline tire/pavement noise. For interior noise, the study concluded that no benefit could be shown for transverse, longitudinal, or skewed tining.

TABLE 12
NORTH DAKOTA TEST SECTION: I-94 AT EAGLES NEST *(4)*

	Exterior (105 km/h)		Interior			
Pvt Section	10.7 m	45.7 m	Ford Tempo	Dodge Shadow	Suburban	Dodge Van
26 mm skew	70*	65	73	74.3	71.3	75.0
19 mm	71	69	74.3	74.9	71.6	75.2
52 mm	69	66	73.9	74.2	72.3	73.9
78 mm	69	68	73.7	73.7	72.2	73.6
104 mm	70	67	72.8	75.1	71.8	74.3
Var.**	67	65	73.1	74.2	71.4	74.4
13 mm	70	69	73.9	74.5	72.7	73.9
19 mm long.	69	69	74.7	74.5	72.1	74.7
26 mm control	69	68	75.1	75.8	72.1	76.7

*All noise measurements in dB(A).
**Variably spaced at 26, 52,78, and 104 mm.
Exterior noise for the 26 mm skew and variable tine spacings are questionable because they are located near an overhead structure. All sections are transversely textured unless otherwise stated.

Belgium

Previously reported results for tined PCC pavement would seem to be supported by a report from Belgium *(65)*. In this case, tining width was taken to the practical limit by using diamond grinding and carbide grinding (soft milling). A roadway test section with transverse tining spacing of 25 mm (1 in.) and a depth of up to 6 mm (0.24 in.) was first evaluated with the statistical passby method, 7.5 meters (50 ft.) from the track of the near lane. Next, the grinding technique formed a groove 2 to 4 mm (0.08 to 0.16 in.) deep, 3.2 mm (0.13 in.) wide, with an intermediate groove spacing of 5.3 mm (0.21 in.) and the measurements were repeated. Significant reductions occurred. The total vehicle noise dropped by approximately 6 dB(A). Test vehicles were also used to determine only rolling noise. Peak passby levels decreased from 1 to almost 5 dB(A). Of note is that the evenness of the road and surface friction were also reported to show marked improvement.

It can be concluded that it is possible to reduce the adverse noise impact with high quality mix design and construction practices. Based on the experiences in Wisconsin *(4)* when random transverse tine spacing is used (minimum 10 mm (0.4 in.) to a maximum of 40 mm (1.57 in.) with no more than 50 percent of the spaces exceeding 25 mm (1 in.)) low noise generation occurs. When longitudinal spacing is used for noise reduction, a uniform tining of 20 mm (0.79 in.), actual tine width of 3 mm ± 0.5 mm (0.12 ± 0.02 in.) with a depth of 3 to 6 mm (0.12–0.24 in.) is recommended. When measured using the sand patch test (ASTM-E 965), the average surface texture depth should be 0.8 mm (0.31 in.) with a minimum of 0.5 mm. (0.02 in.). It was noted that longitudinal tining will lead to more spray and splash and at high speeds may not supply sufficient frictional characteristics.

EXPOSED AGGREGATE

Exposed aggregate pavements have also been evaluated for noise impacts. This PCC surface is accomplished by brushing the surface of the plastic concrete to expose the aggregate, increasing the macrotexture. This surface can also be accomplished by wet scrubbing and/or adding chipping in a final coat. Most noise research has occurred in Europe for this pavement texture, where low noise and high friction characteristics have been reported. In addition, fair results have been reported from Australia. Results have been mixed in the United States. European construction may include multiple applications to produce the final surface, which is not a common practice in the United States.

General European Experience

Normal construction is usually considered to be two layers, wet on wet. However, as noted by the BRITE/EURAM report *(7)*, a wet on dry application is also possible. It is recommended that the top layer be 40 to 70 mm (1.6 to 2.8 in.) thick, contain 30 percent siliceous 0 to 1 mm (0 to 0.04 in.) sand, and 70 percent high quality chips of 4 to 8 mm (0.16 to 0.32 in.). As with other studies, a plasticizer is needed to ensure durability of the surface course. The recommended texture depth is 0.9 mm (0.35 in.) as measured by the sand patch test. Any less depth is reported to result in higher noise level generation. Of interest in the BRITE/EURAM report was the statement that high levels of exposed chips are needed for low noise. Noise levels were stated to be similar to porous asphalt as measured with the ISO statistical passby method.

Although a two-layer approach with a single paver is most often used, a single-layer approach is also possible. If the single-layer approach is used, conventional maximum particle size along with an increased proportion of 4/8 mm or 5/8 chippings may be used. However, for exposed aggregate with small maximum particle size, a two-layer approach is needed for a good final product. The exposed aggregate will also require a brushing operation (washing) for exposing the aggregate. It was reported that the exposed aggregate pavement, using these parameters, resulted in a noise reduction of 5 to 8 dB(A) for an overall sideline noise level (using the ISO statistical passby method) of 65 to 68 dB(A). A combination of grinding and surface dressing resulted in even lower noise levels.

A study done in the United Kingdom (*66*) compared dense asphalt (hot-rolled asphalt) to brushed, brushed/transverse tined, and exposed aggregate PCC pavement. The three concrete surfaces were applied to a 250-mm (9.8-in.) thick, continuously reinforced concrete pavement. The tining of the PCC surface was randomly spaced and details on spacing were not provided. The exposed aggregate used an air-entrained concrete with a polished stone aggregate (coarse aggregate of 10 to 6 mm (0.24 in.) with a texture depth requirement of 1.5 ± 0.25 mm (0.06 ± 0.001 in.). The statistical passby method was used to evaluate the different surfaces. The exposed aggregate surface resulted in lower noise levels, even when compared to the dense asphalt. The brushed surface resulted in the highest measured sideline noise measurements.

A later study from the United Kingdom (*67*) echoed the results of the previous U.K. study. Passby measurements were taken and the results showed that the exposed aggregate concrete noise levels were less than the hot-rolled asphalt by 2.2 dB(A) for light vehicles and 1.1 dB(A) for heavy vehicles. The measurement location was 7.5m (25 ft) from the vehicle track and the vehicles speed was 90 kph (56 mph). The exposed aggregate upper layer was an air entrained concrete mix, 40 mm (1.57 in.) thick. The coarse aggregate size was 10 mm (0.4 in.) with a texture depth of 1.5 mm (0.06 in.) to 0.25 mm (0.01 in.). The hot-rolled asphalt texture depth averaged 1.5 mm (0.06 in.) but was never less than 1.2 mm (0.047 in.). Considerable care was taken during construction of the exposed aggregate road surface and details are provided in the report. Durability was also shown as the noise levels changed little over a 32-month period.

Transversely tined PCC pavement was also measured in this U.K. study (*67*), and found to generate less noise than hot-rolled asphalt, but among PCC pavements, only brushed was greater. The texture depth of the brushed and tined sections were 1.0 mm (0.04 in.) 0.25 mm (0.01 in.) with 20 mm. (0.79 in.) coarse aggregate. The tined pavement was randomly spaced 3 mm (0.12 in.) apart and 0.8 mm (0.03 in.) thick.

Frequency spectra were also investigated in the U.K. study. The research team concluded that the ". . . exposed aggregate surface appears to provide better noise quality characteristics . . . ." The spectra collected show reduced levels at most frequencies. Also of note was the conclusion that the spectra obtained for the tine surface shows significantly higher levels of noise above 1.6 kHz when compared to the exposed aggregate surface.

In Sweden, exposed aggregate surface noise levels using the close proximity method were compared to stone mastic surfaces, the most common pavement type in Sweden (*68*). Two stone mastic surface noise levels were measured, while four exposed aggregate surfaces were considered in the study. The range of levels reported included testing with multiple tire tread types. Before the roadways had been exposed to traffic (new surface) the stone mastic surface ranged from 93.7 to 101.9 dB(A) at 70 kph (44 mph) and 97.5 to 105.4 dB(A) at 90 kph (56 mph). With the exception of one tire type, noise levels were lower for exposed aggregate pavements with aggregate sizes less than 16 mm (0.63 in.). Surfaces with maximum aggregate size of 8 mm (0.31 in.) and 16 mm were tested. The values of the noise levels from the exposed aggregate ranged from 90.2 to 102.4 dB(A) at 70 kph and 94.0 to 104.7 dB(A) at 90 kph.

Similar values were measured one year after the roadway was opened for use. The exposed aggregate now ranged from 99.7 to 102.2 dB(A) at 70 kph and 97.1 to 104.4 dB(A) at 90 kph. Testing was also done with exposed aggregate surfaces at 2 years and 4 years old, using aggregate up to 22 mm (0.87 in.).

The general findings were that if aggregate up to a maximum of about 22 mm (0.87 in.) was used, the roadway generated more noise as measured by the close proximity method than if the maximum aggregate size was limited to 16 mm. The exposed aggregate levels for the smaller aggregate were also very similar to the stone mastic surface after one year. If the maximum size of the exposed aggregate is further reduced to 8 mm, the surface is less noisy than the stone mastic when new and only slightly better after one year.

Frequency spectra were also collected for this project in Sweden and results for two tire tread types are shown in Figure 24. The two surface type spectra are very similar but it appears some energy has been shifted to the lower frequencies when exposed aggregate pavement is used.

This conclusion was echoed by a study in Austria (*69*). An exposed aggregate surface, with a top layer containing a maximum 8 mm (0.3 in.) aggregate size, showed a 5 dB(A) reduction when measured using the trailer method. A frequency analysis showed important reductions in the key audible frequency range of 500 to 2,000 Hz.

Australia

The first trial section of exposed aggregate concrete surfacing in Australia was built in 1993–1994 (*70*). This section was built by applying a surface set retarder to allow controlled exposure of surface aggregates by wet brooming. A single layer of 14-mm (0.55 in.) size aggregate was used. The range of texture depth was measured by the sand patch method to be 1.46 mm (0.018 in.). The major factors for texturing were stated to be the technique of spraying the retarder, the retarder type, and brushing. Surface friction was reported to be good and better than open-graded friction course asphalt. Noise measurements were taken inside a car and externally by using the passby method. Internally, the noise was comparable to the open-graded friction course asphalt, considered to be the quietest surface. However, the external passby measurements showed that the exposed aggregate surface was the second noisiest pavement surface, even exceeding tined concrete. The reason for this result was thought to be the large surface aggregate (14 mm (0.55 in.)). It was concluded that this large aggregate is quieter for trucks, but for automobiles a smaller aggregate (8 mm (0.32 in.)) produced more desirable results, as shown in tests from Europe. Even so, later testing by Dash (*71*) on this section of pavement showed the exposed aggregate surface to be equivalent to dense-graded asphalt in terms of sideline noise.

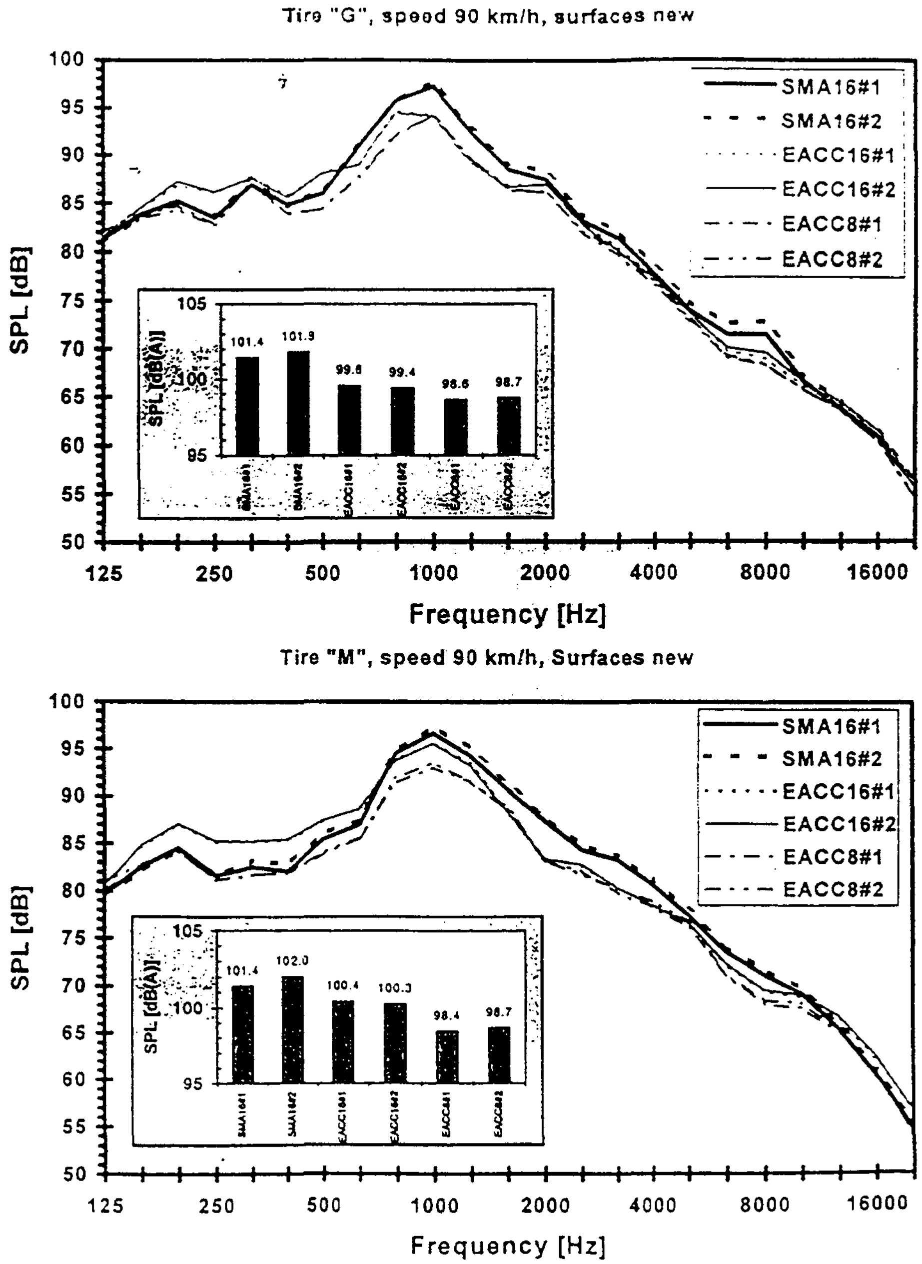


FIGURE 24 *(Top)* Linear tire/road noise spectra for the test tire M ("summer" type); *(Bottom)* G (M + S Type, meant to represent heavy vehicle tires *(67)*. Measurement with CPX method (trailer) at a speed of 90 kph (56 mph).

Michigan

Research in Michigan on exposed aggregate surfacing (two-layer concrete mix, a hybrid German/Austrian design) was compared to Michigan's standard 26 mm (1 in.) transverse tining *(72)*. No change in noise generation over the 2-year period 1993 to 1994 was shown for the exposed aggregate surface. It can be concluded that the surface texture remained constant over the year in this northern environment. Unfortunately, inexperience of the contractor with this European process was listed as leading to lower friction numbers than expected. This was thought to occur for two reasons. First, over-finishing led to the 4- to 8-mm (0.16- to 0.32-in.) particles oriented with the flat side up rather than the rough edges. Second, the sand used was too coarse, being 0 to 4 mm, not 0 to 1 mm, as recommended in Austria.

When compared to the standard Michigan concrete mix, the measured sideline values using the passby method (17 m from vehicle track and at least 1.5 m high) were virtually identical (European exposed aggregate = 75.9 dB(A); Michigan standard = 75.7 dB(A)). The exposed aggregate PCC pavement in Michigan proved to be durable but noise reduction was not shown as in the European studies.

The exposed aggregate process requires very careful construction techniques. Unofficial complaints have been that it is very difficult to follow the necessary procedures. This would seem to be echoed in both Australia and Michigan. Changes in construction processes and aggregate size can greatly influence the final noise production of the roadway. Also, problems have been reported in obtaining a good bond between the epoxy resin and the concrete and the adequate bedding of the aggregate particles in the resin layer when placing chips on a dry surface. Again, good bonding is dependent on construction techniques.

OTHER PCC PAVEMENT TEXTURE CONSIDERATIONS

Other methods are being evaluated in Europe to quiet concrete surfaces. These include: monolithic porous concrete; a porous top layer on dense concrete; and surface treatments using exposed aggregate in conjunction with surface dressing (*7*). It was concluded in this work that the most promising noise emission reduction technique would be a porous top layer using a finely grained epoxy surface dressing. This combination is thought to give similar noise characteristics to drainage (open-graded) asphalt pavement. Measurements verified that the overall noise levels were comparable to porous asphalt. The effective porous concrete needs at least 25 percent accessible porosity for noise control and a layer thickness of about 40 mm (1.6 in.) for motorways (to avoid high noise levels around 1,000 Hz) and for urban areas (with frequency concerns of about 250 Hz). A greater layer thickness results in greater sound absorption potential at lower frequencies. The porosity is achieved by using a very low proportion of fine aggregates. The thickness of the layer depends on the size of the coarse aggregates. Other advantages of porous concrete include less light reflectance, increased driving comfort, less spray/splashing and better drainage (at least 20 percent porosity is needed for drainage). Optimization of the porous surface by texture and porosity is extremely important for noise control and there are several possibilities for optimization. In general, the optimization process is shown in Figure 25.

A problem reported for porous concrete was that not only is it necessary to obtain a certain porosity for acoustic reasons and water removal, but a level of mechanical resistance and adequate durability must also be achieved. To accomplish this goal, new components must be used that differ from the conventional process. One example is the use of acrylic polymers in a thin top layer (4 to 10 cm (1.6 to 3.9 in.)). The use of these new components may add to the cost and/or increase the construction difficulty of getting a good bond between the concrete and top layer.

European studies results indicate that the microtexture provides good pavement friction. The needed macrotexture can be maintained by using polish-resistant materials such as chippings and sand. The macrotexture should have high amplitudes in the 0.5- to 10-mm (0.02 to 0.39 in.) wavelength range to optimize for tire noise, pavement friction, low splash/spray, and low light resistance. Amplitudes in the 10- to 50-mm (0.39 to 2 in.) wavelength directly impact tire/pavement noise. This means that the maximum chipping size should be as low as possible with the chipping having sharp edges (i.e., crushed material).

The BRITE /EURAM report (*7*) also included a discussion of texturing the surface of fresh mortar to produce low-noise dense concrete. When texturing, the surface produced by a jute cloth or comb must be durable. This requires special mortar considerations, such as low water/cement content and the addition of microsilica. An interesting finding was that if only the jute cloth is used and not transverse brooming, a 3 dB(A) reduction in noise levels would be expected, but at the cost of lower pavement friction.

SUMMATION OF PCC PAVEMENTS CONSIDERATIONS

Several specific observations were succinctly stated in the reviewed literature and are summarized here:

- PCC pavements are in general, more noisy than asphaltic surfaces.

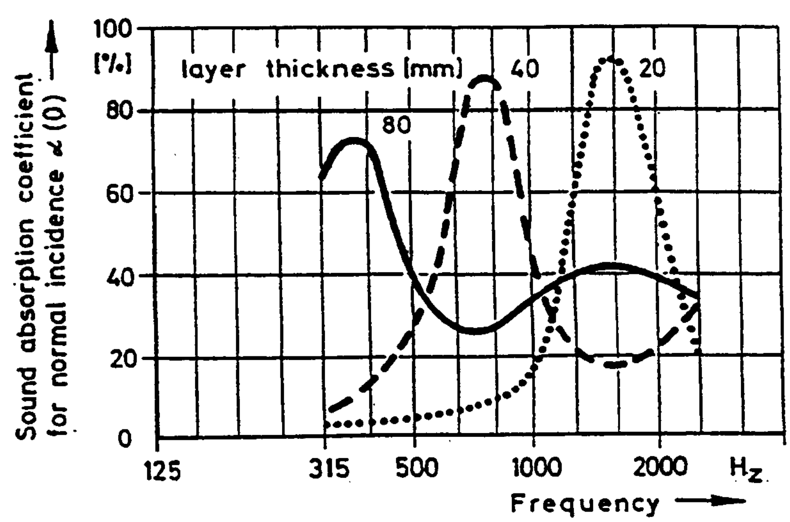


FIGURE 25 Noise absorption in perpendicular direction depending on the frequency and the thickness of a porous asphalt layer *(21)*.

• In general, transverse tining would also seem to cause the greatest sideline noise levels when compared to longitudinal tining or asphaltic surfaces. It would appear that the surface texture of transverse tining, especially if spaced over 26 mm (1 in.), generates the most annoying tire/pavement noise. Randomized tine spacing tends to reduce the annoying pure tone that is generated.

• A significant noise reduction or frequency shift was not shown when a transverse tined surface (26-mm (1-in.) uniform spacing) and European exposed aggregate texture were compared in Michigan. In Europe, the exposed aggregate PCC pavements provided noise attenuation similar to stone mastic surfaces. However, the U.S. experience in Michigan showed the exposed aggregate noise levels to be similar to PCC pavement. These conflicting results could be caused by the different construction techniques and aggregate sizes used at the two locations. It would appear from the European and Australian results that a maximum aggregate size of 8 mm (0.32 in.) should be used. Greater aggregate sizes do not provide the same noise reduction for automobiles. Australian research shows this might be different for the larger tires used on trucks.

• Studies show that the sound generation changes with speed. The pavement with the best results for noise may be different with varying speeds. In addition, the most quiet pavement surface was found to be different for automobiles than for trucks.

• Construction quality is an important consideration for the final overall noise generation.

• Texture depth of the transverse tining also seems to play an important role. In some U.S. cases the greatest noise was generated with the greatest average texture depth. The width of the groove becomes an important parameter in these cases.

• The use of porous PCC pavement also results in a noise reduction along the highway. This surface may provide noise attenuation while also being more durable than asphaltic surfaces.

ASPHALTIC CEMENT CONCRETE PAVEMENT

Asphalt (flexible) is the most used pavement type in the United States (based on survey results (chapter 2) and FHWA statistics (2)). As such, consideration of noise reducing qualities of this pavement type is extremely important. Most of the measurements that have been performed use dense-graded asphalt as a comparative test surface.

Reports from Various Geographical Areas

Again, geographic locations are listed in the order that allows the discussion to follow without dissecting reported research into small fragments.

Wisconsin

Kuemmel (*73*) performed limited testing for asphalt pavements in Wisconsin. Figure 26 shows the spectral data collected during measurements. The asphaltic pavement tire/pavement noise was about 2 to 5 dB(A) less than PCC pavements. [The reader is reminded that the 13 mm (0.5 in.) transverse grooving measurements were later found to be about 2 dB(A) greater.] As with the PCC surfaces, the increase of overall A-weighted levels with speed is clearly shown from the data. Of note is that PCC pavement textured with nylon plastic broom bristles also showed reduced levels, but was not as quiet as the asphalt pavements. In general, the PCC pavements were not as quiet as asphalt surfaces.

Sweden

Ulf Sandberg provided a good overview of the surface texture effects in a recent paper (*11*). Sandberg points out that up to a 15 dB(A) change in noise levels can occur due to surface influences, but in most cases, a 3 to 5 dB(A) change occurs. Just as for PCC surfaces, the complete tire/pavement interaction must be considered. As before, the macro- and megatexture are important not only for noise production, but for frictional characteristics as well. Megatexture should be minimized for good noise control. To accomplish this, large chipping sizes and nonhomogenous application should be avoided. The orientation of the chippings is also important. Rolling the surface permits the main axis of orientation for the chippings to be horizontal and results in less noise production. Chippings with a cubical particle shape could also be used to achieve the same effect as rolling.

The correct texture results in lower vibration of the tires. This effect can be enhanced by increased porosity. Increased porosity results in more favorable drainage, less air pumping noise being created, and sound absorption. To achieve very high porosity requires a different surface type—open-graded asphalt.

OPEN-GRADED ASPHALT

Considerable effort has been expended on research for open-graded or drainage asphalt because of the further noise reduction when compared to dense-graded asphalt. The noise reduction occurs for the same reasons as porous PCC pavement surfaces. Selected research is presented here.

Denmark

Various asphaltic surfaces with attention on open-graded asphalt were evaluated in Denmark (*74*) using the passby method for individual vehicles. The various parameters of the pavements are shown in Table 13, while the resulting noise levels are shown in Table 14. The variations between the road surfaces were on the order of 2 or 3 dB(A). It was concluded

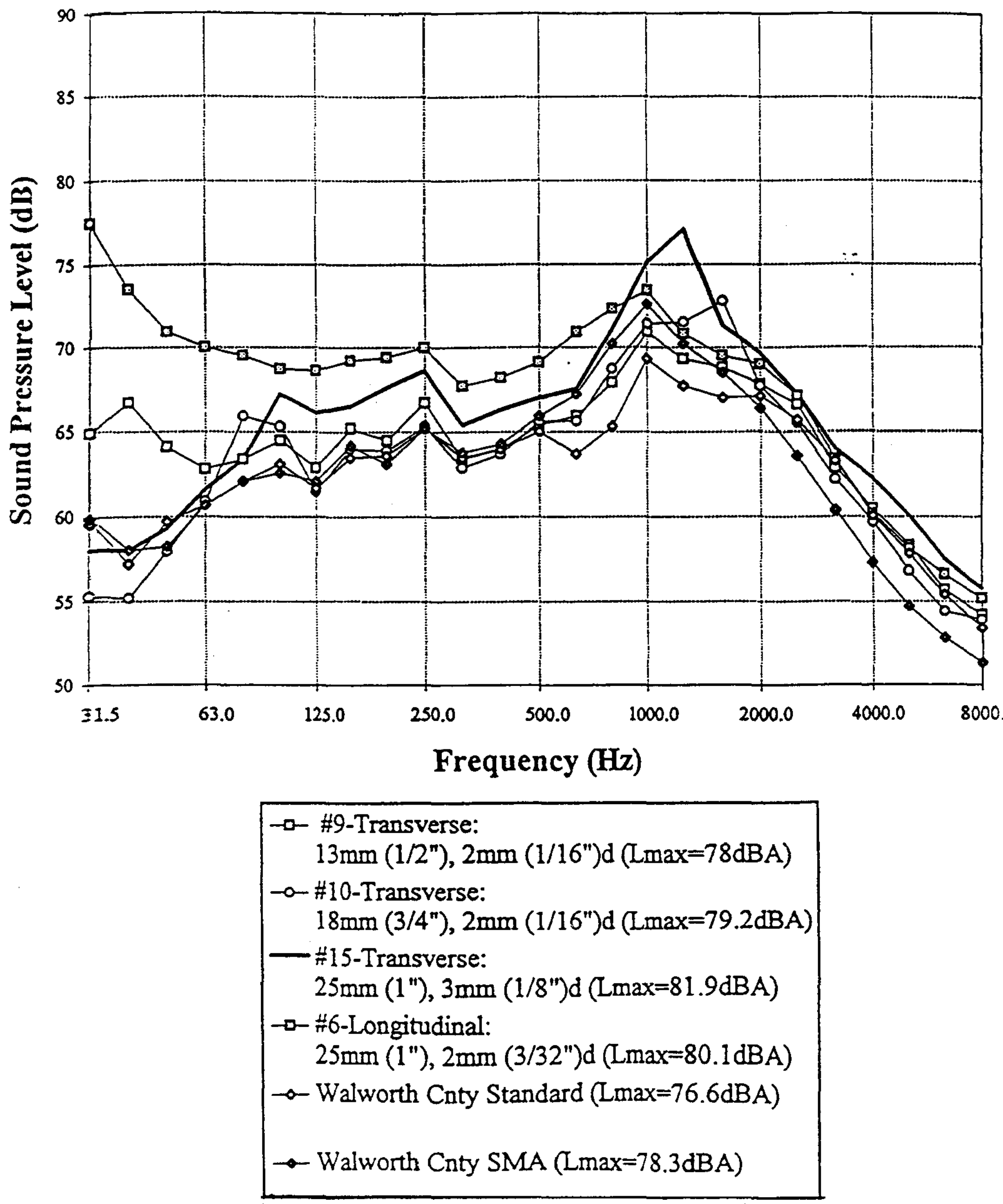


FIGURE 26 Exterior noise spectra for ACP and select PCCP, with passenger car at 96 kmph (60 mph) *(72)*. Passby method and all PCC pavement sections are less than two years old.

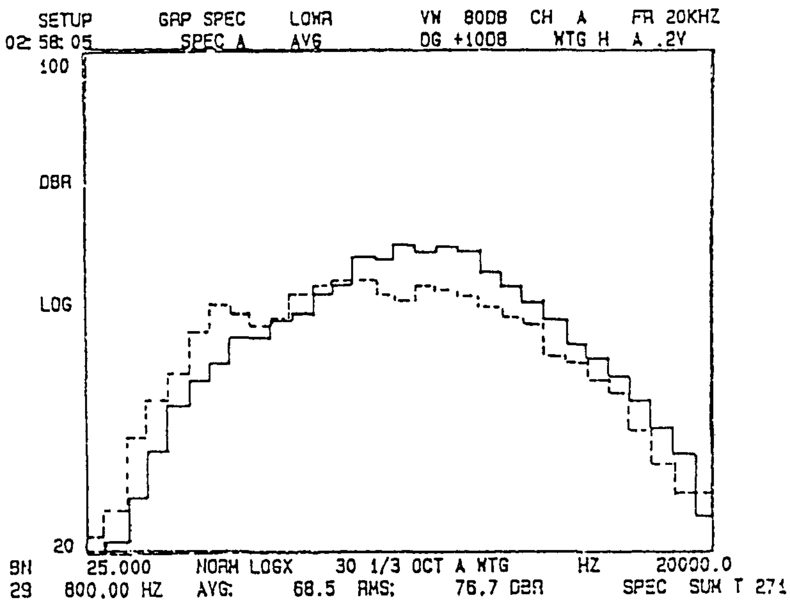
TABLE 13
VARIOUS PAVEMENT PARAMETERS OF TESTING DONE IN DENMARK *(74)*

Description	Age (years)	Texture Depth (mm)	Friction Coefficient (–)	Thickness (cm)	Void (%)
Open-graded asphaltic concrete	3	0.139	0.68–0.71	2.7	9.3
Open-graded asphaltic concrete	3	0.119	0.72–0.77	3.5	8.7
Open-graded asphaltic concrete	3	0.197	0.69–0.74	4.0	5.2
Dense asphaltic concrete with rubber	2	0.069	0.70–0.78	3.1	3.3
Open-graded asphaltic concrete	4	0.125	0.78–0.83	–	3.3
Dense asphaltic concrete	4	0.079	0.79–0.84	2.0	5.7
Special asphaltic concrete (mastiphalt) dense-graded	4	0.108	0.73–0.76	5.0	3.5
Rolled asphalt with chippings	4	0.104	0.80–0.84	–	–

TABLE 14

MEAN VALUES, STANDARD DEVIATION, AND NUMBER OF EVENTS FOR EACH VEHICLE CATEGORY AND TEST SECTION. L_{AE} FOR MIXED TRAFFIC AND THE UNCERTAINTY 0 *(73)*

	Vehicle Category													
	Passenger Cars			Vans			Lorries, 2 Axles			Lorries, > 2 Axles			Mixed Traffic	
Test Section	L_{AE} 80 km/t (dB)	s (dB)	n (–)	L_{AE} 80 km/t (dB)	s (dB)	n (–)	L_{AE} 80 km/t (dB)	s (dB)	n (–)	L_{AE} 80 km/t (dB)	s (dB)	n (–)	L_{AE} 80 km/t (dB)	σ (dB)
70 AB 12a	78.0	1.0	88	80.0	1.5	29	85.0	2.3	30	88.1	1.9	60	79.8	0.14
70 AB 8a	78.2	1.3	99	80.6	1.7	37	84.8	1.7	30	88.0	1.4	51	79.9	0.12
50 AB 8t	78.7	1.2	66	80.5	1.0	20	85.6	1.7	23	89.2	1.3	34	80.5	0.13
60 AB 12a	79.2	1.5	110	80.9	1.5	40	85.8	1.6	48	88.7	1.8	97	80.8	0.11
80 SMA	79.1	1.3	192	81.5	1.8	46	85.7	1.9	43	89.3	1.2	86	80.8	0.10
80 Rubtop 8	79.1	2.4	83	81.0	2.4	17	85.9	2.5	27	89.6	2.3	58	80.9	0.21
90 AB 16a	80.0	1.3	127	81.5	1.4	59	85.5	2.0	33	88.1	1.7	67	81.2	0.11
80 ABS	80.7	1.6	97	82.9	1.8	34	87.4	1.7	28	90.4	2.2	69	82.4	0.13



——— asphalt concrete LEQ 81.0 dB
76.4 dB(A)

- - - - open graded LEQ 84.4 dB
72.9 dB(A)

FIGURE 27 Noise spectra comparing dense graded and open graded asphalt using the coast-by method *(74)*.

that open-graded asphalt (maximum grain size of 8 or 12 mm (0.31 to 0.47 in.)) provided approximately a 1 dB(A) reduction when compared to dense asphaltic surfaces. One-third octave band measurements were also made from a recorded audio tape in the laboratory. It is apparent that the change in overall noise levels is directly related to a shift of the vehicle spectra by the various surface textures. As such, changes in texture result in changes of the source vibration and propagation affecting the overall sideline noise level.

Italy

Open-graded asphalt was compared to dense-graded asphalt surfaces and two other surface treatments (macro seal and spray grip) using coast-bys on Italian roadway surfaces *(75)*. It was reported that the porous surfaces resulted in "... a constant attenuation of noise of 3 dB(A) at all speeds." In addition, the asphalt surfaces that were "lightened with expanse clay" showed very similar results with speed to porous asphalt. It should be noted that the use of the expanse clay resulted in significant void areas and noise reduction was due to the same mechanisms as porous asphalt. The third-octave band measurements also showed interesting results. Figure 27 shows a comparison of the two spectra. The open-graded asphalt shows more low-frequency noise, but less noise in the mid to high frequency range. The increased low-frequency noise can be related to increased tire excitation due to increased macrotexture, while the decrease in high frequencies may be related to the reduced horn effect and reduced air pumping.

Germany

This same frequency effect was confirmed by Steven (*76*) from testing done in Germany. Figure 28 shows the results of this testing. Steven concluded that "The absorbing effect of drainage asphalt surfacing is essentially confined to the frequency range above 1 kHz. Since the largest energy components of vehicle noises lie in the 500 Hz to 4 kHz range, preconditions for a reduction in propulsion noise through absorption effects are evidently favorable." Steven also reported that when newly constructed, porous asphalt resulted in reductions of 2 to 3 dB(A) in built-up areas with average speeds of 40–60 kph (25–37 mph). As much as a 4 to 5 dB(A) reduction outside built-up areas with average speeds of 60–120 kph (37–75 mph) was reported by Steven.

Sweden and France

Studies in Sweden and France also confirm the work in Italy and Germany. Conclusions from testing done by Storeheier (*77*) using the passby method show that on an L_{EQ} basis, a noise level reduction of 3.5 to 4.5 dB(A) was obtained with porous asphalt. This was stated to occur at low traffic speeds. In France, Pipien's report (*78*) echoes that of Storeheier. In this case, drainage asphalt of a 4 cm (1.6 in.) thickness resulted in a noise reduction of 3 to 5 dB(A). Even greater reductions, up to 9 dB(A), were reported for "superthick" porous surfaces (52 cm (20.5 in.)) when compared to impervious surface coatings (all aggregate size types). However, absorption testing indicated that the absorption coefficient essentially became a maximum at 40 cm (15.75 in.). Less spray and interior noise were also noted for these thick surfaces.

Australia

It becomes apparent that open-graded (drainage) asphalt offers potential in noise control. This is stated in many guideline documents. The *Concrete Pavement Manual* of the Roads and Traffic Authority in New South Wales, Australia, states, "There is little doubt that the quietest surfacing used in Australia is open graded asphalt . . . " (*19*).

Maryland

Maryland pursued the benefit afforded by open-graded asphalt by constructing test sections in 1989 (*79*). The statistical passby method was used to compare open-graded asphalt to PCC pavement. Measurements were made 50 ft from the centerline of the outside lanes with the microphones at slightly different heights due to local topography. The test section for the open-graded asphalt sections had a final course of ¾-in. (19 mm) thick porous asphalt (sometimes called popcorn pavement). The asphalt surface was approximately 4½ years old when tested, while the PCC pavement, about 25 years old, was eroded and aggregate was readily visible. Both A-weighted L_{EQ} levels and third-octave band data were measured concurrently with the reference PCC pavement and as such, compared the same traffic. Sites 1 and 4 were along the open-graded asphalt surface while sites 2 and 3 were along the PCC pavement section. Sites 1 and 2 were on a slight downgrade. Sites 3 and 4 had a 1.5 to 2.0 percent upgrade. Speeds ranged from 55 to 65 mph (88 to 105 kph). The data show that for the 5-minute L_{EQ} periods, the open-graded asphalt resulted in sideline noise decreases ranging from 2.3 to 3.6 dB(A). Of

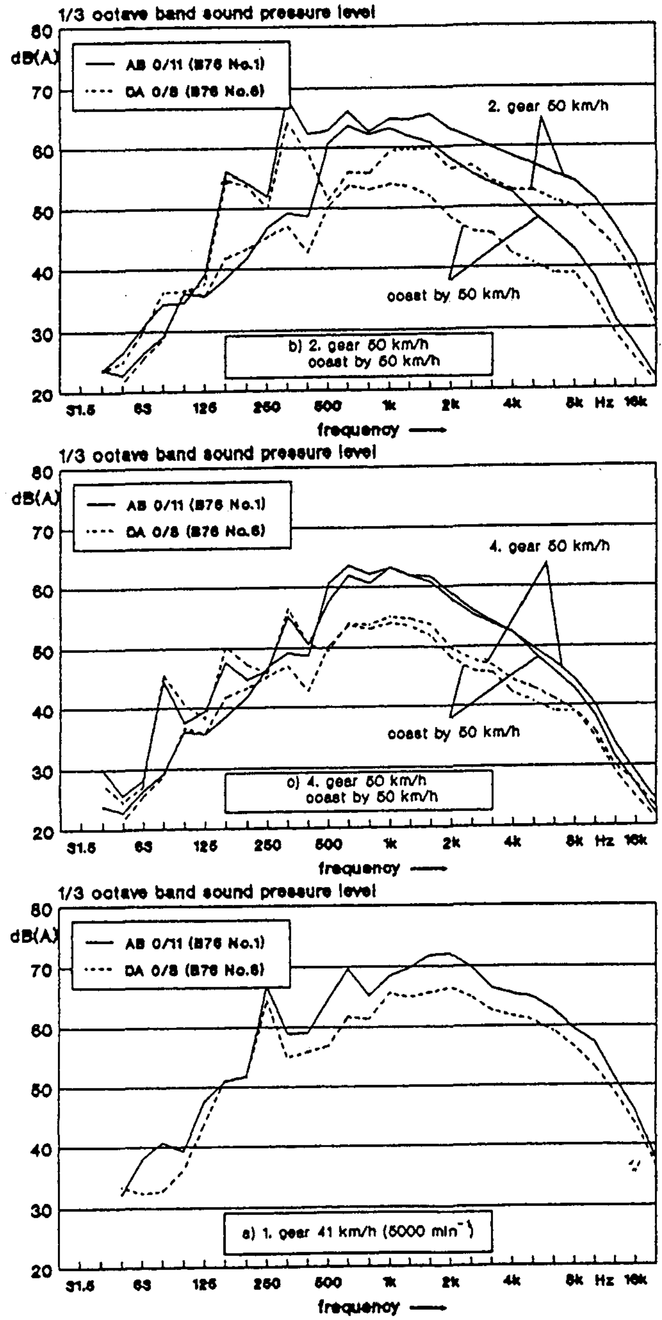


FIGURE 28 Frequency spectra of the noise emission of a BMW 520I with Michelin MXV tyres on open pored road surface (DA) and asphalt concrete (AB) at different operation conditions (*75*).

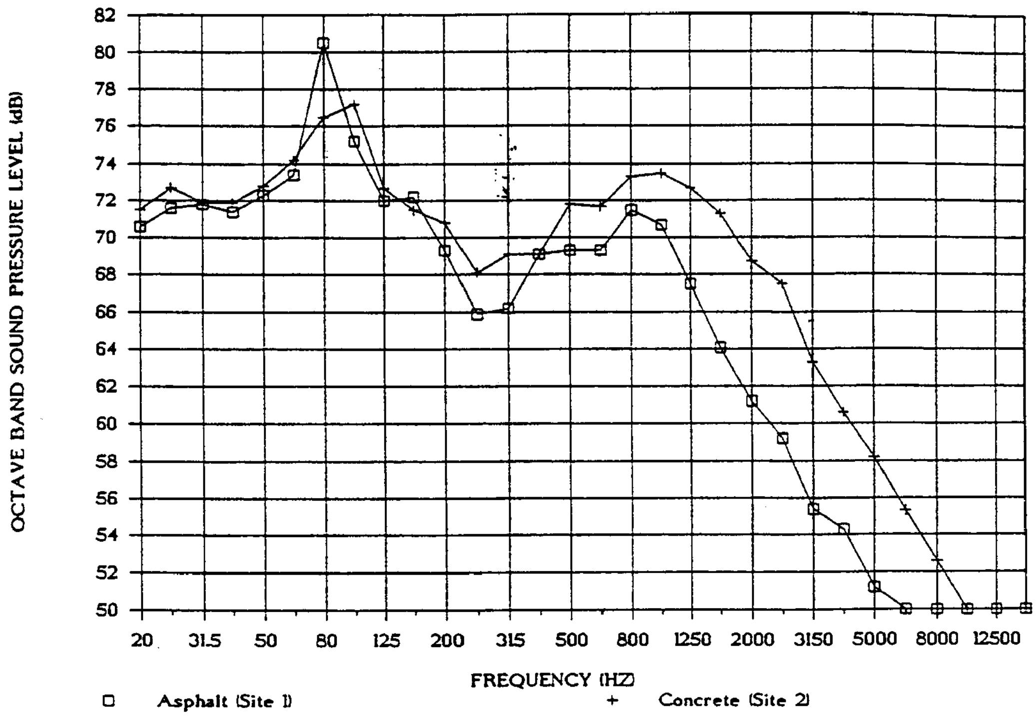


FIGURE 29 Comparison of the third-octave band spectra for sites 1 and 2 *(78).*

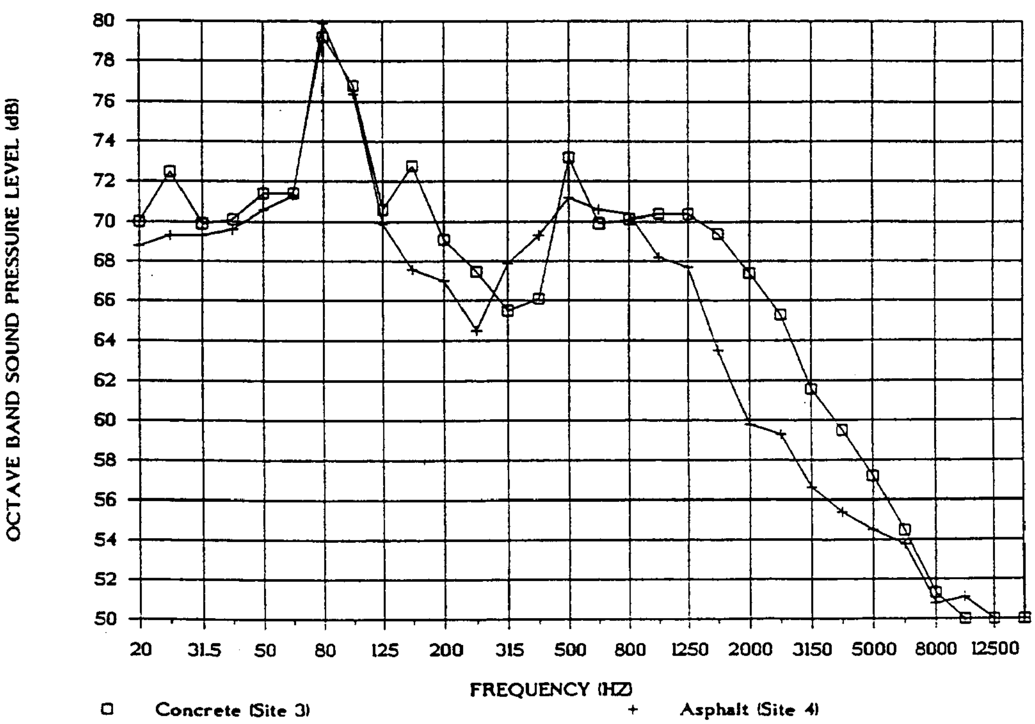


FIGURE 30 Comparison of the third-octave band spectra for sites 3 and 4 *(78).*

interest is the comparison of the one-third octave band data shown in Figures 29 and 30. Hourly average reductions only ranged from 2.8 to 3.1 dB(A) which is likely to have been caused by vehicle mix differences from the 5-minute samples. The noise reduction change due to varying truck percentage was also considered, but no evident correlation was found. When the frequency spectra are compared, significant reductions were noted in the higher frequency bands (1,000 to 5,000 Hz). The frequency comparison showed a reduction of 2 to 4 dB occurring at 1,000 Hz and 6 to 7 dB reductions in the 4,000 Hz range. While absolute values vary, the frequency trend reported in Europe was verified by this research.

Oregon

Porous asphalt was also evaluated by the Oregon Department of Transportation (*80*). The statistical passby method was used to compare older PCC pavement surfaces to new (0- to 1-year old) porous asphalt. Both A-weighted and one-third octave band data were taken. When compared to PCC pavement, the porous asphalt was 5.7 to 7.8 dB(A) less. This is a very substantial difference. It is also interesting to note that two mixes of porous asphalt also showed as much as 4.2 dB(A) difference when compared with each other. This points out the importance of material and construction techniques. In this case, the "F-mix" proved to be quieter than the "B-mix." Of note, and also discussed in this report, is that friction numbers were not always in the favor of the "F-mix", enforcing the idea that frictional characteristics and noise generation can be inversely influenced by the same texturing. The third-octave band data also showed that there were significant spectra differences between the two porous asphalt mixes. As with the other research, the quieter "F-mix" was generally in the mid to high frequency range (630 to 4,000 Hz).

Japan

The Public Works Research Institute in Ibaraki-ken, Japan, has been active in passby measurements. Reports from the institute indicate the same degree of reduced sideline sound levels. Tests done by Meiarashi et al., (*81*) allowed a comparison of dense-graded asphalt to four types of "drainage asphalt" at the Public Works Research Institute. These measurements, made 7.5 m from the running centerline, 1.2 m high, for a variety of speeds ranging from 40 to 120 kph (25 to 75 mph), used three different vehicles. Both power-by and coast-by passes were done for five pavement types. The tests show a very strong speed dependence as usual, but the noise from the various sources was also explored. Unfortunately, only one vehicle of each type was used for the controlled passby testing. For passenger cars with radial ribbed tires, it was reported that ". . . noise reductions for the drainage asphalt pavement of 0-5 dB were observed . . ." when compared to dense asphalt pavement. For light trucks, an overall noise reduction of 2 to 4 dB was reported and for heavy trucks, 2 to 5 dB. Through a series of tests, which included filling the tire grooves with urethane foam and using smooth tires, subsource contributions to the overall sound level were determined. Table 15 shows the noise reduction by subsource or subcomponent.

These results indicate that the pavement surface has a large effect on tire noise due to air pumping, as suspected. Of interest was the effect on the "driving machine" noise mechanism indicating absorption of the vehicle drive train noise as well. Spectral measurements were also done using the impedance tube method to determine the normal incident absorption coefficient. These measurements confirmed that the normal incident absorption coefficient increased with greater porosity and it was concluded that pavement porosity should be kept above 20 percent. This is interesting because the results are similar

TABLE 15

REDUCTIONS WHEN COMPARING DENSE AND DRAINAGE ASPHALT (units = dB) *(80)*

Noise Mechanism	Cars	Light Trucks	Heavy Trucks
Driving machine noise	3–7	2–5	1–5
Tread pattern air pumping noise	0–15	1–10	1–18
Tread pattern vibrational noise	1–12	-4–9	
Aerodynamic and other tire noise	-2–4	1–3	1–5

for porous concrete where a minimum of 25 percent porosity was reported to be required for noise control. During truck measurements, thickness of the layer also affected the absorption ability for some of the drainage asphalt types. It was concluded that the reduced noise level for the driving machine noise (vehicle noise) was due to the reduced multi-reflection between the road surface and underside of the vehicles due to increased absorption. A general model, based on the mean squared sound pressure, was derived based on this assumption. This equation, which represents the change in level when compared to dense-graded asphalt, was:

$$\delta L = 10 \log_{10} (\alpha_p / \alpha_d) \tag{7}$$

where

δL = change in sound pressure level for each frequency range (dB)
α_p, α_d = absorption coefficient for dense and drainage asphalt, respectively.

When all octave band data were combined to an overall noise level, this derived equation showed good agreement with measurements except for heavy trucks on one pavement type. Since aerodynamic noise was not modeled, this may have led to some error in comparison. However, this work does tend to support the research team's assumptions and has led to the final conclusion that for passenger cars below 80 kph (50 mph) the tire noise from air-pumping and tread vibration dominates. Above 100 kph (62 mph) other tire noise and aerodynamic noise dominates for both cars and light trucks. Light trucks were also reported to be dominated by driving machine noise below 80 kph (50 mph). For heavy trucks, driving machine, other tire noise, and aerodynamic noise all contribute below 80 kph (50 mph), while tire air pumping dominated above 100 kph (62 mph).

Meiarashi et al. (*82, 83*) quickly followed with two other reports on asphalt surfaces. Again dense asphalt was compared to porous asphalt. It was not clear if any of the test surfaces were the same as in the earlier report, although the surfaces again were at the test institute. The vehicles were similar to those in the first report but not the same. In these tests, conducted with the same methodology as before, Meiarashi's measurements show that, as the aggregate size becomes larger, the "power-by noise" (engine on) of the passenger car and heavy truck increased. When the dense asphalt was compared to the drainage asphalt, the reductions shown in Table 16 occurred for drainage asphalt. It can be concluded from Table 16 that the 10 mm (0.39 in.) aggregate outperformed the 13 mm (0.5 in.) aggregate. This echoes the opinion from Europe and Australia suggesting aggregate no larger than 8 to 10 mm (0.31 to 0.39 in.) should be used.

TABLE 16

REDUCTIONS DUE TO DRAINAGE ASPHALT *(82)*

Vehicle Type	Reduction (dB) (13 mm aggregate)	Reduction (dB) (10 mm aggregate)
Passenger car	1–7	4–9
Light truck	3–4	3–5
Heavy truck	4–6	5–6

Additional noise reduction was reported to occur with increased drainage asphalt pavement thickness similar to results from Europe. However, this effect was stated to have much less of an impact than aggregate size.

A porous elastic road surface was also evaluated *(83)*. It was reported that this pavement surface type had good potential but several safety and installation problems still exist and must be overcome before it is implemented.

Other asphaltic surfaces, such as the porous elastic road surface in Japan, continue to be evaluated. One such surface providing encouraging results is stone mastic asphalt.

STONE MASTIC ASPHALT

Aggregates are coated with a mastic that contains sand, filler, and asphalt cement, forming stone mastic asphaltic concrete. This is the most often used asphalt surface in Sweden. A European technology (applied in France, Belgium, Sweden, United Kingdom) has been used in New Jersey, Pennsylvania, Texas, Mississippi, and Alabama *(74)*. Extensive work has also been done in Maryland. This proprietary open-graded hot mix asphalt overlay is applied as a thin friction course approximately 13 mm to 16 mm (1/2 to 5/8 in.) thick. Gap-graded coarse aggregates with a large proportion of single size crushed aggregate are used.

New Jersey

The New Jersey Department of Transportation evaluated this overlay type in 1994 (*84*). Two sections of the Garden State Parkway were compared near where residents along the corridor have complained about the noise levels reaching their homes. One section was initially constructed of PCC pavement slabs with 15-ft center joints and the second section was initially paved with bituminous, dense-graded asphalt. Both sections were measured simultaneously during morning and afternoon timeframes for noise levels before and after the resurfacing. Average reductions of the side-line L_{eq} measurements for the resurfaced bituminous concrete corridor section using the passby method were 1.4 and 2.1 dB(A) during the morning and afternoon rush hours, respectively. Vehicle speeds were high, in the 55 to 65 mph (88 to 105 kph) range. The section of portland cement concrete with asphalt overlay produced noise reduction levels that exhibited a more noticeable change of 3.2 dB(A) in the morning and 4.1 dB(A) in the afternoon. The graphing of the data (see Figures 31 and 32) shows variations during the day as the vehicle mix changed. The reductions achieved with the use of the overlay method on the portland cement pavement shows promise. However, the reduction reported is only slightly more than if just dense-graded asphalt had been used.

Maryland

Another application of stone mastic asphalt was done in Maryland and compared to dense-graded asphalt (*85*). This study used the statistical passby method and by using concurrent measurements along the same roadway, similar traffic. The work was not only undertaken for noise reduction but for reported increased durability of the stone mastic surface when compared to open-graded asphalt. Both A-weighted L_{eq} and one-third octave band data were reported. Also, in some cases during low traffic volumes, individual passbys were measured. The average L_{eq} value was found to be approximately 1 dB(A) lower for the stone mastic asphalt, which is very comparable to the results reported from New Jersey. The octave band data showed that a reduction in the higher frequencies (> 1 kHz) occurred from 1 to 5.5 dB. However, a slight increase ranging from 0.5 to 1.5 dB occurred in lower frequencies (< 500 Hz). Figure 33 shows a comparison of the pavement surfaces based on the measurements. It is reported that the slight increase in the lower frequencies was thought to occur because of the increased macrotexture. This is as expected based on other studies. Polcak went on to compare the stone mastic measurements to open-graded asphalt (previously discussed). The third-octave band comparison is shown in Figure 34. The spectra were very similar for the stone mastic and porous asphalt. Both were reported to have very similar sound levels and to be less noisy than PCC pavement.

Wisconsin

Wisconsin's experiences were very similar to those of Maryland and New Jersey (*40*). Again, the passby method was used for both free-flowing traffic and individual passbys. Stone mastic pavement was reported to be approximately 1 dB(A) quieter for the sideline measurements when compared to standard asphalt. One-third octave band data indicated a shift in the higher frequency range (> 1,600 Hz), again similar to the results in Maryland. The limited noise reduction provided by the stone mastic surface in these tests would tend to indicate that research should continue on other asphaltic surfaces.

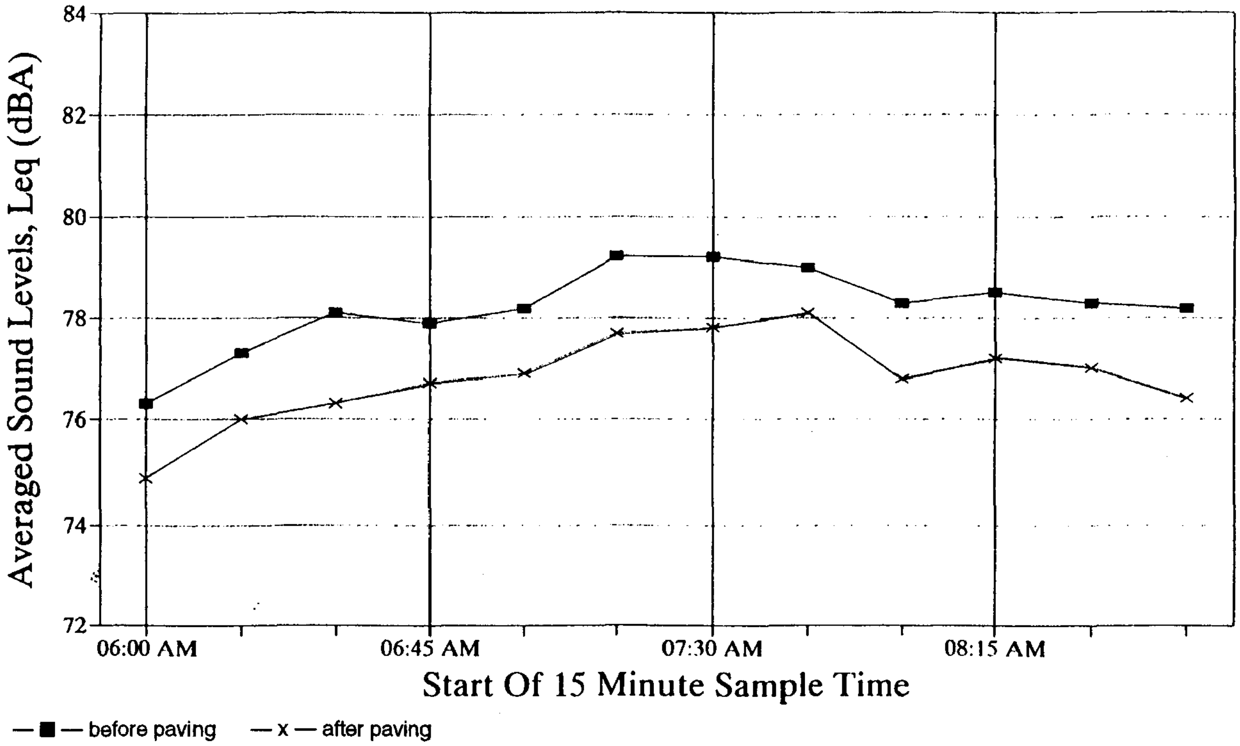


FIGURE 31 Measured sound levels before and after milepost 80.69—northbound side—AM *(83)*. Passby method at speeds of 55 to 65 mph (88 to 105 kph). A proprietary open-graded asphalt overlay is applied as a friction course approximately 1/2- to 5/8-in. thick (13 to 16 mm).

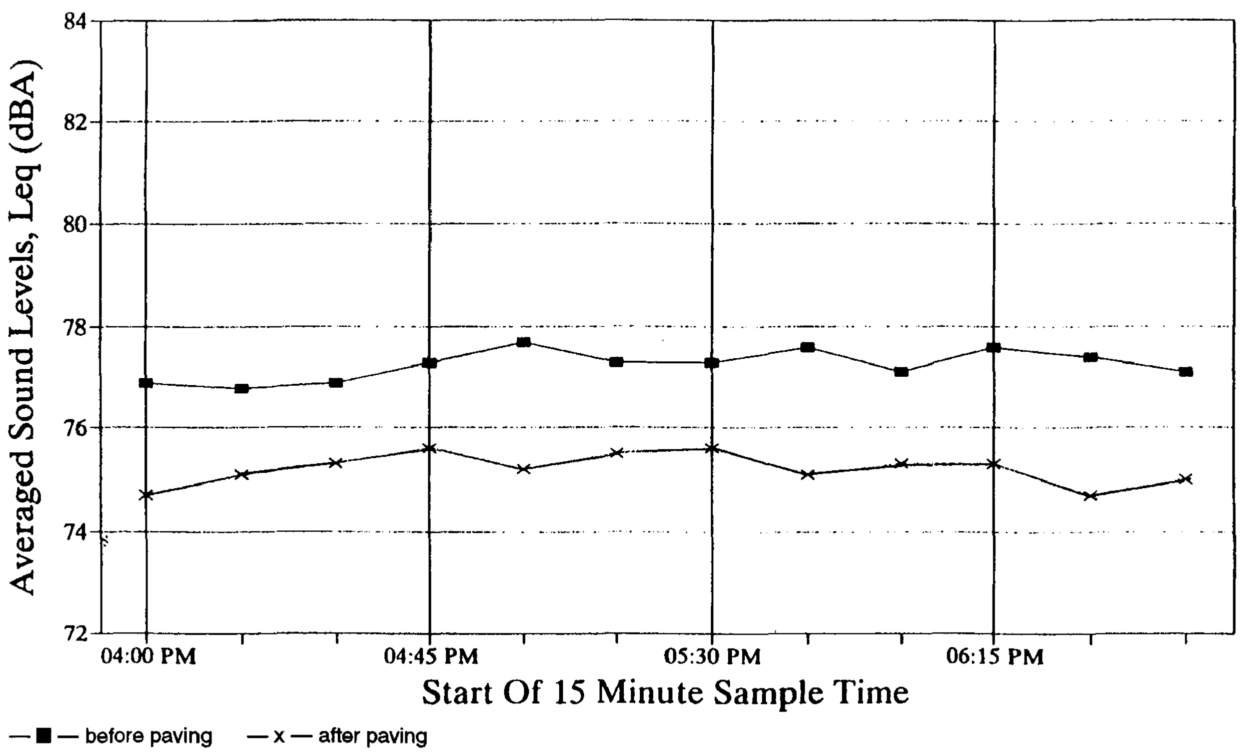


FIGURE 32 Measured sound levels before and after milepost 80.69—northbound side—PM *(83)*. Passby method at speeds of 55 to 65 mph (88 to 105 kph). A proprietary open-graded asphalt overlay is applied as a friction course approximately 1/2- to 5/8-in. thick (13 to 16 mm).

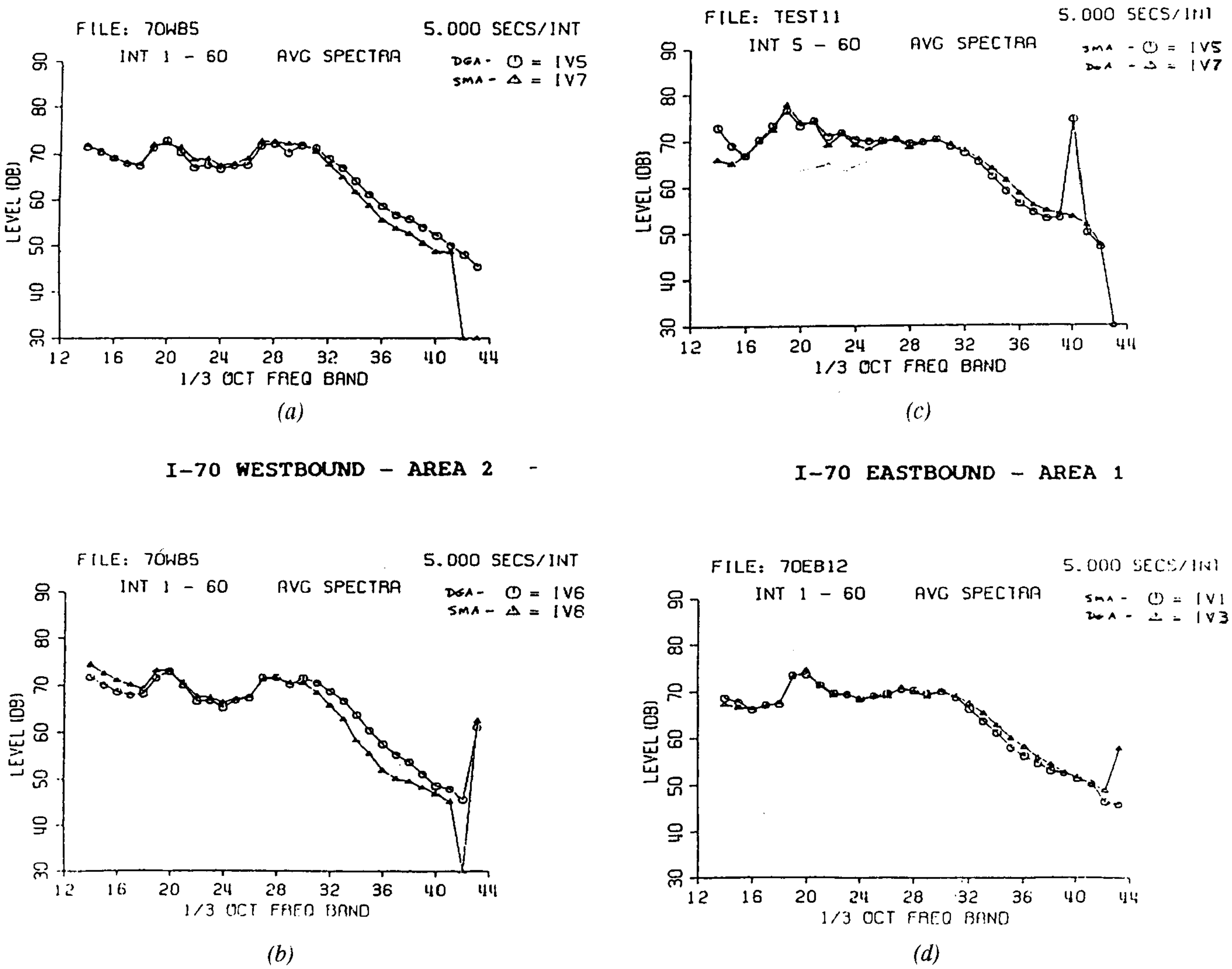


FIGURE 33 Comparison of average frequency spectra for stone mastic asphalt (SMA) and dense-graded asphalt *(84)*.

OTHER ASPHALT TYPES

Kansas

The Kansas Department of Transportation has done research for rubberized asphalt pavement surfacing (*86*). Asphalt rubber pavement is a bituminous mix consisting of blended aggregates and rubberized asphalt. Open-graded asphalt rubber pavement is a bituminous mix consisting of rubberized asphalt and blended aggregates having a high level of voids in the mineral aggregate. Four project test sections were developed and compared to dense-graded asphalt. Results were published for three of these test sections. Table 17 lists the pertinent information about these three test sections. The rubberized asphalt cement contained 16 to 18 percent dissolved crumb rubber. Controlled passby measurements were done under controlled speed conditions at 55 mph. Maximum noise levels of the single vehicle passbys were recorded. The average differences for the tests are shown in Table 18.

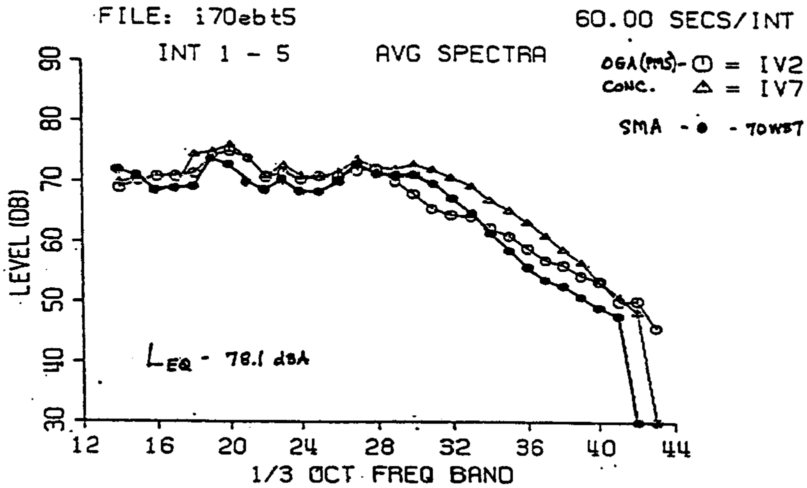
It is obvious from these measurements that the open-graded asphalt always showed a decrease in noise levels. However, when the asphalt rubber pavement was compared to the asphalt surface, both reductions and increases in noise levels occurred. No clear trend emerged.

REPORTED OVERALL CONCLUSIONS REGARDING ASPHALT PAVEMENTS

Before summing up the research, it is interesting to take a look at projects that ranked pavement noise reductions by surface type.

United States

The very large undertaking of Volpe Laboratories resulted in numerous statistical passby measurements in multiple states under well-controlled conditions (*14*). The combined data base for all states shows that for automobiles at 88.5 kph (55 mph) PCC pavements are about 3 dB(A) louder than dense-graded asphalt. Open-graded asphalt is approximately



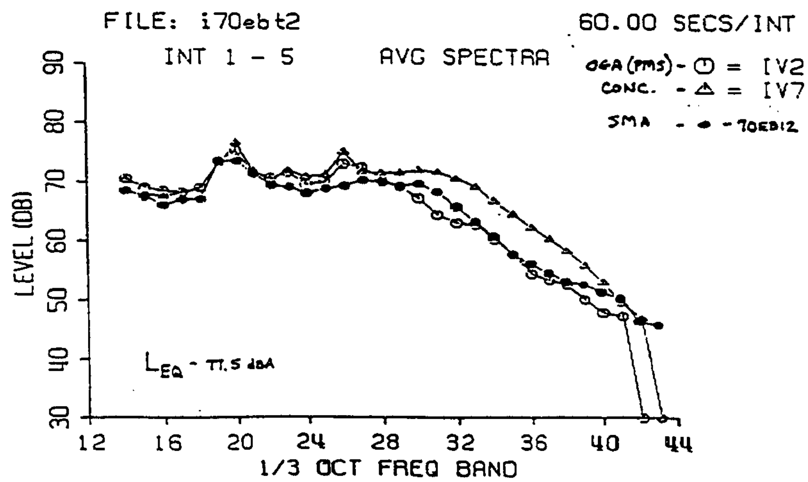


FIGURE 34 Comparison of average frequency spectra of stone mastic asphalt (SMA) and plant mix seal (PMS) and concrete pavements *(84)*.

TABLE 17

COMPARISON OF ASPHALT RUBBER BINDER TO ASPHALT ONLY *(86)*

Section	Year Constructed	Asphalt Rubber Section (%)	Asphalt Only Section (%)
Spec. (80 P-264-R2)			
US-75 Project Osage County	1990	6.3[1]	5.5[2]
Spec. (80 P-264-R2)			
K-2 Project Sedgwick County	1990	7.4[3]	5.75[4]
Spec. (1990 Stand spec.)	1991	6.9[3]	5.25[5]
US-24 Project Jefferson County	(open graded)	8.9[3]	5.25[5]

[1]The asphalt rubber binder is 84 percent VAC-5 and 16 percent reacted crumb rubber.
[2]The asphalt only binder is 100 percent VAC-10.
[3]The asphalt rubber binder is 82 percent VAC-5 and 18 percent reacted crumb rubber.
[4]The asphalt only binder is 100 percent VAC-20.
[5]The asphalt only binder is 100 percent VAC-5.

1.5 dB(A) more quiet than dense-graded asphalt. For medium trucks at the same speed, the PCC pavements are about 2 dB(A) louder and open-graded asphalt about 0.5 dB(A) quieter than dense-graded asphalt. Heavy truck passby noise tends to be about 1 dB(A) less for dense-graded asphalt when compared to PCC pavements and a 2 dB(A) decrease occurs for open-graded asphalt when compared to PCC pavements. These trends are similar to other locations. Important here is that the data base was quite extensive and pavements of varying age were included.

TABLE 18

COMPARATIVE RESULTS [dB(A)] *(86)*

Comparison	Vehicle Type	Cruise	Accelerate	Rolling
Asphalt rubber to asphalt only	Car	-2.3/3.9/-2.8	-2.4/3.5/-2.1	-3.3/3.6/-2.2
	Medium truck	2.5	3.3	3.1
	Truck	-1.5/-2.0	-1.7/-2.6	-1.5/-3.4
	Heavy truck	0.0	-0.9	0.3
Open graded to asphalt only	Car	-1.3	-1.0	0.0
	Medium truck	-3.0	-2.7	-2.8
	Heavy truck	0.4	-1.6	-2.4

TABLE 19

ROLLING NOISE (130 km/h)*(17)*

Rolling Noise (120 km/h)		
	dB(A)	Test Section
Porous asphalt (new)	Reference value	
Porous asphalt (after 7 years)	+ 2.9	
Noise reducing concrete (0-20 mm) with super smoother	+ 3.3	Hasselt
Dense asphalt	+ 4.1	
Concrete after diamond grinding	+ 4.2	
Noise reducing concrete (0-20 mm) without super smoother	+ 4.3	Beringen
Concrete after carbide grinding	+ 5.1	
Exposed aggregate concrete (0-32 mm)	+ 6.2	Beringen
Concrete slabs (old pavement)	+ 7.5	
Transverse grooving: values till	+10.5	

Germany

In Germany, conclusions have been made about various pavement surfaces and a correction value for noise, called D_{StrO}, has been developed (*87*). This correction value is the difference in sideline noise referenced to a particular construction technique. For speeds greater than 60 kph (37 mph) these values are:

+2 dB(A)	traditionally concrete pavements, made without longitudinal smoother and textured with steel broom transversal sweep
± 0 dB(A)	asphalt pavements graded > 0/11
- 2 dB(A)	concrete pavements made with an additional longitudinal smoother and textured with jute longitudinal sweep, and asphalt pavements graded < = 0/11, without chipping
- 4 dB(A)	porous asphalt layer graded 0/11
- 5 dB(A)	porous asphalt layer graded 0/8.

It is apparent that porous asphalt is considered the quietest pavement while transverse tining of PCC pavements results in greater noise levels.

Belgium

Results from Belgium show similar conclusions (*88*). Table 19 shows how rolling noise has been related. Again, porous asphalt is considered to be the most quiet pavement and transverse tining of PCC pavements the loudest.

Australia

These results also seem to be the same for work done in Australia (*89*). Pavement noise rankings taken from sideline measurements are shown in Table 20. Again, open-graded asphalt is listed as the quietest pavement. No clear trend was observed regarding the impacts of different surface textures of PCC pavements. Samuels also reported comparisons in 1996 that were discussed earlier. In these findings, methods to quiet the PCC pavement, resulting in a smaller difference, were reported. Perhaps a better summation was presented in September of 1996 by Samuels (*90*). Figure 35 shows the overall trends for noise data collected between 1992 and 1994 using the controlled passby test with test vehicles. Twenty-four sections of pavement were measured and the pavement surface details are shown in Table 21. All surfaces were reported to have adequate surface friction. Samuels ranked pavement surfaces, as shown in Table 22; open-graded asphalt was the quietest pavement surface for cars, but for trucks, exposed aggregate was quieter.

The Concrete Pavement Manual from New South Wales lists the following typical sideline values in dB(A) for free-flowing traffic, when compared to dense-graded asphalt (*19*):

Open-graded asphalt	-6.0
Hessian dragged concrete	-2.7
Dense-graded asphalt	0.0
Tined concrete	+0.3
Sprayed seal, 14 mm	+2.0

TABLE 20
STATISTICAL PASSBY NOISE LEVELS AT 80 km/h *(88)*

Vehicle Type	Parameter	Site 9	Site 10	Site 12
Car	Number of samples	50	47	50
	Mean noise level [dB(A)]	81.6	79.0	84.1
	Standard deviation of noise level [dB(A)]	1.7	1.8	2.0
Truck	Number of samples	30	33	30
	Mean noise level [dB(A)]	90.0	89.3	93.0
	Standard deviation of noise level [dB(A)]	4.3	2.9	2.7
	Road surface type	DGAC	OGAC	PCC 3/13/LH

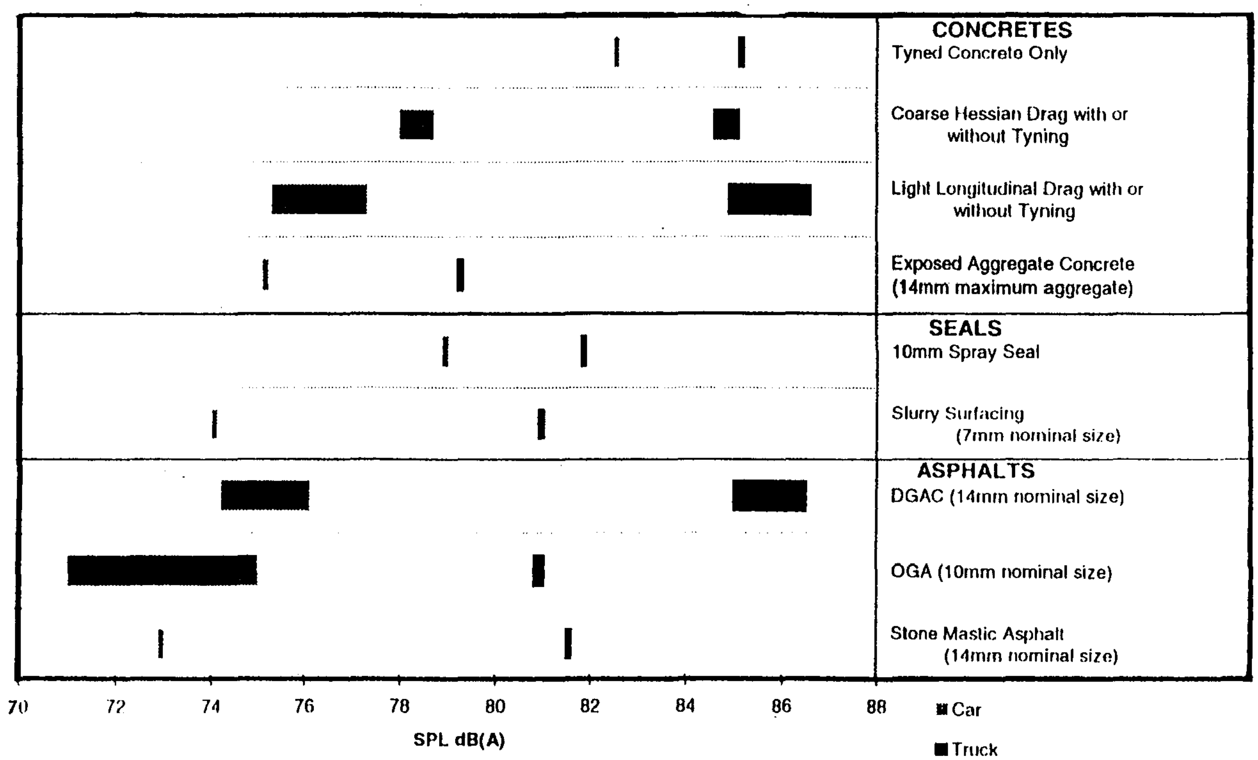


FIGURE 35 Road noise variability *(89)*.

Europe

A good summary was provided by the OECD document (*17*). This summary, shown in Figure 36, restates what the researchers have agreed on. Porous asphalt is the quieter pavement type. Concrete (PCC) pavement is generally the greatest noise producer. Various textures can cause significant changes in the sound level generated. Surfacing is summed in Table 23. Again, this reflects the research reported here.

CONCLUSIONS ON ASPHALTIC PAVEMENTS

Asphaltic pavements are, in general, quieter than PCC pavements. This finding seems quite clear. The surface aggregate size is important and should be kept below 10 mm if possible. Larger chippings have been employed in the surface layers of PCC pavements than in asphaltic surfaces. The increased megatexture generates more low-frequency noise from rolling vehicles due to increased tire vibration. The porous surfaces tend to reduce noise in the higher frequency range, resulting in overall noise reductions.

Open-graded asphalt is reported to be the quietest pavement, based on worldwide results. It is important that the porosity stay high, greater than 20 percent. This is similar to porous concrete requirements.

Other types of asphalt also show benefits for noise reduction. Stone mastic surfaces were reported to reduce the noise about one dB(A) when compared to dense-graded asphalt by several studies. More work is needed in the surface finishing and techniques. New processes, such as rubberized asphalt, still need considerable developmental effort. Tests conducted

TABLE 21

SITE SPECIFICATIONS *(90)*

Site	Year of Test	Location (State)	Surface Type
A	1992, 1994	NSW	PCC: 3/13/CH
B	1992, 1994	NSW	PCC: 3/26/CH
C	1992, 1994	NSW	PCC: CH
D	1993, 1994	NSW	PCC: 3/26/LH
E	1993, 1994	NSW	PCC: 3/26/A19
F	1993, 1994	NSW	PCC: 3/13/A19
G	1992, 1993, 1994	NSW	PCC: 3/13/LH
H	1992, 1994	NSW	PCC: 2/13/LH
I	1992, 1994	NSW	PCC: LH
J	1992, 1994	NSW	PCC: 3/13
K	1993, 1994	NSW	PCC: A19
L	1993, 1994	NSW	PCC: 3/13/LH
M	1993, 1994	NSW	PCC: 3/26/LH
N	1993, 1994	NSW	PCC: 3/26/A10
O	1993, 1994	NSW	PCC: 3/13/A10
P	1993, 1994	NSW	DGAC
Q	1992, 1993, 1994	NSW	OGAC
R	1994	VIC	PCC: EA
S	1994	VIC	DGAC
T	1994	VIC	OGAC
U	1994	VIC	SMA
V	1994	VIC	BSS
W	1994	VIC	SAMS
X	1994	VIC	PCC: TT

Legend: PCC) Portland Cement Concrete; CH) Coarse Hessian Drag; LH) Light Hessian Drag; A19) 19 mm fibre Astroturf Drag; A10) 10 mm fibre Astroturf Drag; 2/13) 2 mm tyne width at 13 mm spacing; 3/13) 3 mm tyne width at 13 mm spacing; 3/26) 3 mm tyne width at 26 mm spacing; DGAC) Dense Graded Asphaltic Concrete, nominal size 14 mm; OGAC) Open Graded Asphalt nominal size 10 mm aggregate; EA) Exposed Aggregate, max size 14 mm aggregate; SMA) Stone Mastic Asphaltic Concrete, nominal size 14 mm aggregate; BSS) Bituminous Slurry Surfacing, nominal size 7 mm aggregate;SAMS) SAM Seal (Sprayed Seal), 10 mm aggregate; and TT) Transversely Tyned.

TABLE 22

PAVEMENT NOISE RANKINGS *(90)*

	Noise Level Variation [dB(A)]		
Surface Type	Traffic Noise	Car	Truck
14 mm chip seal	+4	+4.0	+4.0
PCC: Tyned and dragged	0 to 3	+1.0 to +3.5	-1.0 to +1.0
Cold overlay	+2	+2.0	+2.0
DGAC	0	0	0
PCC: Exposed aggregate	-3	-0.1	-6.7
OGA	-4	-0.2 to -4.2	-4.9

in Japan and in the United States showed no clear trends. Noise reductions were generally small.

In the final analysis, asphaltic surfaces are generally less noisy and open-graded asphalt is the quietest pavement in common use.

OTHER CONSIDERATIONS

Weather

Ambient temperature is also an important consideration for tire/pavement noise generation. In fact, it has been reported that surface type and temperature are the most important parameters influencing coast-by levels (*91*). Figure 37 shows this trend. As temperature increases, so does the sideline noise level. This is an unfortunate situation since it corresponds to times of open windows at residences.

Another impact on sideline noise levels occurs due to atmospheric pressure as shown in Figure 38 (*91*). Other weather impacts include wind speed and temperature profile that can cause refraction of the sound waves, in some cases greatly increasing the sideline noise levels.

Block Pavement

The aesthetically pleasing designs and multiple format possibilities of reusable paving blocks found in many cities throughout Europe provided the incentive to initiate a one-year

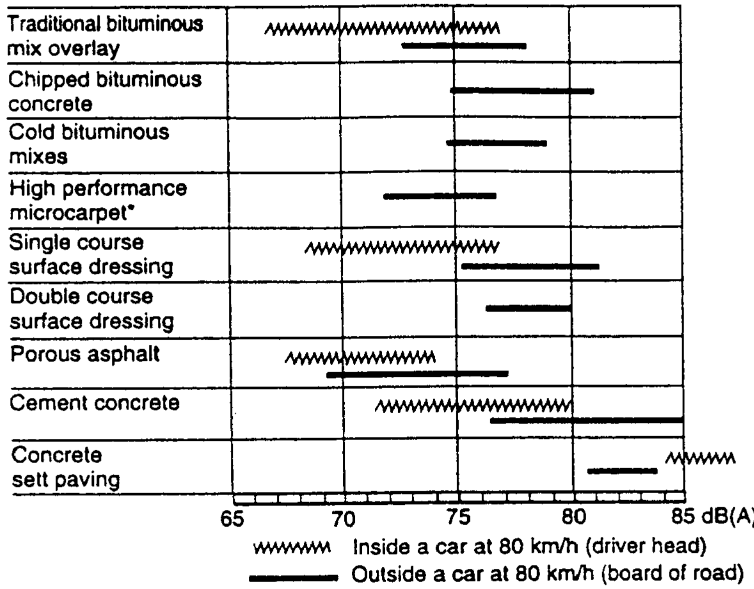


FIGURE 36 Typical range of tyre/road noise levels according to the type of road surface *(17)*.

TABLE 23

SURFACINGS WITH LOW TYRE/ROAD NOISE *(17)*

Type of structure ans anti-noise effectes	Anti-noise elements	Additional functions	Country	Sound absorption coefficient (α) in different frequency bands (Hz) <700 ; 700-1250 ; >1250	Construction problems	Management observations	Notes
A. Microtextured surfacing Traditional (black/white)) 2/3 cm (max) Low S1, excitation of vibration	• Fine and ultrafine bituminous wearing course (e.g. micro-carpets) • Surface treatment (e.g. griproad, micro-griproad and spraygrip) • Exposed aggregate concrete[1]	High skid resistance	D, F, UK, I, S, A	0 0.1 0.1 0 0.2 0.35	To be laid on smooth pre-existing pavement	• Complete information lacking on durability and more information needed on acoustic performance • Limited costs if microcarpets are layed at regular frequency	• Good for use on urban streets and especially on ring roads and by-passes • Sound absorption characteristics can be obtained using porous aggregates
B. Macroporous surfacing ; medium thickness Traditional 3/8 cm Low S2 (sound absorbent)	• Drainage asphalt as wearing course (porosity ranging from 20 to 28%) mixed with normal bitumen or preferably polymer modified bitumen	High permeability which can be maintained also on high speed roads	All European countries	Good absorption at medium frequencies (500-1200 Hz) depending on thickness 0.2 0.45 0.60	To be constructed with impervious and regular subcourses	• Acoustical efficiency over time if porosity does not deteriorate rapidly • Average costs • Good drainability with residual voids > 20% • To maintain permeability, cleaning operations are sometimes required (preventive or curative unclogging) • During winter operations special treatment and de-icing salts are required	• Widespread use on high speed roads • Acoustic effects can be enhanced with use of barriers • Used in road sections with cross profile inversions
C. Macroporous medium and high thickness up to 50 cm Traditional Low S2 (sound absorbent)	• Bituminous or cement concrete in one or several courses (porosity increases with depth)	Good performance in tyre noise reduction, but generally used when water disposal effect is sought	D, F	0.2 0.5 0.65 (15 cm) 0.2 0.5 0.65 (50 cm)	Need of drainage system at bottom (near the subbase)	• Valid over time • High initial costs • Need complex system of deep drainage	• Used when strongly justified by need to reduce size of drainage system (due to high costs)
D. Euphonic 4/6 cm Concrete slab Low S2 (sound absorbent)	• Porous asphalt and continuously reinforced concrete with resonators	• High durability • High evenness • Conceptually efficient over entire frequency range • Can substitute barriers and covers in urban areas	I	0.60 0.45 0.45	Need of drainage system at bottom (near the subbase)	• High initial costs	• Experimental stage • Conceptually very good for heavy freight traffic

[1] Low noise cement concrete pavements can be obtained using small size aggregates in the surface layer and by simple construction techniques, and also with specific treatments such as griding or covering with epoxy resin surface dressings, or a new course of exposed aggregate concrete.

Remark: For B, C, D types, it is possible to intervene on S1 noise level

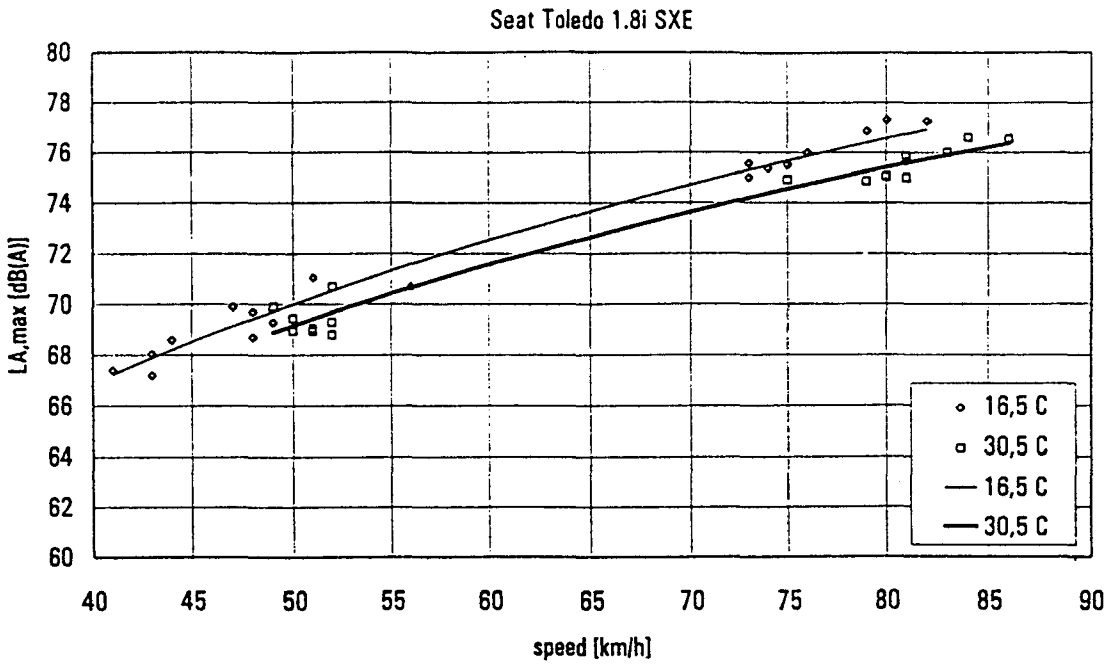


FIGURE 37 Coast-by level as a function of speed with air temperature as parameter *(90).*

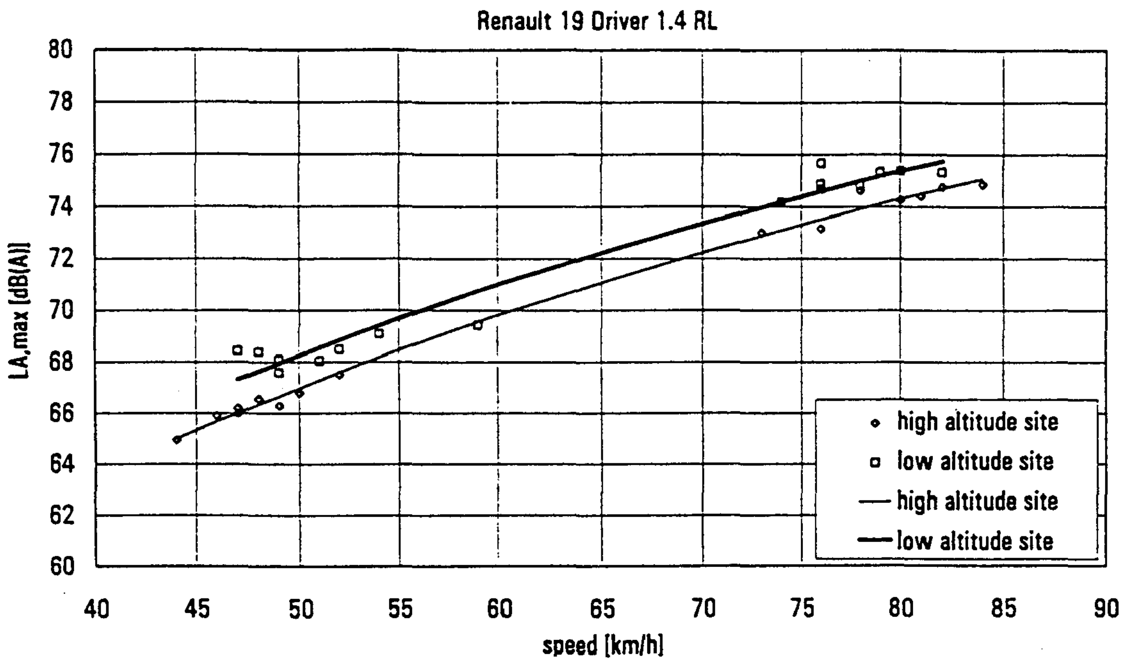


FIGURE 38 Coast-by level as a function of speed with road surface as parameter (normalized to 20°C) *(90).*

Austrian pilot test of 12 different blocks (*92*). This test program evaluated the noise reducing qualities of the blocks, compared to an asphalt concrete road. Results of the first test, in which the sound intensity level was recorded with a microphone and digital tape recorder 7 m (23 ft.) from the side of the blocks, revealed that only three of the blocks tested produced noise levels higher than an asphalt concrete road found near the test site. Since the original asphalt test site was consistently producing values higher than the new paving block sites, the research group decided to test their data against a new asphalt site. This comparison showed that five paving block types still produced noise levels lower than the new asphalt site. This is shown in Figure 39. To verify the results, the standard Austrian measurement procedure, a vehicle noise

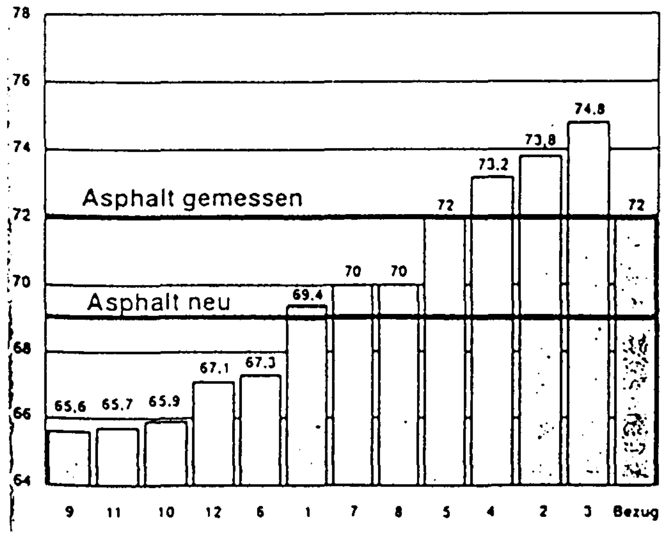


FIGURE 39 Result of different concrete paviours *(91)*. Sound measurement distance: 7 m (23 ft).

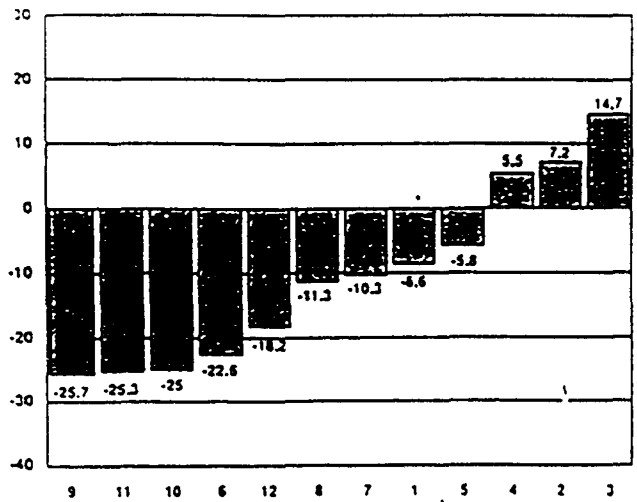


FIGURE 40 Noise level in relation to asphalt *(91)*. Sound measurement distance: 7 m (23 ft).

measurement trailer, was used. Results echoed those of the previous test where only three paving blocks produced noise levels higher than the asphalt test area near the block test site, as shown in Figure 40. "This pilot test confirmed that concrete blocks with certain characteristics are just as suitable for low-noise traffic use in inner city areas as asphalt, or even ultra-low-noise asphalt, in terms of noise production. In addition to being more attractive and cheaper to maintain."

Germany has also experimented with concrete block pavements *(17)*. These controlled passby measurements compared the blocks to a reference pavement, which was an asphalt surface with a maximum grain size of 11 mm (0.4 in.) and with no spreading of chippings. The noise level for this reference pavement was reported to be 61.8 dB(A) ± 1.5 at 30 kph (19 mph) and 68.0 dB(A) ± 1.5 at 50 kph (31 mph).

Twelve other concrete block patterns were also evaluated and are described in Table 24. The data were measured at 30 and 50 kph (19 and 31 mph). The results of the passby measurements are shown in Figure 41 and Figure 42. Notably, seven of the 12 block patterns were reported to be ". . . as low as with asphalt 0/11." They concluded that smooth, plain surfaces (microtexture) offer the least noise generation. This lead to the result that larger block sizes are better with regard to noise reduction because of a smaller proportion of joints.

Studded Tires

Regardless of pavement type, studded tires significantly affect the noise generation mechanism. Figure 43 as reported by Chalupnik and Anderson *(30)* indicates this graphically. Regardless of surface type, studded tires will generate more

TABLE 24
TEST PAVEMENTS *(17)*

No.	Shape and Size		Edge	Surface	Laying Pattern
1	Rectangle	16/24/8 cm	Without chamfer	Smooth	Diagonally laid
2	Rectangle	16/24/8 cm	With chamfer 3/3	Smooth	Diagonally laid
3	Rectangle	16/24/8 cm	Without chamfer	Smooth	Stretcher bond
4	Rectangle	16/24/8 cm	With chamfer 3/3	Smooth	Stretcher bond
5	Rectangle	16/24/8 cm	Without chamfer	Finely roughened (1-3 mm), uneven, lightly scrubbed	Stretcher bond
6	Rectangle	16/24/8 cm	With chamfer 3/5	Roughened (2-5 mm), finely scrubbed	Stretcher bond
7	Rectangle	16/24/8 cm	Without chamfer	Sand blasted	Stretcher bond
8	Rectangle	9.5/19,5/8 cm	With chamfer 3/3	Smooth	Stretcher bond
9	Hexagonal	20[1]/8 cm	With chamfer 2/3	Smooth	Diagonally laid[2]
10	Double T interlocking	16,5/20/8 cm	With chamfer	Smooth	Stretcher bond
11	Around interlocking	11,2/22,5/8	With chamfer 4/6	Smooth	Stretcher bond
12	Rectangle	16/24/8 cm	Rumbled corners and edges	Smooth	Stretcher bond

[1]Measured perpendicularly to the parallel sides.
[2]Two opposite edges parallel to the lane axis.

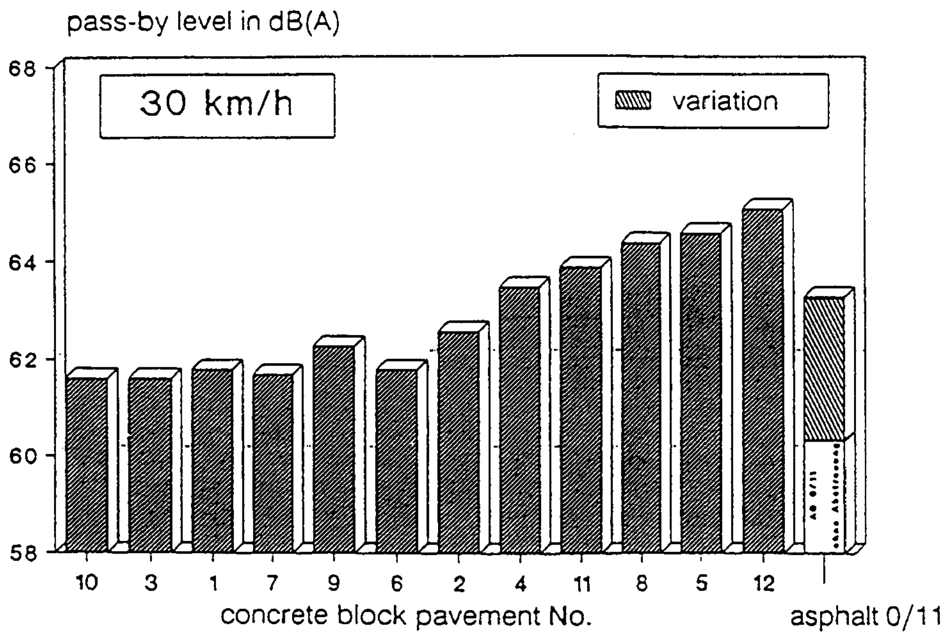


FIGURE 41 Passby level for different concrete block pavements and asphalt 0/11 (variation ± 1.5 dB(A)), speed 30 kph (18 mph) *(17)*. Passby method with a reference surface of asphalt, maximum grain size 11 mm and no spreading chippings. Noise level for reference pavement = 61.8 dB(A) at 30 kph (19 mph) and 68.0 db(A) at 50 kph (31 mph).

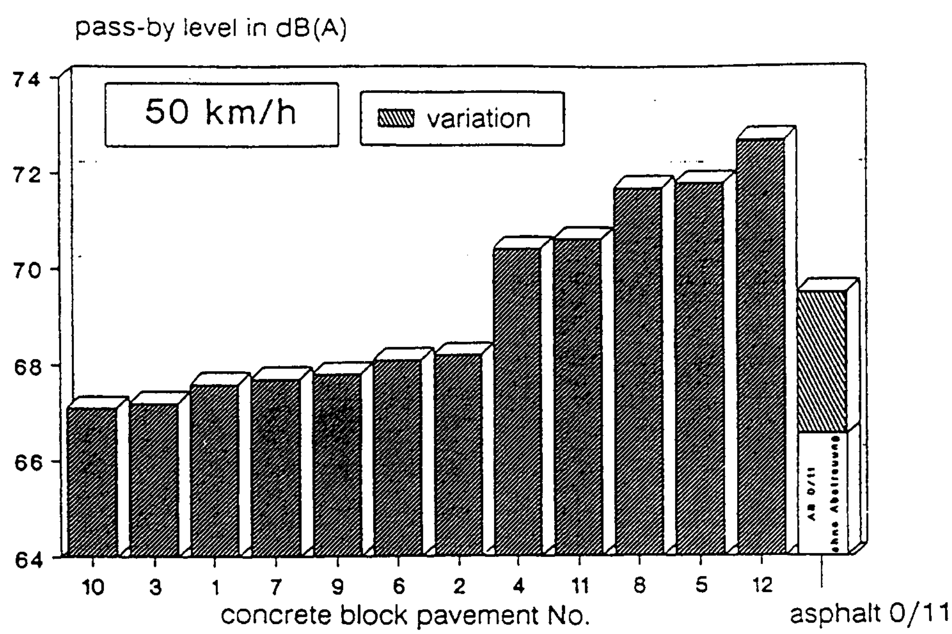


FIGURE 42 Passby level for different concrete block pavements and asphalt 0/11 (variation ± 1.5 dB(A)), speed 50 kph (31 mph) *(17)*. Passby method with a reference surface of asphalt, maximum grain size 11 mm and no spreading chippings. Noise level for reference pavement = 61.8 dB(A) at 30 kph (19 mph) and 68.0 db(A) at 50 kph (31 mph).

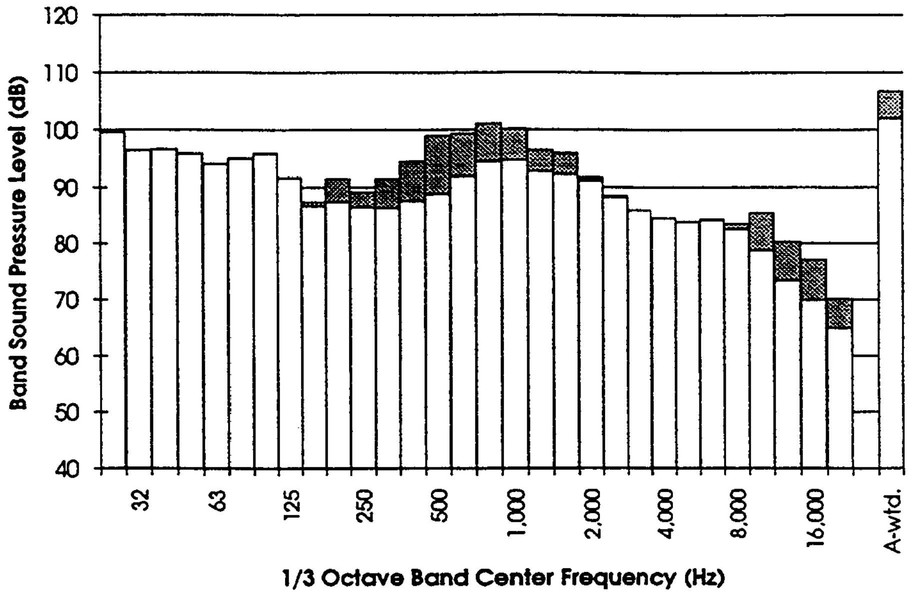


FIGURE 43 Third-octave band noise comparison of a tire with and without studs. The tire design in this case is a Kelly-Springfield "All-Weather" design *(30)*.

noise in the mid- and high-frequencies than non-studded tires. The additional roadway wear due to studs also becomes important.

The impacts of various surfaces and textures have been reviewed. Wear and maintenance must also be considered and are discussed next.

CHAPTER SIX

WEAR AND MAINTENANCE CONSIDERATIONS

An important consideration in selecting a pavement type is the length of time the pavement surface lasts until resurfacing is needed. Other conditions, such as noise considerations, could affect this decision. This makes it extremely important to consider not only initial noise reductions that can be achieved, but how the pavement surface and the sound generation mechanisms change with respect to wear and maintenance.

INCREASE OF NOISE LEVELS WITH TIME

Chalupnik looked at wear trends for pavements up to 29-years old and the effect on noise generation (*30*). Because of time considerations, the age data did not come from the same sections. Data from pavements up to 6 years of age had been tracked semi-annually in previous studies. Pavements older than 6 years were selected from older sections not previously measured and studied for this investigation. The measurements were made over multiple test sections in the state of Washington. Several pavement types were tested and included both PCC pavement and asphaltic pavements. The measurements were done using the trailer test method with the microphone located 20 cm (7.9 in.) from the tire patch. As such, the noise generation is measured, but does not include the surface effects that would occur during sideline propagation. In addition, effects from vehicle noise sources and interaction are not considered using this method.

Chalupnik's study for PCC pavements reports that noise generation decreases for the first several years (approximately 8 to 12 years) and then begins to increase (see Figure 44). It was concluded that this trend occurred because of the wearing of the transverse tining resulting in less tire impact. It should be noted that considerable studded tire and chain use occurs in Washington, contributing to wear. The comb depth was originally set to 0.015 ft. (4.5 mm) depth, one-half in. (13 mm) apart. Surface wear, which results in smoothing with time, causes reduced noise level generation due to less tire excitation as the tining depth decreases. Aggregates begin to appear about the 10th year and the surface becomes rougher and generates more sound. PCC pavements in extreme weather conditions faired slightly worse, showing a general trend to increase in noise generation as early as the first year. The overall increase was typical of that shown in Figure 44. Further results are shown in Table 25.

The reader is reminded that the trailer method was used for this testing, which is a measure of noise generation, not sidelines noise levels. As such, although the tire noise is shown to increase with this test method, it is possible that the greater texture depth and exposing the aggregate could lead to lower sideline noise as reported in the previous chapter.

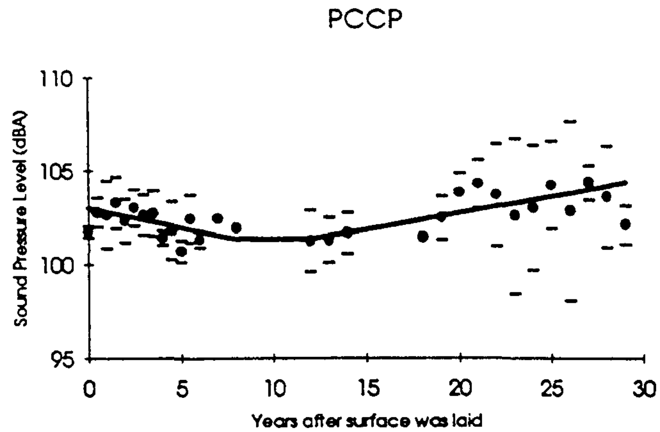


FIGURE 44 Noise data for portland cement concrete pavements with ages ranging from freshly laid to 29 years. These data represent 134 separate roadway sections. The dots mark the mean value; the bars mark the 90 percent confidence interval for the data *(30)*. Measured with close proximity method (trailer) at 20 cm from the tire patch. The surface was transversely tined with a comb depth of 0.015 ft (0.0046 m) and 0.5 in. (13 mm) apart.

All asphalt pavements tested by Chalupnik showed an increase in noise generation over a 6-year time period. With one exception, all asphalt pavements remained quieter than PCC pavement during this time period. The one exception was the Class D open-graded asphalt. Not only did this pavement start with the greatest level among asphaltic surfaces but it increased at a greater rate. Rubber-modified asphalt pavement results were very similar to polyester-modified asphalt.

Again, it must be considered that the increased noise levels for asphalt occur at the tire. Sideline noise could show other trends. Because of this consideration, sideline noise studies were also reviewed.

Results from Belgium (*88*) show that for rolling noise using the passby method at 120 kph (75 mph), A-weighted noise levels increased by 2.9 dB over 7 years for porous asphalt. This would mean that most noise mitigation typically achieved by porous asphalt—as shown by past literature, approximately 3 dB—would only last for about this time period. However, even with this increase with time, porous asphalt was still less noisy when compared to PCC pavements with various surface textures in Belgium.

Another interesting result occurred in Belgium (*65*) for PCC pavements. Diamond and carbide grinding (soft milling) was used to restore surfaces of worn PCC surfaced roads. Small-depth grooves were reported to both decrease the noise and increase the surface friction. The surface friction compared before (more typical transverse tining used) and shortly after the grinding were shown in Table 26. This method could

TABLE 25

NOISE PERFORMANCE OF PAVEMENT TYPES *(30)*

Pavement Type	Starting Noise Level (dB)	Initial Slope 0-6 (8) years (dB/year)	6 (8*)-Year Noise Level (dB)	Mid-Life Slope 8-12 years (dB/year)	12-Year Noise Level (dB)	Aging Slope 12-years (dB/year)	29-Year Noise Level (dB)
PCCP	103.0	-0.21	101.3	0	101.3*	0.18	104.5
LMPCCP	101.8	-0.13	101.1				
PCCP*	101.9	0.13	102.7				
BACP	98.4	0.24	99.9				
DACPOG	99.2	0.70	103.4				
PMACP	97.0	0.41	99.5				
RMACP	97.3	0.60	100.0				

*This is the I-90 section at Asahel-Curtis, which has been subject to numerous freeze-thaw cycles. Snoqualmie Summit data are not given because the data exist for only three years.

TABLE 26

MEASUREMENTS OF BEFORE AND AFTER OF PCC PAVEMENTS *(65)*

Total Noise	Before [dB(A)]	After [dB(A)]
To Liege		
kmpt 29.15	82.6	77.2
kmpt 29.28	85.8	78.8
To Brussels		
kmpt 29.26	84.6	78.3
kmpt 29.16	84.3	78.3
Rolling Noise	Before [dB(A)]	After [dB(A)]
Slow lane		
100 kph	85.1	80.3
120 kph	87.9	83.4
Central lane		
100 kph	87.7	83.7
120 kph	90.3	89.2
Skid Resistance	Before [dB(A)]	After [dB(A)]
To Liege		
Slow lane	54	98
Central lane	58	101
Fast lane	76	104
To Brussels		
Slow lane	54	84
Central lane	64	101
Fast lane	76	104
Evenness	Before [dB(A)]	After [dB(A)]
To Liege		
EC_{25}	27 30 38 40	24 21 23
$EC_{10.0}$	45 85	38 27 55
$EC_{40.0}$	45 90 169	39 77 163
To Brussels		
EC_{25}	26 31 26	20 22 29
$EC_{10.0}$	39 56 51	32 43 45
$EC_{40.0}$	69 83 111	65 84 109

extend the service life of PCC pavements, which are already significantly longer than asphaltic surfaces. There is concern however, on how long this extended life may last before complete resurfacing is needed.

Work continues on ways to extend the life of porous asphalt. Sandberg presented a comparison of porous asphalt to dense-graded asphalt (*93*) where the porous asphalt was a modified porous pavement being tried in Sweden that promised an extended acoustical lifetime and benefits, even on low speed roads. Initial testing shows good potential for noise reduction, particularly at frequencies greater than 400 Hz. Time will tell if the new mix maintains its noise reduction capability.

ENVIRONMENTAL CONSIDERATIONS

Also of interest was the seasonal effect of noise generation from asphaltic pavements as reported by Caestecker (*65*). The effect was reported to be greater on open-graded surfaces. It was postulated that the asphalt softens with increased temperature which leads to a "more cushioned ride for the tire."

Steven reported a more short-term problem with open-graded asphalt (*76*). Noise reduction characteristics of the open-graded surface were found to decrease significantly with dirt accumulation. Maintenance, such as high-pressure cleaning roughly twice per year, may be required to prevent clogging. The measured values of this effect on noise levels is shown in Figure 45; the "dirtied" surfaces have the highest noise levels. This would require special cleaning to be considered for the porous asphalt surfaces during the service life of the surface. Sandberg (*68*) states that "When a surface has reached a certain degree of clogging, the surface obeys the same design rules as a dense surface." In this case, the aggregate becomes of prime concern because of the generated tire vibrations since the porosity no longer offers absorption or reduced air pumping.

Reduction of surface friction due to ice cover is an environmental factor that is an important safety consideration. In a "mild" winter in Wisconsin (*73*) no problems were reported for longitudinally tined sections of PCC pavement. Only minor, infrequent reports occurred for the transverse tined sections of PCC pavements, but stone mastic asphalt and the Strategic Highway Research Program asphalt types (SHRP pavement) required two to three times the salt to avoid slippery conditions. This may have occurred because the porous surface carried away the deicing agent from the surface. Also, sanding of porous surfaces could lead to clogging. However, an open-graded asphalt roadway was treated with liquid calcium

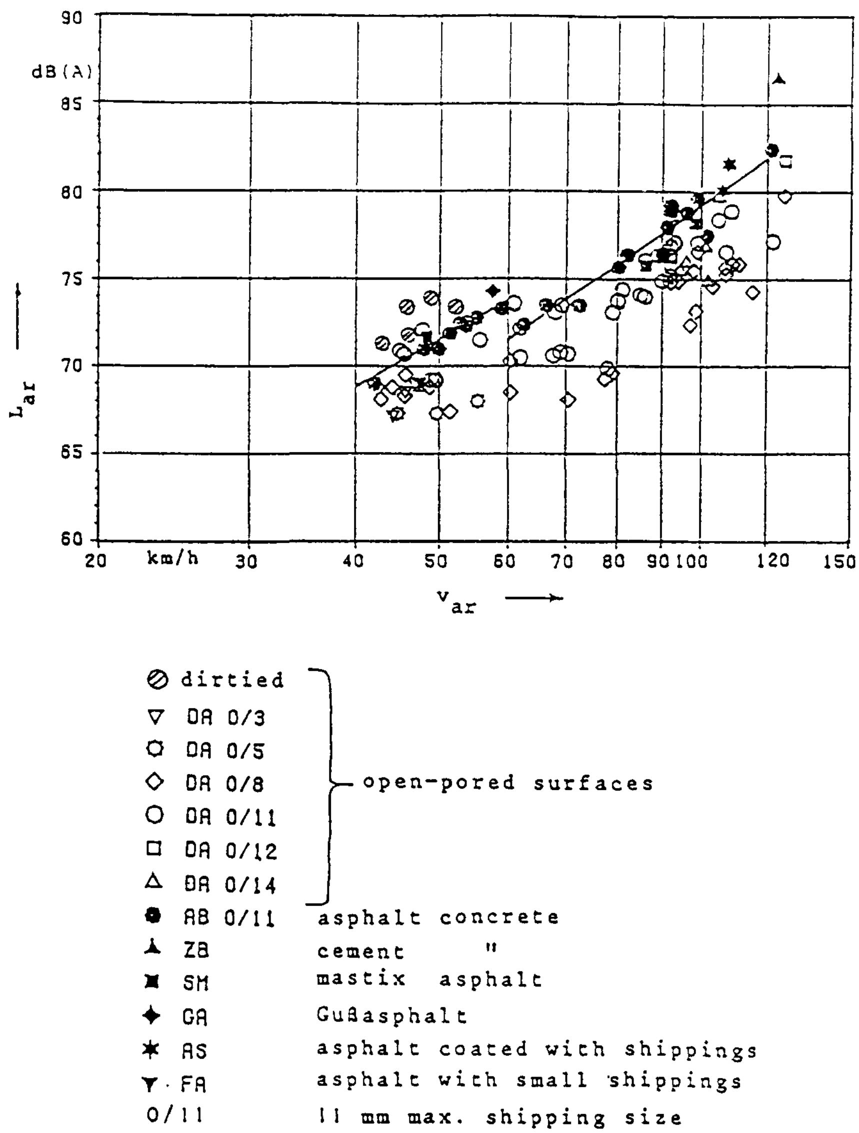


FIGURE 45 Average passby levels from passing cars (7.5 m distance, 1.2 m height) on open-pored road surfaces versus average vehicle speed *(75)*.

chloride in Massachusetts and good results were reported (*94*). The road did not freeze and was easier to plow and maintain safely. This same report noted that tining of concrete pavements reduced the effectiveness of salt brine residue in Wisconsin as well. Accordingly, deicing presents particular problems for various surfaces, but proper methods may overcome these difficulties.

With porous surfaces, whether dense concrete or an asphaltic surface, the freeze/ thaw cycle becomes very important. For porous asphalt, the selection of the polymer is extremely important. Acrylic polymers have been found to give the most satisfactory results (*7*). The addition of silica fume to concrete pavements is also reported to further improve resistance to effects of the freeze/thaw cycle. Porous surfaces have also been shown to reduce spray, splashing, and light reflectance. Preliminary results have shown that porous concrete is more resistant to wear than porous asphalt.

CONCLUSIONS ON MAINTENANCE AND WEAR

PCC pavements are longer lasting and usually require less maintenance due to wear than asphaltic surfaces. Even after long wear there are methods to restore the PCC surface texture without repaving. PCC surfaces become polished with wear, reducing tire vibration and resulting in less noise generation. As wear continues, and the aggregate becomes exposed, noise generation increases.

Sideline (passby) noise levels have been reported to increase for porous surfaces over time as wear occurs. Increases have been reported to be about 3 dB(A) over a 7-year period. However, even with the increased noise levels, the porous asphalt surfaces remain quieter than PCC pavements. Unfortunately, porous surfaces have a tendency to fill with grit and dirt and may require special cleaning techniques. This clogging could reduce the noise reduction to that of dense surfaces. Porous surfaces are also more susceptible to degradation from the freeze/thaw cycle. Splash and spray, along with surface friction, always are important considerations. Finally, more deicing agents or a change in deicing methods may be required on the porous surfaces.

CHAPTER SEVEN

SAFETY CONSIDERATIONS

The frictional components of the surface are of primary importance for controlled turning and stops and have been discussed in general until this point. The microtexture and macrotexture are extremely important to the development of surface friction. The microtexture is the critical component for surface friction at high speeds. Macrotexture is the primary means to remove water for better surface friction from the microtexture at high speeds. The construction techniques have a large impact on these parameters and macrotexture is often increased for increased surface friction. However, increasing the macrotexture may result in greater noise generation, as previously discussed. As such, a close relationship between noise generation and safety exists and must be considered.

Dense-graded asphalt surfaces primarily provide surface friction by the nature of the texture provided by the exposed aggregate. Standard dense-graded asphalt typically has friction numbers in the range of 40 to 50 at 64 kph (40 mph) as measured by the ASTM towed friction (skid) trailer method with a ribbed tire. Open-graded asphalt or concrete provides even better surface friction by providing higher levels of macrotexture than the dense-graded asphalt. Hydroplaning is also reduced by porous surfaces by allowing better drainage of the water through the pore openings in the surface. If the surface aggregate is stable and polish-resistant, good frictional characteristics last longer. As previously discussed, it has been reported that porous asphalt needs periodic maintenance (cleaning about twice per year) because particles such as sand and salt may plug the surface pores. This plugging would not only reduce the drainage capability but also the frictional characteristics.

PCC pavements may use hard fine aggregate to provide significant surface friction. Tining allows good drainage characteristics and may add additional surface friction. Transverse tining has the additional benefit of good frictional characteristics for long time periods (up to 30 years) for PCC pavements and in general provides the greatest surface friction. Longitudinally tined PCC pavement may have good frictional characteristics initially, but not as good as transverse tining, and it tends to degrade more quickly with time. Exposed aggregate PCC pavement can have friction numbers close to or equivalent to transversely tined surfaces. In addition, the frictional characteristics of exposed aggregate generally increase with time. The same problems experienced with porous asphalt occur with porous PCC. If the porous surface is kept free of clogging, very good frictional characteristics are maintained. The use of two-layer PCC pavement construction provides good surface friction by allowing placement of higher quality materials in the upper level.

Noise reduction techniques sometimes conflict with methods to increase surface friction. As such, research is continuing in many areas for various pavements and surface treatments. A brief summary is presented here.

SELECTED RESEARCH BY GEOGRAPHIC LOCATION

Oregon

A comparison of friction numbers was presented by Huddleston comparing open-graded asphalt and PCC pavement (*95*). Good frictional characteristics were reported when the open-graded asphalt was new. Changes with time tended to decrease the effectiveness of the surface friction. Later testing, also done in Oregon, shows similar results to Huddleston's study. Typical friction numbers and the decrease in friction number with speed is shown in Figure 46 (*80*).

Minnesota

Testing for both asphalt and PCC pavements was also done by Minnesota in 1979 (*58*). Although the sideline noise levels were reported to be less for the asphalt pavements, frictional characteristics were also less for the asphalt surface. Table 27 shows the results of the friction testing.

Spain

Varying from the studies such as in Wisconsin, researchers in Spain (*63*) reported that longitudinal texturing techniques were long lasting and ". . . provide excellent surface friction even at high speeds." Results of the testing are shown in Figures 22 and 23; the surface friction constants ranged from 53 to 83. Later comparisons listed these friction coefficients similar to values of 0.21 to 0.29 as tested in the United States.

Virginia

Virginia has also done testing on longitudinally tined pavement (19-mm (0.75 in.) tine spacing with 3.2-mm (0.125 in.) wide tines, preceded by a burlap drag, with a mean texture depth 0.89 mm (0.035 in.)) (*4*). Using the ASTM E274 towed friction trailer method and blank tires, friction numbers of 37 to 48 were measured. This compared to values of 35 to 41 for an adjacent dense-graded asphalt surface. Again, the PCC pavements showed better frictional characteristics than the dense-graded asphalt overlay, even with longitudinal tining.

Australia

The Concrete Pavement Manual: Design and Construction, from the New South Wales, Australia Roads and Traffic

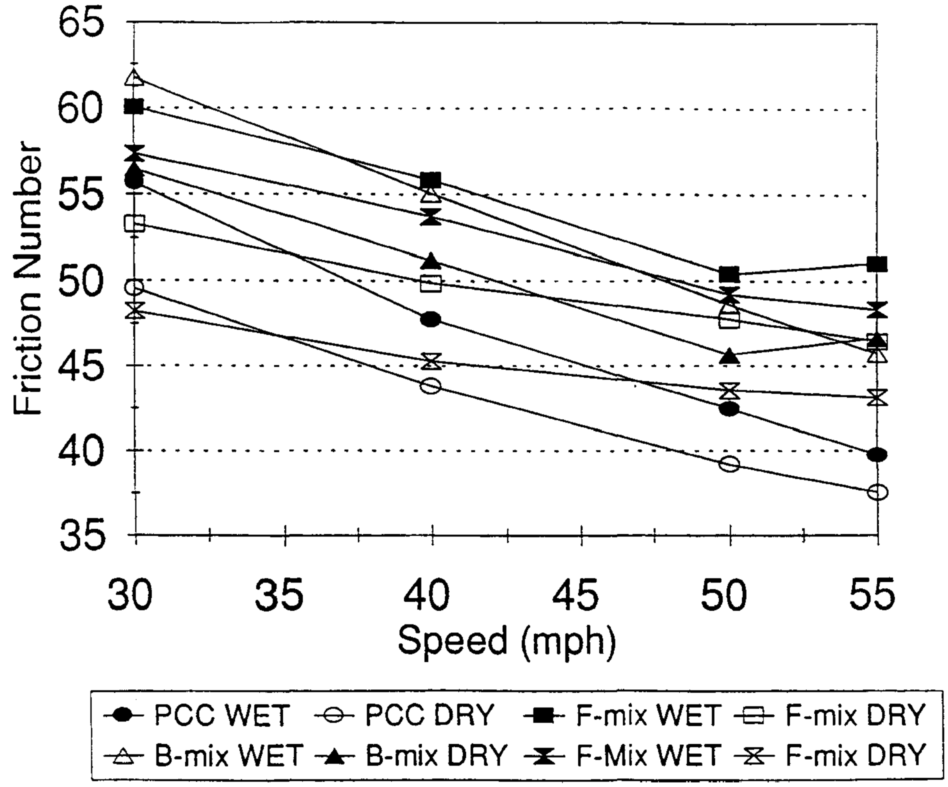


FIGURE 46 Frictional testing results *(79)*.

TABLE 27

FRICTION TESTS *(44)*

Location	Texture	East Bound FN 40	East Bound FN 55	West Bound FN 40	West Bound FN 55
Station					
1209–1219	Astrograss only	43.8	36.5	43.7	34.3
1219–1229	2371 Quartzite	41.4	36.8	42.0	35.8
1229–1239	2361 W–Granite	48.4	39.8	48.6	42.7
1239–1249	2361 E–Taconite	62.3	55.8	60.2	53.0
1258+50–1264+50	Astrograss w/1-3/4 in. trans. tine	49.0	39.6	48.6	42.0
1264+50–1270+50	Astrograss w/2 in. trans. tine	50.8	45.0	50.3	43.9
1270+50–1276+50	Astrograss w/2-1/2 in. trans. tine	51.1	42.7	50.8	41.9
1276+50–1282+43	Astrograss w/3 in. trans. tine	51.0	41.8	52.0	40.8
1282+43–1285+76	Astrograss w/variable trans. tine	51.4	41.1	48.0	40.5
Balance of project	Astrograss w/1 in. trans. tine	46.5	43.9	–	–
MP 60.04 thru 63.00 and 65.00 thru 67.17		Range @ 40 36.1-52.4			

Authority, was last released in February of 1994 and presented several noise issues from a 1991 update. It was reported that longitudinal grooving is viewed as unsatisfactory for stopping distance and rotational stability of a braked vehicle at high speeds.

Missouri

Results from Missouri show that frictional characteristics exhibited dependence upon the texture depth, average daily traffic per lane, and the aggregate size. The type of fine aggregate when mixed with limestone coarse aggregate made a significant difference in surface friction for combed PCC pavement surfaces *(52)*.

California

As summarized by Hibbs, in California, friction numbers for longitudinally tined (19 mm (¾-in.) spacing) pavement with a smooth tire, towed friction trailer were above 40 at 96 kph (60 mph). This is good resistance. Wider tine spacing was

TABLE 28

FRICTION TESTS *(44)*

California 1994 Friction Test Results (ASTM E 274 Trailer)						
Tire Type	*Ribbed (E 501) Tire			*Smooth (E 524) Tire		
Texture Type	96 km/h	80 km/h	64 km/h	96 km/h	80 km/h	64 km/h
Long. Broom	30	33	38	14	15	19
Trans. (13 mm)	29	35	39	16	23	28
Trns. (19 mm)	35	37	39	26	30	31
Long. Astroturf	27	32	37	11	14	17
Long. (19 mm)	50	54	57	40	48	53
Long. (13 mm)	47	52	57	25	29	36

California 1994 Speed Gradient						
Speed Gradient	G (96-80)		G (80-64)		G (96-64)	
Texture Type	Rib.	Sm.	Rib.	Sm.	Rib.	Sm.
Long. Broom	0.38	0.14	0.49	0.40	0.44	0.27
Trans. (13 mm)	0.39	0.21	0.52	0.28	0.46	0.25
Trns. (19 mm)	0.35	0.69	0.34	0.41	0.34	0.35
Long. Astroturf	0.46	0.20	0.51	0.40	0.48	0.30
Long. (19 mm)	0.24	0.43	0.42	0.81	0.33	0.62
Long. (13 mm)	0.51	0.74	0.49	0.36	0.50	0.55

generally reported to increase the friction number (19 mm (0.75 in.) vs. 13 mm (0.62 in.)). Results for longitudinal and transverse tining are reported in Table 28 using the ASTM E 274 trailer method.

Colorado

In Colorado (*96*), nine test sections of transverse and longitudinal tining were also tested using the ASTM trailer method. Variable transverse tining had the highest friction numbers and greatest texture depth. Table 29 shows the test results for all pavement types. The pavement test sections are numbered as previously shown in chapter 5. It should be noted that the friction numbers dropped considerably from 1994 to 1995.

Iowa

Iowa conducted tests in 1985 on pavement that was first transversely tined and then changed using longitudinal grinding for noise control (*62*). The friction numbers, using the ASTM E-501 tire, are shown in Table 30 for the before-and-after case. The reduction in surface friction for the less traveled lanes is readily apparent. A follow-up study was done in January 1987. The results of the noise measurements are shown in Table 31. Both the A-weighted and one-third octave band data showed very similar results. Frictional testing was also redone. Again, results showed only very minor changes from the earlier study. This tends to point out the durability of PCC pavement surfaces.

Nine test sections were also tested in Iowa by the state DOT and reported on by Hibbs (*4*). The pavement textures included:

Section	*Description*
1	Transverse tining, 13 mm spacing (0.5 in.), 3 to 5mm (0.12-0.2 in.) deep
2	Transverse tining, 13 mm spacing, 1.5 mm (0.59 in.) deep
2A	Transverse tining, 19 mm (0.75 in.) spacing (standard)
3	Longitudinal tining, 19 mm spacing, 1.5 mm deep
4	Longitudinal tining, 19 mm spacing, 3 to 5 mm deep
5	Transverse tining, 19 mm spacing (var.), 3 to 5 mm deep
6	Transverse tining, 19 mm spacing (var.), 1.5 mm deep
7	Longitudinal astroturf drag
8	Milled surface
9	Transverse grooving (hardened concrete), 13 mm spacing

Reported results for the ASTM trailer method are reported in Table 32. These results show that transversely tined pavement usually has the greatest surface friction as previously reported.

Michigan

In Michigan, limited testing was done on a European style exposed aggregate surface (*72*). The results from the ASTM E274 skid trailer testing were 37.6 in 1993 and 42.1 in 1994, which are fair. Even though there was some increase in the year, the numbers are still about 10 points lower than Michigan's standard tined surface, which were 46.0 in 1993 and 53.2 in 1994. Construction techniques such as over-finishing the exposed aggregate surface (over-brushing) were suspected to decrease the surface friction numbers because the particles were oriented with the flat side up rather than an edge pointing up. The sand used was also 0 to 4 mm (0 to 0.16 in.)

TABLE 29

COLORADO TEST SECTION I-70 *(4)*

Colorado Test Section: I-70 at Deertrail						
	Test Results: Noise (dB(A)) at 105 km/h					
	Inside Vehicle		7.5 m from Road		Wheel Well	
Pvt. Section	1994	1995	1994	1995	1994	1995
1	68	67	89	87	104	107
2	67	66	87	83	102	104
3	68	68	90	88	103	106
4	68	68	87	86	102	105
5	66	67	88	86	103	106
6	67	67	87	86	102	105
7	66	66	85	82	99	103
8	66	65	84	82	99	101
9	68	67	88	84	101	104

Test vehicle was a 1994 Oldsmobile Cutlass station wagon.

	Test Results: Friction (ASTM Method E 274)					
	64 km/h		80 km/h		96 km/h	
Pvt. Section	1994	1995	1994	1995	1994	1995
1	*56/54	56/43	58/48	50/41	52/45	46/35
2	68/48	52/22	68/40	45/18	52/35	40/14
3	69/67	59/52	68/58	52/50	58/52	51/45
4	68/62	59/55	68/58	56/55	58/55	57/49
5	60/59	52/50	60/52	50/45	49/45	46/41
6	60/55	56/42	59/49	50/39	51/43	49/35
7	54/55	50/48	52/49	48/46	44/41	39/32
8	52/30	49/20	48/21	39/16	39/19	33/11
9	65/57	55/50	61/52	52/49	51/44	42/36

*Ribbed-tire/Smooth tire

TABLE 30

REPRESENTATIVE BEFORE AND AFTER L_{eqs} AT EACH STUDY SITE *(62)*

	Morning Peak		Evening Peak		Off-Peak (Midday)	
Site	Before	After	Before	After	Before	After
1	69.7	69.4	68.8	70.2	67.7	68.6
2	69.8	68.7	68.7	69.9	66.9	67.4
3	70.9	70.4	72.4	72.1	68.5	69.3
4	77.0	74.7	75.4	75.0	73.3	73.4
5	74.0	72.1	72.8	72.1	70.1	70.3
6	67.2	67.0	67.0	67.7	64.4	66.1
7/8*	67.8	66.6	66.1	67.7	64.3	65.5

	Morning Before NB	Morning Before SB	Morning After NB	Morning After SB	Evening Before NB	Evening Before SB	Evening After NB	Evening After SB	Off-Peak Before NB	Off-Peak Before SB	Off-Peak After NB	Off-Peak After SB
Autos	207	548	352	967	805	475	850	457	360	269	410	318
M Trks.	6	7	16	15	6	8	7	4	9	11	11	15
H Trks.	12	11	15	15	10	22	13	29	20	14	31	20

*"Before" measurements were made at Site 8; "After" measurements were made at Site 7.

and not 0 to 1 mm (0 to 0.039 in.) as recommended by the Austrian designers.

European Research

As pointed out by the BRITE / EURAM report *(7)*, surface friction for dense concrete depends on the sharpness of the aggregate at the surface, the polishing resistance, the size of the aggregates, and the texture depth; surface structure direction is less important. High surface friction can be achieved on all types of surface structures if appropriate materials are used and sufficient texture depth is provided. As previously discussed, the direction of the surface structure can have a large affect on noise generation. Since the microtexture has a decisive influence on surface friction, but only small effects on noise levels, it should be kept high.

TABLE 31

SUMMARY OF FINAL 24-HOUR SAMPLES AT SITE *(62)*

	Hourly L_{eq}, dBA		
Time	Before Grinding*	After Grinding**	Final Sample***
0100	61	63	61
0200	59	59	61
0300	59	59	60
0400	59	59	59
0500	60	60	59
0600	63	63	62
0700	67	67	66
0800	69	69	68
0900	68	68	68
1000	67	68	67
1100	67	67	67
1200	67	69	67
1300	67	68	67
1400	67	68	67
1500	67	68	68
1600	67	69	68
1700	68	70	68
1800	68	69	68
1900	67	67	66
2000	67	66	65
2100	65	65	64
2200	64	65	64
2300	64	64	63
2400	61	63	61

* September 5, 1985
** October 28, 1985
***January 21, 1987

TABLE 32

IOWA TEST SECTIONS *(4)*

Iowa Test Sections				
Test Result: Texture (E 965) and Friction (E 274)				
		Friction		
Pvt. Section	ASTM 965 mm	56 km/h	72 km/h	90 km/h
1	1.00	57/50*	52/46	48/43
2	0.94	60/52	63/47	51/45
2A	0.95	58/51	53/47	50/43
3	1.12	49/42	44/36	44/34
4	0.85	46/46	41/40	40/39
5	0.76	47/45	43/41	43/37
6	0.37	51/46	46/40	43/36
7	0.90	48/42	42/28	37/26
8	0.90	49/39	45/34	42/30
9	0.93	53/52	50/45	49/44

*Ribbed-tire (E 501)/Smooth-tire (E 524)

The megatexture is also important for good surface friction and is extremely important for noise control. Accordingly, the maximum chipping size should be as low as possible and the chippings should have sharp edges. It is desirable for the macrotexture to have high amplitudes in the 0.5 to 10 mm (0.02 to 0.4 in.) wavelength range to lower tire noise while maintaining surface friction and reduced spray, splash, and light reflectance.

Macrotexture should be kept as low as practical—in the 10- to 50-mm (0.4 to2 in.) range—to reduce noise, but not at the price of good surface friction. An interesting finding by Nelson in the U.K. is ". . . surfaces that are slightly noisier [within 5 dB(A)] generally have better wet weather friction characteristics *(97)*."

In the United Kingdom, surface friction was measured for four pavement types using the sideways force coefficient

TABLE 33

RESULTS OF SKIDDING MEASUREMENTS *(66)*

Type of Surface	Average Texture of 50 m Sections (mm)	Average Change in SFC 59–90 km/h (%)	Average Change in BFC 50–130 km/h (%)
HRA	1.66	-24	-33
Brushed	1.06	-8	-31
Tined	1.04	-18	-55
Exposed aggregate	1.41	-21	-35

(SFC) and the braking force coefficient (BFC) methods. These results are shown in Table 33. It is interesting that the brushed surface produced the least change in SFC from 50 to 90 kph, but both the exposed aggregate and tined surfaces were only marginally better than the asphalt surface.

A more recent study in the U.K. *(67)* also included exposed aggregate surfaces. SCRIM testing and the BFC measurement using the locked wheel trailer method were accomplished. Other surface types were also tested, including hot-rolled asphalt and PCC pavements, both brushed and tined. The SCRIM showed similar results for all surfaces tested, both before opening to traffic and after. Before opening to traffic, the locked wheel trailer at low speeds (50 kph (31 mph)) showed the brushed and tined surface friction to be similar, but significantly greater than the hot-rolled asphalt and exposed aggregate surfaces, which were also similar to each other. However, at higher speeds (130 kph (81 mph)) all surfaces were shown to be similar, with the brushed-only surface having the braking force coefficient. Of particular interest was that both testing methods showed a decrease in surface friction after opening to traffic and, after just less than 3 years, the values were similar for all surfaces with both testing methods. It was stated that even after the decrease over time, all pavements exceeded design standards.

CONCLUSIONS ON SAFETY

It should also be remembered that the primary purpose of surface texture is to help reduce the number and severity of wet weather accidents *(4)*. Both FHWA and AASHTO recommend that safety not be compromised for a slight reduction in noise levels. It is the federal policy that small reductions in noise not affect safety. Dense-graded asphalt, although generally quieter than PCC pavements, has less surface friction. Porous asphalt provides low noise levels and among the best surface friction for asphalt surfaces that is adequate for safety considerations. Unfortunately, additional maintenance costs may be required since cleaning of the porous surface may be needed to prevent plugging. Porous concrete also provides a noise reduction when compared to tined surfaces and good surface friction but requires the same maintenance as porous asphalt. Longitudinally tined PCC surfaces provide good surface friction, but not as good as transversely tined PCC surfaces. Although transverse tining generally provides the best frictional characteristics, it can lead to undesirable noise impacts, especially a clearly audible "whine." The frequency of the whine is a factor of the tining spacing and vehicle speed. Random spacing of the tining is reported to help reduce or even eliminate the whine. Random spaced transverse tining, proceeded by longitudinal artificial carpet dragging or burlap drag continues to be the most desirable PCC pavement surface texture method for high-speed major highways.

CHAPTER EIGHT

INTERIOR NOISE

A large amount of data on interior noise has been gathered by the vehicle manufacturers, the Society of Automotive Engineers, and the American Automobile Manufacturers Association. However, these data were taken for product improvement and they vary greatly with the cost and intended use of the vehicle. In this report, efforts were concentrated on in-situ measurements where sideline noise measurements were also available.

RESEARCH REPORTS

Wisconsin

During the Wisconsin study, Kuemmel et al. also measured in-situ interior vehicle noise *(73)*. The measurements were made because of subjective reports by project personnel that an annoying dominant frequency existed for transversely tined PCC pavement. This dominant frequency is often reported in the literature as whistling, whining, or humming (*98, 99*). As with sideline sound for transverse grooved pavement, the dominant frequency varies with tine spacing and vehicle speed. Testing was done for 13 test pavements. Three passenger cars were used for the testing: a luxury car, a mid-size and a compact. The results of the testing, shown in Figure 47, clearly show a trend of the dominant frequency peaking due to the tine spacing/speed relationship. Of significant note, when the transverse tining was random, the peaks diminished significantly (see Figure 47). More work is planned using narrow band frequency analysis.

The tests demonstrated that the greatest sound level in the car for various surfaces did not necessarily result in the greatest passby noise levels. The most complete set of data was for the compact car. Table 34 shows the average A-weighted sound level measured in the vehicle. It should be noted that sound levels in the mid to high 60 dB(A) range would make conversation difficult.

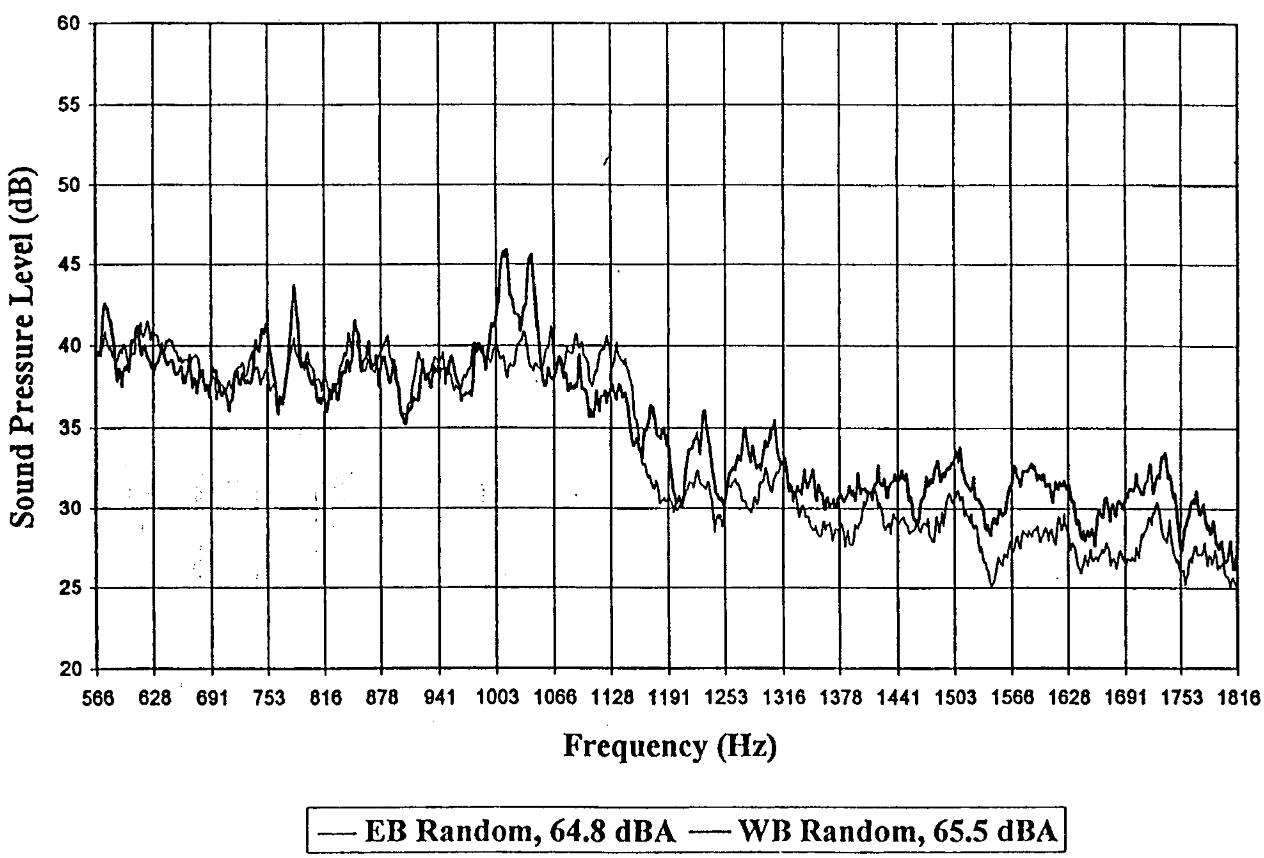


FIGURE 47 Interior noise spectra for transverse-tined PCCP with large predominant frequencies, Ford Escort at 96 kmph (60 mph) *(72)*.

TABLE 34

INTERIOR A-WEIGHTED SOUND LEVELS *(72)*

Test	Texture	Noise (avg. dB(A))
3	38 mm (1-1/2 in.) (transverse, 3 mm (1/8 -in.) depth	67.4
15	25 mm (1 in.) transverse, 3 mm (1/8in) depth	66.1
11	Random transverse (wide spacing) 3 mm (1/8 in. depth[a]	65.7
16	Skidabrader	64.9
EBrndm	Random transverse (narrow spacing), 3 mm (1/8 in.) depth	64.8
8	25 mm (1 in.) skewed 1:6, 5 mm (1/16 in.) depth	63.8
10	18 mm (3/4-in.) transverse, 3 mm (1/8 in.) depth[a]	63.6
ground	Diamond ground longitudinally	63.1
6	25 mm (1 in.) longitudinally tined, 2 mm (3/32 in.) depth	63.1
9A	13 mm (1/2 in.) transverse, 3 mm (1/8 in.) depth	63.1
SMA	Stone mastic asphalt (9 mm or 3/8 in. aggregate) Waukesha County	62.9
Std.	WisDOT standard dense graded APC, Waukesha	62.6
SHRP	SHRP APC mix, Waukesha	61.1

[a]Texture depth not fully achieved throughout the test location.

TABLE 35

INTERIOR SOUND LEVELS FOR POROUS ASPHALT AND PCC PAVEMENTS *(80)*

	Seven Oaks to Jackson Interior		
Matches	L_{eq} dB(A)	L_{eq} dB(A)	L_{eq} dB(A)
PCC–B-mix South	75.1	68.5	6.6
PCC–B-mix North	73.5	70.5	3.0
PCC–F-mix South	75.1	71.4	3.7
PCC–F-mix North	73.5	72.5	1.0
B-mix–F-mix South	68.5	71.4	-2.9
B-mix–F-mix North	70.5	72.5	-2.0
	Battle Creek to N. Jefferson Interior		
B-mix–F-mix	72.7	72.0	0.7
	Halsey to Lane County Line Interior		
B-mix–F-mix	72.0	72.0	0.0

Michigan

Hibbs also supplied information from ongoing work in Michigan comparing the standard concrete mix to a European exposed aggregate style PCC pavement. Measurements were made inside a Dodge Dynasty van traveling at 80 kph with the windows open and again with the windows closed. The A-weighted values reported show very little difference between the measurements for the two surface types. These values with closed windows were 64.5 dB(A) for the European pavement and 65.2 dB(A) for the standard Michigan concrete mix. Of course these numbers increased for the open window case, 2.3 dB(A) for the European and 2.4 dB(A) for the Michigan texture. Again, these levels are undesirable for conversation.

North Dakota

Work was also reported from North Dakota. These measurements, previously reported in this document, indicate that interior noise levels do not vary greatly by vehicle type or pavement type (it usually takes a 5 dB(A) change to be readily noticeable). However, these overall measurements do not cover the tonal quality that may occur. Hibbs (*4*) points out that interior noise studies do not show a large range of change for overall noise levels for various pavements, but some surfaces can cause pure tones that are objectionable to the vehicle passengers.

Oregon

Oregon also measured interior noise levels for porous asphalt and PCC pavements (*80*). These measured values are shown in Table 35. When compared to the porous asphalt, the PCC pavement resulted in greater interior noise levels. This was the same general trend for sideline measurements made for the same project. However, the "F-mix" was generally the quietest pavement for the sideline measurements but in some cases was as much as 2.9 dB(A) greater for the interior noise. This seems to follow the results of the other studies where the sideline and interior noise rely on different generation/attenuation methods and are not directly comparable. Interior noise is related to tire vibration and is not as affected by propagation as are measurements at the side of the road. As such, sideline measurements may not correlate with interior vehicle measurements. By this same logic, trailer measurements should be directly related to interior noise since the tire vibration directly results in vehicle vibrations through direct transfer.

CONCLUSIONS REGARDING INTERIOR NOISE

Interior noise levels, measured concurrently with passby noise, were in the low to high 60 dB(A) range. Interior noise levels in the mid to high 60 range make conversation difficult. Sideline (passby) and interior measurements do not appear to be correlated. The vibration in the car is directly related to tire/frame excitation and does not include the propagation effects experienced at passby locations. Noise reductions achieved by pavements for highway neighbors may not achieve the same goal inside the vehicles.

Overall noise levels do not adequately describe the tonal qualities that may occur inside the vehicle. Tonal peaks, generated from transverse tining, may be particularly annoying. This generation of pure tones can be significantly reduced by the use of random tine spacing.

CHAPTER NINE

CONCLUSIONS

Numerous measurements have been made of pavement/tire noise using both the trailer and the passby methods, although no significant correlation between the methods has been shown. Summaries of select sample sets are included in this report to allow comparisons by the reader. Combining these types of data would be suspect since so many variables differ in each data set. Although a large undertaking, development of an "average" data base for various pavement types, speeds, and vehicles (multiple tire types) would be of great benefit to the end users.

In the absence of combined data sets, certain trends still seem clear from the literature review. PCC pavements have the advantage of durability and superior surface friction when compared to dense-graded asphaltic pavements. However, PCC pavements generally create more noise along the highway. Transverse tining seems to cause the greatest sideline (passby) noise levels. It also appears that the surface texture of uniform transverse tining, especially if spaced over 26 mm (1 in.), generates the most tire/pavement noise and the most annoying tones. However, researchers have reported that random spacing may reduce and even eliminate the annoying pure tone generated by transverse tining.

Longitudinal tining was found to reduce the overall noise levels, but at a cost of reduced surface friction when compared to transverse tining. Also, surface friction decreases more rapidly over time for longitudinal tining than transverse tining.

Texture depth of the transverse tining also seems important to sideline noise levels from PCC pavements. Australian test results showed that an increased depth led to a slight noise benefit, while trends for U.S. data showed even more benefit from increased depth. Some conflicting data in the United States suggest that other surface characteristics, such as tine spacing, construction techniques, and aggregate size, must also be considered concurrently.

Results show that the ". . . exposed aggregate surface appears to provide better noise quality characteristics. . ." This surface also has good frictional characteristics and could provide durability as well as noise reductions. This conclusion was echoed by several European studies. For example, an exposed aggregate surface with a top layer containing a maximum 8 mm (0.31 in.) aggregate size, showed a 5 dB(A) reduction when measured by the trailer method. A frequency analysis showed important reductions in the 500 to 2,000 Hz range that can cause annoyance as well. A significant noise reduction or frequency shift was not shown when U.S. researchers compared a transverse tined surface (26 mm (1 in.) uniform spacing)) with a European exposed aggregate texture design. Two states showed only a 1 dB(A) reduction. Construction techniques were thought to be the problem, especially aggregate size used in the final course. Similar construction problems in Australia reinforce this idea.

Porous PCC pavements may offer a variable noise abatement option. However, these pavements suffer from plugging, deterioration with freeze/thaw cycles, and reduced effectiveness when using deicing agents.

In general, when dense-graded asphalt and PCC pavement are compared, the dense-graded asphalt is quieter by 2 to 3 dB(A) and even more benefit is shown if the dense-graded asphalt is compared to transversely tined PCC pavements. The noise benefits of the asphaltic pavement are reduced with surface wear. Also, the dense-graded asphalt does not have the strong frictional characteristics of PCC pavements nor the durability.

Open-graded asphalt shows the greatest potential for noise reduction for passby noise. Reductions when compared to dense-graded asphalt ranged from 1 to 9 dB(A). However, the noise reductions seem to decline with surface age and in approximately 5 to 7 years, the noise benefit diminishes, although the surface is still quieter than most PCC pavements. Porous asphalt suffers in a fashion similar to porous PCC pavements from plugging, freeze/thaw impacts, and reduced effectiveness of deicing agents. Fortunately, frictional characteristics seem to be good for porous asphalt.

Other asphaltic surfaces, such as stone mastic and rubberized asphalt, also were thought to hold promise, but do not appear to give the noise reductions of open-graded asphalt or they have implementation problems.

Construction quality is an important consideration in the final overall noise generation, no matter which pavement type or texture is selected. It was shown that large variations in noise levels and frictional characteristics can occur from the same type of pavements if construction techniques or materials are varied.

Safety must always be considered. Some surfaces that may lead to noise reduction also have low friction numbers. It is the official FHWA policy that a small amount of noise reduction is not worth sacrificing safety or durability. This means that the practicing highway design engineer must try to find a "happy medium" between noise control and safety. This may result in decisions unpopular with highway neighbors.

A survey was also conducted to help guide this synthesis. The important findings included:

- About half of the 55 respondents had investigated noise effects from pavement surfaces.
- Standard pavement types are specified by a factor of 3 to 1 by states, territories, countries, and agencies.
- Most respondents would consider changing pavement types for noise abatement.
- The majority of road surfaces are asphaltic, PCC pavements rank second by a wide margin, and open-graded asphalt makes up the remaining fraction.
- The three areas considered most important for noise abatement are texture, speed, and tire tread.

More data is needed on safety considerations, such as wet weather accident rates for various textures. The pavement microtexture is extremely important in reducing wet weather accidents but not important for noise generation/propagation. However, macrotexture is needed for surface friction and is directly related to noise generation and propagation. The two must be considered together to reduce noise, but without sacrificing safety. Smaller aggregate sizes, less than 10 mm (0.39 in.), are needed for asphaltic surfaces to provide adequate frictional effects and result in reduced noise levels.

Differences in sound transmission mechanisms result in different trends for interior noise and exterior, sideline noise. The quietest pavement for interior noise may not be the same for noise at the side of the roadway.

In sum, more research is needed to address the issues of noise created by the tire/pavement interactions. Further analysis of the varying test results and findings is necessary to allow direct comparisons of different surface textures. New examinations should address potential improvements in the noise environment, without reducing overall safety or pavement durability. Work is also needed on standardizing test methods to properly measure and characterize tire/pavement noise and permit direct comparison of data by various researchers and regions. This would help lead to better design practices and construction. International Standards Organizations working groups are in search of such methods. Finally, additional guidance and direction should be developed to improve the decisionmaking process for pavement design and construction. This process must appropriately consider the relationships of safety, durability, noise, and economic cost. At present it is FHWA's official policy that a small noise decrease must not come at the expense of safety. However, the possible use of pavement type and surface texture for highway noise abatement seems a viable alternative.

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APPENDIX A

Survey Form

WE NEED YOUR HELP

Recent interest has centered around the varying amount of tire noise generated by different pavement types. Directly related to this has been the impact of surface textures on tire noise. Overwhelming evidence from studies have documented that variances in noise emissions do indeed occur from various pavement types and surface textures. However, the extent and specific impact of these changes in noise emission need to be further evaluated.

The intent of this request is to request your help in developing a comprehensive synthesis of what has been accomplished. *We need your help to make this possible.* Please answer the following questions as completely as possible and return to this questionnaire at your earliest convenience to:

Dr. Roger L. Wayson, Assistant Professor
University of Central Florida
Civil and Environmental Engineering
P.O. Box 162450
Orlando, Florida 32816-2450

You may also contact Dr. Wayson at:

telephone: (407) 823–2480
fax: (407) 823–3315
e-mail: wayson@pegusus.cc.ucf.edu

YOUR NAME: ______________________________

YOUR ADDRESS: ______________________________

____

____

TELEPHONE: ______________________________

FAX: ______________________________

E-MAIL: ______________________________

DATE: ________________

PLEASE NOTE: TO HELP WITH COMPLETING THIS SURVEY, QUESTIONS HAVE BEEN GROUPED ACCORDING TO EXPERTISE. QUESTIONS 1-8 ARE BEST ANSWERED BY NOISE ANALYSTS WHILE QUESTIONS 9-18 ARE BEST ANSWERED BY PAVEMENT/DESIGN ENGINEERS. QUESTION 19 APPLIES TO BOTH GROUPS.

1. Have you or your organization ever evaluated or investigated noise effects from various pavement types, surface treatments, or textures?

   YES NO (circle one)

   if YES, proceed.
   if NO, skip to question 4.

2. Please list and *briefly describe* any noise studies or measurements involving specific pavement types or surface textures that have been accomplished by you or your organization.

   [Please attach additional pages if necessary.]

3. Could you or someone in your organization be contacted in regards to projects or reports listed in question 2?

   YES NO (circle one)

   if YES, please provide telephone number or address.
   if NO, please continue.

4. Are you aware of any studies by other individuals or organizations involving pavement noise created by motor vehicles that you feel is important to the highway community?

YES NO (circle one)

if YES, please list below.
if NO, proceed.

5. Have you or your organization conducted studies on the effects of speed on noise emissions from various pavement types or surface textures?

YES NO (circle one)

if YES, please list below.
if NO, continue with Question 6.

6. Have you or your organization conducted studies on the effects of different tire tread types on noise emissions?

YES NO (circle one)

if YES, please list below.
if NO, continue with Question 7.

7. Have you or your organization conducted studies on the effects of different pavement types or surface textures on vehicle interior noise levels?

   YES NO (circle one)

   if YES, please list below.
   if NO, continue with Question 8.

8. What technical details do you consider to be the most important concerning tire/pavement noise (please list)?

9. What relative percentages of pavement types are used in your State, Territory, Country or Region? For example, asphalt (open-graded, dense-graded, overlay on jointed PCC), concrete (pourous or exposed aggregate), etc.

10. Does your State, Territory, Country or Region use standardized practices in specifying pavement types?

YES NO (circle one)

if YES, please list where the standard may be obtained.
if NO, proceed with Question 11.

11. Would your organization consider use of different pavement types for noise abatement?

YES NO (circle one)

if YES, what types.
if NO, please provide <u>brief</u> reason.

12. Has your State, Territory, Country or Region done any long term studies in regards to pavement wear?

YES NO (circle one)

if YES, please list below.
if NO, continue with question 13.

13. What types and relative percentages of pavement texturing are used in your State, Territory, Country or Region (as appropriate)?

14. Does your State, Territory, Country or Region use standardized practices in specifying pavement texture types?

YES NO (circle one)

if YES, please list source of standard below.
if NO, proceed with Question 15.

15. Would your organization consider use of different pavement textures for noise abatement?

YES NO (circle one)

if YES, what textures.
if NO, please provide reason.

16. Has your State, Territory, Country or Region done any long term studies in regards to pavement wear using different surface textures?

YES NO (circle one)

if YES, please list below.
if NO, continue with question 17.

17. Have you or your organization conducted studies on the effects of different pavement types or surface textures on surface friction?

YES NO (circle one)

if YES, please list below.
if NO, proceed with Question 18.

18. Have you or your organization conducted studies on the effects of different pavement types or surface textures on drainage or comfort of ride?

YES NO (circle one)

if YES, please list below.
if NO, proceed with Question 19.

19. If you listed any documents in Questions 2, 4-7, 12, and/or 16-18 would you provide them for use in this synthesis?

YES NO (circle one)

if YES, please send with survey or send as a separate mailing if possible.
if NO, please advise as to the availability of such documents.

THANK YOU! It is through the efforts of individuals such as yourself that permit these important studies to be completed.

PLEASE MAIL at your earliest convenience.

APPENDIX B

Acoustical Terms and Symbols

A-weighted noise level — A-weighted sound pressure level of an unwanted sound.

A-weighted sound pressure level (dB(A) — Sound pressure level measured by a system or an instrument (e.g., an SLM) that weights sounds at different frequencies in such a way as to mimic the human response to sounds. For instance, humans are less sensitive to sounds at low frequencies in the audible range; therefore, the contributions of sounds at low frequencies are "attenuated" by the A-weighting system. The system is usually an electrical circuit built into a sound level meter.

Absorption — In acoustics, the changing of sound energy to heat.

Absorption Coefficient — The dimensionless ration of absorbed to incident sound energy from a single interaction between a sound wave and a surface. Values range from 0 to 1.

Day-night sound level — The 24-hour equivalent sound level, in decibels, obtained after addition of 10 decibels to sound levels in the night from midnight up to 7 a.m. and from 10 p.m. to midnight (0000 up to 0700 and 2200 up to 2400 hours).

Decibel (dB) — One-tenth of a Bel, the unit used to compare the powers (or energies) of two signals. In acoustics, the signals are the sound pressure levels of two sources. The Bel is the logarithm of the ratio of two power-related quantities; thus, the decibel is ten times that ratio. In acoustics, the acoustical power is proportional to the sound pressure squared; hence, in acoustics, the decibel is 20 times the logarithm of the measured pressure to some reference pressure. Mathematically, $10 \log (p^2/p^2_{ref})$ or $20 \log (p/p_{ref})$, where p_{ref} is taken to be the threshold of hearing for the average listener at 1,000 Hz under free field conditions. Because the decibel is derived from the Bel, which in turn was named to honor Alexander Graham Bell, it is abbreviated "dB."

Diffraction — The act of sound waves traveling around obstacles.

Diffusion — The act of sound waves spreading out over a wide area after reflecting off a convex or uneven surface.

Equivalent sound level — A sound level typical of the sound levels at a certain place in a stated time period. As used in practice, the equivalent sound level in decibels is the level of the mean-square A-weighted sound pressure during the stated time period, with reference to the square of the standard reference sound pressure of 20 micro-pascals.

$$L_{eq} = 10 \log_{10} \left[1/T \int 10LA^{(t)/10}\, dt\right]$$

where

T is the length of the time interval during which the average is taken, and $LA^{(t)}$ is the time varying value of the A-weighted sound level during the time interval T.

Helmholtz resonator — A reactive, tuned, sound absorber (i.e., a perforated cover or slats at the entrance to a cavity).

Hertz (Hz) — A unit of frequency. One Hz is equal to one cycle per second. The unit was named to honor Heinrich Hertz, who conducted research in the area of pitch (and frequency) discrimination.

Hourly equivalent sound level — Equivalent sound level, in decibels, over a one-hour time period, usually reckoned between integral hours. It may be identified by the beginning and ending times, or by the ending time only.

Impedance (acoustic) — The ability of a medium to restrict the flow of acoustic energy, related to the cross-sectional area of the propagation path.

Impulse sound level	In decibels, the exponential-time-average sound level obtained with a squared-pressure time constant of 35 milliseconds.
Instantaneous sound pressure, over-pressure	Pressure at a place and instant considered, minus the static pressure there.
Maximum sound pressure level	Same as peak sound pressure level, provided that the time interval considered is not less than a complete period of a periodic wave.
Newton (N)	The force required to accelerate one kilogram at a rate of one meter per second per second. One Newton is equivalent to about 0.225 pound of force. The unit was named in honor of Sir Isaac Newton, who performed fundamental research in the area of particle dynamics.
Night sound level	Equivalent sound level, in decibels, over the nine-hour period from midnight to 7 a.m. and from 10 p.m. to midnight (0000 up to 0700 and 2200 to 2400 hours).
Noise	Any unwanted sound.
Noise level	Same as sound level, for sound in air. Some people use "noise" only for sound that is undesirable. A sound level meter does not, however, measure people's desires. Hence there is less likelihood of misunderstanding if what is measured by a sound level meter is called sound level, rather than noise level.
Octave	In music, a span of eight diatonic notes in pitch. (Written "8va" in musical shorthand.) In acoustics, one tone is an octave above another if its frequency is twice that of the other. Mathematically, two tones are an octave apart if the ratio of the frequencies of the tones is two to the first power. Two octaves are represented by a ratio of two to the second power, and so forth. Human response to pitch is approximately logarithmic; thus, the human perceives an octave between two notes as approximately the same, regardless of where the two notes occur in the audible range. Because the octave is a human subjective metric, it is used in evaluating the annoyance of noises in the field of psycho-acoustics. Ten octave bands cover the audible range for humans.
One-third octave (1/3 8va)	One-third of an octave, or two raised to the one-third power (26 percent). Acoustical engineers recognize that one octave is a rather broad range in frequencies, so the audible band has been subdivided into 30 (one-third octave bands in order to better understand the nature of noises.
Octave band	A band of frequencies 1/1 (1/3) octave wide, identified by the geometric mean frequency of the band. The 1/1 octave band center frequencies in the audible range are 31.5, 63, 125, 250, 500, 1,000, 2,000, 4,000, 8,000 and 16,000 Hz. The 1/3 octave band center frequencies in the audible range are 25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1.0k, 1.25k, 1.6k, 2.0k, 2.5k, 3.15k, 4.0k, 5.0k, 6.3k, 8.0k, 10.0k, 12.5k, 16.0k, and 20.0k Hz.
Octave band level	The sound pressure level of a given sound in a given 1/1 (1/3) octave band.
One-third octave band format	A format in which the 1/3 octave band levels are plotted against the corresponding 1/3 octave band center frequency. Since the values of these frequencies represent a geometric progression, they are equally spaced when plotted to a logarithmic scale.
Peak sound level	Greatest absolute instantaneous sound pressure in a stated frequency band, during a given time interval. (Also called peak pressure.)
Peak sound pressure level	In decibels, 20 times the common logarithm of the ratio of a greatest absolute instantaneous sound pressure to the reference sound pressure of 20 micro-pascals.
Reflection	Sound, impinging on surfaces that are large compared to the wavelength, will change direction where the angle of incidence is equal to the angle of reflection.
Refraction	The act of sound waves bending or changing propagation direction due to changes in medium or medium condition.
Slow sound level	In decibels, the exponential-time-average sound level measured with the squared-pressure time constant of one second.

Sound exposure	Time integral of squared, A-frequency-weighted sound pressure over a stated time interval or event. The exponent of sound pressure and the frequency weighting may be otherwise if clearly so specified.
Sound exposure level	The level of sound accumulated over a given time period or event. It is particularly appropriate for a discrete event such as the passage of an airplane, a railroad train, or a truck. Sound exposure level is not an average, but a kind of sum. In contrast to equivalent sound level, which may tend to stay relatively constant even though the sound fluctuates, sound exposure level in decibels is the time integral of A-weighted squared sound pressure over a stated time or event, with reference to the square of the standard reference pressure of 20 micro-pascals and reference duration of one second.
Sound level	The weighted sound pressure level, which reduces to a single number the full information about sound pressure levels across the frequency range 20 Hz to 20 kHz. It can be measured by a sound level meter that meets the requirements of American National Standard Specification for Sound Level Meters S1.4-1971. In these guidelines, fast time-averaging and A-frequency weighting are understood, unless others are specified. The sound level meter with the A-weighting is progressively less sensitive to sounds of frequency below 1000 hertz (cycles per second), somewhat as is the ear. With fast time averaging the sound level meter responds particularly to recent sounds almost as quickly as does the ear in judging the loudness of a sound.
Sound pressure	Root-mean-square of instantaneous sound pressures over a given time interval. The frequency bandwidth must be identified.
Sound pressure level	In decibels, 20 times the common logarithm of the ratio of a sound pressure to the references sound pressure of 20 micro-pascals (0.0002 micro-bar). The frequency bandwidth must be identified.
Vibratory acceleration level	In decibels, 20 times the common logarithm of the ratio of a vibratory acceleration to the reference acceleration of 10 micrometers per second squared (nearly one-millionth of the standard acceleration of free fall). The frequency bandwidth must be identified.
Wavelength	The distance between successive repeating portions of a pure tone sound wave.
Yearly day-night sound level	The day-night sound level, in decibels, averaged over an entire calendar year.

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