ROADSIDE TIRE NOISE

WA-RD 329.1

Final Report
March 1994

Washington State
Department of Transportation

Washington State Transportation Commission
Transit, Research, and Intermodal Planning (TRIP) Division
in cooperation with the U.S. Department of Transportation
Federal Highway Administration

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
WA-RD 329.1		

4. TITLE AND SUBTITLE	5. REPORT DATE
ROADSIDE TIRE NOISE	March 1994
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
James D. Chalupník and Don Anderson	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. WORK UNIT NO.
Washington State Transportation Center (TRAC) University of Washington, JD-10 University District Building; 1107 NE 45th Street, Suite 535 Seattle, Washington 98105-4631	11. CONTRACT OR GRANT NO. Agreement T9233, Task 30
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Washington State Department of Transportation Transportation Building, MS 7370 Olympia, Washington 98504-7370	Final report
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

This study investigated the noise produced by a single passenger vehicle tire heard at the roadside. This report presents the study's equipment and the development of the data reduction techniques. To choose test sites, selection criteria were applied that would prevent extraneous artifacts from influencing the results of the study. Special care was taken to minimize microphone wind noise caused by the high-speed turbulent flow of the measurement process. Measurements were taken on both old and new Class B asphalt, Class D asphalt, and portland cement concrete pavement. The results are presented in graphical form. The results indicated that the Class D asphalt surfaces measured in this study did not produce lower roadside tire noise, and these surfaces were no more acoustically absorbent than the other road surfaces.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Noise, traffic noise, tire noise, tire/surface interaction, roadway noise	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
None	None	35	

Final Report
Research Project T9233, Task 30
Roadside Tire/Pavement Noise Levels

ROADSIDE TIRE NOISE

by

James D. Chalupník
Professor
Department of Mechanical Engineering
University of Washington, FU-10
Seattle, Washington 98195

Donald S. Anderson
Acoustical Engineer
Environmental and Special Services
WSDOT District 1, 15700 Dayton Avenue N.
Seattle, Washington 98133

Washington State Transportation Center (TRAC)
University of Washington, JD-10
University District Building
1107 NE 45th Street, Suite 535
Seattle, Washington 98105-4631

Washington State Department of Transportation
Technical Monitor
Donald S. Anderson
Environmental and Special Services
WSDOT District 1

Prepared for

Washington State Transportation Commission
Department of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

March 1994

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Washington State Transportation Commission, Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Table of Contents

Abstract

This study investigated the noise produced by a single passenger vehicle tire heard at the roadside. This report presents the study's equipment and the development of the data reduction techniques. To choose test sites, selection criteria were applied that would prevent extraneous artifacts from influencing the results of the study. Special care was taken to minimize microphone wind noise caused by the high-speed turbulent flow in the measurement process. Measurements were taken on both old and new Class B asphalt, Class D asphalt, and portland cement concrete pavement. The results are presented in graphical form. The results indicated that the Class D asphalt surfaces measured in this study did not produce lower roadside tire noise, and these surfaces were no more acoustically absorbent than the other road surfaces.

Introduction

The principal source of noise from modern passenger automobiles are tires. Many studies have investigated the nature of tire noise and the interaction of the tire with the pavement, but little research has investigated the propagation of tire noise to the roadside and, particularly, the effect of the road surface on this propagation. One reason that this type of study has not been performed is that the noise generated by an individual tire is very difficult to isolate from noises produced by other sources such as the engine, transmission and differential, fan, aerodynamics, and the other tires. Some researchers have measured the noise generated by an individual tire by placing the measuring microphone very near the tire/road contact patch. This location is said to be in the "near field" of the noise source because the sounds arrive at the microphone from different directions, and the distance from the source to the microphone is much less than one wavelength of the sound being measured. No general models are available for predicting the sound level of a particular source from the sound level measured in the near field of that source. Each configuration must be evaluated separately. Thus, the purpose of this study was to create such a predictive model. Additionally, the effects of reflecting surfaces near the source have a profound effect on the propagation of sound to the far field, and the effects of such a surface must be included in any successful predictive model. Some road surfaces are believed to absorb more acoustic energy than others, resulting in lower noise levels at the shoulder of the road. This study investigated the interaction of the acoustic energy emitted by a passenger tire and six road surfaces as the noise propagate to the roadside.

Tire Noise

The mechanisms that produce tire noise are not fully understood, but they include sidewall and tread vibrations, tread impact on the roadway surface, and air pumping in the tread voids. Because there are many sources of tire noise, the effective position of the source is hard to identify. This leads to problems in measuring tire noise close to the tire in the near field. The spectrum and intensity of tire noise vary with position around the tire. In this study, the two microphone positions (90 and 135 degrees from the direction of travel) that are thought be most representative of the noise heard at the roadside were used.

Certain characteristics of the road surface -- notably, roughness, porosity, and compliance -- are also thought to affect the mechanisms that produce tire noise. In addition, some manufacturers and researchers claim that certain types of asphalt surfaces result in lower roadside noise levels. In particular, Class D asphalt (also known as open graded asphalt and drainage asphalt) is thought to be more acoustically absorbent than other road surfaces. The effect of this acoustic absorbency was studied in this project by measuring the noise generated by an isolated tire near the tire and then comparing the measurement with noise levels measured at the roadside for three types of roadway surface, portland cement concrete pavement (PCCP) Class B asphalt concrete pavement (ACP) and Class D ACP.

Study Goals

The goal of this study was to develop a model for predicting the level of tire noise at the roadside from measurements taken near the tire with the trailer method. The study will also evaluated the effect of the roadway surface on the propagation of noise from the source of tire/road noise (near field) to the roadside (far field). Because the roadside is in the far field of the noise, these data can be used to predict noise levels in the community by applying conventional laws that govern the propagation of sound.

In this study, a mathematical model was developed to predict the roadside noise level of a passenger vehicle tire at any roadside location for three pavement types on the basis of measurements taken with the trailer method. Evaluating the model required that microphones be placed in the near field of the tire and on the shoulder of the road. The mathematical model is referred to as the Magnitude Transfer Function (MTF). The MTF indicates changes in the characteristics of the noise between the two locations. Once the MTF has been determined, it can be easily applied to other data gathered with the trailer method.

Study Benefits

Use of the MTF model can help the Washington State Department of Transportation and other planning agencies improve the accuracy of their predictions when they assess the impact of building and resurfacing roads and reduce their costs.

To illustrate how the results of this study might be used, consider the following. The most common solution to a roadside noise abatement problem is to build noise abatement barriers. Noise barriers are expensive and work only in certain situations. In hilly areas, they can only protect a portion of the community. Another alternative is to resurface the road with a product that is less noisy or more sound absorbent. The advantage of this approach is that it may benefit properties near the roadway and it usually costs less than barriers. However, vendors are quick to extol the virtues of their products, but slow to substantiate their claims. Products for which remarkable acoustical properties are claimed may be no better than other, possibly less expensive, alternatives.

Tire noise measurements taken with the trailer method are simple and straightforward, and they can be performed quickly. This method can be used to quickly evaluate new surface treatments and processes, or even to "qualify" certain vendors' products or contractors' performances in installing roadway surfaces. Because the trailer method analyzes long stretches of road surface (as opposed to a single measurement point analyzed by roadside methods), the results are statistically more significant and more accurate than other methods used to rate tire/road noise. Roadside measurements are more difficult because of the need to isolate the noise of the test tire(s). The difficulties in measuring roadside tire noise were addressed in this study.

The MTF method can also be used with existing data obtained with the trailer method. The University of Washington Sound and Vibrations Research Laboratory (SVRL) has catalogued tire noise data taken with using the trailer method on over 180 sections of roadway around Washington State.

Study Design

Several different issues had to be considered to complete this project. These are discussed in the following sections.

Theoretical Considerations

A "transfer function" is a mathematical description of how a signal changes when it is acted on by a system element. To simplify the explanation, the system element can be thought of as a black box with an input and an output. The transfer function is the output divided by the input, if that mathematical operation can be performed. In the most general case, the transfer function describes the change in amplitude and the change in phase of the signal as a function of frequency. In this study, the "system element" was the path of propagation from a location near the tire to one at the side of the road, and the "signal" that changed was the Sound Pressure Level (SPL). A Magnitude Transfer Function (MTF) is similar, except that phase information is not included in the function, and only the magnitude of the amplitude ratio is given.

Test Setup

This study relied on positioning two microphones at precisely known locations, one near the contact patch of the tire/road interface and one at a standard roadside location. The SVRL has experience in taking measurements near the tire/road contact patch with the trailer method. The trailer used in the earlier studies was used in this study; however, it had to be modified substantially, as noted below. The chosen roadside location was one of the standard configurations used in traffic noise measurements, that is, 7.5 m from the lane of travel with an intervening lane and 1.2 m above the level of the roadway. The purpose of the intervening lane is to allow the sound to propagate over a representative section of surface treatment so that the way in which the surface affects the sound propagation can be observed.

Trailer and Tow Vehicle Configuration

Because of the constraints posed by the new test protocol, the trailer that had been used in the previous studies had to be modified. These modifications are discussed in the following sections.

Tow Vehicle

The tow vehicle used in this study was a 1985 Dodge half-ton, full-sized van provided by the WSDOT. The tow vehicle was equipped with a Class 5 type hitch. This type of hitch is rated for a maximum tongue weight of 140 kg and a maximum trailer weight of 1600 kg.

Trailer

The trailer was a 1.2- by 1.5-m flat-bed utility type with a single axle. To simulate the weight on a single axle of a typical passenger vehicle (an intermediate sedan), the trailer bed was loaded with approximately 600 kg of concrete blocks, for a total weight of 775 kg. The tires were Sears Superguard size 185/75R14. The configuration of this trailer before modification is given in reference described by Chalupník (1992) [1].

Placement of Trailer Microphones

Two trailer-mounted microphones were used in this study. The SVRL standard microphone position is 90 degrees relative to the direction of travel, 20 cm from the outboard edge of the contact patch and 45 degrees above the road surface. The other microphone position is similar, but 135 degrees relative to the direction of travel.

Tow Vehicle Noise

The tow vehicle provided by the WSDOT had performed satisfactorily in previous tests because the noise was measured only 20 cm from the tire/road contact patch. The nearest noise source on the tow vehicle in those tests was nearly 3 m from the microphone. In that configuration, the signal-to-noise ratio was computed to be greater than 24 dB, which is acceptable. However, the signal-to-noise ratio for the test tire at a roadside location with that configuration (less than 4 dB) would have been unacceptable. In order to improve the signal-to-noise ratio, it was decided to lengthen the trailer by extending the tongue as far as possible.

The maximum trailer length permitted on Washington State highways is 14.6 m (RCW 46.44.030). This trailer length would provide about a half-second gap between the tow vehicle and the trailer at maximum permissible highway speed limit of 89 km/sec. This gap would be just enough for this study.

The design of the tongue extension was not trivial. With almost 15 m between the rear axle of the tow vehicle and the trailer axle, the combination was difficult to maneuver on city streets between the University of Washington campus and the nearest interstate access. The trailer tongue extension had to be removable for transport and storage, and it had to be easy to assemble and disassemble at a test site. In the final configuration, the tongue extension was made of two 6-m lengths of 10-cm square extruded aluminum box beam that could be assembled and disassembled in the field by two people using conventional hand tools. A guy-and-spreader arrangement was employed to stiffen the tongue. The disassembled tongue was transported to and from the test sites on a roof rack on the van. The extension was assembled at the test site with eight bolts. The guy wires were attached with shackles and were tensioned with large turnbuckles. Setup took about 30 minutes for all the hardware and electronic equipment associated with the trailer.

The tow vehicle/trailer combination was one of the longest vehicles on the road. A sign warning motorists was mounted on the rear of the trailer, and two rotating flashing lights and four running lights, in addition to the required running, brake, and license plate lights, were added to the trailer. The trailer was designed to withstand a 1900-N load applied to the rear of the trailer for protection from minor rear-end collisions.

Roadside Instrumentation Configuration

Test Site Selection

The first criterion of a test site was that the pavement surface be the proper type and age. The three types of road surfaces in this study were Class B asphalt, Class D asphalt (also known as open graded and drainage asphalt), and portland cement concrete pavement (PCCP). The effects of age are also included in this study; therefore, a new and old section of each surface type are included. For the purposes of this study, a new surface are one that was laid within the last two years, and an old surface are one that are older than 6 years for asphalt and older than 20 years for PCCP. The life expectancy of an asphalt surface are typically 8 to 10 years, whereas PCCP can last for as long as 30 years.

An initial survey was made of all the road sections in WSDOT District 1 that might be used in this study. The list was shortened to include only sections of the types listed above and of appropriate age, where the posted speed limit was at least 89 km/hr, and where the sections were flat and straight.

The criteria used to determine test site acceptability were based on a United States Department of Transportation (USDOT) report entitled "Sound Procedures for Measuring Highway Noise" [3] and a report by the Swiss Road and Traffic Research Institute on the evaluation of the trailer coast-by method [2]. The test site requirements for this study follow.

1. The test site had to consist of a level open space free of large reflecting surfaces, such as parked vehicles, signboards, buildings, or hillsides within 30 m of either the vehicle path or the microphone.
2. The microphone had to be located 7.5 m from the centerline of the traffic lane that the tow vehicle was traveling in and 1.5 m above the road surface.
3. The sound should travel over one entire lane width before being measured by the roadside microphone.
4. No obstruction could be within 15 m of a microphone position or the lane of travel at the passing point.
5. The surface of the ground within the measurement area had to be free of snow and could be hard ($\alpha = 0$) or soft ($\alpha = 1/2$).
6. The vehicle path had to be relatively level (less than 2 percent grade), smooth (free of seams, potholes, and other discontinuities), dry (open graded asphalt had to be dry for at least 48 hours), and free of extraneous material such as gravel.

7. The existing sound level (including wind effects) coming from sources other than the individual vehicle being measured (including other vehicles) had to be 10 dBA less than the test vehicle. The tow vehicle noise had to be at least 6 dBA less than the trailer tire noise if there was to be compensation for the tow vehicle noise.

The test site requirements were not particularly difficult to satisfy, but finding a safe, wide shoulder was difficult. This problem severely constrained the search, and only five of the required six sites were found in District 1. Missing was a new section of Class D ACP. The search was extended to adjoining highway districts, and a suitable section was found in District 3 south of Chehalis.

Table 1. Test Sites Included in Study.

Surface type	Road	Age	Section
Old Class B	SR 530	8 years	NB MP 5.0
New Class B	SR 202	2.5 years	WB MP 22.2
Old Class D	I-5	9 years	NB MP 138.5
New Class D	I-5	20 months	SB MP 72.0
Old PCCP	I-5	30 years	SB MP 148.0
New PCCP	I-405	4 years	NB MP 0.2

Instrumentation

Roadside Microphones

The two roadside microphones were placed 30 m apart and 7.5 m from the center of the lane of travel of the tow-vehicle/trailer combination. Having two microphones in this configuration provided double the data per run and better average sound levels of the road surface. The roadside microphone that the trailer traveled past first was called channel 1, and the other was called channel 2.

A noise shield was placed on the downstream side of each roadside microphone to block the noise from the tow vehicle when the trailer was closest to the roadside microphones. This improved the signal-to-noise ratio of the system by several decibels and resulted in a signal-to-noise ratio of between 6 and 10 dB, depending on which side of the van the roadside microphones were.

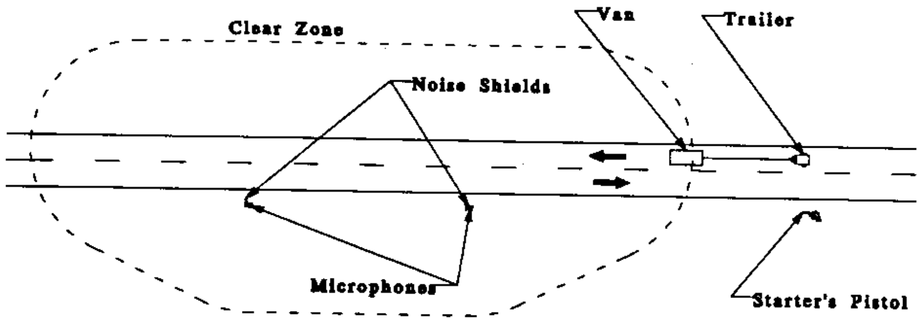

Figure 1. Test site configuration for a two-lane highway. The configuration for multiple lane highways was similar.

The noise shields were 1.2-m wide and 1.5-m high. They were constructed from 5- by 10-cm lumber and 6.4-mm plywood. The shields had three legs, one of which folded to facilitate transporting them. Each leg was anchored by a 18-kg concrete pier block. This configuration resulted in a very stable structure that could be quite close to a traffic lane without wiggling from the wind produced by passing traffic (even large trucks). The plywood was covered with a 2.5-cm fiberglass duct-board sound absorber to avoid reflecting unwanted sounds into the roadside microphone. The absorption coefficient for this material ranged from 0.6 to 0.95 in the frequencies of interest.

Other Instrumentation

This study required an extensive collection of instruments. For consistency, each piece of equipment was used in the same position for all data taken in this study.

The four microphones used in this study were all 1/2 in. diameter. Two of them were B&K models 4133 and 4165, one was a Larson Davis Labs model 2560, and one was an ACO model 7012. Two of the preamplifiers were B&K models 2619 and 2639, and the other two were Nagra model OJ.IV. The microphones were always calibrated with the same B&K 4230 calibrator. The calibrator had a calibration level of 93.6 dB for the omni-directional microphones used in this study.

Each microphone used on the trailer was covered by a B&K UA 0386 bullet-shaped nose cone, a B&K UA 0237 foam wind screen, and a custom-made wire-frame wind screen (discussed earlier) over both microphones. The roadside microphones were fitted B&K UA 0237 foam wind screens. The B&K preamplifiers were powered by a B&K 2804 phantom power supply, and a custom-made phantom power supply provided power for the Nagra preamplifiers and polarization voltage for the microphones.

The data were recorded on two Teac DA-P20 portable dual-channel DAT recorders. Each tape recorder had an internal rechargeable battery pack for field use. The DAT recorders had sequential serial numbers.

The data were transferred to a computer through the digital output of the DAT recorders and a data acquisition card in the computer. The data acquisition card was a Digital Audio Labs model "The CARDD" with "The I/O CARDD" daughter board. The CARDD was for analog input and output, and The I/O CARDD was for digital input and output. The boards came with a simple program to record and play data on the computer. Once recorded on the DAT recorders, the data were manipulated in digital form.

The computer used to analyze the data in the SVRL was a Tektronix PEP 301 16-MHz 386-class machine with 3 MB of RAM, a math coprocessor, and a 120-MB integrated device electronics (IDE) hard disk. This computer was the minimum configuration that would work with The CARDD. The data from each test site occupied approximately 20 MB of disk space. Because of the lack of storage space on the SVRL computer, the data were transferred to the author's computer (which was a more capable 486DX computer) for the data reduction and ultimately archived on an HP workstation. If needed in the future, the data can be retransferred to the computer from the DAT recorders or retrieved from the HP workstation.

Testing Procedures

The temperature of the road surface was recorded with a pyrometer before any data were taken at a test site and then again after all data had been taken. One problem was the question of how temperature affects the binder in asphalt. Tire noise has been noted to change with temperature [1]. Because Class D asphalt is thought to be more acoustically absorptive, its acoustic properties may be particularly temperature dependent. However, because the Class D asphalt was measured at night, there was little difference in temperature between test sites.

Data from previous studies were used to calculate a temperature dependency of the tire noise. Approximately 50 sets of data were available for Class B asphalt, Class D asphalt, and PCCP. The temperature/sound-pressure-level relationship is shown in Table 2. They can be applied to pavement with a temperature of between 4°C and 38°C.

Table 2. Temperature Dependency of Tire Noise.

Pavement type	Temperature dependency (dB/°C)
Class B asphalt	-0.059
Class D asphalt	-0.139
PCCP	0.031

Wind velocity was also noted. Tests were not performed if the wind speed was above 8 km/hr.

All tests were performed on open, public roads. It was not safe to perform tests using the coast-by method with a tow vehicle on these roads. Also, the trailer was required to maintain 89 km/hr through the test section for this study, which was extended because of the two microphones. The speed was monitored with the vehicle speedometer, which was calibrated.

The data were recorded on two identical DAT recorders. One recorder was placed in the tow vehicle, where it recorded the trailer microphones, and the other recorder was placed on the roadside to record the roadside microphones. The recorders had an absolute time counter that was recorded on the tape. The exact time displayed on each recorder was noted for each pass-by, along with any other information, such as traffic, that contaminated the data.

A starter's pistol was used to insert a timing mark in the data recorded by both of the DAT recorders. The starter's pistol was positioned 45 m up the road from the first roadside microphone. The pistol was fired as the tow-vehicle/trailer combination was driven past, at the point where the trailer was abreast of the pistol operator.

Two-way radios were used to coordinate activities in the tow vehicle and the roadside personnel. On two-lane roads, use of the radios allowed the tow vehicle to wait until oncoming traffic had passed the test site. The radios also were used to notify roadside personnel of the tow vehicle's approach so they could start the data recorders and fire the starter's pistol. Even with the radios, approximately half the data runs were discarded because of traffic and data recorder coordination problems.

Typically, the time required for the driver to turn around and reposition the trailer for another run ranged from 7 to 30 minutes. To perform 10 to 12 runs, a data collection session would last from 2 to 4 hours. Of the 10 to 12 runs, usually 5 or 6 were acceptable.

The roadside microphones were calibrated before and after a data collection session. The trailer microphones were calibrated beforehand because of the time required to assemble the wind screens and microphone bracket. To ensure that the record levels would not change on the DAT recorders, the record level controls were secured.

Analysis

Data Analysis

The products desired from this study were the MTF using a short time average, the MTF at the maximum (both resolved to third octaves), and the maximum roadside A-weighted SPL for each test surface. These calculations had to be performed on a data series that was only 250 msec long.

After inspecting the specifications for all of the instruments available in the Department of Mechanical Engineering, the researchers concluded that none would perform the desired task quickly enough to work in this application. Instruments that perform real-time, one-third-octave band analysis are available, but they are expensive. Brüel & Kjær manufactures one, for instance, but the price is $29,900, and that far exceeded the equipment budget allowed for this study. Even with that instrument, problems would still have arisen in to synchronizing the signals.

Data were stored on the DAT recorders in digital format, which is a very stable form of storage, and, of course, digital computers use this form of storage in their memory. A decision was made to import the data from the DAT recorders to a computer where they could be further analyzed. This would not be in "real time," but with the data in digital form, real-time computation was no longer a requirement.

Two approaches to analyzing the data are available on a computer. The most common method is the Fast Fourier Transform (FFT) method. An alternative method is the Digital Filter (DF) method. Computer codes for performing FFT analysis are readily available, but it converting the output from these codes into one-third-octave bands is awkward, and using this approach for samples of short duration creates further complications. On the other hand, the DF approach works well in one-third-octave bands and provides a pseudo real-time output in these bands.

Computer code that incorporated a filter set conforming to the American National Standards Institute (ANSI) standard S1.11-1966 (R1976), Class III, type E, was written in the C programming language for implementation on IBM compatible PCs [4]. This type of one-third-octave filter is the highest quality filter defined in the ANSI standard. The ANSI standard specifies filters by the allowable transmission loss in the stop bands and the maximum allowable ripple and loss in the pass band. These filters are typically constructed by cascading second-order, or two-pole, bandpass elements. A Class III filter may be constructed with six, eight, or more poles. Computational time increases with the number of poles used, so the minimum number was used for each filter section. Our filter set was made up of 30 six-pole filters.

Averaging Technique

The one-third-octave filters have a time constant of about five periods of the filter center frequency. This results in time constants that vary from about a quarter of a second for the 20-Hz filter to less than a millisecond for the 20-kHz filter. The settling time for the one-third-octave filters is about 10 periods of the filter center frequency. This is different than the time constant commonly used in sound level meters.[1] Because the critical one-third-octave filters are the ones between 400 Hz and 10 kHz, which have time constants that are much less than the desired 125 ms, all the one-third-octave bands were run through an exponential averaging filter with the desired 125 ms time constant. The output file after time averaging had taken place varied slowly with time, so it was possible to reduce the size of these records by a process of decimation.

Implementation on a Computer

Personal computers (PC) running Microsoft DOS were chosen as the platform for the digital signal processing because the processing requirements for this project were reasonable for a PC, the data were collected on a PC, and the programmer's development tools for a PC were among the best that can be obtained. Another advantage of the PC was that the disk storage requirements for this study were about 100 MB. Finding this amount of storage on a campus computer was quite difficult. None of the systems the author inquired about could offer these resources.

This program required about 5 MB of memory for working space. This meant that a 16-bit compiler would not work, so a 32-bit compiler was needed (which also meant that the computer had to have either a 386 or a 486 processor). The C programming language was chosen because C compilers are generally the most robust, and the executable program produced by a good C compiler is usually second in speed only to assembly language. The 32-bit Whatcom C compiler was chosen for its robustness and reputation.

A series of routines were written to transfer the data from the DAT to the computer, filter the data into one-third-octave bands, exponentially average the data in the bands and decimate these signals, then write the data into storage files. All of these routines were written in C.

[1] There are actually two time constants, or meter response, settings on most sound level meters. The "fast" meter response corresponds to 125 ms and the "slow" response corresponds to 1.0 sec.

Visualization in Excel

The Microsoft electronic spreadsheet Excel contains convenient tools for handling data interactively and for presenting and formatting data graphically. Excel is quick and interactive, and it can handle large data files using virtual memory. The data were imported into Excel, where the running A-weighted sound pressure level of the MTF was calculated and displayed. Figure 2 is a sample chart of a portion of the filtered data from a roadside microphone. The timing signal from the starter's pistol is visible at 0.25 sec. The trailer data are essentially constant with time.

All data from a test site were kept in a subdirectory created for that test site. The raw data files were archived to an HP workstation after they had been filtered (they could always be retrieved from the HP workstation or from the DAT tapes at a later time). There were three groups of data: 1) the near field of the trailer tire, 2) the van and trailer combination recorded from the roadside, and 3) the van alone. The last data set was used to remove the van noise from the van-and-trailer data to further improve the signal-to-noise data. Details of how this was done can be found in the thesis describing this project.

The tire noise level at the roadside location was mostly dependent on the distance between the tire and the roadside microphones. This dependency can be calculated from simple geometry and the inverse-square law of acoustics. In this study, this dependency was calculated, and the inverse relation applied to the data after the van noise had been removed from the roadside data. This allowed us to average over a longer time period when calculating the MTF.

The maximum A-weighted roadside sound level was computed using the band levels after the van noise had been removed, but before any distance compensation had been applied. The band levels were A-weighted and combined into a total level, and the maximum level was recorded.

There were four MTFs (a maximum value and an average MTF for each trailer channel) and one maximum roadside A-weighted SPL. These results were very compact and are summarized in a final spreadsheet (Appendix B). From this summary, comparisons and plots were easily made (see Results).

Error Analysis

The sources of errors in this study can be broken into three categories. The first category includes the study design and the environment in which the study was performed, the second includes the equipment, and the third includes the analysis techniques applied to the data. The errors are summarized in a table at the end of this section.

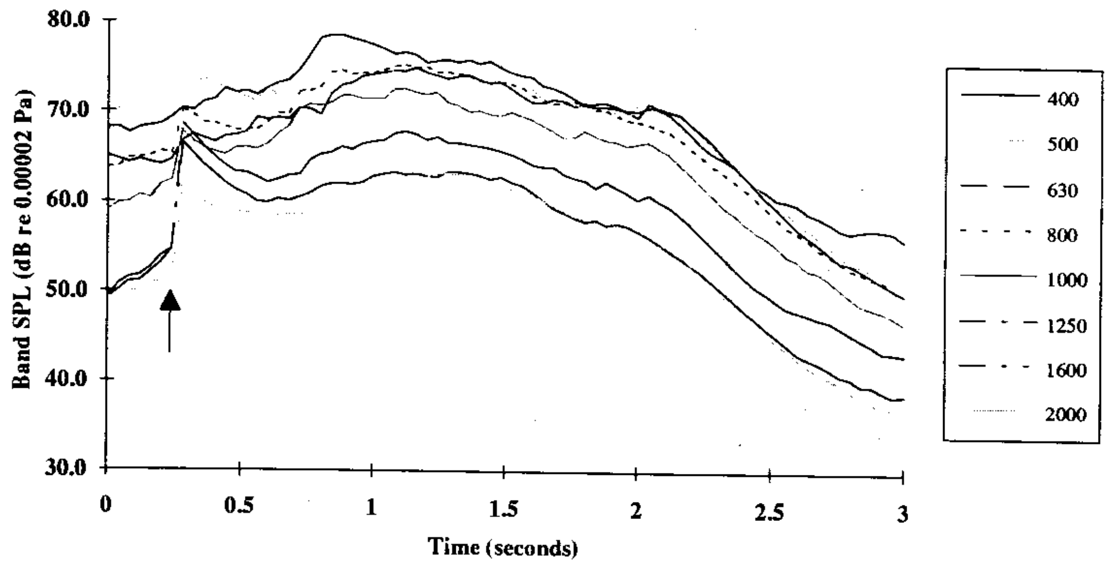

Figure 2. Sample Filtered Output of Roadside Measurements. The timing signal from the starter's pistol is visible at 0.25 sec.

An error can be classified as either systematic or random. A systematic error occurs consistently in magnitude and direction relative to the true value of a point. A random error varies in both magnitude and direction from the true value. The distribution of random errors in this study was assumed to be Gaussian (also known as a normal distribution).

An error that originated from the source and was measured by all four microphones would have affected the MTF in a systematic way. Because the MTF is the ratio of the roadside noise levels to the near-field noise levels of the tire, an error originating from the source would be divided out of the MTF. Because this type of error would have no effect on the MTF, this type of error is classified as systematic. Some equipment errors would also have this effect on all four microphones and therefore divide out of the MTF. All other errors would affect both the MTF and the maximum roadside level.

Error Sources From Study Design and Environment

Sources of error from the study design and environment included the following: noise from the tow vehicle, inconsistencies in the tow vehicle speed and track from run to run, variability in the road surface texture, temperature dependency of the noise-generation mechanism in the road surface, effects of topography on the roadside microphones, ambient wind velocity, and wind noise in the trailer microphones.

Tow vehicle noise was the only noise competing with noise from the trailer tire (the other trailer tire was shielded) and was the single largest error source in this study. The signal-to-noise ratio, then, was the ratio of trailer tire noise to van noise. Every effort was made to reduce the noise from the van, as described above. In addition to using an elongated tongue on the trailer, noise barriers were strategically placed near the roadside microphones to further improve the signal-to-noise ratio. With the noise shields in place, signal-to-noise ratios ranging from 6 to 10 dB were obtained. The signal-to-noise ratio was also frequency dependent. The van noise was removed from the total noise measured by the roadside microphones using the method described previously. The systematic effects were removed by this operation, leaving only the random effects.

Tire noise is strongly dependent on vehicle speed. The tow vehicle speedometer was checked against measured miles along certain stretches of freeway. The driver of the tow vehicle kept the tow vehicle within 3 km/hr of 89 km/hr. Any time the tow vehicle speed deviated from 89 km/hr by more than 2 km/hr, the data collected during that time were discarded. This error was measured by all four microphones and did not have an effect on the MTF. Because variations in the vehicle speed were random (because the speedometer was correct), the effects on the roadside SPL were random, also.

There are no ruts or wear patterns on a newly laid road surface, so the path of the tow vehicle on a new road should not affect tire noise. On a worn road surface, particularly the PCCP surface, ruts develop and the large aggregate is exposed. It was important that the trailer tire travel in this rut to produce the noise in the proper location and of the proper spectrum. In the cases of deep ruts in the roadway, the center of the lane was considered to be the center of the two ruts. Typical ruts were wide enough that it was not especially difficult to drive down their middles, and the ruts had a centering effect on the trailer. The data collected when the trailer was not in the rut or worn section of an old roadway were discarded.

Inconsistencies in the road surface would affect the noise output from the trailer tire. Road surfaces at the test sites were inspected for imperfections and inconsistencies, and only sites free of cracks, chuck holes, and obvious imperfections were used in this study. Any inconsistencies that passed the inspection produced only minor changes in the tire noise. A section of the road was also averaged; therefore, a small local imperfection would have a much smaller effect on the result. Furthermore, this error systematically affected all four microphones and therefore did not affect the MTF. This source of error would also systematically affect the maximum roadside level.

There is some temperature dependency on the noise-generation mechanism in the road surface, particularly with asphalt surfaces. All data for this study were taken during the same time of the year, so the temperature differences were not large, but it is desirable to factor the effects of temperature into the results of this study to improve their accuracy.

The previous study [1] showed that tire noise changes from winter to summer. This dependency is not fully understood, but the temperature difference encountered was assumed to be solely responsible for the change in tire noise, as other factors were held constant. The trend is for tire noise to be lower with warmer asphalt surfaces. How the absorptive properties, if any, of the road surface are affected by temperature is unknown. An attempt was made to minimize the temperature differences between the old and new road surfaces tested in this study. If the absorptive properties of the road changed, this would affect both the MTF and the maximum roadside SPL as a systematic error. Temperature-induced changes in tire noise would not affect the MTF, but they would affect the maximum roadside SPL as a systematic error. Because of the uncertainty in temperature dependency, the error for this effect was chosen to be equal to the correction factor used for the maximum roadside SPL.

The criteria for selecting a test site were based on a report published by the USDOT [3] and are discussed in a previous section. Test sites selected had no obstructions (such as buildings, signs, hills, Jersey barriers, guard rails, or curbs) within 50 ft of the centerline of the lane of travel. Because no obstructions were present, they should not have produced errors in the results of this study.

Wind can affect noises in two ways important to this study. The first is wind noise in the roadside microphones and the second is the tendency for wind to carry the sound, changing the effective distance between the trailer tire and the roadside microphones. Foam wind screens were used over the roadside microphones, which effectively eliminate wind noise in the microphones from wind speeds of up to about 16 km/hr. As a conservative measure, the study was not performed with ambient winds above 8 km/hr. Error contribution from the ambient wind should have been negligible.

Wind noise in the trailer microphones was a significant problem. With only a foam wind screen, the turbulent flow dominated the tire noise in the one-third-octave bands below 630 Hz. The special wind screen built for this study improved this, so that only the one-third-octave bands below 400 Hz were dominated by wind noise. The one-third-octave bands below 630 Hz or 400 Hz, depending on the wind screen used, were not included in the analysis of the MTF. Information from the trailer microphones were not used in determining the maximum roadside SPL, so the low-frequency end of the audio spectrum was included in that analysis.

Motion of the trailer produces a Doppler shift in the sound of the moving trailer observed at the roadside. The shift varied from +5 percent to zero to -5 percent during the period when the data were accepted for this study. A five-percent shift corresponds to one-fifth of a third octave -- a very minimal effect (considering that there were no pure tones contained in the data), which was ignored in the analysis.

Error Sources From Equipment

The microphones, preamplifiers, calibrator, DAT recorders, and the computer constituted the components of the second category of errors. The microphones, preamplifiers, and calibrator were instrument-grade products. When the microphones were properly calibrated using the calibrator, these errors were insignificant when compared to other errors present in the study.

There were three potential errors from the DAT recorders: 1) ripple in the frequency response, 2) quantization errors, and 3) A/D converter errors. The specifications stated that there be less than 1-dB ripple in the frequency response through the audible band (20 Hz to 20 kHz). The quantization errors from data that were digitized in 16-bit samples were 0.002 percent when the record level was set so that the signal peaked at the maximum level. A typical record level used in this study was 20 dB less than maximum, which resulted in a quantization error of 0.02 percent. This error was so small that it was assumed to be negligible. The DAT recorders had a clipping indicator, and the filter program also checked for clipped data. No data were used where the signal was clipped.

Error Sources From Analysis Techniques

The third category of error sources arose after the data had been collected and transferred to the computer. The filtering was done with digital filters, and then the runs were averaged and plotted using Microsoft Excel.

Aliasing was the only cause for distortions with the digital filter. The distortion from aliasing grows rapidly as the frequency of a signal approaches the Nyquist frequency. Qualitative checks indicated that the distortion ranged from a few percent at 10 kHz to well over 10 percent at 20 kHz. The amount of energy in typical tire noise above 10 kHz is small, and sounds in these higher bands are easily attenuated. Because the amount of distortion is questionable in the highest one-third-octave band, these bands were also discarded. These errors were negligible for the range of the audio spectrum used for both results.

Tire noise is random in nature, and therefore, the plots of the data were not perfectly smooth, making it difficult to time-align each of the runs to better than 0.05 sec (corresponding to the trailer traveling 1.2 m). Peaks in the noise level were significantly broader than 0.05 sec; hence, this type of error was rather small.

Each of these errors is listed and summarized in Table 3, below.

Table 3. Summary of Errors.

Error	Error size	Effect MTF	Effect maximum roadside level
Tow vehicle noise	±1.2 dB	Yes	Yes
Vehicle speed	±0.25 dB	No	Yes
Road surface	±0.5 dB	No	Yes
Temperature of road	±0.25 dB	No	Yes
Wind noise	Negligible at or above 400 Hz	Yes	No
Frequency response of DAT recorders	±1 dB	Yes	Yes
Aliasing	Negligible below 10 kHz	Yes	Yes
Averaging	±0.25 dB	Yes	Yes

The errors listed in the table represent the 90-percent confidence interval of the error. The expected error was calculated using the root sum square (RSS) method.

$$Expected\ Error = 10\,\mathrm{Log}_{10}\left(1+\sqrt{\sum_i\left(10^{\frac{Error_i}{10}}-1\right)^2}\right)\ dB \quad (4\text{-}1)$$

This total error in the MTF was ±1.5 dB, and the total error in the maximum roadside SPL is ±1.6 dB. For comparison, the 90-percent confidence interval in the measured MTF data is ± 0.7 dB. The 90-percent confidence interval in the measured roadside maximum SPL data was ± 0.4 dB. This shows that the predicted errors in Table 3 are conservative.

Results

The data were processed using the one-third-octave filtering program developed for this study and then further reduced using Microsoft Excel, as described in the previous section. This process reduced the data to just a few pages in the final spreadsheet that can be found in Appendix B. This final spreadsheet, called *results.xls*, contains the averaged MTFs, the maximum MTFs, the roadside noise levels in third octaves, and the A-weighted SPL in decibels. The overall tire noise of each microphone channel on the trailer in A-weighted decibels is also summarized in this spreadsheet.

Channel 1 and Channel 2 of the trailer microphones recorded slightly different sound spectrums and intensities because various mechanisms produce tire noise. Channel 1 was more sensitive to the sidewall vibration because of the proximity and orientation to the sidewall. Channel 2 was more sensitive to tread vibrations because there was a line-of-sight path from the microphone to the tire tread. Both trailer channels were compared to the same roadside data in the MTFs. For the averaged MTF, the roadside data were distance compensated and averaged over time. For the maximum MTF, the data sample was taken at the instant the trailer was abreast of the roadside microphones. The differences between the Channel 1 and Channel 2 MTFs were a result of differences in the placement of the two trailer channels.

The temperature dependency was found only for the overall noise levels. Data were not available on this subject in third octaves.

Averaged Magnitude Transfer Functions

The averaged MTFs are shown in figures 3 and 4 for Channel 1 and Channel 2 of the trailer, respectively. The error band on the MTFs was ±1.5 dB, as discussed previously. The averaged MTFs are useful for showing the spectral differences. The overall differences are presented later.

Both the new and the old Class B asphalt had an interesting maximum in the 1600-Hz one-third-octave band of the Channel 1 MTF. It is likely that this peak had something to do with the aggregate size in the asphalt. An aggregate size of 5/8 in. would induce 1600-Hz vibrations in the tread. This peak indicates that the Channel 1 microphone was not picking up the tread vibrations as much as they were heard on the roadside, or the asphalt was particularly nonabsorbent at this frequency band. The peak at 1600 Hz was about 5 dB higher than the surrounding points. It is unlikely that the asphalt was 5 dB less absorbent at this frequency band than at the adjacent frequency bands.

The Channel 2 MTFs for the six asphalt types were more tightly grouped with less randomness. The size of the MTF in the midrange bands (630 Hz to 1600 Hz) for this channel also corresponded well to overall drop in A-weighted SPLs.

In the Channel 2 MTFs, higher frequencies had less attenuation. The two possible reasons for this are that the asphalt was significantly less absorbent or the Channel 2 microphone position was not receiving much of the high-frequency information. This trend may have been a result of the microphone placement for two reasons. First, the far field was closer to the source with higher frequencies, and, therefore, the signal would be attenuated close to 6 dB per double the distance. The total attenuation should have been approximately 25 dB if the microphone marked the beginning of the far field (which was not unreasonable for the 10-kHz one-third-octave band). Second, it is unlikely that all road surfaces have this same trend. Therefore, much of the high-frequency noise was probably produced by the sidewall of the test tire.

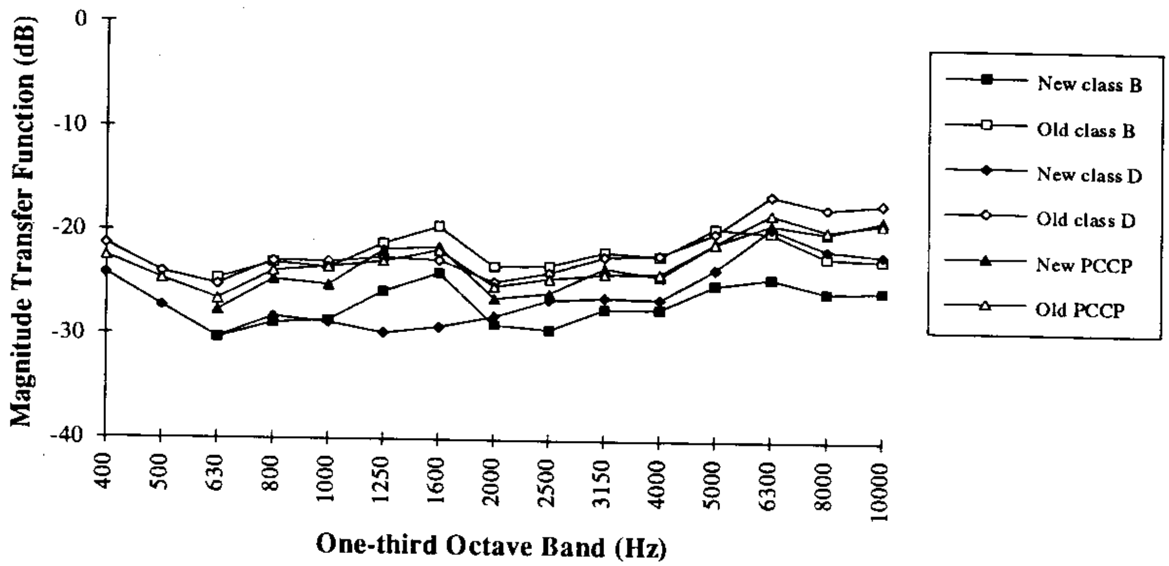

Figure 3. Averaged magnitude transfer functions using Channel 1 trailer data. (Error band, ±1.5 dB)

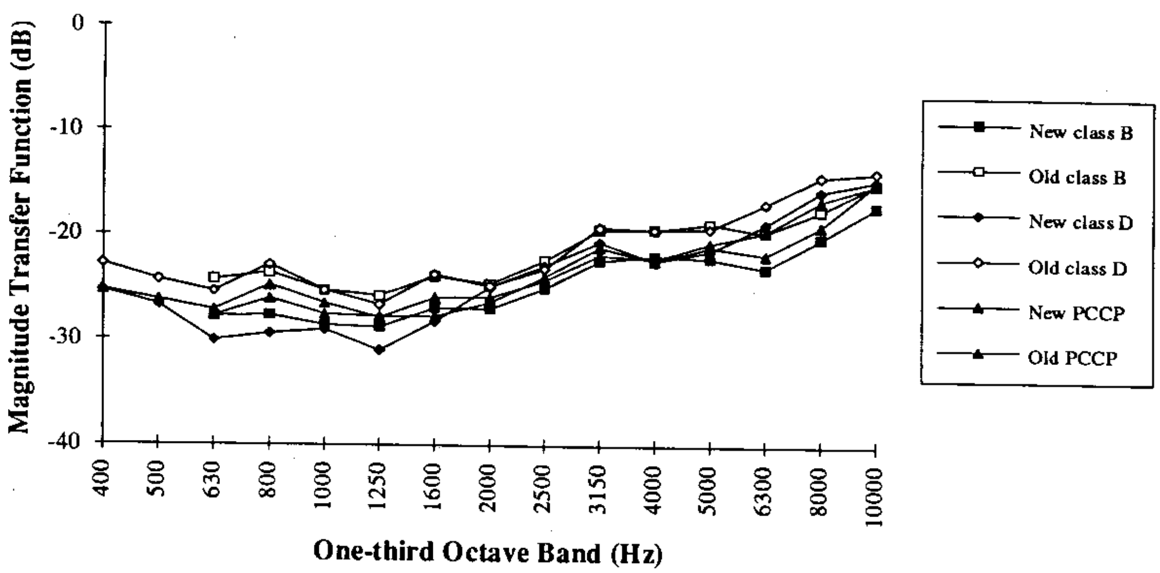

Figure 4. Averaged magnitude transfer functions using Channel 2 trailer data. (Error band, ±1.5 dB)

Maximum Magnitude Transfer Functions

Figures 5 and 6 show the MTFs at the maximum of the roadside noise levels (corresponding to the trailer being abreast of the roadside microphones). The MTFs at the maximum roadside level closely followed the peaks and the trends present in the MTFs that were averaged. This result implies that the roadside microphones were, indeed, in the far field of the trailer tire, and that most of the sound absorption in the asphalt occurred near the source.

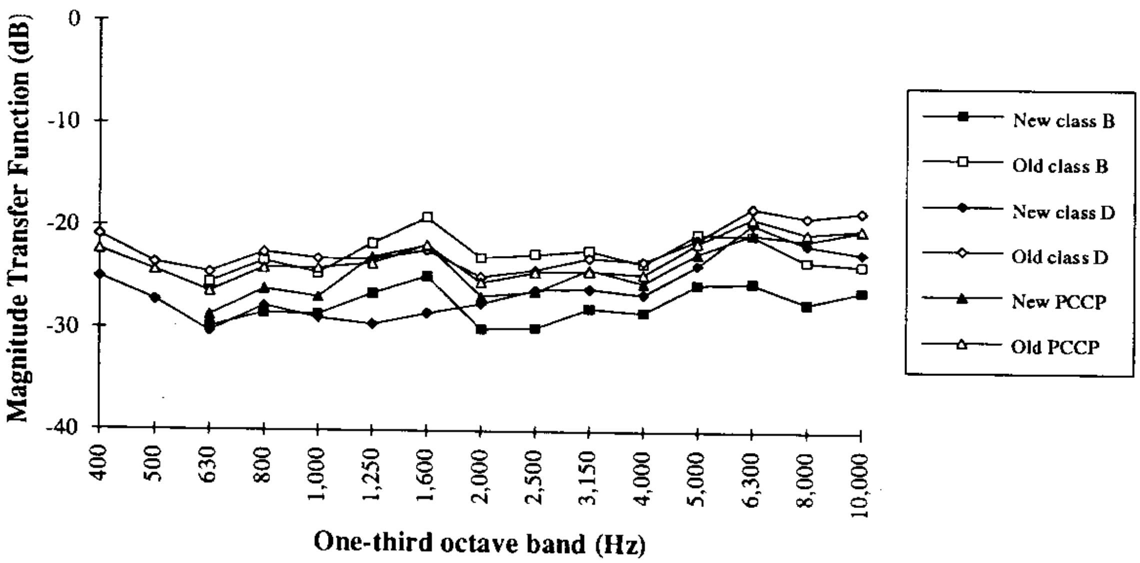

Figure 5. Magnitude transfer functions at roadside maximum A-weighted level using Channel 1 trailer data. (Error band, ±1.5 dB)

5.3 Roadside Noise Levels

The one-third-octave roadside noise levels are shown in Figure 7. The noise levels are for the trailer tire alone (the tow vehicle noise was removed). The error band for the roadside noise levels was ±1.6 dB, as discussed previously. The trailer tire noise ranged from 5 dB to 10 dB louder than that of the tow vehicle. The noise was loudest in the 1-kHz region of the spectrum. This correlated well to the noise spectrum near the tire and indicated that external noise, such as engine or exhaust noise from the tow vehicle, was minimal. The engine and exhaust noises were loudest in the lower frequencies, and the roadside sound shields attenuated low frequencies the least.

5.4 Overall Noise Levels

The SPLs and the differences between the trailer noise levels and the roadside noise levels are listed in Table 4. Figure 8 is a chart of the SPLs. Figure 9 is a chart of the differences in the SPLs. These values are also listed in Appendix A with the temperature corrections.

The A-weighted roadside SPLs of all the new road surfaces were similar in value. The old Class B road surface was significantly quieter than the other old road surfaces. The high old Class D and old PCCP sound levels were probably a result of the exposed aggregate in the road's ruts. The old Class B asphalt was worn, but it did not have deep ruts.

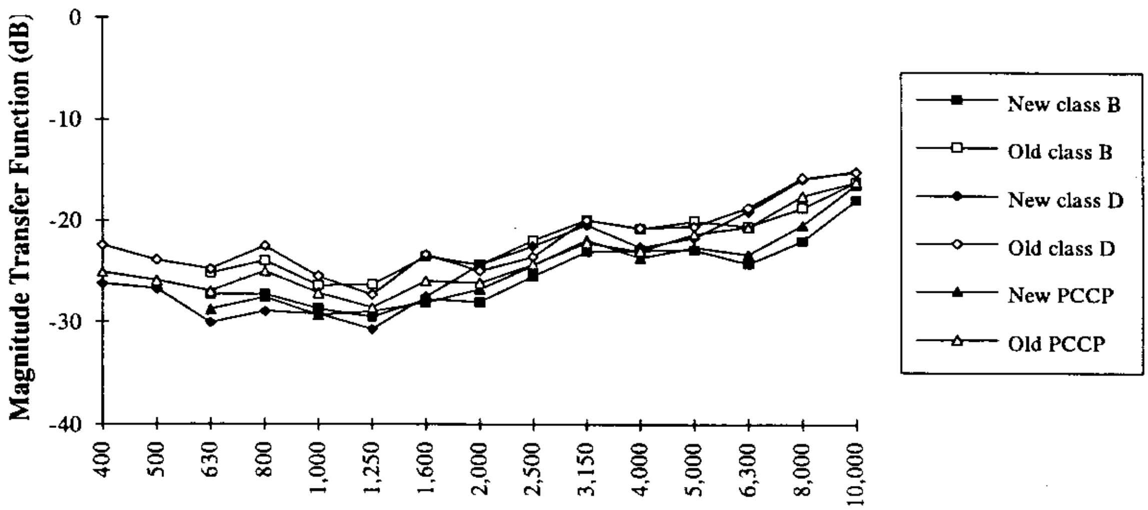

Figure 6. Magnitude transfer functions at roadside maximum A-weighted level using Channel 2 trailer data. (Error band, ±1.5 dB)

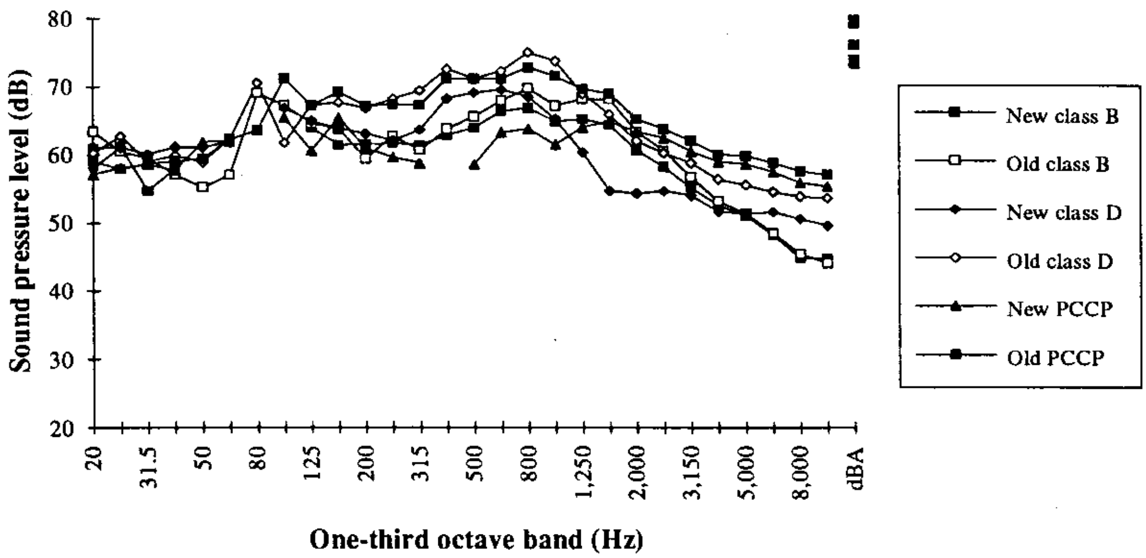

Figure 7. One-third-octave noise levels corresponding to time at which the roadside level reached the maximum A-weighted level. (Error band, ±1.6 dB)

For reasons mentioned above, Channel 2 on the trailer was more representative of the roadside noise. New Class D asphalt had the largest A-weighted decrease in SPL. The old Class D asphalt had the smallest change in the SPL. The Class B followed this same trend, but it was not as pronounced. In the PCCP data, the drop in SPL was less than 1 dB between the new and old surfaces. Given these data, it appears that both the Class B and Class D pavements absorb sound when new but lose their absorptive characteristics with age. In the case of Class D pavement, this change can be attributed to clogging of the surface voids with debris. No explanation for this phenomenon for the Class B pavement was observed.

Table 4. Sound Pressure Levels.

Road surface	Roadside (dB)	Trailer Channel 1 (dB)	Trailer Channel 2 (dB)	Channel 1 change in SPL (dB)	Channel 2 change in SPL (dB)
New Class B	73.7	102.1	101.7	-28.4	-28.0
Old Class B	77.0	100.3	102.1	-23.3	-25.1
New Class D	74.5	102.9	103.2	-28.4	-28.7
Old Class D	80.4	103.5	104.9	-23.1	-24.5
New PCCP	73.5	99.0	100.8	-25.5	-27.3
Old PCCP	79.3	103.4	105.7	-24.1	-26.4

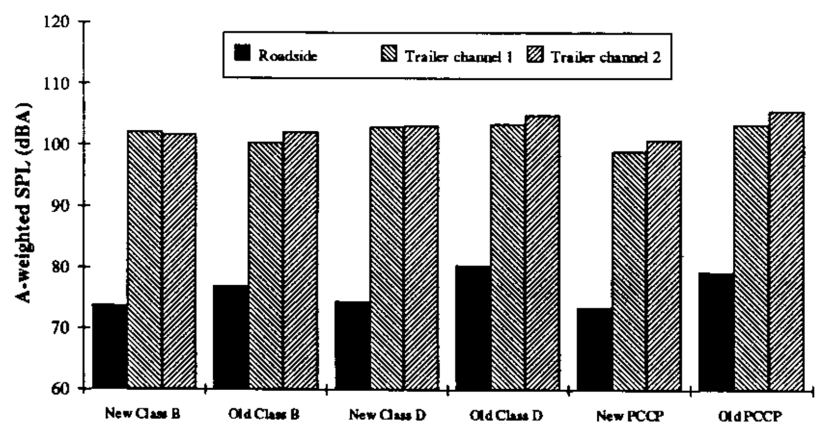

Figure 8. Average A-weighted sound pressure levels for different pavement types.

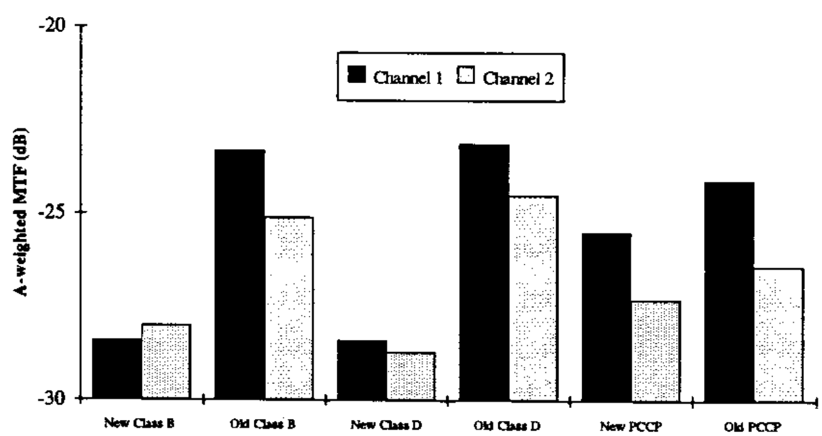

Figure 9. A-weighted Magnitude Transfer Function for different pavement types.

For comparison, a previous study [5] found a 6-dBA reduction in the roadside noise level from a new asphalt. The methods used by Foss [5] were not the same as those used in this study; therefore, this comparison is for qualitative purposes only.

Roadside Tire Noise Prediction

The SPL at the roadside is the combination of near-field and far-field propagation effects. The MTF quantifies the near-field effects of the propagation of tire noise. After the sound has propagated to the shoulder of the road, the sound is in the far field of the tire. In the far field, the SPL is reduced by 6 dB per doubling of distance. The formula for predicting tire noise at a point in the far field requires knowing the SPL at the Channel 2 microphone position and the distance to the listening position. Equation 1 shows this relationship.

$$\mathrm{SPL}(r) = 20\,\mathrm{Log}_{10}\left(\frac{r}{R}\right) + MTF + SPL_{Tire} \qquad (1)$$

The variable ***r*** is the distance from the listener to the source in feet ***R*** is the distance from the tire to the roadside microphones used in this study (6.4 m) ***MTF*** is the averaged MTF for the type of pavement being considered and SPL_{Tire} is the SPL measured in the near field of the tire. MTF can be either in third octaves or A-weighted, depending on the result desired.

Conclusions and Recommendations

Using the techniques described in this study, near-field noise data obtained with the trailer method can help predict the level of tire noise in the far field, that is, to the side of the roadway. In this technique, the magnitude transfer function, MTF, for the particular pavement type is applied to the trailer data to obtain the roadside sound pressure level. From this point, standard acoustical formulas for propagation of sound waves can be applied to predict SPLs at distant points. The MTFs obtained in this study can be used for surfaces of similar construction; however, it may be necessary to determine the MTFs of surfaces that differ significantly from these test sections.

The results of this study showed that a new surface (one that is smooth) produces lower roadside tire noise. The road surfaces that produced the loudest roadside tire noise had large exposed aggregate. The difference between the loudest (old Class D asphalt) and quietest (new PCCP[2]) roadside noise levels was 7 dBA. Future work in this area

[2] This is contrary to earlier studies performed by SVRL and WSDOT that showed new PCCPs to be louder than ACPs in trailer studies. Variations in the traction enhancement surface treatment applied to

might investigate the correlation between surface roughness and roadside tire noise and the feasibility of producing smooth surfaces that wear in an acceptable manner.

The results of this study did not show that Class D asphalt lowers roadside tire noise. For the surfaces studied in this investigation, noise level appeared to depend more on surface texture than on the surface type. In Europe[6,7,8,9,10,11,12], Australia[13], and Asia[14,15], studies that have indicated reductions in roadside tire noise have used asphalts similar to Class D. (These are also called "porous," "drainage," or "pervious" pavements.) The test sections used in these studies had up to 25 cm of new drainage asphalt, in comparison to the just under 4 cm of Class D asphalt on the roads tested in this study. However, differences in construction techniques make it difficult to apply the results of studies performed in other countries to those performed in the United States.

The test site selection criteria applied in this study are recommended for future investigations. The criteria were compiled from many other studies and represented good compromises among them. These criteria will allow future work performed on roadside tire noise to be compared readily and will build a database on this subject.

Neither trailer microphone position used in this study completely recorded the tire noise heard on the roadside. The channel abreast of the tire shielded from the tread noise, and the channel positioned 135 degrees from the tire was insensitive to sidewall noise. If only one microphone is to be used, the 135 degree position seems to be a better choice.

Acknowledgment

The principal investigators on this study were Dr. James D. Chalupník and Mr. Don Anderson, Senior Acoustical Engineer, Environment Section, District 1, Washington State Department of Transportation. Mr. Dan Haakenson managed the data collection and data analysis for the project. He was ably assisted by Mr. Bruce Farrar of the Washington State Department of Transportation, District 1, who handled the numerous coordination activities with that unit. Mr. Farrar also was responsible for identifying the test sections used in this study and for providing information on highway construction techniques and materials. This study was the basis of Mr. Haakenson's Master's Thesis, entitled *Roadside Noise,* upon which this final report was based. The project manager was Mr. Art Lemke of the Washington State Department of Transportation Headquarters Office, located in Olympia.

PCCP surfaces (raking, brushing, or grooving) can account for this anomalous condition. By the nature of this study, this would have had no effect on the determination of the MTF for PCCP pavements.

The author wishes to particularly acknowledge the invaluable contributions made by Mr. Don Anderson to this and previous related projects. His knowledge of the problems of controlling highway noise is both helpful and inspirational. I would like to express my gratitude to undergraduate students Miklin Halstead and Jason Sampson, who worked diligently on these past research projects and without whose help the projects would have never been finished. Finally, appreciation is expressed to the Washington State Department of Transportation and the Federal Highway Administration for sponsoring this project.

References

1. Chalupník, J. D., and D. Anderson, "The Effect of Roadway Wear on Tire Noise," Final Report of WSDOT Agreement WA-RD 276.1, August 1992.

2. Ejsmont, J. A., and U. Sandberg, "Evaluation of the Trailer Coast-By Method for Tire/Road Noise Measurements," Swedish Road and Traffic Research Institute, Linköping, Sweden, 1992.

3. Alexander, M., and F. M. Kessler, "Sound Procedures for Measuring Highway Noise: Final Report," United States Department of Transportation, Report FHWA-DP-45-1R, August 1981.

4. "Specification for Octave, Half-Octave, and Third-Octave Band Filter Sets," American National Standards Institute, Standard S1.11-1966, revised 1977, New York.

5. Foss, R. N., "Tire Noise Study on a Newly Resurfaced Section of Interstate 5," Internal Report, APL-UW 7316, Applied Physics Laboratory, University of Washington, November 1973.
6. von Meier, A., von Blokland, G. J., and Heerkens, J. C. P., "Noise Optimized Road Surfaces and Further Improvements by Tyre Choice," Proceedings of the International Tire/Road Noise Conference 1990, Gothenburg, Sweden, 8-10 August, 1990.
7. Kragh, J., "Traffic Noise Measurements at Asphaltic Road Surfaces," Proceedings of the International Tire/Road Noise Conference 1990, Gothenburg, Sweden, 8-10 August, 1990.

8. Steven, H., "Recent German Experience with Open-Pored Surfacings," Proceedings of the International Tire/Road Noise Conference 1990, Gothenburg, Sweden, 8-10 August, 1990.
9. Storeheier, S. Å., and Arnevik, A., "Traffic Noise Reduction through Optimization of Void Distribution in Road Binder Layer and Wearing Course," Proceedings of the International Tire/Road Noise Conference 1990, Gothenburg, Sweden, 8-10 August, 1990.
10. Hamet, J. F., Berengier, M., and Jacques, M., "Acoust Performances of Pervious Surfaces," Proceedings of the International Tire/Road Noise Conference 1990, Gothenburg, Sweden, 8-10 August, 1990.
11. Pipien, G, and Bar, P. "Superthick Porous Pavements as a Noise-Reducing Means," Proceedings of the International Tire/Road Noise Conference 1990, Gothenburg, Sweden, 8-10 August, 1990.
12. Ohlsson, S., "Porous Asphalt - Experiences from the City of Gothenburg," Proceedings of the International Tire/Road Noise Conference 1990, Gothenburg, Sweden, 8-10 August, 1990.
13. Samuels, S., "Australian Road Surface Treatments to Minimize Tyre/Road Noise," Proceedings of the International Tire/Road Noise Conference 1990, Gothenburg, Sweden, 8-10 August, 1990.
14. Tatsushita, F., Yamanokuchi, H., Inoue, T., and Yagi, Y., "Application of Low Noise Pavement to Urban Arterial Road," Proceedings of the International Tire/Road Noise Conference 1990, Gothenburg, Sweden, 8-10 August, 1990.
15. Iwai, S., Miura, Y., Yokokawa, T., and Kobayashi, H., "Tire/Road Noise Reduction Effects of Porous Pavement and Pavetex Pavement," Proceedings of the International Tire/Road Noise Conference 1990, Gothenburg, Sweden, 8-10 August, 1990.

APPENDIX A: Temperature Data

Road Surface	Slope dB/F)					
Class B	-0.033					
Class D	-0.077					
PCCP	0.017					
Place	Road Type	Lane	Direction	Surf.Temp.	SPL (dBA)	Slope
Swamp Creek	Class B	1	NB	88	99.2	
				44	101.5	-0.052
		2		76	102.1	
				63	102	0.0077
		1	SB	88	100.3	
				63	101.5	-0.048
		2		80	102.3	
				45	102.6	-0.0086
Dahlgren Road	Class B	1	NB	82	98.4	
				88	97.7	-0.12
		1	SB	82	98.7	
				92	98.2	-0.05
King County Airport	Class B	1	SB	69	96	
				55	96.7	
				66	94.8	
				48	94.2	
				94	93.6	
				82	94.9	
				95	94.5	-0.027
		1	NB	69	96.1	
				55	97.7	
				66	95.4	
				48	94.7	
				94	95	
				82	95.4	
				95	94.6	-0.026
Puyallup River	Class D	2	SB	88	100.8	
				55	103.4	-0.079
		1	NB	88	99.4	
				55	101.9	-0.076
Asahel Curtis	PCCP	1	EB	75	103.5	
				67	103.3	
				36	102.9	
				59	101.6	
				51	101.4	0.025
		2		75	102.1	
				67	101.4	
				48	101.4	
				36	101.4	
				59	101.2	
				51	102.3	0.0084

APPENDIX B: Spreadsheet of Results

Average Transfer Function (dB)															
Third-Octave Band (Hz)	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
New class B			-30.3	-28.9	-28.6	-25.8	-24.0	-28.9	-29.4	-27.3	-27.4	-24.9	-24.3	-25.7	-25.5
Old class B			-24.6	-23.0	-23.5	-21.1	-19.5	-23.3	-23.2	-21.8	-22.2	-19.4	-19.9	-22.3	-22.5
New class D	-24.2	-27.2	-30.3	-28.3	-28.8	-29.8	-29.2	-28.1	-26.6	-26.2	-26.4	-23.4	-19.4	-21.5	-22.0
Old class D	-21.3	-24.0	-25.2	-22.9	-22.9	-22.5	-22.8	-24.8	-23.9	-22.3	-22.1	-20.0	-16.3	-17.6	-17.1
New PCCP			-27.7	-24.6	-25.2	-21.8	-21.5	-26.4	-25.9	-23.4	-24.2	-21.0	-19.1	-19.9	-18.6
Old PCCP	-22.5	-24.7	-26.6	-23.9	-23.4	-22.9	-21.8	-25.2	-24.4	-24.0	-23.9	-20.9	-18.1	-19.7	-19.0
Third-Octave Band (Hz)	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
New class B			-27.8	-27.7	-28.7	-28.8	-26.9	-27.0	-25.0	-22.4	-21.9	-22.2	-23.1	-20.2	-17.1
Old class B			-24.3	-23.6	-25.3	-25.8	-23.9	-24.6	-22.4	-19.4	-19.4	-18.8	-19.7	-17.6	-14.9
New class D	-25.3	-26.7	-30.1	-29.4	-29.1	-31.0	-28.3	-24.9	-22.8	-20.6	-22.4	-21.4	-18.8	-15.6	-14.6
Old class D	-22.8	-24.3	-25.4	-22.9	-25.3	-26.7	-23.7	-24.8	-23.2	-19.2	-19.4	-19.3	-16.9	-14.3	-13.8
New PCCP			-27.8	-26.1	-27.6	-27.8	-27.7	-26.4	-24.0	-21.1	-22.3	-21.0	-21.8	-19.0	-14.8
Old PCCP	-25.3	-26.2	-27.2	-24.8	-26.5	-27.9	-26.0	-25.9	-24.3	-21.8	-22.2	-20.7	-19.6	-16.6	-14.9
Error Band (+/- dB)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Transfer Function at Peak (dB)															
Third-Octave Band (Hz)	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
New class B			-29.8	-28.5	-28.6	-26.5	-24.9	-30.0	-29.9	-28.0	-28.3	-25.6	-25.4	-27.4	-26.2
Old class B			-25.6	-23.4	-24.6	-21.7	-19.1	-23.0	-22.7	-22.3	-23.6	-20.7	-20.8	-23.4	-23.7
New class D	-25.1	-27.3	-30.3	-27.8	-29.0	-29.5	-28.5	-27.5	-26.2	-26.0	-26.6	-23.7	-19.7	-21.7	-22.5
Old class D	-20.9	-23.6	-24.6	-22.5	-23.1	-23.2	-22.3	-24.9	-24.2	-23.0	-23.3	-21.2	-18.1	-19.0	-18.5
New PCCP			-28.7	-26.1	-26.9	-23.0	-21.8	-26.8	-26.3	-24.2	-25.5	-22.5	-20.7	-21.3	-20.2
Old PCCP	-22.3	-24.4	-26.4	-24.1	-24.1	-23.6	-21.8	-25.5	-24.4	-24.3	-24.6	-21.5	-19.1	-20.6	-20.2
Third-Octave Band (Hz)	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
New class B			-27.3	-27.3	-28.7	-29.5	-27.8	-28.1	-25.5	-23.0	-22.9	-22.8	-24.2	-21.9	-17.9
Old class B			-25.2	-24.0	-26.4	-26.3	-23.5	-24.3	-21.9	-19.9	-20.7	-20.0	-20.5	-18.7	-16.1
New class D	-26.2	-26.7	-30.1	-29.0	-29.2	-30.8	-27.5	-24.4	-22.5	-20.4	-22.6	-21.7	-19.0	-15.9	-15.1
Old class D	-22.4	-23.9	-24.8	-22.5	-25.5	-27.3	-23.3	-24.9	-23.5	-19.9	-20.7	-20.5	-18.6	-15.7	-15.2
New PCCP			-28.8	-27.6	-29.4	-29.0	-28.1	-26.8	-24.4	-21.8	-23.7	-22.6	-23.3	-20.4	-16.4
Old PCCP	-25.1	-25.9	-27.0	-25.0	-27.2	-28.6	-26.0	-26.1	-24.3	-22.1	-22.9	-21.3	-20.6	-17.5	-16.1
Error Band (+/- dB)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Peak Roadside SPLs (dB)															
Third-Octave Band (Hz)	20	25	31.5	40	50	63	80	100	125	160	200	250	315	400	
New class B	60.9	61.2	54.7	57.9		62.3			64.0	61.5	61.5	61.7	61.5	62.9	
Old class B	63.4	60.5	59.5	57.1	55.2	57.1	69.1	67.3	64.6	63.8	59.5	62.8	60.7	63.9	
New class D	58.0	61.1	60.1	61.1	61.1	61.8		66.8	65.0	64.0	63.2	62.2	63.7	68.3	
Old class D	60.2	62.7	59.0	59.9	58.9	62.4	70.5	61.7	67.3	67.7	66.8	68.3	69.5	72.7	
New PCCP	57.1	58.1	58.5	57.7	61.8	62.0		65.5	60.7	65.5	61.0	59.7	58.8		
Old PCCP	59.1	57.9	58.8	59.0	59.4	62.2	63.6	71.2	67.3	69.2	67.2	67.5	67.3	71.3	
Error Band (+/- dB)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	
Peak Roadside SPLs (dB)	(Continued)														
Third-Octave Band (Hz)	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000	dBA
New class B	64.0	66.5	66.9	65.0	65.3	64.5	60.8	58.3	55.3	52.7	51.1	48.3	44.9	44.9	73.7
Old class B	65.7	68.0	69.9	67.3	68.3	68.3	63.5	60.7	56.8	53.3	51.5	48.6	45.5	44.1	76.3
New class D	69.2	69.7	68.6	65.4	60.5	54.8	54.5	54.8	54.1	51.8	51.4	51.7	50.6	49.7	74.2
Old class D	71.3	72.4	75.2	73.9	69.1	66.0	62.2	60.4	58.9	56.5	55.7	54.6	53.9	53.7	80.0
New PCCP	58.6	63.4	63.9	61.6	64.2	65.0	63.6	62.6	60.6	59.1	58.7	57.6	56.0	55.5	73.6
Old PCCP	71.2	71.3	73.0	71.7	69.7	69.1	65.4	63.9	62.2	60.1	60.0	58.9	57.7	57.2	79.5
Error Band (+/- dB)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	
									Temp.						
A-Weighted SPLs @ 50F	R/S	Ch. 1	Ch. 2	Ch. 1	Ch. 2		Temp.	Correction			Temp.				
(in dBA)				Drop	Drop		deg. F	Factor (dB/F)			Correction				
New class B	73.7	102.1	101.7	-28.4	-28.0		50		-0.033		0				
Old class B	77.0	100.3	102.1	-23.3	-25.1		70		-0.033		0.66				
New class D	74.5	102.9	103.2	-28.4	-28.7		54		-0.077		0.308				
Old class D	80.4	103.5	104.9	-23.1	-24.5		55		-0.077		0.385				
New PCCP	73.5	99.0	100.8	-25.5	-27.3		53		0.017		-0.051				
Old PCCP	79.3	103.4	105.7	-24.1	-26.4		59		0.017		-0.153				