Technical Report Documentation Page

1. Report No. FHWA/TX-07/0-5185-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Research Plan for Measuring Noise Levels in Highway Pavements in Texas		5. Report Date July 2006; Revised November 2006 6. Performing Organization Code
7. Author(s) Manuel Trevino and Terry Dossey		8. Performing Organization Report No. 0-5185-1
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 0-5185
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Technical Report December 2003-July 2006 14. Sponsoring Agency Code
15. Supplementary Notes Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration. Project title: Noise Level Adjustments for Highway Pavements in TxDOT		
16. Abstract This report evaluates available technology for measuring pavement noise, and gives recommendations for equipment, protocols, and test sections in Texas.		
17. Key Words pavement noise, onboard sound intensity, OBSI, CPX trailer, quiet pavements, PFC, porous pavements, roadside noise	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161; www.ntis.gov.	

19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 164	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

A Research Plan for Measuring Noise Levels in Highway Pavements in Texas

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CTR Research Report:	0-5185-1
Report Date:	July 2006; Revised November 2006
Research Project:	0-5185
Research Project Title:	Noise Level Adjustments for Highway Pavements in TxDOT
Sponsoring Agency:	Texas Department of Transportation
Performing Agency:	Center for Transportation Research at The University of Texas at Austin

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

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Acknowledgments

The authors wish to express their appreciation to the following TxDOT Project Management Committee members who have provided expert guidance at every step of the way throughout the project: Gary Graham, Project Director, Mike Shearer (TxDOT Environmental Division), German Claros (RTI), John Wirth, Jeff Seiders, and Magdy Mikhail. We also gratefully acknowledge support and material (as noted within) from Ken Fults, Bruce Rymer, Fred Garcia, Larry Scofield, Mike NcNerney, and especially, Dr. Paul Donavan who is currently at the forefront of pavement noise measurement and has given generously of his time on numerous occasions.

Products

Chapters 3 and 4 contain Product P1, the comprehensive plan for Phase II testing, which was also furnished to the Project Management Committee earlier as a tech memo. Note that the Product P1 contained in this report has been revised from that earlier version.

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1. Introduction

This report, the first one corresponding to Research Project 0-5185, "Noise Level Adjustments for Highway Pavements in TxDOT," presents the initial activities undertaken in the study, such as the literature review, the equipment selection for the sound testing, and the process for identifying potential pavement sections in Texas that are suitable for testing. As the project develops, subsequent reports will document the procedures and results of such tests.

1.1. Background

Traffic noise, defined as an unwanted sound produced by any component of traffic, has increasingly become a nuisance and an environmental concern for the general public as well as for transportation agencies all over the country and the world.

The concern with increasing traffic noise has yielded the development of one of the most common mitigation strategies: the use of traffic noise barriers. This research project attempts to address the potential application of "quieter" pavements for both impact avoidance and noise abatement.

The Federal Highway Administration (FHWA), the federal agency in charge of developing policies and guidelines for the national highway system, allows a state to spend federal-aid highway funds for noise abatement projects along highways. Most states would consider changing pavement types for noise abatement purposes. However, the FHWA stipulates that pavement type or texture cannot be considered a noise abatement measure. Furthermore, the policy states that "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," and that additional research is needed to determine to what extent different pavement types contribute to traffic noise. This policy, cited in Reference 1, applies to all federally funded projects. The implication of this policy is the restriction of noise reduction measures for evaluation by highway engineers and planners.

In accordance with the aforementioned policy, the current FHWA approved traffic noise and barrier modeling software, TNM, is restricted, for the time being, for use only with an "Average Pavement" option, in spite of the fact that the program has other options enabled for modeling the pavement type that would render quieter noise levels, such as the "Open-Graded Asphalt Concrete." This applies to impact avoidance.

Notwithstanding the policy, investigating impact avoidance at the chief source of the noise, the tire-pavement interaction, is a sensible endeavor. There are advantages to reducing the noise at the source rather than placing a barrier between the source and the receiver. First, all receivers, including drivers, can benefit. Second, the benefit can be achieved in situations where barrier construction is not feasible or reasonable, or when barriers may be objectionable for aesthetic reasons. If a pavement can be designed to be quieter, and it is able to retain those quiet characteristics over its service life with reasonable maintenance, then the use of quiet pavements may be approved by the FHWA in the future as a measure for impact avoidance and noise abatement. Moreover, if this design is achieved, the quiet pavement could even eliminate the need for sound barriers in neighborhoods.

Research has concluded that a very significant component of traffic noise is produced at the tire-pavement interface. Other components of traffic noise are generated by the engine, exhaust, and aerodynamic characteristics, but at higher speeds, the dominant source is the tire-pavement noise. Evidently, the surface characteristics of the pavement have a key influence in the generation of noise. Protecting individual receivers by reducing pavement noise at the source rather than by means of traffic noise barriers may result in substantial cost reductions.

Attending all these concerns and facts, the Texas Department of Transportation initiated this study, which investigates the noise produced at the tire-pavement interface for various types of pavement surfaces, both flexible and rigid. TxDOT's concerns in this matter include both impact avoidance as well as noise abatement. This project will test the candidate pavements and quantify their acoustic properties over time. The research will enable the department to select the most desirable qualities for pavements materials and identify construction characteristics conducive to the design of low-noise surfaces that satisfy durability and safety standards, and that are cost-effective.

1.2. Objectives

The project pursues the following goals:

1. ***Remove FHWA restrictions***. The project pursues the elimination of two restrictions from FHWA, namely:

    1) The exclusive use of "average" as pavement type in TNM. The removal of this restriction would allow the use of other specific pavement types with which the software is equipped, which could in turn result in a better estimation of noise levels.
    2) The prohibition on the use of "quieter" pavement as noise abatement. The elimination of this restriction would allow the possible consideration of quieter pavements as noise abatement.

    The FHWA policies specify that "unless definite knowledge is available on the pavement type and condition and its noise generating characteristics, no adjustments should be made for pavement type in the prediction of highway traffic noise levels." Thus, this project attempts to contribute to the definite knowledge on the matter.

2. ***Long-term noise monitoring***. The research performed will allow TxDOT to meet and exceed the current practice in other states for noise measurement and monitoring. Recommendations from this study will include an updated design for portable noise measuring equipment that incorporates the latest techniques and technology into a comprehensive program for statewide pavement noise abatement. This recommended program may include regular monitoring with noise trailers and/or roadside noise measurement using models and techniques developed under the study. It may also include a "user hotline" for reporting pavement noise problems as is currently in place in Arizona.

3. ***Pavement noise models***. At the end of the study, a large database of pavement noise characteristics and their possible change with time will have been created. This information can be used by pavement designers in conjunction with the FHWA TNM program to design quieter pavements specifically for high traffic areas where noise is likely to be a problem. The models developed from the database will allow designers

to predict the noise characteristics of the pavements over time with a high degree of confidence. Additional data from the long-term monitoring described in objective (2) of this list can be used to further validate and calibrate the models as needed.

The objectives of this report are as follows:

1. To present the background information gathered for this study in the literature review
2. To recommend the most suitable equipment for noise measurement for the experimental part of the project
3. To present the research approach along with the candidate pavement sections for future investigation from information collected from the various TxDOT districts

1.3. Report Organization

The items covered in this report are organized in the following way:

- Chapter 1 presents the objectives of the report and its organization.
- Chapter 2 presents the literature review, which includes research experiences of other agencies in the United States, as well as those from other countries, mainly European.
- Chapter 3 provides an overview of the various noise measurement gear that has been evaluated and/or tested by the researchers, and recommends the devices and protocols that will best suit the needs of the study.
- In Chapter 4, the proposed activities for the testing phase of the project are presented. This chapter also includes the candidate pavement sections compiled from information furnished by TxDOT districts, as well as the factorial for the selection of pavement sections.
- Chapter 5 summarizes the conclusions and recommendations developed in the preceding chapters.

2. Literature Review

This chapter presents the literature review conducted on the subject of tire/road noise. The review focuses on what various agencies have researched and investigated on this topic in recent years. It is a topic that a few years ago was not a major concern for transportation agencies, nor for the general public, and thus there was not much available research about it. However, it has become an environmental and quality of life issue of growing interest among the general public. This, coupled with the technological advancements in acoustics and sound-measuring devices, has enabled the progress of the research in this area, prompting state and government agencies, as well as private companies, to embark on an increasing number of projects that deal with tire/road noise.

Reviewing these experiences and gauging the current state of knowledge throughout the world is an important component of this research project. Experiences from agencies in the United States and elsewhere have been reviewed and compiled. The literature review is supplemented by some notes from recent conferences and seminars on the topic.

2.1. Experiences of Agencies in the United States

In the United States, the Departments of Transportation of California and Arizona have invested the most resources in traffic noise research. In the subsequent sections, some of the sound-related studies conducted in these two states are presented, followed by some noteworthy studies in other states.

2.1.1. California

The California Department of Transportation, commonly known as Caltrans, has been one of the leading agencies in conducting noise research, studying "quiet pavements" as an alternative to noise barriers. Caltrans has distinguished itself in characterizing tire/road noise generation for existing and experimental highway surfaces, and in developing noise measuring procedures.

Caltrans has developed numerous studies to evaluate tire/road noise on different pavement types by various procedures, including sound pressure, sound intensity, and close proximity techniques, as well as wayside measurements, conducted in California and in other states such as Arizona, with which Caltrans has cooperative research ventures. A description of some of those studies is presented here.

A recent project evaluated methods for quantifying tire-pavement noise, and developed a near-field procedure for sound intensity measurement, to characterize noise performance of highway pavements. This project is described in detail in [Donavan 03]. The paragraphs that follow summarize this report. The on-board technique was implemented as an alternative to wayside, pass-by or trailer methods. The overall goal was to aid in the decision process for determining when and how effective pavement selection can be used to reduce highway noise levels.

As an alternative to the Close Proximity (CPX) and the sound pressure measurement methods, sound intensity (SI) has been successfully used previously to evaluate pavement surfaces on test tracks. As a near-field technique, sound intensity is ideally suited, as it measures only the acoustic energy propagating away from the tire. As a result, good correlation to pass-by data has been demonstrated in previous work. Because of the directive nature of sound intensity, other sources of noise contamination such as power train noise and noise from other vehicles are eliminated. Sound intensity methods can also be easily and economically implemented, as they require only an inexpensive fixture, such as the one utilized by Caltrans, and instrumentation comparable to other methods. Bruce Rymer, the CTR contact at Caltrans, confirmed that their sound intensity approach is quick, accurate, and repeatable; and that the equipment cost is about $35,000. The equipment is illustrated in Figures 2.1 and 2.2. It is important to emphasize that, even though this device was developed for specific sound intensity testing purposes, Caltrans acknowledges that other sound measuring techniques are useful as well. The methodology to be used depends on the purpose of the study in question. In this case they wanted to characterize many different road surfaces in California.

This methodology uses two intensity probe locations, one opposite the leading edge and one opposite the trailing edge of the tire-contact patch. The probe positions are 75mm above the ground and 100mm out from the tire sidewall. The probe is supported by a fixture mounted to the wheel studs of the test tire/wheel. The probe consists of two 25mm-diameter, phase-matched condenser microphones spaced 16mm apart and fitted with nose cones (although the usefulness of the nose cones has recently come into question, as there have been tests showing that such devices are not necessary).

Figure 2.1. Sound intensity fixture being installed on test vehicle

Figure 2.2. Sound intensity fixture

Note that the Center for Transportation Research has purchased a fixture like the one depicted in Figure 2.2 for the development of the experimental part of this project. At the time this report is being prepared, the SI gear has arrived and will be assembled shortly.

Another very important development in regards to SI is that a draft that will standardize the use of this measuring technique has been prepared, and will become an ASTM and an AASHTO standard specification in the near future. The specification is entitled “Standard Practice for Measurement of Tire-Pavement Noise Using the Close Proximity Sound Intensity Method;” a copy of the current draft is included in Appendix A of this report for the benefit of the reader.

In the Caltrans study, measurements were made separately at the leading and trailing edges of the contact patch and later averaged together on an energy basis to determine the sound intensity for a given tire or pavement. The device was tested and calibrated in the lab and then tests were performed on a test track. The results of the near-field sound intensity data were compared to the pass-by levels, which corresponded to the average from four pass-bys of the test vehicle operated under a pseudo coast mode (transmission in neutral, engine idling). The result of this comparison is shown in Figure 2.3. Also shown is the best 1-to-1 linear fit to these data, which gives an offset between the sound pressure and sound intensity of 23.9 dBA. All data points were within +/- 0.5 dBA of this line. It was found that the differences measured in the near field are quite similar to those measured at the pass-by position. It was also found that difference between coast and cruise pass-by levels was less than 0.5 dBA at 60 mph (97 km/h).

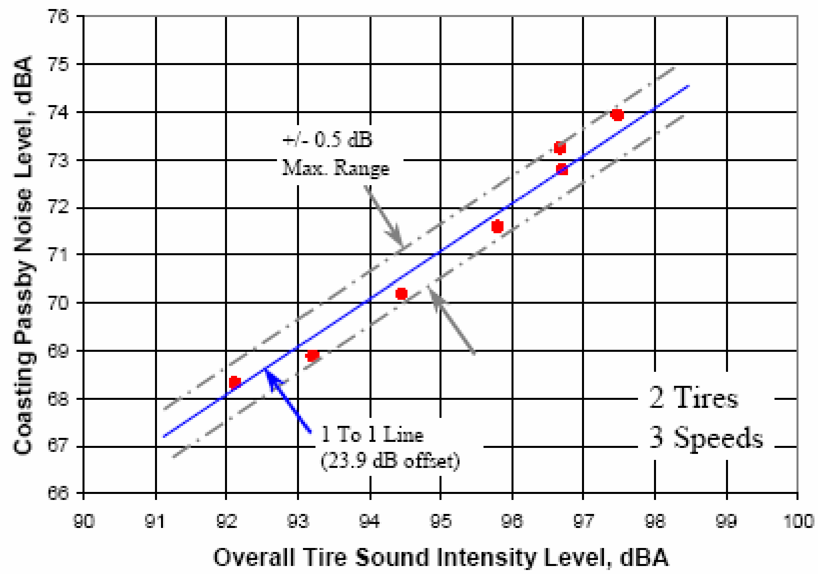

Figure 2.3. Relationship between sound intensity and pass-by measurements (Caltrans track)

With the good correlation demonstrated between near-field sound intensity and pass-by levels in a test track environment, testing was performed on a variety of actual highways in California, including both asphalt concrete (AC) and portland cement concrete (PCC) surfaces. The AC pavements included rubberized, open-graded (porous), dense-graded (non-porous), and chip seal and stone mastic pavements. The PCC roadways have included longitudinal tined, ground, and other surfaces of varying ages. A 1/3-octave band composite of these results is presented in Figure 2.4.

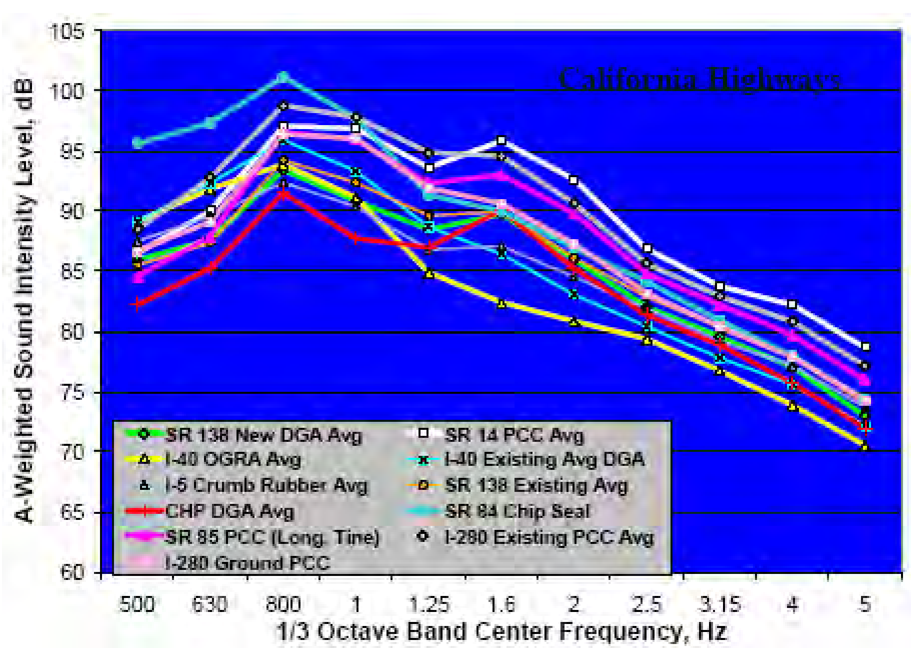

Figure 2.4. Range of pavement noise in California pavements

To analyze the data, Caltrans considered several groupings of these pavements. The first of these includes representatives of four significantly different types of pavement. These are a crumb rubber asphalt concrete (RAC), an open-graded rubberized asphalt concrete (OGRAC), a dense-graded asphalt concrete (DGAC), and a PCC surface. The resultant spectrum for these categories is shown in Figure 2.5, where it can be seen that the OGRAC noticeably drops in level, relative to the other surfaces, starting at about 1250 hertz. This is a common characteristic of porous surfaces as seen in the California data as well as data in the literature. Starting at about 800 hertz, the PCC surface has significantly higher levels than any of the other surfaces. Interestingly, the surface of the pavement appeared to be the smoothest among those studied. It was noted, however, that this pavement produces definite "slaps," which are associated with the joints and are perceivable by an observer standing alongside of the freeway. Given the frequency of occurrence of these joints, their effect in the sound produced could not be separated from the sound generated by the rest of the pavement. For the three asphalt pavements, the lower frequency performance (below 800 hertz) is associated with apparent roughness, given by the amount of exposed aggregate, i.e., a coarser texture. The lower frequency noise level apparently increases with increasing roughness. With the exception of the porous surface, the opposite trend can be seen in levels for the frequencies above 1000 hertz for these data.

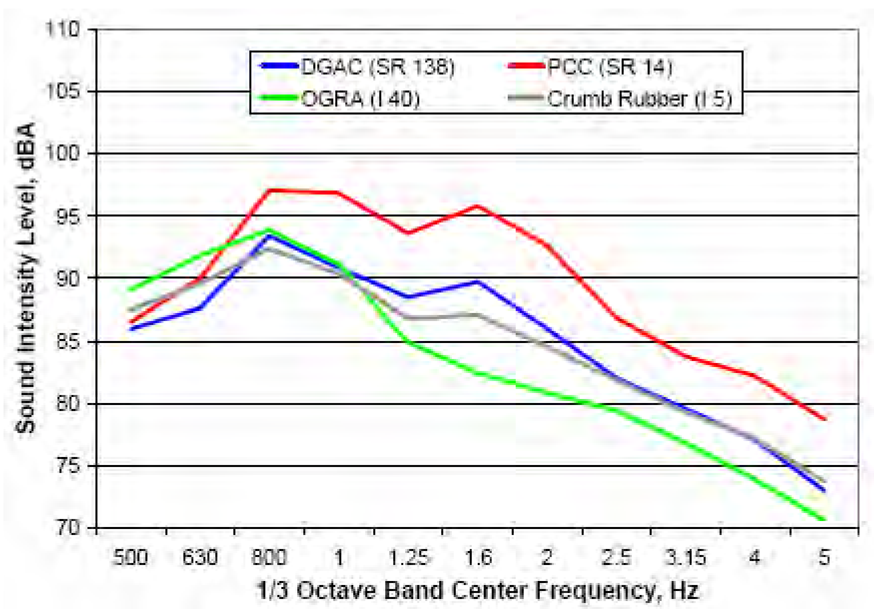

Figure 2.5. Sound intensity comparison of different pavement surfaces

In order to further investigate roughness, another set of pavement surfaces was measured for sound intensity, involving a wide range in apparent surface roughness. These surfaces are the fine aggregate DGAC of the Caltrans test track, and a chip seal pavement. The latter is formed by rolling aggregate into an asphalt binder, instead of the typical process of mixing aggregate and asphalt binder together, and then laying it. The results for these surfaces are given in Figure 2.6.

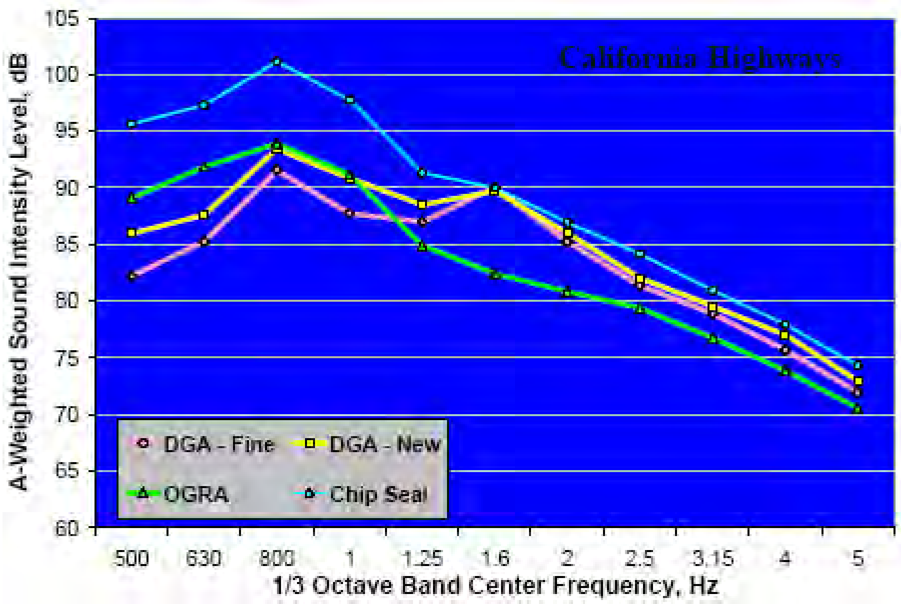

Figure 2.6. Sound intensity comparison for AC surfaces with a wide variety of roughness

As noted in Figure 2.6, the lower frequency levels seem to correlate well with surface roughness, with the roughest surface more than 10 dBA higher than the smoothest. In the higher frequencies, however, the inverse relation speculated for Figure 2.5 is not apparent. With the exception of the porous pavement, the smoothest surface is equal to or lower than the other asphalt surfaces over the entire frequency range.

With the exception of the chip seal surface, the PCC as a group produced higher noise levels. Within the PCC, some differences have been noted that can be attributed to surface texturing and/or the state of the PCC slabs and joints. Every PCC has some amount and type of texturing. As a pavement ages, the texturing wears, reducing noise; also, there is often a relative displacement between the slabs or faulting, which causes increased impulsive noise at the joints. To lessen this effect, PCC surfaces are often rehabilitated by various grinding techniques, which retexture the pavement as well as re-level the slabs. Another subset of data evaluated by Caltrans in the study included the sound intensity for four PCC surfaces in various states of age and texturing, which is shown in Figure 2.7. The data indicate that new grinding of a PCC surface may represent some reduction in noise level over an older surface. Also, applying longitudinal tining to an existing surface may show some improvement while producing noise levels somewhat comparable to freshly ground surfaces.

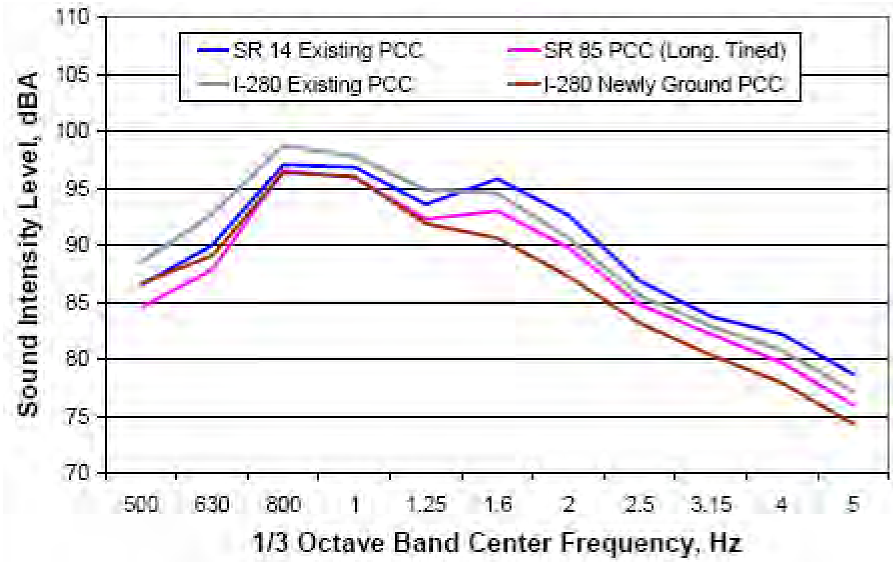

Figure 2.7. Sound intensity comparison of PCC highway surfaces

In addition to surveying different pavement surfaces, sound intensity measurements were also used to support other pavement studies. In order to evaluate the long-term performance of open-graded asphalt concrete, Caltrans produced wayside traffic noise measurements from a section of OGAC that was installed over four years ago on a high volume, multilane portion of Interstate 80 near Davis, California. Compared to the existing DGAC, this section of OGAC has consistently demonstrated a 5 to 6 dBA reduction in traffic noise levels. As another method of demonstrating the performance of this “quiet” surface, wayside traffic noise levels were recently measured along IH-80 in areas of new DGAC and existing PCC near the OGAC site. As expected, the OGAC was about 6 dBA quieter than the PCC for similar traffic volume and mix. The sound intensity produced by the test tire was also measured on these three sections of roadway.

The trends seen in the near-field measurements are quite similar to those of the wayside traffic (Figure 2.8). This is quite encouraging, as the traffic data includes not only a variety of light vehicle and tire types, but also medium and heavy-duty trucks. These data tend to confirm the assertion that tire/road noise and pavement type are dominant factors, which need to be considered when modeling highway traffic noise. Under current traffic noise models, the noise level from these three sites would be predicted to be the same. However, compared to PCC, the reduction measured for the OGAC is on the order of the reduction that would be expected for a sound wall installed alongside the roadway.

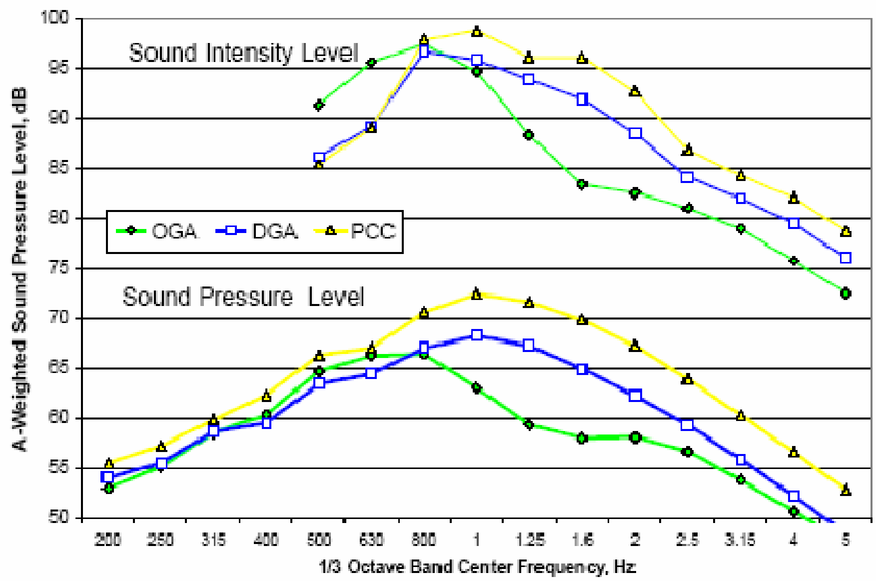

Figure 2.8. Sound intensity and wayside traffic noise measurements on IH-80

In summary, this study concluded that, as a group, PCC surfaces produced higher noise levels than batch mixed AC surfaces. Of the highway pavements tested, those AC surfaces that were open graded, rubberized, or both, produced lower noise levels. For AC surfaces, as reported by others, a relationship between apparent surface roughness and lower frequency noise level was found.

Other studies performed by Caltrans have focused entirely on wayside measurements. Such is the case of a series of studies developed in conjunction with the Volpe Center Acoustics Facility. One of these studies focused on the acoustic properties of rigid pavements with different finishes. This study is presented in [Rochat 03/03], and the following paragraphs summarize it. Three PCC surface treatments were tested in Mojave, CA, on a new stretch of highway between Route 58 and Route 14. The objective was to determine differences in tire/road noise. The treatments investigated were longitudinal tining, burlap drag, and broom finishing. A microphone was set on a tripod 50 ft away from the center line of the highway travel lane, and 5 ft above the roadway plane, as shown in Figure 2.9, in conjunction with a radar gun, and a thermometer/anemometer.

Figure 2.9. Field measurement set-up for wayside noise recording

The test vehicle was a Subaru Outback, equipped with Goodyear Aquatred tires. The experiment consisted of multiple runs through each test section at four different speeds: 40, 45, 60, and 70 mph. The results are summarized in Figure 2.10, which shows the variation of noise with speed by surface.

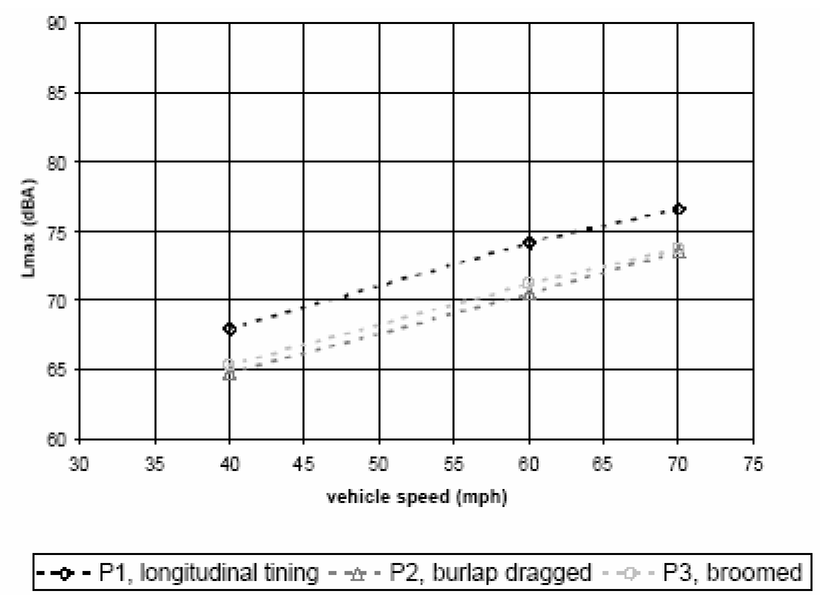

Figure 2.10. Caltrans wayside noise measurements on three PCC treatments

Hence, the quietest of the PCC surfaces was the burlap-dragged, followed by the broomed, and finally, the longitudinally tined. Acoustic differences between the three kinds of surface treatments grouped by vehicle speed at four speeds are illustrated in Figure 2.11.

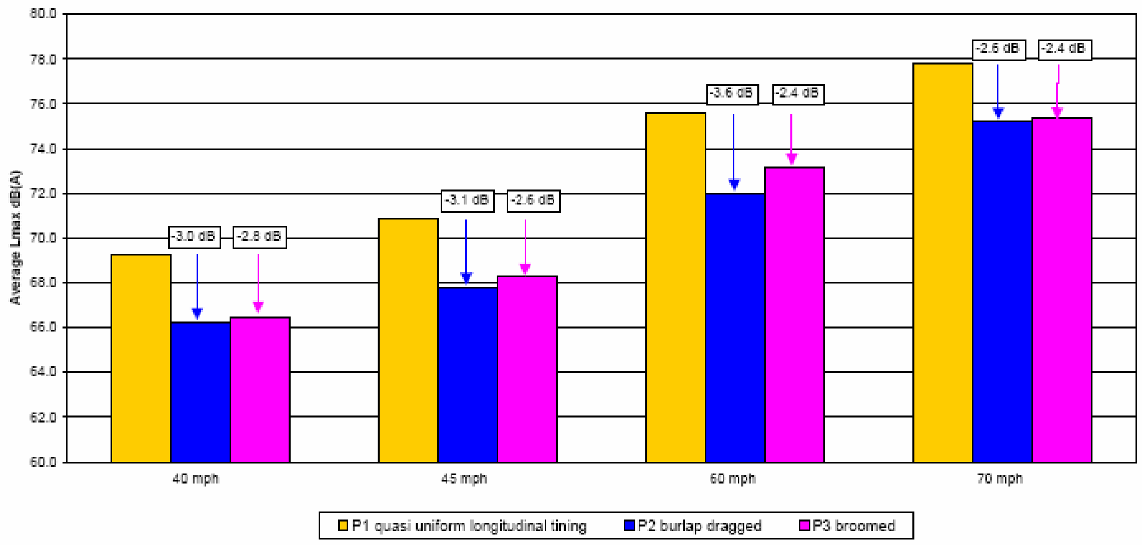

Figure 2.11. Average sound for three PCC surface treatments by vehicle speed

From the results of this study, it was concluded that a burlap drag or a broom surface finishing on PCC yields a pavement in which tire/road noise is less than on a longitudinally tined PCC. The acoustical conditions of the burlap-dragged surface are slightly better than those of the broomed surface. Without attention to safety and durability considerations, the best treatment for PCC is burlap drag, which provides about a 3-dBA reduction in noise levels compared to the longitudinal tining.

Another one of the Volpe Center's wayside noise studies in California tested a reference section and four test sections, twice a year for five years, with the purpose of observing any degradation in the acoustic qualities of the pavements over time [Rochat 10/03]. This is an AC noise study, started in 2001, which is conducted on a 4-mi. stretch on Route 138, about 80 mi. north of Los Angeles. At the beginning of the study, the pavement on Route 138 was dense-graded AC estimated to be 20 years old. This is the surface associated with the first set of measurements. The pavement was subsequently resurfaced with a leveling course of new DGAC; this is the pavement associated with the baseline set of measurements. Finally, five overlays were placed over the DGAC leveling course. The pavement surfaces of the sections are as follows, with section 1 considered the reference section:

S1 –Dense-Graded Asphaltic Concrete (DGAC) 30-mm thick

S2 –Open-Graded Asphaltic Concrete (OGAC), 75-mm thick

S3 –Open-Graded Asphaltic Concrete (OGAC) 30-mm thick

S4 –Rubberized Asphaltic Concrete Type O (RAC type O) 30-mm thick

S5 –Bonded Wearing Course (BWC) 30-mm thick

These five AC pavements are associated with all post-overlay measurements.

The results of the measurements are shown in Figures 2.12 and 2.13, in which SPBI is the Statistical Pass-By Index. The SPBI pairs the pavement analysis of each surface with the reference, in this case section S1, using identical vehicle sets for paired data. Figure 2.12

corresponds to pre-overlay measurements, while Figure 2.13 shows results obtained four months after the overlays were placed.

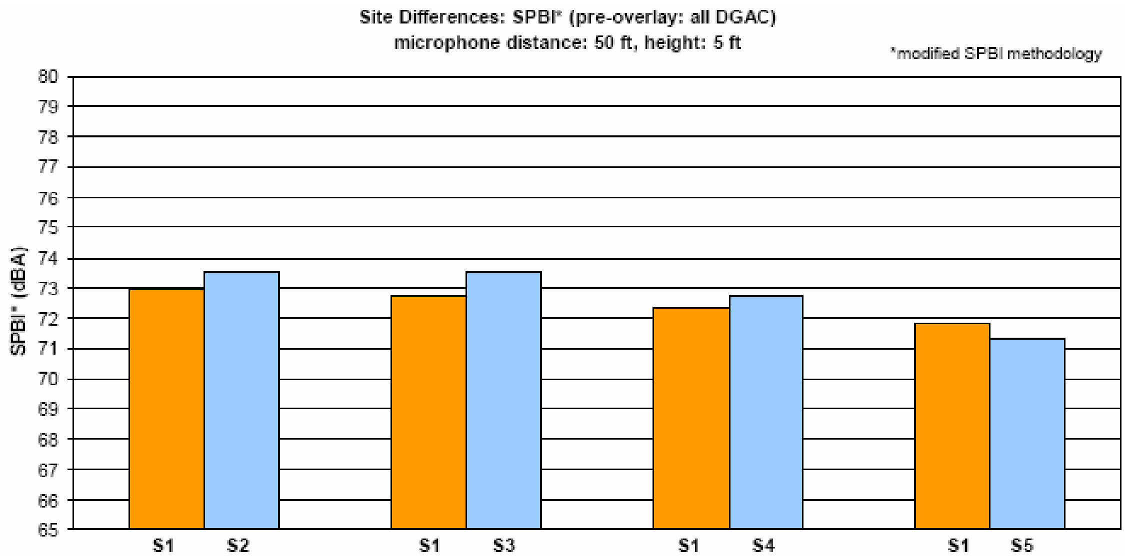

Figure 2.12. Pre-overlay results

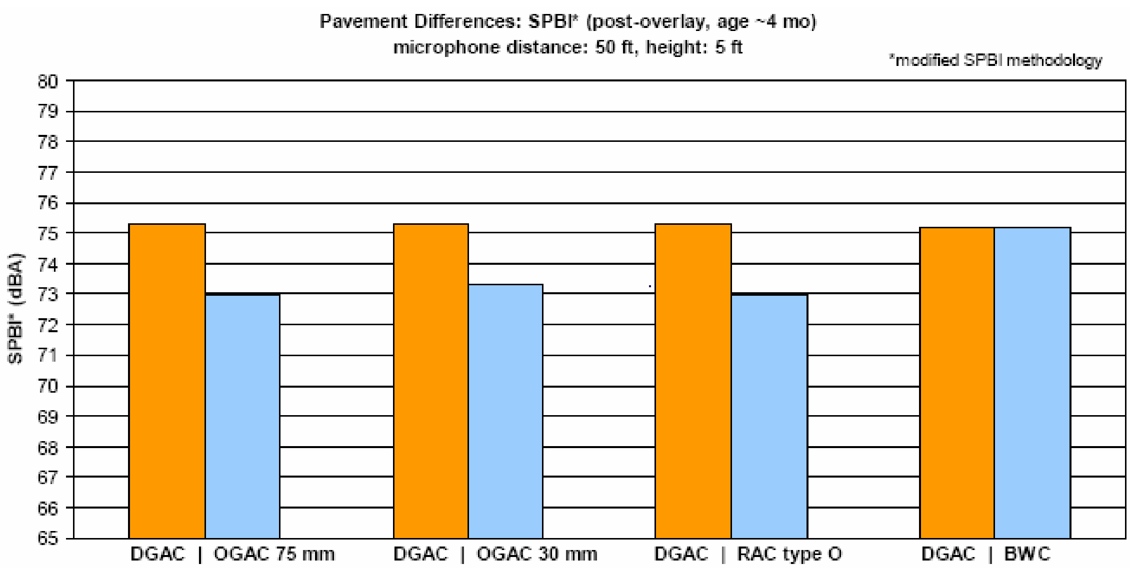

Figure 2.13. Post-Overlay results

Also, the sound as a function of the vehicle speed was studied. Figure 2.14 shows how the sound varied with speed for the case of passenger cars for two of the sections analyzed, S1 and S4.

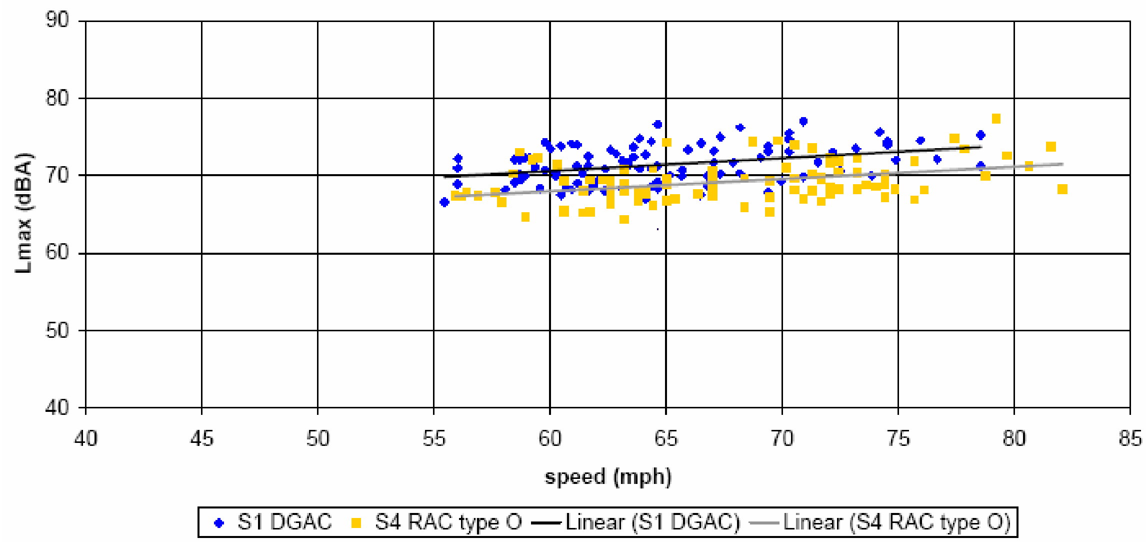

Figure 2.14. Sound as a function of vehicle speed for passenger cars

The results for all five pavement types, obtained by averaging multiple pass-bys of the Subaru test vehicle with the Goodyear Aquatred tires for each speed (40, 50, 60, and 70 mph), are shown in Figure 2.15.

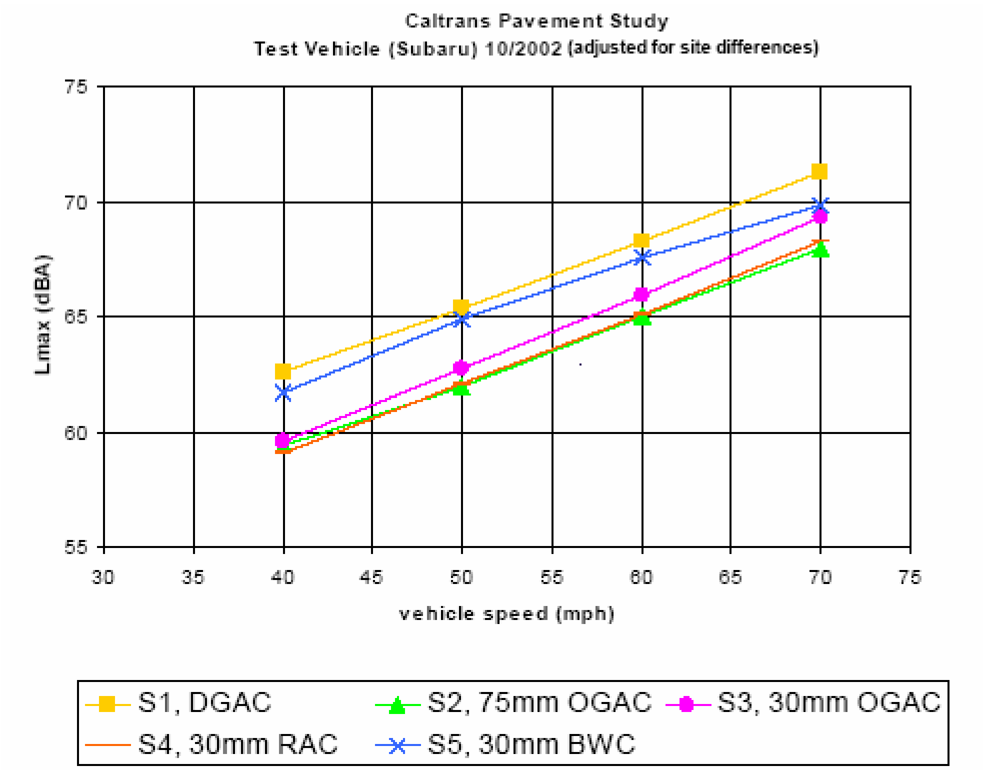

Figure 2.15. Sound as a function of speed for all pavement types with test vehicle

The study concluded that, for new pavements, the 75-mm thick OGAC and the 30-mm thick RAC Type 0 were the quietest surfaces, achieving a benefit of about 2.3 dBA over the DGAC. The test sections, ranked from loudest to quietest are as follows:

1. DGAC and BWC
2. 30 mm OGAC
3. 75 mm OGAC and 30 mm RAC Type 0

Test vehicle data showed that noise reduction attributable to pavement type is about equal over speeds ranging from 40 mph to 70 mph.

2.1.2. Arizona

Arizona, through its noise mitigation program, became the first state to attain pilot status with the FHWA to allow pavement surface type as an alternative noise mitigation strategy. This allows the Arizona Department of Transportation (ADOT) to take a 4 dBA credit for using “quiet pavements,” to eliminate noise walls or reduce their height. The information that follows is outlined in [Scofield 04], which presents the historical development of ADOT research activities on quiet pavements.

A foremost characteristic of the ADOT strategy for noise mitigation is the widespread use of asphalt rubber friction course (ARFC) overlays. The implementation of the ARFC overlay system for PCC began in 1973 with a two-layer system. The two-layer system was quickly replaced with a three-layer system in 1975. The three-layer system was eventually replaced by a one-inch-thick ARFC. The first use of the ARFC strategy occurred on I-19 near Tucson, Arizona in 1988, when a one and one-half mile section of southbound I-19 was overlaid with a one-inch ARFC. The one-inch-thick ARFC surfacing used in Arizona consists of a 3/8” minus, open-graded aggregate. Typical asphalt-rubber binder contents range between 9 and 9.4% by total mix weight. This overlay strategy was used for most of the PCC overlay placements since 1988.

The use of this surfaces increased the public awareness about traffic noise and quiet pavements, which was conducive to ADOT’s first formal research effort in this area, with a study that included both roadside and roadway-based noise measurements.

The roadway-based testing was accomplished by means of a low-cost device, consisting of a microphone positioned within a special windscreen and mounted approximately 10 inches away from the rear tire of a 1995 Dodge Caravan (Figure 2.16).

Figure 2.16. Microphone Attachment on 1995 Dodge Caravan

Subsequently, it was found that the device was not able to consistently characterize the noise properties of the pavement surfaces, and this led to the completion of a Close-Proximity Noise Trailer in 2002 by the National Center for Asphalt Technology (NCAT), illustrated in Figure 2.17. ADOT started a collaborative research effort with Caltrans, gaining valuable expertise and technology, and enabling the implementation of noise intensity testing in Arizona pavements.

Figure 2.17. NCAT Close Proximity Trailer

The reason FHWA is reluctant to accept pavement surface type as a noise mitigation strategy is mainly because the noise mitigation properties that make these surfaces “quiet pavements” are known to diminish with age, making them a non-permanent solution. Therefore, one of the focuses of ADOTs research has been to characterize the pavement surfaces at various ages, testing projects between 3 and 12 years old in the Phoenix area. The results of this investigation are summarized in Figure 2.18, which shows, despite a few outlying data points, how the pavements became noisier with age.

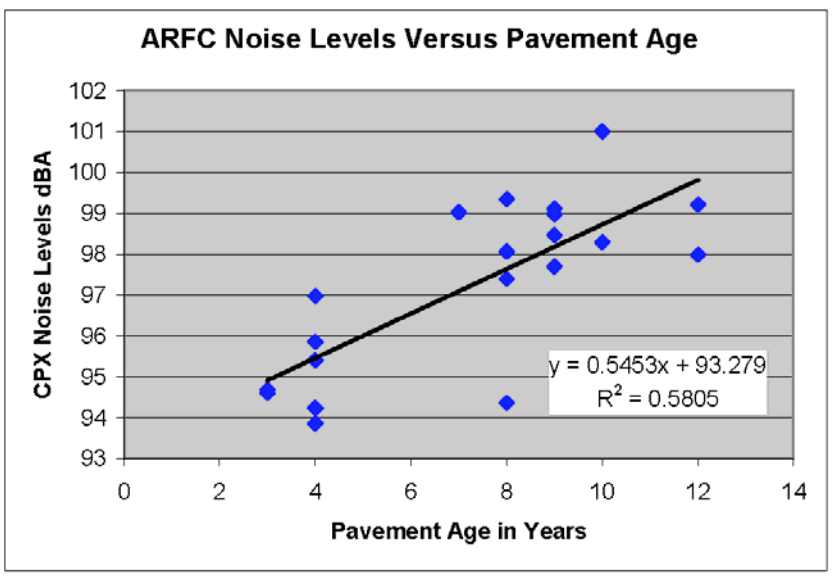

Figure 2.18. ARFC Noise levels and pavement age in Arizona

ADOT has also experimented with PCC surfaces. In 2002, a project incorporated noise testing on existing uniformly spaced transverse tined concrete pavement, on new uniformly spaced longitudinal tined PCC, and on new randomly spaced transverse tined PCC. This project was conducted by the Volpe Center Acoustics Facility, and it was similar to the Caltrans wayside sound measurement studies outlined in the previous section. For each type of surface, 32 vehicles representing three categories (passenger car, medium truck and heavy truck) were driven at 60 and 70 mph for the roadside pass-by tests, which results are shown in Figure 2.19. Uniform longitudinal tining was the quietest surface. This texture produced, approximately, a 5-dBA reduction over the standard uniform one inch transverse tining. The higher speed (70 mph) represented a 2-dBA increase over the noise generated at the lower speed (60 mph).

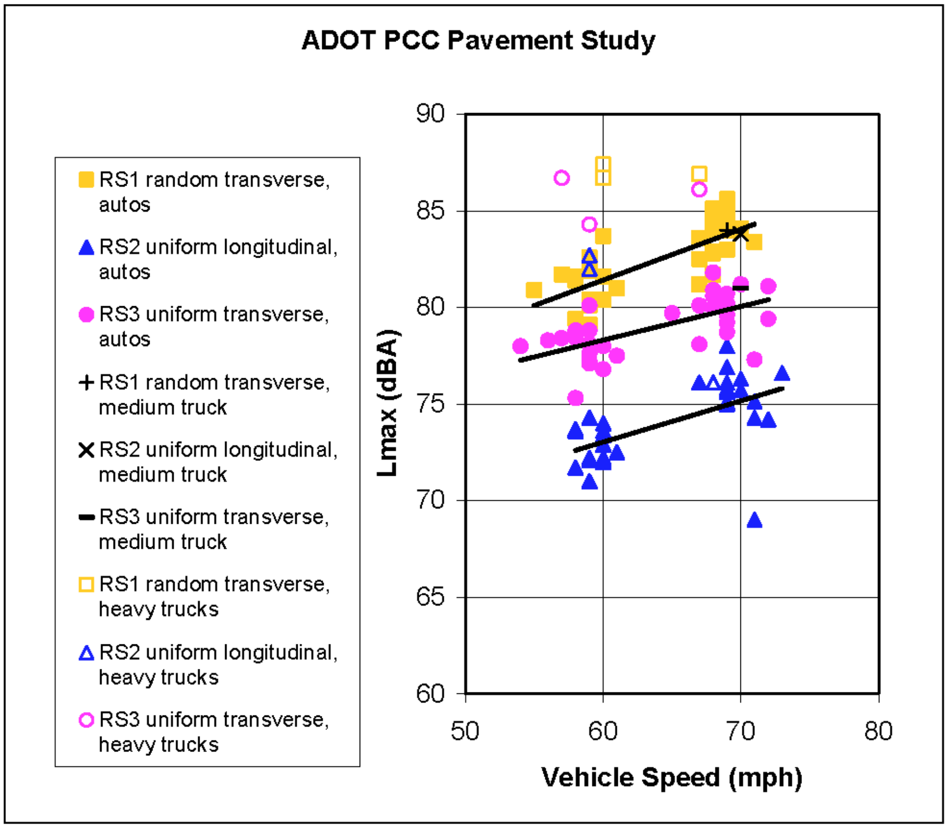

Figure 2.19. Sound properties of various PCC tining patterns in Arizona

ADOT is conducting another PCC noise experiment on a diamond ground section that will not be overlaid with ARFC on SR202 in Phoenix. This section is 3000 ft long, and the surface was finished with uniformly spaced (3/4 in.) longitudinal tining. Four different grinding techniques, with varying spacing between grinding blades, different amounts of head pressure and beam lengths are being tested. This is a new project sponsored by the concrete industry, which will be monitored by ADOT for three years. The results from the first acoustic measurements and the section layout are shown in Figure 2.20.

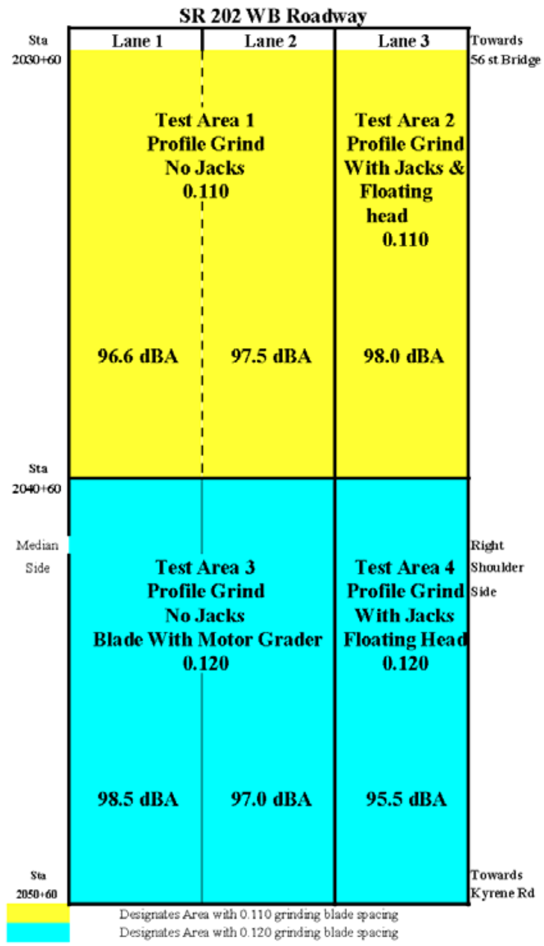

Figure 2.20. Diamond grinding test sections layout

Arizona's Quiet Pavement Research Program is comprised of three independent but inter-related research efforts. The three research efforts include the FHWA/ADOT Quiet Pavement Pilot program (e.g., composite pavement program), the flexible pavement program, and the rigid pavement program.

The following paragraphs briefly describe these programs.

FHWA/ADOT Quiet Pavement Pilot Program

This program is designed to evaluate the efficacy of using pavement surface type as a noise mitigation strategy. The research consists of evaluating the acoustic properties of ARFC surfaces, one inch in thickness, placed upon existing and newly constructed PCC roadways. The research will evaluate the acoustic properties of the ARFC surfaces for the length of their original service life (which is expected to be a minimum of ten years). Both near-field and far-field acoustic measurements will be obtained. The research objectives are to:

- Validate the minimum 4-dBA reduction allowance for ARFC surfaces
- Quantify the acoustic properties of ARFC surfaces over time
- Determine the correlation between near-field and far-field acoustic measurements

- Evaluate selected pavement material properties for correlation to acoustic performance
- Validate the use of CPX and sound intensity measurement systems for evaluating acoustic properties of ARFC surfaces
- Determine the usefulness and benefits of using pavement surface type as a noise mitigation strategy
- Develop site/pavement specific Reference Energy Mean Emission Levels (REMELs), used in the FHWA Traffic Noise Model, for improved noise modeling
- Validate combining the CPX/SI measurement systems onto the same wheel of the trailer and conducting different tire measurements simultaneously
- Evaluate the seasonal or environmental aspects of the acoustic properties of the ARFC over time
- Determine the acoustic variability of an ARFC surface within a given construction project

Flexible Pavement Research Program

In addition to ARFCs used on PCC, additional surface types and applications are being evaluated under the flexible pavement program. Approximately 84 test sections have been placed since 1999 to evaluate six different surface types, which include Permeable European Mixture, Stone Matrix Asphalt, ARFC, Neat-Asphalt Friction Course, Polymer-Modified Friction Course, and Terminal-Blend Asphalt Friction Course. In the near future, it is anticipated that additional test sections employing a two-layer friction course, different thickness of ARFC, and additional terminal blend test sections will be constructed and included in this program.

The primary focus of this research effort is to evaluate the acoustic properties of different wearing course types placed over flexible pavements and to improve the performance of the ARFC strategy. Since construction of test sections on urban freeways is undesirable, improvements in wearing course design and construction will be evaluated in this program prior to implementation in the FHWA/ADOT Quiet Pavement Program (e.g., Composite Pavement Program).

This research is also focused on developing procedures for evaluating acoustic properties of pavement materials during the mix design stage. That is, in addition to designing for structure and durability, ADOT wants to develop a methodology for evaluating mixtures for their acoustic properties prior to construction. This should allow for development of test procedures for conducting quality control testing during construction. The research objectives are to:

- Evaluate the acoustic properties of selected wearing course surfaces over time
- Develop correlations between near-field and far-field acoustic measurements
- Develop test procedures for evaluating mixtures in the mix design phase and for conducting construction quality control tests.
- Evaluate selected pavement material properties for correlation to acoustic performance
- Evaluate the seasonal or environmental aspects of the acoustic properties of the wearing courses over time

- Evaluate the network level acoustic performance of wearing course surfaces over time
- Validate combining the CPX/SI measurement systems onto the same wheel of the trailer and conducting different tire measurements simultaneously.

Rigid Pavement Research Program

The rigid pavement research program is primarily concerned with establishing the acoustic properties of PCC at the network level. This will allow characterization of these properties as a function of PCC age prior to being overlaid with ARFC.

In addition to the network level evaluations, selected PCC test sections involving grinding, tining, and transverse contraction joint design will be undertaken to support the overall quiet pavement program. The research objectives are to:

- Evaluate the acoustic properties of selected PCC surfaces over time
- Determine the correlation between near-field and far-field acoustic measurements
- Validate the use of CPX and sound intensity measurement systems for evaluating acoustic properties of PCC surfaces
- Develop site/pavement specific REMELs for improved noise modeling
- Evaluate the seasonal or environmental aspects of the acoustic properties of the PCC over time
- Determine acoustic variability within a given construction project.

Summary of Findings

Regarding the acoustic comparison of surface types, these are the findings from ADOT's experiments:

As shown in Table 2.1, there is over a 10-dBA spread between the noisiest and the quietest surface types.

The average ARFC value shown in Table 2.1 is lower than anticipated based upon the results of the network level analysis previously reported. This is presumably due to the fact that ARFC overlays are constructed one inch thick on PCC instead of 1/2 inch thick as on flexible pavements.

Table 2.1. Comparisons of Pavement Noise Result [Scofield 03]

Surface Texture Type	**CPX Noise Level Measured at Tire (dBA)**
Random Transverse (Wisconsin Spec)	104.9
ADOT Uniform Transverse tined (3/4")	102.5
ADOT Uniform Longitudinal Tined (3/4")	99.1
Whisper Grinding	95.5 (As-Constructed)
ARFC	91.8

About the various methods for acoustical evaluation, the results from the controlled test vehicle pass-bys were found to correspond very well to on-board sound intensity during the PCC texture testing. This fact suggests that further research is needed to verify whether sound intensity measurements, controlled pass-by, quasi-statistical, or statistical pass-by testing is the best method for managing a pavement network.

Both the CPX and sound intensity methods appeared to characterize the pavements noise characteristics very well. However, the sound intensity measurement method offers significant operational advantages and allows a more rigorous theoretical approach. ADOT's current plans are to continue simultaneous testing with both measurement systems for approximately one year of complete data collection, and then to migrate the program to sound intensity.

2.1.3. Colorado

Colorado does not have a specific noise program. However, recently, the NCAT developed a study [Hanson 04] for the Colorado DOT in which noise tests were conducted using a Close-Proximity Noise Trailer such as the one in Figure 2.17. Near-field tire-pavement noise consists of measuring the sound levels at or near the tire-pavement interface. In the CPX method, sound pressure is measured using microphones located near the road surface.

Eighteen pavement sections of various ages were tested, 12 AC and 6 PCC, at 60 mph. Two types of tire were used for the tests: Goodyear Aquatred and Uniroyal Tiger Paw. The quietest AC pavement tested was an open-graded friction course surface. The noisiest pavement was the transverse-tined PCC, which also happened to be the oldest of the pavements tested (eleven-year-old pavement). Following is the summary of results, showing average values:

1. AC Pavements:
   a. Open-graded (fine gradation) mixes – 93 dBA
   b. Dense-graded HMA – 95 dBA
   c. Stone Matrix Asphalt Mixes – 96 dBA
   d. Open-graded (coarse gradation) mixes 97 – dBA
   e. Average variability over a one-mile section – 3.8 dBA

2. PCC:
   a. Diamond ground – 98.1 dBA
   b. Longitudinally tined – 98.8 dBA
   c. Longitudinally grooved – 101.6 dBA
   d. Transverse tined – 102.6 dBA
   e. Average variability over a one-mile pavement section – 4.4 dBA

The study concluded that the age of an AC pavement can have an important effect on its surface noise level, that the type of texturing on recently constructed PCCs did not make much difference in noise levels, and that the quietest pavement was the OGFC.

Another important finding is that the acoustic characteristics of an OGFC depend on three factors:

- Air voids in the mixture
- Layer thickness
- Gradation of the mixture

2.1.4. New York

New York does not have a quiet pavement research program either, however, the New York State Thruway Authority and FHWA came up with a study that provides interesting noise comparisons of concrete pavement texturings [Burge 02]. FHWA requires surface texturing of PCC pavements to reduce skidding under wet conditions. Transverse tining is the most common of the treatments applied for this purpose. Alternate surface treatments, such as diamond-ground texturing, are occasionally considered in an attempt to reduce tire-pavement noise associated with tining. These treatments, however, should not compromise the safety, durability, service life, or other pavement characteristics only for the noise-reduction benefits. This study provided a comparison between longitudinal diamond-ground and transverse-tined pavement surface texturing for newly constructed plain jointed concrete pavement. The study area is located along portions of the Niagara section of the NYS Thruway, IH-190, in Buffalo, New York. The experimental surface treatment (longitudinal diamond-ground texturing) was implemented adjacent to noise-sensitive areas in lieu of the conventional transverse tining currently approved by FHWA. The two PCC surface treatment types under evaluation were compared based on safety, noise, construction cost, service life, riding quality, handling, and maintenance requirements. Analysis of the initial testing indicated that the relative skid resistance of the experimental longitudinal diamond-ground surface is as good as or better than that of the transverse-tined surface. The results of the noise analysis indicated that the longitudinal diamond-ground surface is 2 to 5 dBA quieter depending primarily on the traffic vehicle mix. Noise and skid resistance measurements conducted 1 year later showed little change. Although less construction time was required for the transverse-tined pavement compared with that for the diamond-ground pavement, the actual cost difference is not quantifiable. However, a higher initial cost for longitudinal diamond grinding would likely be partially offset by an extended service life.

2.2. Experiences of European Countries

European highway agencies have found that the proper selection of the pavement surface can be an appropriate noise abatement procedure.

Specifically, they have found that a low noise road surface can be built while considering safety, durability, and cost, by means of one of the following approaches [Sandberg 02]:

1. A surface with a smooth surface texture using small maximum size aggregate
2. A porous surface, such as an open-graded friction course (OGFC) with a high air void content
3. A pavement wearing surface with an inherent low stiffness at the tire-pavement interface.

The following paragraphs present various research endeavors conducted in European countries on tire-pavement topics, including the different approaches with which each nation has attempted to solve their noise problems. The sources for this valuable information are a desk scan on quiet pavement systems [Fults 03] conducted at CTR, and the scanning tour conducted in the spring of 2004 by an international team of researchers [Fults 04]. Both research efforts were led by Mr. Ken Fults of CTR. During the European tour, the team visited and investigated innovative pavement surfaces in various nations identified as leaders and/or innovators in the design, construction, maintenance, and operation of low noise pavements. Transportation professionals from Denmark, The Netherlands, France, Italy, and the United Kingdom hosted the team. The issues discussed ranged from high-level policies on highway noise to specific noise modeling equations and measurement techniques.

The efforts in Europe to mitigate traffic noise have not been isolated. The existence of the European Union has facilitated the exchange of information, policies, standards, equipment, and technology in general, as well as the implementation of joint programs. One of such undertakings is a new project called SILVIA—Sustainable Road Surfaces for Traffic Noise Control. Developed as a pan-European joint effort, SILVIA aims to provide decision-makers with a tool that will allow them to rationally plan traffic noise control measures. To this end, the work will aim at filling three major knowledge and technical gaps, namely by setting up classification and conformity-of-production procedures of road surfaces with respect to their influence on traffic noise; investigating and improving the functional and structural durability of low-noise pavement construction and maintenance techniques; and developing a full life-cycle cost/benefit analysis procedure for traffic noise abatement measures. The main final product will be a document titled "European Guidance Manual on the Utilisation of Low-Noise Road Surfacings," integrating information on low-noise surfaces with other traffic noise control measures including vehicle and tire noise regulation, traffic management, and other noise abatement measures.

The European Union also developed a program called SI.R.U.US. (Silent Road for urban and extra-urban Use), a multi-partner research project financed 50% by the EU Commission for the Brite-Euram program (BRPR CT98 –0659). It was started in September 1998. The main goal of the SI.R.U.US. project has been the development of low-noise multi-layer pavements with different surface and structural functions, as to permit full-scale implementation of innovative solutions capable of controlling road traffic noise mainly by optimizing the texture, roughness, hydraulic conductivity and sound-absorption characteristics, seeking a balance between their structural and acoustical performance over time and their life-cycle costs.

France, Italy, Netherlands, the United Kingdom, Austria, and Denmark are some countries that have distinguished themselves as leaders in traffic noise research. Their research approach and some of their developments are outlined in the subsequent sections.

2.2.1. France

France has been the source of some important research on the relationship between the road surface characteristics and noise emissions. There are 32 proprietary low-noise pavements used in France, which indicates the significance of tire-pavement noise reduction for the French public.

To reduce the traffic noise arising from contact between the tire and the road surface, French road contractors have developed effective surfaces that can reduce the noise by several decibels. The performance of the surface coatings utilized for this purpose is essentially obtained from a reduction in the particle size of the components of the surface layer and an increase in the proportion of voids in the asphalt. One of those types of surfaces developed in France is called Epsibel, a roadbed consisting of two layers of high-porosity draining bituminous concrete with various aggregate sizes. The lower layer is thicker and porous, with high noise absorption capability, and limited clogging. It is 1.5 to 2.5 in. thick, with 2.5% of bitumen. The thin upper layer, 0.75 in. thick with a small aggregate size, consists of 4.5% highly cohesive modified bitumen and 0.8% glass fiber. This thin layer helps reduce noise emission, while the porous structure absorbs engine noise and other vibrations, plus, it withstands traffic stresses. This kind of road is also designed to provide outstanding anti-rutting performances.

Another French development to combat tire-pavement noise is called Colsoft asphalt, a proprietary mix designed by Colas. In addition to low road noise, it has a matte appearance, which improves visibility by reducing reflections from light sources. Porous asphalts, which have been effective at noise suppression but have also the potential of losing their acoustic capabilities when the voids get clogged with debris, are experiencing renewed popularity.

Colsoft was designed, approved and certified in 1994 to reduce traffic noise on roadways. It was awarded the 1995 Golden Decibel Award by the French Ministry of Environment. Colsoft is a gap-graded 0/6 or 0/10 mm mix using crushed aggregates and a modified binder with crumb rubber from tires. The gap in the 0/10 mm mix is achieved as follows: Use 15-20% of the 0-2 mm aggregate; replace the 2-6 mm aggregate fraction with about 2% crumb rubber and then complete with the 6-10 mm portion. This mixture would require about 6.5% binder and is placed at 30 mm lift thickness. It's estimated cost is about 10-15% higher than conventional asphalt. Colsoft has been documented to reduce noise by 4 to 7 db when compared to the French reference mix (dense graded). Additionally, Colsoft has very good skid resistance.

Very thin asphalt mixes were initially designed to provide good skid resistance, especially at high speeds. They have increasingly come into use because they can provide both structural and functional benefits. They contain a large proportion of single-sized aggregate; medium aggregate size is typically 10 mm. Such wearing courses have actually given an open surface macrotexture, which has resulted in good skid resistance at high speed. Macrotexture is defined as a deviation of a road surface from a true planar surface with the characteristic dimensions along the surface of 0.5 mm to 50 mm, while microtexture refers to a deviation of a road surface from a true planar surface with the characteristic dimensions along the surface of less than 0.5 mm [Sandberg 02]. The level of microtexture required for sufficient low-speed skid resistance has been obtained by selecting the aggregates, or, more precisely, the rock and quarry from which they have been produced. A number of sections have been monitored. The results show that skid resistance at high or medium speed depends mainly on aggregate gradation. On the other hand, in situ measurements done at a variety of wearing course ages have proved that the binder—the coating mastic—properties largely influence the durability of macrotexture and the longitudinal braking force coefficient. Examples of evolution under traffic are presented, which illustrate the skid resistance durability obtained, either with fiber-modified mixes, or with elastomer-modified bitumen. The reduction of rolling noise was not a major goal for the mixes of this type. Indeed the noise measurements have shown that a medium level of acoustic performance has been obtained. In the meantime, the need for low rolling noise wearing courses had been steadily increasing. Specifically designed mixes have emerged, which combine high porosity and small-size aggregate (typically 6 mm). The porous structure absorbs a fraction of the acoustical energy. Due to the small size of the aggregate, the impacts of the tire on the rolling surface are limited. Very thin wearing courses of this type have been extensively developed in urban areas, where their thinness is a major advantage.

Traffic noise is considered by the French population as a primary environmental nuisance, therefore, the prediction of road traffic noise and development of efficient noise control techniques has become a major subject of investigation in that country. The approach undertaken has been to analyze the source, as a first step. Most of the noise is produced at the contact between tires and the road pavement. Many efforts have been devoted to the assessment of a reliable measurement method, and a classification of road pavements in relation to noise has been established for some years. To abate road traffic noise, special attention has been paid to low-noise pavements. Thus, the modeling of the absorption properties of porous asphalts has been particularly studied in the past 10 years.

The second step is to understand the physics of sound propagation outdoors, especially the effects of the weather on road traffic noise levels. Both theoretical and experimental approaches have been undertaken. Finally, traffic noise has also been studied from the receivers' standpoint; the effect of road noise barriers on road noise levels and their interaction with porous road surfaces have been investigated using numerical models.

2.2.2. Italy

Italy has experimented with double-draining layer (DDL) pavements as well, and has implemented a project to compare these surfaces with traditional thin porous layer (about 1.6 in. or 40 mm)**.** The Italian DDL pavement is composed of a 1.6-in. (40 mm) thick bottom layer (grading 0/18) and a 1-in. (25 mm) thick top layer (grading 0/10). Comparisons have been also made between the acoustic behavior of an existing 4-year old porous asphalt pavement and that of the test sections. The research program includes both laboratory investigations and field tests. In situ measurements on pavement are scheduled twice a year over a period of 3 years of continuous service under traffic. Laboratory tests include the following measurements: acoustic absorption coefficient in the impedance tube, airflow resistance, percentage of communicating voids, water permeability, indirect tensile stress resistance. In situ tests include the following measurements: friction, texture, evenness, drainage coefficient, pavement surfacing absorption factor, and sound equivalent level variability. A-weighted levels and spectral composition of noise emitted from vehicles outside and inside the vehicle itself for different speeds. The long-term objectives of the investigation are to compare the effects of surface characteristics, wear and aging of porous asphalt materials on acoustical performances.

On the subject of surface treatments, in recent years the possibility of modifying microtexture and macrotexture, permeability and rolling noise of road and airfield pavements has been studied in Italy, in order to improve the functional properties by means of single surface dressings of epoxy resin and synthetic aggregates. Of the surface dressings that have been applied, one of the most efficient has proved to be the Italgrip System (IS)**.** The treatment consists of spreading a two-component epoxy resin with an aggregate covering (the so-called MC-1), obtained by crushing a melted highly basic chromium mineral without any compaction on the pre-existing wearing course. The experimental study of this treatment has been carried out in Italy's major roads, motorways, local roads and, more recently, on airfields, where its capacity to improve the functional properties of surfacings (drastically decreasing the accident rate at road black spots) has been confirmed in all cases. Further tests are being done to ascertain if the IS treatment is effective in restoring adhesion to porous asphalts.

2.2.3. The Netherlands

Over half of the roadways in the Netherlands are constructed with porous asphalt. It is estimated that the primary network surfacing consists of more than 60% porous asphalt for the purpose of addressing noise issues. Multiple layer roadways are currently only constructed when necessary or for specific testing purposes. Design practices have not changed since 1990, which include stone gradations specifically to reduce construction weight and have a thickness of 2 in. The need for maintenance or replacement of the surface course is overwhelmingly caused by raveling from UV-radiation, oxidation and water penetration. Skid resistance values are generally low immediately after construction, but improve after three to six months to levels above dense-graded asphalt. Researchers are only now beginning to investigate how to maximize the noise reducing properties of porous asphalt and have constructed a trailer that meets ISO specifications. The researchers hypothesize that single layer porous asphalts with 1-in. thick and small aggregates will result in noise reduction properties similar to double layer construction. Researchers continue to aggressively seek means to maintain optimal noise reduction properties and durability of porous pavements.

After a decade of noise reduction policy in the Netherlands, there are still cases that go beyond the maximum accepted noise level. Because of this, a financial model was developed with the aim of solving the traffic noise pollution problem. The basic concept of the model is that 'exceeding the highest acceptable level of noise costs money.' The owner of the guilty infrastructure has to pay. It is expected that after several years there will be enough money to finance the badly needed noise reduction works.

Increasing traffic loading and tire pressures, environmental requirements like noise reduction, and special solutions, including unconfined loading situations, put increasing demands on the materials used in pavement structures with special focus on the upper layers. For flexible pavements it is necessary to search in certain applications for modified materials because of failing performance of AC mixtures. Temperature susceptibility, and in the case of porous asphalt mixtures, low durability due to raveling problems are examples of this. In a number of cases PCC is then used instead of even modified AC mixture. To keep the advantages of flexible structures, some researchers in the Netherlands endeavored in the development of new materials for the upper part of the pavement structure. As a result of this effort, a synthetic wearing course was developed. The material concept is similar to porous AC, with the major difference being the replacement of the bitumen with very flexible polyurethane. Just like with porous AC, the voids can be filled with a cement mortar. In this paper the mechanical properties of open synthetic wearing courses are discussed and compared with AC and PCC. Important conclusion is that the strength properties, even at high temperatures, are at such a level that even unconfined loading situations are possible.

Additionally, the Netherlands Ministry of Transport, Public Works and Water Management, and the Ministry of Environmental Affairs have initiated a sizeable research and development program to reduce road traffic noise. This program has set firm strategic goals to reduce noise and its effects on the receivers. The focus is on source-oriented measures which are generally more cost-efficient than effect-related measures. The Noise Innovation Program (IPG), with a budget of more than 50 million euros, will address the following topics:

- investigation of the possible noise reductions by road surfaces, tires and vehicles and enhanced noise barriers;
- scientific research to develop the knowledge needed to realize the reduction effects;
- development of the technologies and products to a level of general application in the national main road system and vehicle population. The program must result in a significant reduction of the noise production (including shielding effects) of the main road network system. An 8-dBA noise reduction will be feasible on a national level within 4 years, as the IPG works to combine noise reduction technology and products.

In the Netherlands, both the Noise Innovation Program and the Roads To The Future Program (WnT) have recently constructed test sections with quiet pavements. IPG focuses on the short term and it has developed some of the quieter roads currently available. However, it does not implement any new technique or materials. On the other hand, WnT focuses on the long term and on very silent roads preferably laid with innovative, fast construction techniques. IPG's state-of-the-art two-layered porous test sections should have a reduction of 6 dBA after construction and an average of 4-dBA noise reduction during the expected life time of eight years. The futuristic third generation silent pavements of WnT claim a noise reduction of 6-10 dBA directly after construction. The acoustic (CPX, SPB and absorption spectra) and constructive properties (e.g., rutting and raveling resistance) of all the pavements are measured thoroughly directly after construction and during the pavements' lifetime.

Major research is ongoing by the IPG to develop even more silent wearing courses such as twin layer porous asphalt, for which some proprietary products already are in use. This involves a large number of test sections but also many other types of research.

To develop measurement of sound, the ROEMER has been developed in the Netherlands, a CPX Sound measurement trailer.

2.2.4. United Kingdom

The U.K. has implemented a specification for a minimum average depth of texture for newly constructed road surfaces to ensure adequate skid resistance, and to calculate the influence of different road surfaces on traffic noise. Noise corrections for concrete and asphalt road surfaces are based on empirical linear relationships derived from noise and texture measurements on a large sample of surfaces. For porous surfaces, such as AC, a fixed reduction in noise level is assumed. In recent years, it has become apparent that new methods of controlling the surface finish of roads can result in significantly lower levels of traffic noise than predicted from their measured texture.

One of the most innovative highway projects in the U.K. started its construction in 1998. The A449 Coldra-Usk rehabilitation project in South Wales claims two firsts for the U.K.: the first overlay of a CRCP with no remaining life, and the first full-scale use of two-layer exposed aggregate "whisper concrete." It is expected this will provide a 3dBA noise reduction compared to conventional broomed concrete.

There have been other experiments with whisper concrete pavement, which, as mentioned, is based on exposing the coarse aggregate of the concrete, using one-layer or two-layer approaches. Whisper concrete has been found to be safe, durable, and quieter than most conventional surfaces, but it is not quite as quiet as a new porous asphalt surface. However, unlike porous asphalt, it does not appear to suffer from increased noise as it gets older. Studies by means of controlled pass-by tests done in the U.K. have shown that, when compared to Stone Mastic Asphalt, the maximum noise levels from "whisper concrete" were only -0.1 and 1.2 dBA different. And compared to HRA surface, the maximum noise levels were 5 and 3.7 dBA lower.

The following information, on both PCC and AC surfaces, was furnished by Dr. J. C. Nicholls, from the Infrastructure Division, TRL Limited, in the U.K. by e-mail, as reported in [Fults 03]:

> Experimental sections of exposed aggregate concrete with a two layer slab and highly polished stone aggregate were constructed as part of M18 highway repairs. Other sections were built with tined and broomed surfaces. The exposed aggregate section has been reported by drivers to be as quiet as the adjacent asphalt surface. The A564 highway between Foston and Hilton consists of a section of CRCP with exposed aggregate at the surface, adjacent to sections of CRCP concrete pavement with

bituminous overlays. The exposed aggregate section had the highest construction cost. Durability of the surface and pavement structure is unknown, so researchers will continue to monitor this section.

Back to the subject of AC surfaces, the use of porous asphalt (PA) in the U.K. stopped fairly soon after PA became a permitted surfacing material for trunk roads by its inclusion in the Specification for Highway Works in 1994. The dismissal of PA can be ascribed to the perceived risk in using the material following some failures, as exemplified below, and to proprietary thin surfacings, introduced around the same time, providing much of the advantages achieved with PA. However, PA is widely used in several other European countries, in particular the Netherlands.

The most infamous failure of PA was on the A34 Newbury bypass where the whole surfacing had to be replaced within 6 months of its placement. Ensuing heated exchanges about liability that nearly ended in court preceded its dismissal. Such incidents have discouraged designers from calling for it, and contractors from bidding reasonably for it thereafter.

Proprietary thin surfacing systems are now used widely in the U.K. as the preferred flexible surfacing material. They can, theoretically, be almost any bituminous mixture, but are generally either based on the German stone mastic asphalt, or the French very thin surfacing layer, both of which types have reduced noise characteristics. Spray-reduction is less often required because there is no quantitative method of measuring it directly. The Highway Authorities Products Approval Scheme (HAPAS) of the U.K. has recently introduced type approval for proprietary thin asphalt surfacings. The main criterion for specifying such thin surfacings is the BBA-HAPAS certificate of approval.

There are about 32 approved proprietary types of quiet pavements that meet safety and noise requirements. To obtain approval as a quiet pavement mixture, noise reduction factors are referenced to hot rolled asphalt (HRA): the pavement in question must get at least a 2.5 dB noise reduction compared to HRA. The approval system requires safety, strength and noise testing. Some noise pavements are cheaper than HRA. Because HRA is no longer used in the U.K., the new reference pavement will be SMA.

Even though the British experimented with exposed aggregate concrete (EAC) pavements as a quiet pavement solution, thin layer quiet pavements have taken over as the preferred alternative, mainly because of the higher costs associated with the EAC. The standard concrete surfacing was a brushed surface texture (1.2 mm average) and the EAC was reported to achieve a 3 dbA reduction. The current policy does not allow concrete pavement to be used as the finished surface. Any new concrete pavement is considered as a "supporting base" with a required "quiet pavement" surfacing. Even so, 40% of new roads are CRCP, with a thin surface layer. Most CRCP is built using gravel with a higher coefficient of expansion (COE) and therefore it develops more cracks. The strength control is changing from compressive to flexural. Both the base and subbase for CRCP must be bound (stabilized). The public has responded favorably to the use of noise-reducing surfaces, especially because of the improvement in riding quality. The thin surfacing mixes are similar to SMA but are proprietary. They are not as difficult to construct and maintain as the porous mixes and have reported service lives of 12 years compared to the hot rolled asphalts that lasted 15 years. The primary differences in porous asphalts and thin surfacings are costs (thin surfacings are cheaper) and texture. Porous asphalts tend to be positive textured and thin surfacings are negative textured. The primary failure mode of the thin surfacing mixes is raveling. These mixes must pass a wheel-tracking test at either 45ºC or 60ºC.

2.2.5. Austria

A research project conducted in Austria [Herbst 95] has concluded that even after seven years of service, porous asphalt roads will exceed conventional concrete pavement in noise reduction by 6 dBA. There is also a correlation between the drainage quality and noise reduction in porous asphalts. Porous pavements with 20–23% void contents (by volume) provide superior drainage and noise reduction characteristics. When void space is reduced to 15% (by volume), noise reduction significantly decreased. Porous pavement surfaces are thought to require more maintenance than dense pavements during winter due to increased frost formation. Porous pavements are adequately resistant to abrasion resulting from interaction with passing tires, but are sensitive to strong mechanical and chemical impacts. Additionally, because of its propensity to exhibit reflection cracks, saw cutting of joints is recommended on porous asphalt overlays on new concrete pavements.

2.2.6. Denmark

A research project was started in Denmark in 1999 [Bendtsen 99, Larsen 02, Bendtsen 02], with the purpose of developing noise reducing road surfaces for urban roads with speeds around 50 km/h. Three test sections with two-layer fine grade porous drainage pavements and a reference section have been constructed on an urban road. The sections characteristics and thicknesses are as follows:

1. (DA8-70), Top – 8mm chippings, Total Thickness – 70mm
2. (DA5-55), Top – 5mm chippings, Total Thickness – 55mm
3. (DA5-90), Top – 5mm chippings, Total Thickness – 90mm
4. (AC8dense), 8mm maximum chipping size. Dense asphalt concrete.

The pavements are cleaned twice a year by high-pressure water spraying and sucking. Some hypotheses on noise reduction, durability and traffic safety have been defined. A multi-disciplinary research group has established a comprehensive measurement program to test these hypotheses. This program includes acoustics (pass-by noise, road surface sound absorption, and noise inside vehicles), permeability, surface texture using laser, study of plane and thin sections from drill cores, friction, traffic safety, social surveys of annoyance, and an economic evaluation. The measurements are repeated every year. The goal is to continue for the entire lifetime of the pavements. Testing results after 3 years of measurements of noise reduction, porosity and surface characteristics indicate that new pavements had a 4-6 dBA noise reduction relative to dense asphalt concrete of the same age. Also, the two-layer drainage asphalt with the smallest chipping size had the best noise reduction after placement, but in years 1 and 2 the noise reduction is approximately the same for the pavements with 8 and 5 mm chippings. The pavement with 8mm chipping has the best porosity after 2 years. There are some tendencies of clogging on the pavement with 5 mm chippings. High pressure cleaning will keep their porosity and high noise reducing capacity with the largest chippings, but there are clogging tendencies with smallest chippings.

On porous asphalt, air pumping (which generates high-frequency noise) is reduced because the air is pumped down into the pavement instead of being forced away in front of and sucked behind the area of contact between the tire and the road. Porous asphalt also absorbs noise emitted by vehicles. The thicker the layer of asphalt, the lower the frequency at which the maximum absorption occurs. From a project in 1990, while porous asphalt was proven to be an effective means of noise reduction on roads with high traffic speeds (70 km/h), on urban roads, it proved of little value due to clogging of the pores. However, with two-layer asphalt and high-pressure cleaning once or twice a year, clogging can be avoided.

2.3. Experiences of Other Countries

The information obtained on other countries' experiences was obtained from the aforementioned Desk Scan Report [Fults 03] and the Scan Tour Report [Fults 04]. Two other countries that have developed projects on tire-pavement noise are South Africa and Japan. In this section, some of their research is presented.

2.3.1. South Africa

Quiet pavements have not been a foremost priority for the Department of Public Transport, Roads and Works in South Africa, mainly because they are considered expensive. A single porous AC overlay placed there raveled after only 4 years of service, resulting in a bad experience for this agency. However, even if there have not been pavements placed for noise mitigation purposes in mind, some research projects have studied the noise properties of existing pavements as outlined in the following paragraphs.

A research project conducted by CTR, Project 2957 (the predecessor of this project), investigated the noise properties of some South African pavements. This research consisted of field-testing fifteen different pavement types found in Texas, in coordination with six pavement types in South Africa. A test procedure was developed using standard test microphones to simultaneously record noise levels at roadside and onboard the test vehicle within a few centimeters of the tire of a towed trailer. The results, measured on the standard A-weighted scale, indicated a range of 7 dBA of roadside noise levels on the fifteen test pavements in Texas and a roadside noise level on one specially constructed pavement in South Africa to reduce noise that was measured as 3 dBA quieter than that of any Texas pavement measured in the study.

Another project investigated noise generative mechanisms and the characterization of tire-pavement noise, generated by a test vehicle at 100km/h on seven South African road surfaces, measured with a far-field and close proximity technique. Results showed that the high porosity pavement surfaces produce the lowest noise levels. Also, dense-graded asphalt surfaces produce lower noise levels than the surfacing seals. The frequency at which the highest sound pressure levels occur is around 1 kHz. Spectral analysis indicates that the air pumping effect becomes less significant with increase in the coarseness as well as the porosity of the surface and that noise measured near the contact patch indicates that the air pumping effect is more significant to the rear of the contact patch and attenuates quickly with increase in distance from the contact patch. There does not seem to be a simple uniform trend between the macro texture depth and the noise levels produced on the various road surfaces.

2.3.2. Japan

The application of porous asphalt pavement is rapidly increasing in Japan for noise reduction purposes in urban areas. In Japan heavy-traffic roads pass through overpopulated cities, making noise reduction an important characteristic for pavements. A Two-Layered Porous Asphalt Pavement system, known as TWINLAY, has been developed. As per recent policies, newly constructed roads must comply with noise regulations on specific projects in Japan. TWINLAY has proved effective in those cases, with high durability and good noise reduction effect.

The Japan Highway Public Corporation has been using porous asphalt pavement effectively for both its drainage and noise reduction properties. It is now necessary to test whether snow melting equipment that is being used and has been used on normal asphalt pavements prior to the induction of porous asphalt pavements is sufficient for the new porous pavements.

Highway traffic noise in urban areas of Japan is a serious problem, not only for residents along highways, but also for highway administrators. Only 13 percent of urban highways have met the environment standard for noise. Noise barriers cannot be used as a noise countermeasure on the majority of highways on which access is not controlled. This problem is impeding new highway construction in urban areas. The Public Works Research Institute (PWRI) has, since 1993, been developing a new low-noise pavement named “Porous Elastic Road Surface” (PERS). This new pavement has a porous structure composed of granulate rubber made from old used tires as its aggregate and urethane resin as its binder. The pavement was first proposed in Sweden in the 1970s, however, Swedish researchers have failed to implement it as a practical pavement. It is estimated that the potential noise reduction levels in Leq exceed 10 dBA. More than 90 percent of highways in urban areas would meet the standard if this noise reduction level were achieved.

2.4. Conferences

During the course of this project, one of the authors has had the opportunity to attend various conferences and seminars in the area of pavement-tire noise. Valuable information related to the current state of affairs in various areas of this project’s scope is exchanged in meetings of this nature. It was deemed appropriate to make reference to it in this chapter, thus, the review on this topic is supplemented by some notes taken at those events. In this section, a brief description of the conferences is presented; featured in Appendix B of this report are the detailed notes submitted to the project staff after each of these events.

The conferences, in chronological order, are:

1. **Tire-Pavement Noise Strategic Planning Workshop**
   Sponsored by the FHWA, and hosted by Purdue University, this workshop was held at the Purdue campus from September 14-16, 2004. Its purpose was to gather the expertise of the foremost specialists on the topic in the nation to develop ideas and design a course of action for the FHWA and State DOTs to improve procedures and policies toward the establishment of a nationwide noise program.

   The objective was accomplished; however, the task is far from being finalized: it is recognized that this is only the first step in a long path. Thus, forthcoming meetings of this nature should be expected to follow up on the progress of the initiatives agreed upon at Purdue.

2. **Transportation Research Board 84th Annual Meeting, held in Washington, DC, January 9-13, 2005**

   The TRB meeting offers numerous presentations on issues related to transportation, many of which are related to tire-pavement noise, such as noise policy, environmental effects, and pavement characteristics. On this occasion, most of the noise presentations were assembled into three sessions:

   - Basics of Noise Generation for Pavement Engineers
   - Quiet Pavements: Noise Mitigation Using Hot-Mix Asphalt Overlays
   - Constructing Desirable Characteristics of Portland Cement Concrete Pavement

   As mentioned before, specific notes on the presentations of these sessions can be found in Appendix B.

3. **2005 Summer Meeting/Conference of the Transportation Research Board ADC40 Noise and Vibration Committee**

   Somewhat similar to the winter meeting, but much smaller and with a more specific focus on noise, this conference presented a series of presentations addressing an array of issues on the topic, encompassing a broader scope than only tire-pavement noise. This TRB committee investigates transportation-related noise and vibration, and meets annually, in the summer time, to discuss relevant issues and showcase studies and research in the subject area. The presentations of this conference were featured in six sessions:

   a. Noise Policy and Public Issues
   b. Vibration
   c. Tire-Pavement Noise
   d. Noise Sources and Movement
   e. Construction Noise
   f. Underwater Noise

The details of the sessions are featured in Appendix B.

2.5. Acknowledgements

The research team is grateful to Bruce Rymer, from Caltrans, Fred Garcia from ADOT, and Ken Fults from CTR, for their valuable information and contributions to this chapter.

3. Equipment Evaluations and Recommendations

This chapter describes the equipment the research team has evaluated and now has available for measuring tire-pavement noise and roadside noise levels. Equipment and methodology for evaluating noise absorption characteristics of different pavement designs, both from lab specimens and cored pavement sections, is also given. Contrasts and comparisons are drawn between the various methodologies, with an emphasis on the strengths, weaknesses, and practicalities of each. At the conclusion of the chapter, recommendations are given as to which devices and protocols should be used in gathering the data needed to meet the goals of the project as outlined in Chapter 1.

3.1. Direct Measurement of Roadside Noise Levels

Although the objective of this study and most other pavement noise research is to measure the noise from a moving vehicle, any such measurement must correlate well with roadside noise levels in order to provide a useful determination of noise impact on the receivers, i.e., the homes, businesses, and people experiencing the traffic noise from the nearby road. Direct measurement of roadside noise using calibrated Type I instruments (handheld or tripod-mounted sound pressure level meters) is and always will be the gold standard by which environmental traffic noise is measured. However, "pass-by" testing requires extensive amounts of time and is labor intensive (requiring a 240 vehicle minimum sample); it will never be feasible or reasonable to perform the large number of these tests that would be required to evaluate an entire pavement network. The objective of the research, therefore, is to find a vehicle-mounted or towed noise measurement protocol that can be used quickly and reliably to estimate the roadside noise levels indirectly.

3.1.1. ISO 11819-1: Statistical Pass-By Testing

The protocol and methodology for Statistical Pass-By Testing is well established as an international standard, documented as ISO 11819-1; this document is attached as Appendix C, and can be summarized in the following paragraphs.

In the Statistical Pass-By (SPB) method, the maximum A-weighted sound pressure levels of a statistically significant number of individual vehicle pass-bys are measured at a specified road-side location together with the vehicle speeds. Each measured vehicle is classified into one of three vehicle categories: "cars," "dual-axle heavy vehicles," and "multi-axle heavy vehicles". Other vehicle categories are not used for this evaluation, since they do not provide any additional information regarding road surface influence.

For each of three speed ranges defined in Section 3.3, as well as for each of the three vehicle categories, a nominated reference speed is given. Each individual pass-by level together with its vehicle speed is recorded, and a regression line of the maximum A-weighted sound pressure level versus the logarithm of speed is calculated for each vehicle category. From this line, the average maximum A-weighted sound pressure level is determined at the reference speed. This level is called the Vehicle Sound Level, commonly abbreviated as L_{veh}.

For the purpose of reporting the acoustic performance of road surfaces, the Vehicle Sound Levels for cars, dual-axle heavy vehicles and multi-axle heavy vehicles are added on a power basis, assuming certain proportions of these vehicle categories, to give a single "index" that constitutes the final result. This index is called the Statistical Pass-By Index (SPBI) and can be used for comparison of road surfaces so that their influence on sound level of a mixed traffic flow can be determined. It is not suitable for determining actual traffic noise levels [ISO 11819-1:1997 E].

For the purposes of this study it is important to note that sampling enough pavement sections using the SPB procedure would be an adequate and totally defensible method for establishing the noise benefit of quiet pavements. Some SPB testing will be performed under this project to generate an initial estimate of the noise reduction afforded by quiet pavements, and the data will be used to compare field observations for these pavements to predictions given by the TNM noise modeling program, which is the FHWA standard for noise barrier analysis.

Unlike the vehicle mounted systems, the SPB method gives results for three classes of vehicles, specifically (1) cars, (2) dual axle heavy vehicles, and (3) multi-axle heavy vehicles. Although quiet pavement is expected to provide noise reduction for all classes of vehicles, it is expected that less benefit will be obtained for the larger vehicles.

3.1.2. Comparison to On-Board Vehicle Measurements

As noted, true SPB testing requires classification of vehicle type and some of that testing will be performed under this project to facilitate use of the TNM computer program and assist the TxDOT Environmental Division in obtaining a possible noise credit from FHWA for quiet pavements.

However, the larger scale use of the pass-by measurements in this study will be for comparison to the vehicle onboard noise measurement systems. By simultaneously recording and measuring tire noise from the moving vehicle, and comparing it to the pass-by noise recorded at roadside, it will be possible to build up a database that can be used to estimate roadside noise without the need for the more time-consuming direct measurement with sound meters. As reported in Chapter 2, this effort is well underway by other states and agencies, and data collected under this project will be compared to their findings.

3.1.3. Necessary Equipment and Use

The larger scale use of the pass-by measurements in this study will be for comparison to the vehicle onboard noise measurement systems. Figure 3.1 shows a typical Class 1 Sound Pressure Level (SPL) meter, in this case a B&K Type 2250. This particular instrument was chosen and purchased for the project because it has the unique characteristic of being able to automatically record not only the SPL measurements, but also the raw sound data itself, making it possible to reanalyze the data later if necessary, without the need for additional recording devices on the roadside. The data can be reanalyzed internally by the meter, or downloaded to a personal computer for further analysis.

Figure 3.1. B&K Handheld Recording SPL Meter.

In practice, two meters are generally used at the roadside, mounted on tripods located precisely 7.5 meters from the center of the travel lane, with the measurement microphone elevated 1.2 meters above the plane of the roadway. The measurement must be taken in a "free field" acoustic environment, meaning a minimum of reflected noise such as that caused by barriers or nearby buildings. Measurement is not possible during windy conditions or when the roadway is wet. Figure 3.2 shows a typical roadside setup as performed by the researchers on the Decker Lane test section.

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Figure 3.2. SPL Meter Setup for Roadside Measurement

The roadside measurements consist of recording maximum A-weighted SPL levels at the moment the test vehicle passes. Care must be taken that no other vehicles are near the test vehicle at the time it passes the roadside meters, or else another pass must be made. Speed of the test vehicle at the time of passing is critical, and should be 60 mph. Communication between the driver/operator and the roadside personnel is accomplished via handheld radios.

3.2. Measurement of Noise Levels from a Moving Vehicle

As reported in Chapter 2, the technology for measuring pavement/tire noise onboard a moving vehicle is advancing rapidly. Several devices and protocols currently coexist, each with characteristic advantages and disadvantages. Much work comparing the results from these devices to roadside noise levels has been done and reported in the literature by various agencies nationally and internationally. All such systems have the purpose of measuring noise quickly and directly at the pavement-tire interface in order to isolate this source from other sources such as engine or drive train noise, reflected noise from nearby barriers, or other nearby vehicles.

Though the systems employed are quite diverse, they are all either mounted on the vehicle itself, or on a towed trailer. Within the trailer systems, there are open or “free field” trailers, and enclosed trailers. Two towed trailer systems and one onboard device were considered for this study as detailed below.

3.2.1. Free Field CPX Trailer System

Figure 3.3 shows the second of two free-field CPX trailers built for a previous study, TxDOT Project 2957. The trailer is termed “free field” because there is no enclosure around the microphones, and “CPX” because it employs microphones in close proximity to the noise source. The trailer is weighted to simulate a standard passenger car [McNerney, 2000].

Figure 3.3. Project 2957 CPX test trailer

The CPX trailer requires an elaborate setup procedure once the test area has been reached (Figure 3.4). Operators must extend the trailer tongue, attach a mounting hoop, fasten the two calibrated microphones at precisely measured distances, connect all wiring, and set the tire pressure so that the contact area is constant between tests, all according to ISO Draft Standard 11819-2.

Figure 3.4. Field Setup Procedure for CPX Trailer.

Figure 3.5 shows overhead and plan views for the microphone placements. This arrangement of microphones is termed the "inner position" in ISO Standard 11819-2.

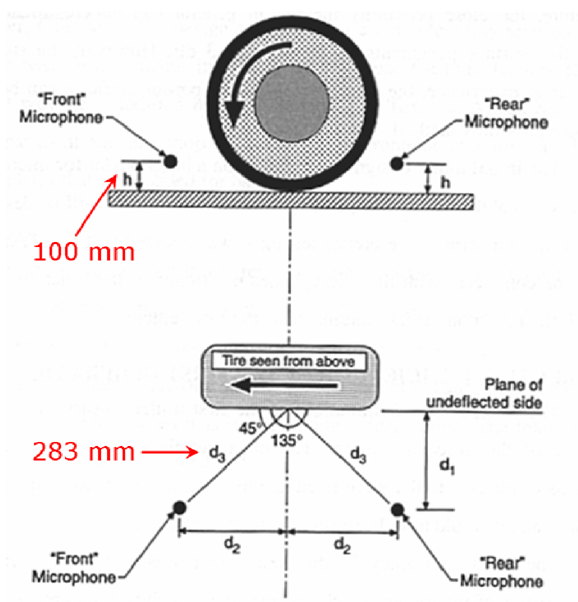


Figure 3.5. Inner position microphone placement for CPX trailer

The microphones are calibrated, then connected through a conditioning amplifier for recording onto either a laptop PC recording system (Figure 3.6) or, optionally, onto digital audio tape (DAT). The use of a laptop system is preferred, as it enables visualization of the data during the testing, and also facilitates time synchronization with other computer based devices such as

Global Positioning Systems (GPS), which can record position and speed very accurately. The noise data must be analyzed later from the recording.

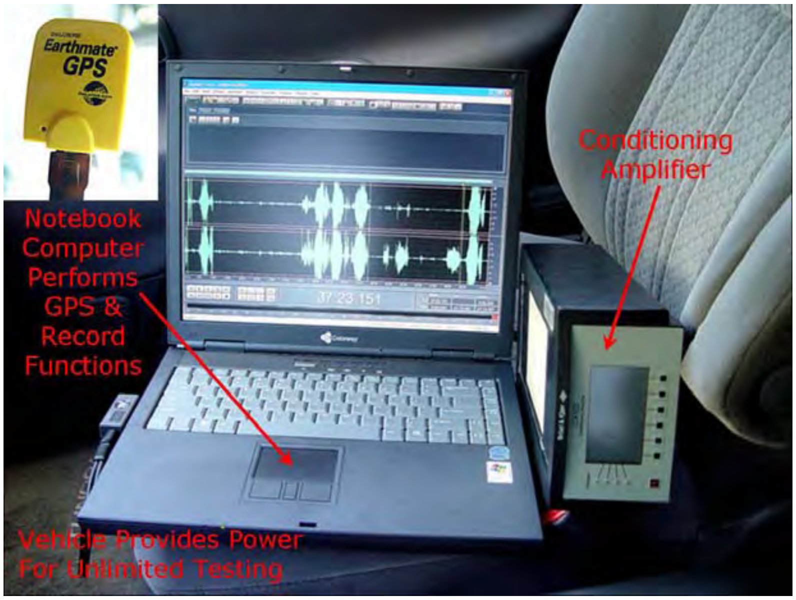


Figure 3.6. In-vehicle instrumentation for CPX trailer.

Post processing the data simply requires spectral analysis of the recorded noise followed by conversion to SPL A-weighted equivalent for each microphone (Figure 3.7).

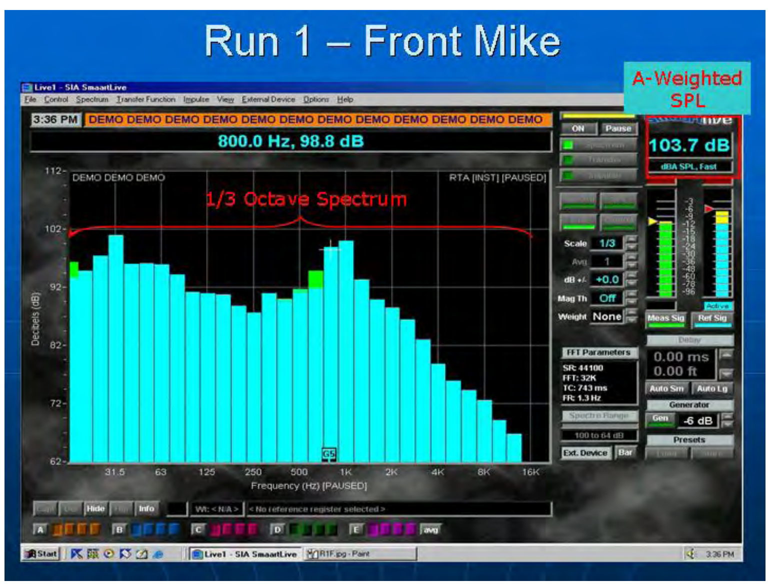


Figure 3.7. Post-processing of recorded noise data

Using the CPX trailer as described, a test run was conducted in December 2004 on the Decker Lane test section frequently studied under Project 2957. Figure 3.8 shows the same characteristic noise profile for the section, with about a 4dB increase in noise level with a maximum peak just below 1kHz. This result was considered reasonable since the section had not been overlaid in the interim, and provided some evidence that the re-instrumented noise trailer was working correctly.

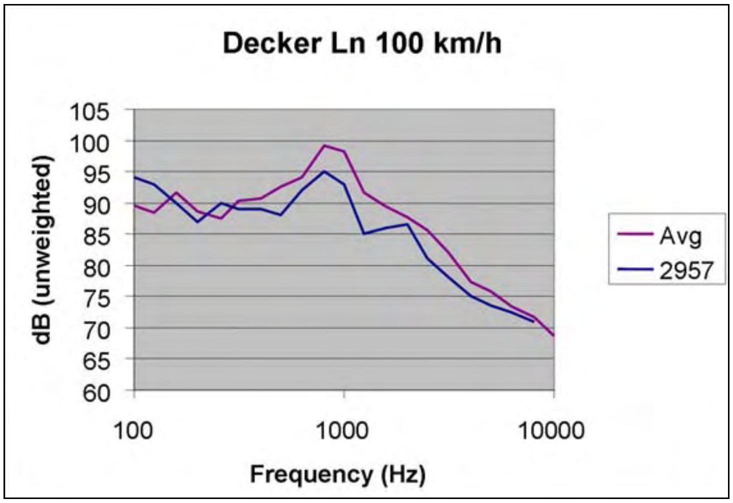
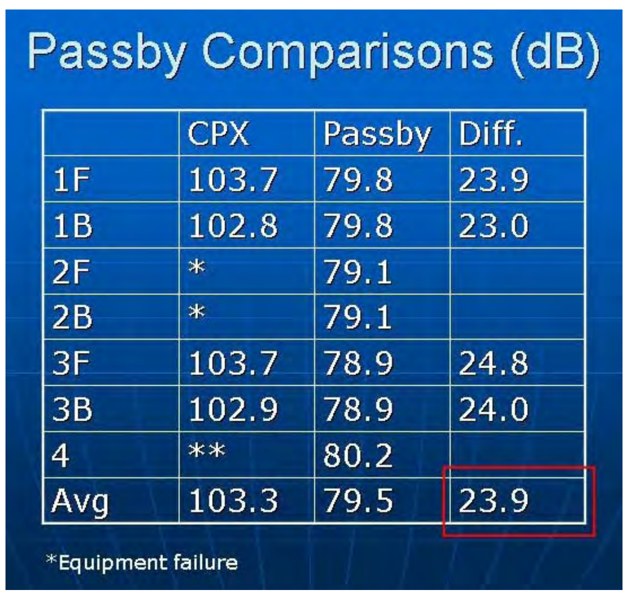


Figure 3.8. Comparison of Decker Lane test section: 1997 vs 2004

Figure 3.9 compares the noise levels at roadside to the CPX trailer measurements. The asterisks indicate data that could not be used due to an intermittent cable, but overall a fairly constant difference of around 24dB was noted, which corresponds well to the comparisons measured by CalTrans (Fig 2.3).



Passby Comparisons (dB)

	CPX	Passby	Diff.
1F	103.7	79.8	23.9
1B	102.8	79.8	23.0
2F	*	79.1	
2B	*	79.1	
3F	103.7	78.9	24.8
3B	102.9	78.9	24.0
4	**	80.2	
Avg	103.3	79.5	23.9

*Equipment failure

Figure 3.9. Comparison of roadside noise to CPX trailer, Decker Lane

3.2.2. Enclosed CPX Trailer System

An alternative towed system for pavement noise measurement using enclosed microphones was also evaluated for possible use in this study. This trailer, developed by the

National Center for Asphalt Technology (NCAT) is discussed in Chapter 2. The NCAT trailer encloses the test wheels and microphones in an attempt to reduce outside noise from barrier reflection and traffic (Fig 3.10).

Figure 3.10. Enclosed wheel space and absorptive foam used in NCAT trailer

The NCAT trailer retains the strategy of positioning the microphones away from the engine and drive train noise of the towing vehicle, and adds the advantages of preserving the test tires (a separate axle is used for transport) and attenuating some extraneous noise.

However, a new problem must be considered with the introduction of modes, wherein internal reflections within the enclosed compartment combine in and out of phase with the source noise at various frequencies, resulting in nulls and peaks that can substantially affect the test results. The thin Sonex foam is intended to decrease internal reflections, but no test data showing either the modal response of the enclosure or the transmission losses afforded by the closed panel have been published, so far as the researchers were able to determine.

Spectral comparisons of roadside noise to closed trailer measurements taken using the NCAT trailer [Donavan 2005] indicate similar overall levels but substantial differences in the mid frequencies between 500 Hz and 2 kHz (Figure 3.11), possibly due to modes in the enclosure.

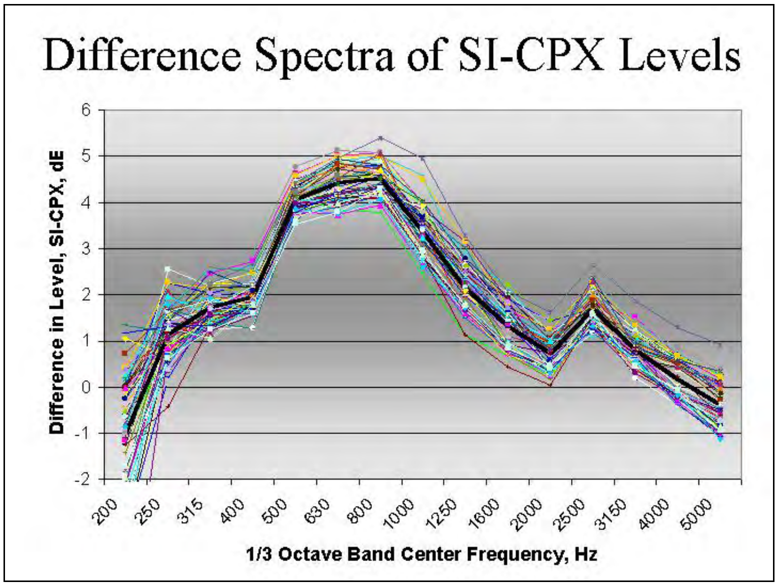


Figure 3.11. Apparent frequency response of the NCAT trailer

3.2.3. On-Board Sound Intensity System

The third pavement noise measurement system evaluated by the research team was the On-Board Sound Intensity (OBSI) system developed by Dr. Paul Donavan for CalTrans. It uses the industry-standard sound intensity measurement technique adapted for a moving vehicle, using a jig that fastens the microphone assembly to the vehicle wheel (Fig 3.12). Background on this device is given in Chapter 2.

Figure 3.12. OBSI jig being attached to wheel hub on test vehicle

A vertical stabilizer rod secures the jig to the fender of the vehicle, accommodating distance adjustments and up and down suspension movements, but not rotation of the jig. (Fig 3.13).

Figure 3.13. Attachment of vertical stabilizer rod to vehicle body

The microphone position must be 70 mm above the pavement, 100 mm from the tire sidewall, and aligned with the leading or trailing edge of the tire contact (Fig 3.14).

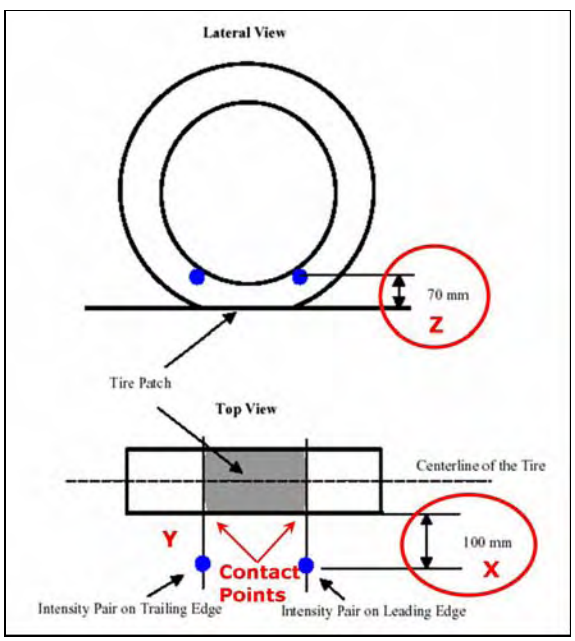


Figure 3.14. Microphone position for OBSI test

Figure 3.15 shows the distances between the microphones, pavement, and tire. Figure 3.16 shows the completed microphone assembly with windscreen attached, and microphones run into the vehicle compartment.

Figure 3.15. Checking the microphone holder distances

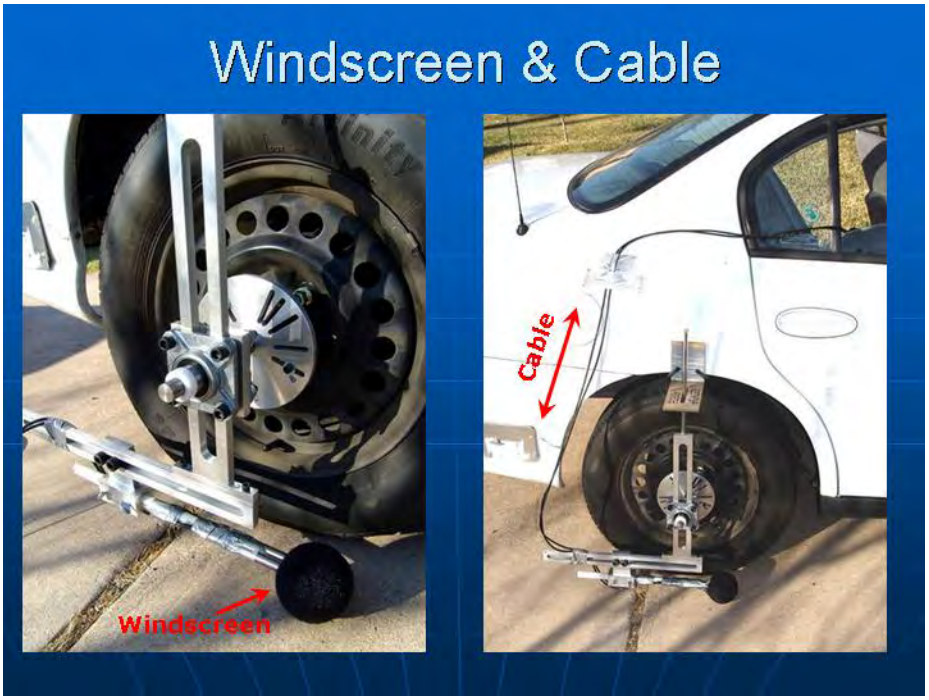


Figure 3.16. Completed assembly on vehicle

Inside the vehicle, the microphone cables are connected to an analyzer that calculates the sound intensity (amplitude and direction) in real time, storing the data internally each time the operator pushes a button. The Larson-Davis 3000 Analyzer (Fig 3.17) provides power to the microphones, calculates the sound intensity for each frequency band, and performs a number of other useful functions either under internal battery power or connected to the 12 volt power supply from the vehicle. Data stored in the analyzer can be downloaded to a PC for further analysis or archival.

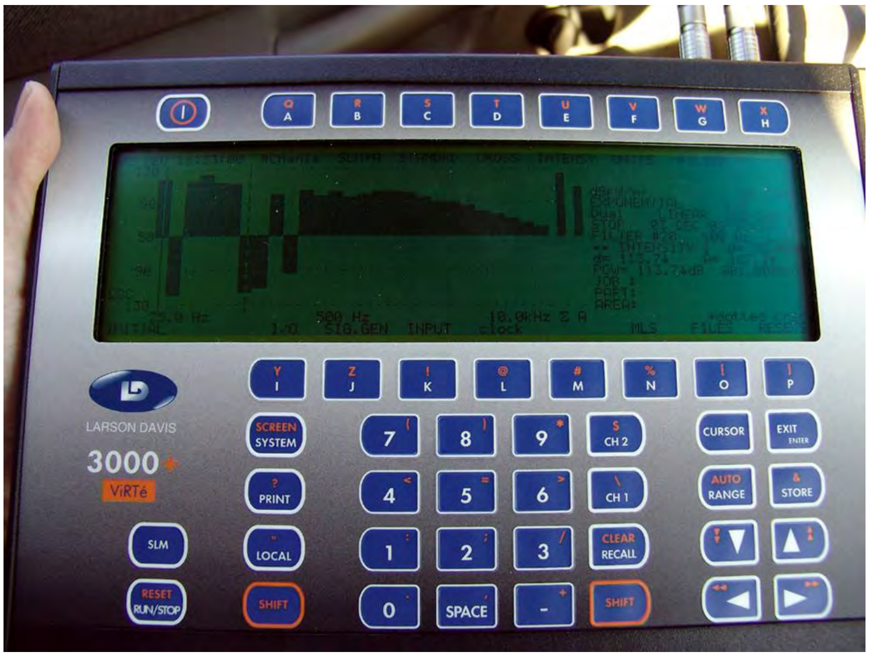


Figure 3.17. Larson-Davis 3000+ Analyzer

3.3. Useful Ancillary Systems

The sound intensity microphones, the jig, and the analyzer are all that is strictly needed to perform pavement noise measurements. However, the research team recommends the use of additional equipment in the vehicle for various purposes. In order to combine all the following functions into the minimum amount of additional gear, and to be able to relate the various data to each other by time and location, a combined solution using a single laptop PC was implemented. (Fig 3.18). The various functions of this system, the rationale for each, and the method by which the data is referenced to each other, is presented in the following sections.

Figure 3.18. Single laptop implementation

3.3.2. Recording Systems

The LD 3000+ analyzer does not record raw audio; it only stores the calculated sound intensities from each run. Therefore, reanalyzing the noise data later requires an external recording device.

This function can be performed by a number of digital devices, including Digital Audio Tape (DAT) recorders, flash media digital recorders, or by software running on a laptop computer. In all three cases, the audio is recorded digitally, using 48kHz or 96kHz sampling, with a bit depth of 24. Using 24-bit recording affords a dynamic range of more than 128dB, accommodating all ranges of pavement noise and allowing the operator to run and forget the recording software without worrying about levels or any loss of data precision due to digitization.

The advantage of using recording software on the laptop as compared to a dedicated hardware device is that the laptop computer can run several different software packages at the same time, each sharing the common time and date stamp maintained by the computer operating system. This facilitates reconstructing the time, date, and location each measurement was taken, which can often be of great value when analyzing the data.

Laptop soundcards are not generally of adequate quality for scientific work, so it is recommended that a high quality 2496 PMCIA audio card be installed. Figure 3.19 shows one of many PC recording software packages capable of recording noise data in real time.

Figure 3.19. Adobe Audition recording software with screen shot

Figure 3.20 shows the PMCIA interface card in use, an Echo Indigo 2496, and an alternative recording device sometimes used instead of the laptop based system, the Edirol R09 flash recorder. The R09 records 24-bit audio direct to a flash memory card, when the GPS capability of the laptop is not needed.

Figure 3.20. Echo Indigo soundcard for laptop, and Edirol flash recorder

3.3.3. Real Time Monitoring Systems

A vehicle traveling over the roadway at 60 mph is a hazardous environment for delicate recording equipment. Vibration, road noise, equipment problems, and nearby environmental noise (horns, backfires, etc.) all happen during road testing and ruin the data being collected at the time. Some gross malfunctions such as disconnected cabling, loose microphone heads, etc. can be visually detected using the laptop but the best device available for detecting odd noises of all sorts is still the human ear. Therefore, it is important to have a means for listening to the noise data as it is being collected, or for review of the recorded audio while still in the field, in case additional runs are needed.

Earphones for monitoring road noise must be sufficiently loud and/or isolated from outside noise to hear the microphone signal at a comfortable level. They must also be responsive and accurate enough so that the operator can detect and judge any possible problem as it occurs. Currently, the researchers use a pair of Shure E5c earbuds, which fit inside the ear and exclude outside noise almost entirely (Fig 3.21). The accuracy of the earphones is quite good, as they use separate internal drives for high and low frequencies. The E5s may also be used for critical review of the recorded noise files at a later time. They should not be used by the driver of the vehicle for safety reasons.

Figure 3.21. Shure E5c in-ear monitors

3.3.4. Global Positioning Systems

Inexpensive Global Positioning Systems (GPS) are now available and able to resolve location to within 10 ft. These devices and their associated software can be used in a moving vehicle to log the vehicle's location and speed precisely over time. The data captured by the GPS software can be used to verify the exact location of the test site, the time and date of the test, and whether vehicle speed during any test varied enough to invalidate the data. The captured data may be imported by standard spreadsheet software such as Microsoft Excel. Figure 3.22 shows an Earthmate GPS system recording vehicle position and speed during testing on the Austin Decker Lake test section. Figure 3.23 shows an Excel spreadsheet of the logged data.

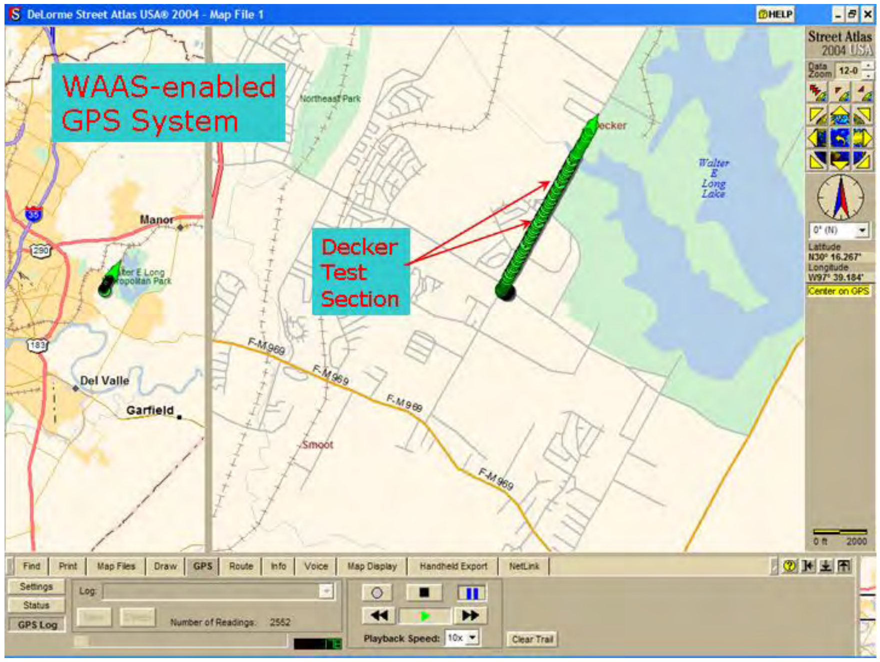


Figure 3.22. GPS mapping software display, Decker Lake test section

	A	B	C	D	E	F	G	H	I
1	Number:	stat	lattitude	longitude	date	time	heading	speed	altitude
2	135:00:00	5	30.29817	-97.6234	03-Dec-04	11:41:55	29.46	60.19404	659.4797
3	136:00:00	5	30.29838	-97.6233	03-Dec-04	11:41:56	29.57	60.55696	660.5253
4	137:00:00	5	30.2986	-97.6231	03-Dec-04	11:41:57	29.69	60.81344	661.947
5	138:00:00	5	30.29881	-97.623	03-Dec-04	11:41:58	29.58	61.02327	661.3382
6	139:00:00	5	30.29903	-97.6228	03-Dec-04	11:41:59	29.47	60.66033	665.1927
7	140:00:00	5	30.29924	-97.6227	03-Dec-04	11:42:00	29.47	60.66033	666.2398
8	141:00:00	5	30.29946	-97.6226	03-Dec-04	11:42:01	29.37	60.2976	662.8245
9	142:00:00	5	30.29967	-97.6224	03-Dec-04	11:42:02	29.15	59.57279	662.5929
10	143:00:00	5	30.29988	-97.6223	03-Dec-04	11:42:03	29.13	59.10655	661.986
11	144:00:00	5	30.30008	-97.6222	03-Dec-04	11:42:04	29.23	58.42953	664.5627
12	145:00:00	5	30.30029	-97.622	03-Dec-04	11:42:05	28.89	57.91654	667.1399
13	146:00:00	5	30.30049	-97.6219	03-Dec-04	11:42:06	29.11	57.60106	666.9097
14	147:00:00	5	30.30069	-97.6218	03-Dec-04	11:42:07	29.22	57.39024	671.0155
15	148:00:00	5	30.30089	-97.6217	03-Dec-04	11:42:08	29.21	56.92398	671.9383
16	149:00:00	5	30.30109	-97.6215	03-Dec-04	11:42:09	29.23	56.81722	670.4296
17	150:00:00	5	30.30149	-97.6213	03-Dec-04	11:42:11	29.35	56.60665	669.4693
18	151:00:00	5	30.30168	-97.6211	03-Dec-04	11:42:12	28.89	56.77047	667.5858
19	152:00:00	5	30.30188	-97.621	03-Dec-04	11:42:13	29.02	57.02542	665.7027

Figure 3.23. GPS log showing time, date, location, and speed of vehicle during test

3.3.5. Climate Monitoring Devices

The draft specification for OBSI testing specifies "continuous monitoring" of air and pavement temperature during the test. Fortunately, an inexpensive device exists that meets this need without requiring the test crew to make periodic measurements. Figure 3.33 shows the Thermochron i-Button, developed by Dallas Semiconductor and currently in use for many pavement-related applications. In practice, both Thermochrons are programmed to log temperature every ten minutes, one being placed on the pavement and the other being placed on any suitable nearby structure (e.g., traffic sign) to monitor ambient air temperature. An internal time and date stamp (synchronized to the laptop computer used for the GPS and recording function) allows the temperature data to be accurately associated with the other data collected.

Figure 3.24. Themochron i-Button temperature logging device

3.4. Estimation of Pavement Noise Characteristics From Material Specimens

Previous research conducted under TxDOT study 2957 [DeMoss, 1999] demonstrated that pavement noise absorption characteristics can be readily measured using a standard device employed by acousticians, the impedance tube (Figure 3.25).

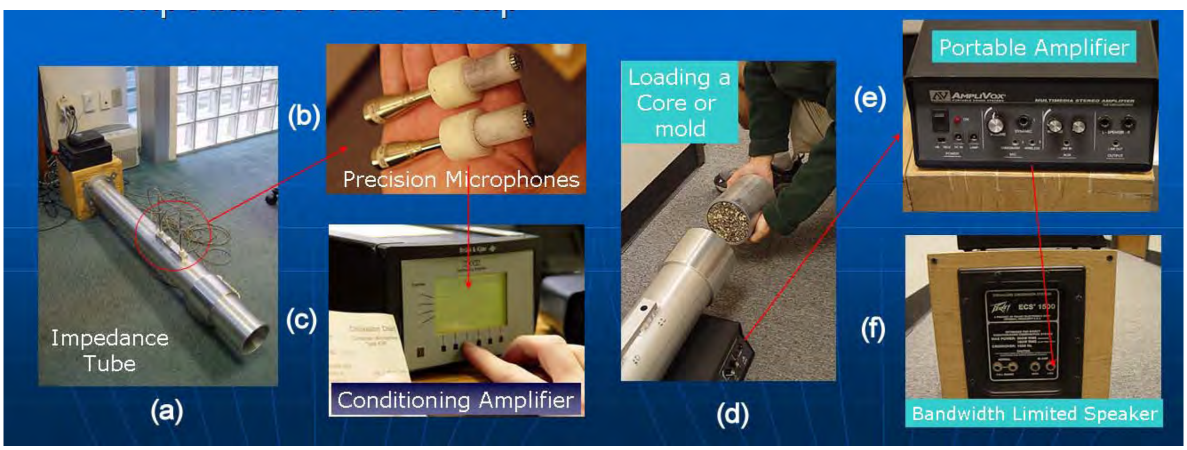


Figure 3.25. Use of the impedance tube to measure acoustic absorption

The impedance tube system consists of a long aluminum tube with a microphone mounting block near the end of the tube where the sample is to be placed (Fig 3.25a). Two precision microphones (Fig 3.25b) are inserted into the air column within the tube, at one of several spacings chosen to correspond to the wavelengths of interest. Signal from the microphones is passed through a conditioning amplifier (Fig 3.25c), which allows calibration of the microphones and measurement of the difference in amplitudes caused by standing waves in the tube.

The impedance tube constructed under Project 2957, and now used by this study, is designed to accommodate 4 in. diameter cores or lab molds either taken directly from asphalt or concrete pavements under study, or fabricated in the lab to estimate the absorption effects of various mix designs before they are used in paving. Either way, the specimen is loaded into the open end of the impedance tube and a metal plug is placed behind it to seal the tube (Fig 3.25d).

Swept sine wave tones or pink noise is then fed to an amplifier (Fig 3.25e) and the output is bandwidth limited by a high pass filter (Fig 3.25f) to drive the internal speaker, which in turn excites the air column in the tube and produces standing waves at various frequencies. The amplitude at each microphone location is a function of the tube length, the distance from the specimen. and the absorptivity of the specimen, the latter varying by frequency. The net result is a plot of specimen absorptivity by frequency.

Figure 3.26 shows an absorption plot for thin acoustic foam, as a reference. Note that the foam is very good at absorbing frequencies at 500 Hz and above. (The current impedance tube does not give accurate results above 1kHz at the present time; efforts are underway to improve the high frequency performance by moving the microphone block closer to the end of the tube.)

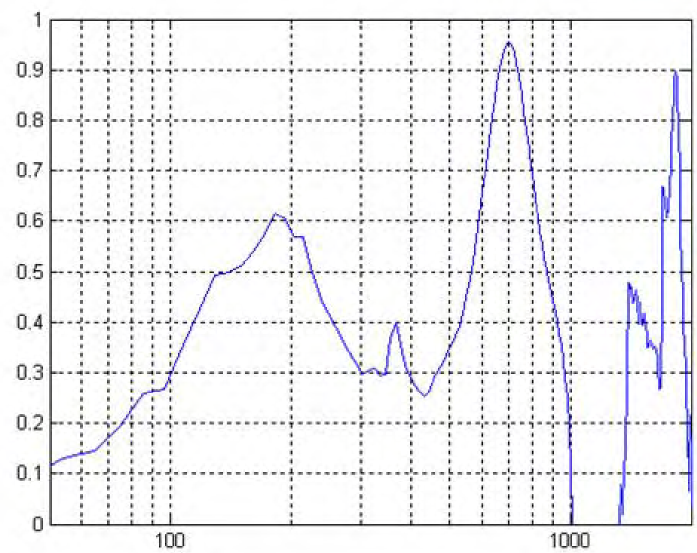


Figure 3.26. Absorptivity of acoustic foam in the impedance tube

Figure 3.27 shows the same absorption test using a 4 in. conventional asphalt specimen. It can be seen from the figure that the dense asphalt specimen is much less absorptive than the foam, especially at high frequencies. Work is currently underway to both improve the performance of the purpose-built impedance tube, and to apply it to porous asphalt specimens in order to investigate the effect of variables such as thickness, air void content, use of crumb rubber, etc. on noise absorption.

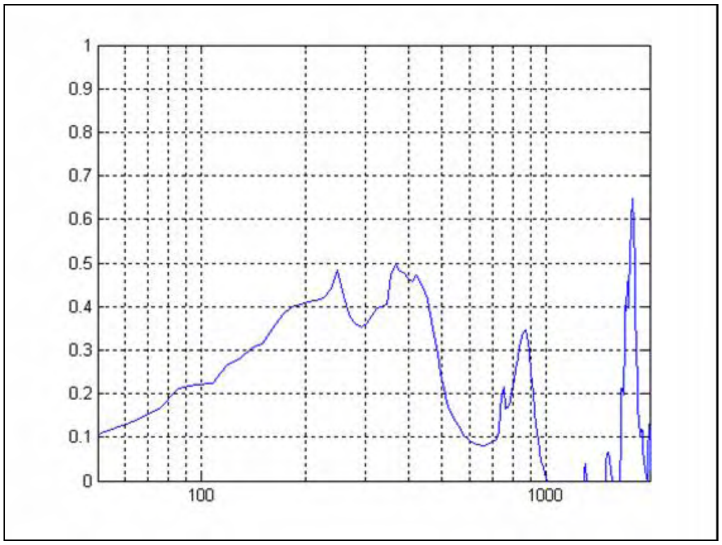


Figure 3.27. Absorption results for dense-graded ACP specimen

3.5. Conclusions & Recommendations

The following sections summarize the chapter, and provide conclusions and recommendations regarding noise measurement equipment to be used in accordance with the proposed test plan given in Chapter 4.

3.5.1. Conclusions

The devices presented in this chapter all measure pavement noise. The first group of devices measure roadside noise, and are well-established as the “gold standard” for quantifying environmental noise caused by vehicular traffic. All other devices must correlate well to the roadside SPL meter data if they are to be used for purposes of noise avoidance/abatement.

The second group of instruments are mounted on or towed by a test vehicle. They are intended to measure noise at the pavement/tire interface, providing a surrogate measurement of roadside noise that can be taken quickly and safely from a moving vehicle. These systems include open (free field) and closed CPX trailers, as well as the OBSI gear that eliminates the need for a trailer system while attenuating off axis noise such as that caused by reflective barriers or other sound unrelated to tire/pavement contact.

The tradeoff for the increased convenience of using these devices is that they measure only the portion of the environmental noise propagating from the tire contact. However, as reported in Chapter 2, in most cases this accounts for the largest portion of the vehicle noise and, in any case, serves as an adequate comparison method to evaluate the acoustic differences between pavements.

Finally, the impedance tube represents a third and unique sound measurement device that can be used to study the mechanisms causing one pavement to be quieter than another. This technique may be used to predict the acoustic performance of new pavement designs, or to investigate changes in the noise quality of existing pavements (through the use of cores).

All the devices evaluated and/or tested perform adequately when used within the known limitations of their test capabilities. Therefore, selection of the devices to be used for each function during this study is largely a matter of practicality and cost. Specific recommendations are given in the following section.

3.5.2. Recommendations

The following equipment is recommended for purchase to accomplish the goals of the study. Table 3.1 establishes the use, purpose, and justification for each device.

Table 3.1. List of recommended noise measurement gear

Equipment	Use	Purpose	Justification	Status
(2) B&K 2250 meter	Roadside	Pass-by Test	Validation of onboard tests to accepted standard	Purchased and in use
(1) OBSI system	In vehicle	Rapid noise test from moving vehicle	Emerging national standard	Purchased and in use
(1) CPX Trailer	Towed	Road test under ideal conditions	Comparison to OBSI system	Retained from Project 2957
(1) GPS System	In vehicle	Record location and speed of test vehicle, mark sections	Facilitate re-analysis of data, if needed	Purchased and in use
(1) Laptop PC	In vehicle	Run recording and GPS software	Preserve raw data for reanalysis or review	Purchased and in use
(2) Adobe Audition	In vehicle	Record raw noise data	Archive noise data	Purchased and in use
(1) Indigo card	In vehicle	Record noise data	Laptop sound card inadequate	Purchased and in use
(1) Edirol recorder	In vehicle	Record noise data	Backup for laptop system	Purchased and in use
(1) Earthmate GPS	In vehicle	Record position and speed of vehicle	Correlate noise measurements to location and time	Purchased and in use
(1) Impedance Tube	Office	Test molded specimens and cores for sound absorption	Meet project goal of correlating acoustic properties to pavement design	Retained from Project 2957, in use, modifying
(1) Shure E5c buds	In vehicle	Monitor noise during testing	Identify problems during testing	Purchased and in use

4. Work Plan

This chapter presents the proposed pavement sections that have been selected for testing in the next phase of this project. The research team's process of identification of those candidate pavement sections is described.

The main task in work plan development for the testing stage is the identification of suitable pavement sections throughout the state. The pavement sections are identified by means of a factorial; its design and component variables are detailed in this chapter. From the candidate sections identified, the factorial will indicate the number and type of sections that will be the subject of the on-board sound intensity testing. Some of the sections in the factorial will be the subject of statistical pass-by testing as well.

4.1. Pavement Sections

The pavement sections to consider for the testing phase of this project have to be representative of the roads in Texas where noise issues are more likely to arise and become an environmental concern. Even though the project encompasses a wide variety of pavement types available in the state, the research will focus on certain types, specifically those that are found to be "quieter," and which quietness could last for a span comparable to the life of the pavement. To determine the sections to be tested, a factorial considering a number of variables was designed.

4.1.1. Factorial Variables

The design of the factorial experiment includes variables that have an effect on the acoustic properties of the surface, such as pavement type, pavement age, and geographic location.

Pavement Type

The first consideration when evaluating the acoustic properties of a pavement in regards to the tire-pavement interaction is the type of pavement. The distinction between a bituminous pavement (commonly referred as flexible) versus a portland cement concrete (PCC) pavement (also referred as rigid) has a definite influence in the noise produced at the tire-pavement interface. The general consensus is that the rigid pavement surfaces are noisier than the flexible ones, but this is not necessarily true. Perhaps this perception is a result of the widespread practice of tining PCC pavements, which in many cases makes these surfaces loud. Within pavement types, there are many other variables that come into play, such as the type of aggregate, aggregate gradation, type of finishing, pavement layer thickness, and percentage of voids.

Among asphalt concrete (AC) pavements, the porous surfaces are regarded as the quietest. Open-graded friction courses (OGFC), commonly known in Texas as permeable friction courses (PFC) have delivered excellent results in terms of their acoustic characteristics, even though in Texas they have not been designed and constructed with this purpose in mind.

In the first phase of testing in this project, it has been decided that the research will focus on PFC pavements. Subsequently, other types of AC pavements will be studied as well, such as dense-graded AC surfaces. Similarly, PCC pavements will also be tested in subsequent stages of the project.

Pavement Age

It is generally accepted that as a pavement surface ages it becomes louder, but this general perception is not necessarily true. The common hypothesis supporting this premise is that, with time, the pavement air voids become clogged with dust and other debris, and when the voids are filled with material, they can no longer absorb sound, making the surface louder. This is true in many cases, and the desirable acoustic properties can be restored with cleaning of the porous surface. However, the usefulness of cleaning procedures is the subject of debate. An instance in which an aging pavement does not become louder with time is when a non-porous riding surface (e.g., a concrete pavement) gets polished with use and loses its texture, making it smoother and hence, quieter.

The change in acoustic properties with age is a foremost research subject in this study. For FHWA to accept that "pavement type" can be used for noise mitigation purposes, it has to be demonstrated that such properties can be maintained in "perpetuity," i.e., that a pavement that is constructed quiet will remain quiet.

Pavement Location

The geographic location of the sections is considered a variable in this factorial because it has an influence on the weather conditions, mainly regarding precipitation and temperature. It is hypothesized that these two environmental aspects might have an impact on tire/pavement noise, and it is proposed to investigate it in this study. There is a wide variety of climatic conditions that occur in the State of Texas. However, for the purpose of this study, to simplify the factorial, the climatic conditions within the state have been grouped into four categories, which also correspond to four regions within the state:

1. Wet and freeze
2. Wet and no freeze
3. Dry and no freeze
4. Dry and freeze

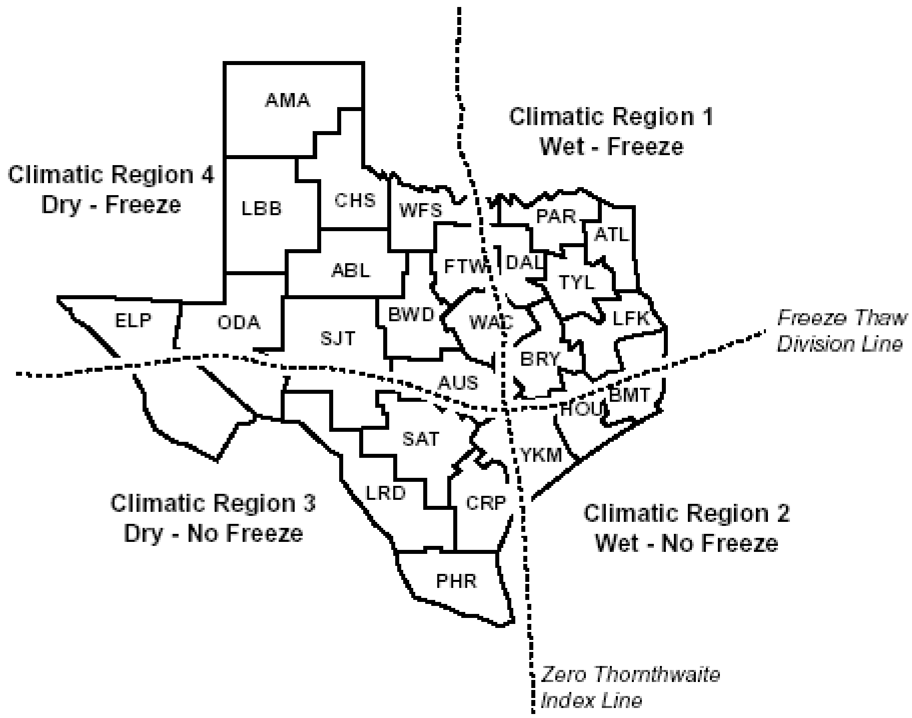


Figure 4.1. Climatic region classification in Texas, showing TxDOT districts

The geographic location of the four regions is determined by two lines dividing the state into quadrants. One line, close to a horizontal line, separates the region prone to freezing temperatures from the region in which temperatures remain above freezing for the most part, while the other line divides the state into wet and dry regions as shown in Figure 4.1. This line is based on the Zero Thornthwaite Index, which separates regions with water deficiency from regions with water surplus.

It should be noted that the boundaries of the four regions are not absolute, meaning that given the variability of climatic conditions with time, the location of the lines that determine the quadrants may change. Also, the location of those lines sometimes fall within districts, making some districts have areas in two or more climatic regions.

4.1.2. Section Selection

The preliminary selection of pavement sections for testing was drawn primarily from two sources: sections that were initially investigated under Project 2957, and sections that were chosen in agreement with TxDOT district contacts.

It is proposed to investigate pavements that possess the following characteristics:

- Pavements that may differ significantly from “average” values used by FHWA in noise analysis
- Open-graded, PFC and rubberized plant mix seals
- PCC pavements with different types of texturings, such as transverse tining, longitudinal tining and carpet drag

The sections considered for Project 2957, some of which might be tested again in this project, are presented in Table 4.1 [McNerney 00].

Table 4.1. Texas Pavements Considered for Project 2957

	PAVEMENT TYPE	PAVEMENT LOCATION	TEST DATE
1	Typical TxDOT Asphalt Pavement — New	Loop 1604 — San Antonio	1/22/97
2	Typical TxDOT Asphalt Pavement — Aged	MoPac @ Braker — Austin	1/26/97
3	TxDOT Asphalt Pavement with Microsurfacing	MoPac @ 45th — Austin	1/26/97
4	Grooved Asphalt Pavement	Robert Mueller Airport Runway 13R/31L	11/20/96
5	Chip Seal Pavement	SH 16 northwest of Helotes	1/22/96
6	TxDOT Coarse Matrix High Binder Asphalt Section	S. MoPac — 3 mile section south of Slaughter Lane — Austin	11/13/96
7	CRCP with Transverse Tining — New	Houston	2/17/97
8	CRCP with Transverse Tining — Aged	Houston	2/17/97
9	Novachip — New	So. Padre Island Dr. — Corpus Christi	3/2/97
10	Novachip — Aged	US 281 just south of SH 46 — San Antonio	1/10/97
11	Asphalt with Longitudinal Grooving	US 281 — San Antonio	Canceled
12	JRCP Ungrooved	Bergstrom AFB, Taxiway 17R	11/18/96
13	JRCP Grooved Transversely	Bergstrom AFB, Taxiway 17R	11/18/96
14	JRCP Grooved Diagonally	Bergstrom AFB, Taxiway 17R	Canceled
15	TxDOT Asphalt Pavement with Microsurfacing	So. Padre Island Dr. — Corpus Christi	3/2/97
16	Control Section — Decker Lane	Decker Lane — Austin	2/21/97
17	CRCP Untined	I-820 — Fort Worth	3/17/97

The 2957 sections were tested approximately 10 years ago. If the riding surfaces for some of those pavements are still in place, those sections offer a good opportunity to compare old and current results, and to analyze whether there has been a change in the acoustic properties of the pavements. The Decker Lane control section (number 16 in Table 4.1) has been already measured in this project, during the initial evaluation of the noise trailer and pass-by equipment described in Chapter 3.

As mentioned, for the first stage of tests, the research team has decided to focus on the porous AC pavements. To find out which districts use open-graded friction courses, CTR prepared an on-line survey on use, mix design, construction, performance and maintenance on PFC pavements. This survey, prepared mainly for Project 0-4834, “Cold Weather Performance of New Generation Open-Graded Friction Courses,” was sent out to pavement and laboratory managers in the 25 TxDOT districts, and its results have provided valuable information. Twentythree replies were received from TxDOT personnel. From those replies, it was found that 12 districts currently use this type of pavement surfaces. The districts that currently have PFCs in place, according to the survey's respondents, are:

- Corpus Christi
- Houston
- Austin
- Fort Worth
- El Paso
- Lufkin
- Odessa
- Pharr
- Tyler
- Waco
- Wichita Falls
- Yoakum

Additionally, an experimental PFC located in Amarillo identified in Project 0-4834 was added to the list.

Follow-up e-mail messages were sent to those respondents to find out more specific details about the PFC sections in each district; all respondents provided further information, except for the first two from the list above.

The district contact personnel from the various districts kindly provided details on the PFC sections in their districts. In some instances, however, they were not able to provide all the details for those sections. At that stage, the list was sent to John Wirth at TxDOT, who sent it to other district personnel asking for their help in gathering the missing information. Finally, German Claros of TxDOT recommended the researchers contact TxDOT's Magdy Mikhail and ask for his assistance with the completion of the list. The list of candidate sections, with accompanying comments, is presented in Table 4.2.

Table 4.2. List of Candidate AC Sections

District	Roadbed	Surface Type	Aggregate Size	Void Content	Year Constructed	Section Length (mi)	Site Description Comments
Amarillo	SH 136	PFC			2001	0.3	approximately 5 miles north of Amarillo, experimental PFC section, Potter County
Austin	US 183	Item 3231 - PFC	1/2" nominal	Not tested in place	2003	2	from North Fork San Gabriel R. to Seward Junction (SH 29)
	FM 1431	Item 3231 - PFC	1/2" nominal	Not tested in place	2005	1.2	from Trails End Rd. to 0.2 mi west of Vista Ridge
	RM 620	Item 3231 - PFC	1/2" nominal	Not tested in place	2004	3.558	from SH 45 to IH 35
	IH 35	Item 3231 - PFC	1/2" nominal	Not tested in place	2006	1.744	from the Colorado River to Ben White
	IH 35	Item 3231 - PFC	1/2" nominal	Not tested in place	2005	9	from Loop 4 to Yarrington Rd.
El Paso	US 90	PFC w/ 8.5% A-R	Grade 4	0.22	2002	28	from RM 505 to Marfa, Presidio County
Fort Worth	US 81	Similar to PFC, 1" Thick	3/8"-1/2" max size	20% est.	1993	0.2	southbound exit ramp to FM 730, in Decatur, Wise County. AC mix is similar to PFC.
	FM 1658	Plant Mix Seal, 1" Thick	3/8"-1/2" max size	15%-18% est	1994	3.427	from US 380 to the Lake Bridgeport Dam, west of Bridgeport, Wise County. Plant mix seal was placed in 1994. It may have a low air void content.
	FM 1884	Plant Mix Seal, 1" Thick	3/8"-1/2" max size	15%-18% est	1987	7.872	from IH 20 to the end. Parker County, The plant mix seal surface was placed in 1986. May also have a low air void content.
Houston	US 90	ACP			2003		from IH 10 east of Peach Ridge rd. to FM 359, let in December 2003; West Harris Area Office
	SH 6	ACP			2004	26.7	from Harris Co. Line to US 90A, let in January 2004; Fort Bend Area Office
	IH 45	ACP			2005	6.9	from North of FM 1959 to Clear Creek, let in April 2005; South Harris Area Office
	IH 45	ACP			2005	9.8	from Loop 336 to FM 1097, let in February 2005; Montgomery Area Office
	SH 242	ACP			2005	13.1	from San Jacinto River to US 59, let in February 2005; Montgomery Area Office
	Loop 336	ACP			2005	2.8	from SH 105 to East of RR Overpass, let in February 2005; Montgomery Area Office
	FM 2855	ACP			2004		from 158' North of US 90 to FM 529, let in May 2004; West Harris Area Office
	SH 146	ACP			2005	10.1	from FM 519 to IH 45, let in March 2005; Galveston Area Office
	US 59	ACP			2005	1.9	from FM 762 to 1.1 Mile W. of FM 2759, let in May 2005; Fort Bend Area Office
Lufkin	US 59	Type C PFC 68%- GRANIT MOUNTIAN GR 3 27% Eagle Mill TY C 5% Chico Screenings 6% Asphalt Fina 1% Lime 0.3% Cellulose Fibers	1/2	18-15 %	2003	1.429	1.126 miles N of FM 1818 To 0.303 miles S of FM 1818 this section run through the city of Diboll,Tx.
	US 59	Type C PFC 74% Delta TY-D 21% Delta TY-C 4%TXI Sand 1% Lime 5.8% Asphalt Fina 0.3% Cellulose fibers	1/2	15-18	2004	2.437	0.32 Miles S. of Alexander Creek To 0.45 miles N of Milton Creek. Section is south of Leggett, Tx. In the south bound lanes.

Table 4.2 List of Candidate AC Sections (continued)

District	Roadbed	Surface Type	Aggregate Size	Void Content	Year Constructed	Section Length (mi)	Site Description Comments
Odessa	IH 20	Plant Mix Seal with rubber	½"	18%	1994	5.797	from near Loop 214 east of Stanton to near Loop 214 west of Stanton (from RM 159+0.467 to 153+0.680), plant mix seal with rubber, Martin County
	IH 20	Plant Mix Seal with rubber	½"	18%	1995	3.787	from Loop 214 east of Stanton to the Howard County line (163+0.252 to 159+0.467), Martin County
	IH 20	Plant Mix Seal with rubber	½"	18%	2000	11	from west of Pyote to west of Monahans (65-0.462 to 76-0.277), Ward County
	IH 20	Plant Mix Seal with rubber	½"	18%	2000	8.62	from BI 20-B west of Monahans to BI 20-B east of Monahans (76-0.277 to 85-0.752), Ward County
	IH 20	Plant Mix Seal with rubber	½"	18%	2001	4.474	from Martin County line to 4.474 miles west (149+0.657 to 146-0.817), Midland County
	IH 20	Plant Mix Seal with rubber	½"	18%	2001	18.279	from Ector County line to 0.3 miles east of SH 349 and from 1.6 miles east of FM 307 to 1.7 miles east of BI 20-E (141+0.733 / 122+0.00), Midland County
	SH 349	Plant Mix Seal with rubber	½"	18%	2004	3.262	from Indiana St. in Midland to south of Loop 250 (328+0.530 / 324+1.230), Midland County
	IH 20	Plant Mix Seal with rubber	½"	18%	2004	9.675	from Midland County line to BI 20-F east of Stanton (159+0.468 / 149+0.793), Martin County
	IH 10	Plant Mix Seal with rubber	½"	18%	2005	8.625	from SH 17 to 6.4 mi west of Pecos County line (212+0.142 / 220+1.057), Reeves County
	IH 20	Plant Mix Seal with rubber	½"	18%	2004	5.788	from near BI 20 east of Stanton to near BI 20 west of Stanton (159+0.468 / 153+0.680), Martin County
	Loop 250	Plant Mix Seal with rubber	½"	18%	2005	3.536	from SH 158 to Midkiff Rd. (274-0.139 / 276+1.396), Midland County
	IH 20	Plant Mix Seal with rubber	½"	18%	2005	3.787	from east of Stanton to Howard County line (163.25 / 159.463), Martin County
	IH 20	PFC with rubber	½"	18%	2005	9.819	from FM 1936 to 0.8 miles east of FM 1601 (111+0.817 / 102+0.021), Ector County
	SH 302	PFC with rubber	½"	18%	2005	9.796	from BI 20-E to SP 450 (Kermit Hwy), (266-0.330 / 268+1.355), Ector County
Pharr	US 83	PFC	1/2 "	20%	2004	2.6	from Sugar Rd. E. to FM 1426, Hidalgo County
	US 77/83	PFC	1/2 "	20%	2004	3.004	from 0.25 mi. south of FM 511 to 0.5 mi. north of FM 3248, Cameron County
	US 77/83	PFC	1/2 "	20%	2004	2.202	from 0.5 mi. north of FM 3248 to 0.5 mi. north of FM 802, Cameron County
Tyler	US 79	PG76-22	Class B (PFC)	16.40%	2004	1.51	from 374+0.49 to 376+ 00; mix is PG76-22 with Class B aggregate. This starts at the west city limits of Jacksonville and goes west. Placed in June 2004.
	US 69	PG76-22AR	Class A (PFC)	18.40%	2005	0.97	from 366+0.62 to 366+1.59; mix is PG76-22AR with Class A aggregate. This is approximately half way between Jacksonville and Rusk (south of Jacksonville). Placed in August 2005.
Waco	IH 35	PFC	3/4"	18-22%	2003	2.57	Main lanes at Craven Ave, placed in 2003, 1 ½ inches of PFC, McLennan County
	Loop 340	PFC	3/4"	18-22%	2000	Intersection	at IH 35 @ Loop 340 (Intersection), 1 ½ inches of PFC, McLennan County
	SH 6	PFC	1/2"	18-22%	2005	8.692	from BU 77 to SH 164, McLennan County

Table 4.2 List of Candidate AC Sections (continued)

District	Roadbed	Surface Type	Aggregate Size	Void Content	Year Constructed	Section Length (mi)	Site Description Comments
Wichita Falls	US 287	PFC	1/2"	20%	2001	12.25	SB, from 300+00 to 312+.25, 1 ½ inches of PFC, Wilbarger County, placed in the fall of 2001
	US 287	PFC	1/2"	20%	2002	5.65	SB, from 366+1.20 to 372+.85, 1 ½ inches of PFC, Clay County, placed in the summer of 2002
	US 287	PFC	1/2"	20%	2002	7.33	SB, from 372+.85 to 380+.18, 1 ½ inches of PFC, Clay County, placed in the summer of 2002
	US 287	PFC	1/2"	20%	2003	1.25	SB, from 380+.18 to 380+1.43, 1 ½ inches of PFC, Clay County, placed in the summer of 2003
	US 287	PFC	1/2"	20%	2003	6.1	SB, NB, from 314+.25 to 316+00 SB and 316+00 to 310+1.65 NB, 1 ½ inches of PFC, Wichita and Wilbarger Counties, placed in the summer of 2003
	IH 44	PFC	1/2"	20%	2003	17.8	EB, WB, from 2+0.60 to 11+0.50 EB and 11+0.50 to 2+0.60 WB, 1 ½ inches of PFC, Wichita County, placed in the fall of 2003
	US 82	PFC	1/2"	20%	2005	5.93	WB, from 620+1.75 to 614+1.82, 1 ½ inches of PFC, Cooke County, placed in the spring of 2005
	US 82	PFC	1/2"	20%	2005	4.72	WB, from 614+1.82 to 610+1.10, 1 ½ inches of PFC, Cooke County, placed in the summer of 2005
Yoakum	US 290	PFC	1/2"	Not Available	2004	7.6	from Washington County Line to Lee County Line, Fayette County
	IH 10	PFC	1/2"	Not Available	2003	15.4	from US 77 Overpass to Hattermann Lane, Fayette and Colorado Counties
	IH 10 Eastbound	PFC	1/2"	Not Available	2005	10.7	from 10.7 mi. West of Austin Co. Line to Austin Co. Line, Colorado County
	IH 10 Westbound	PFC	1/2"	Not Available	2005	14.1	from 14.1 mi. West of Austin Co. Line to Austin Co. Line, Colorado County
	IH 10	PFC	1/2"	Not Available	2001	9	from FM 609 to US 90 at Waelder, Fayette and Gonzales Counties
	IH 10	PFC	1/2"	Not Available	2006	20.7	from US 90 at Waelder to US 183, Gonzales and Caldwell Counties, under construction
	US 59	PFC	1/2"	Not Available	2005	8.8	from Spur 91 to South of Loop 463, Victoria County
	Spur 91	PFC	1/2"	Not Available	2005	1	from US 77 to US 59, Victoria County
	US 87	PFC	1/2"	Not Available	ongoing	6.9	from Victoria County Line to 1.90 miles west of SH 35, Calhoun County, under construction
	US 87	PFC	1/2"	Not Available	2006	3.5	from Placedo to Calhoun County Line, Victoria County
	US 59	PFC	1/2"	Not Available	2002	4.8	from Wharton County Line to FM 710, Jackson County

The table includes information on various properties that will be useful to characterize the sections and to correlate those properties with the sound test results, such as void content, type of mix, and age.

Regarding PCC sections to be tested in subsequent stages of this project, it is expected that there will be no difficulties in locating them, as there is no shortage of rigid pavements in the major urban areas, where noise is more likely to be a concern. Likewise, there will be plenty of dense-graded asphalt sections to choose from in the following phases of the experimental part of the project.

4.2. Statewide Collection Factorial

As stated, the variables considered for the factorial were pavement age, pavement type, and geographic location. For pavement age, only two categories have been established, with an arbitrary limit: sections with more than five years of service are considered old, and sections of less than five years' service are classified as new.

This classification has been established only for the purposes of developing this factorial. One of the most important goals of this research is to determine the longevity of the acoustic properties of the pavements. Thus, once a significant amount of experimental data has been collected, it is expected that a more substantial boundary can be established to distinguish whether an "old" pavement is indeed louder than a "new" one, if this occurs at all.

The tests will concentrate on three types of AC pavements: plant mix seal, PFC, and dense-graded AC. Regarding rigid pavements, the main focus of the testing will be on transversely tined surfaces, which encompass most of the PCC pavements in the state, but some other types of finishings (e.g., carpet drag) will be considered as well, depending on their availability. Therefore, for rigid pavements there are two categories in the factorial, i.e., tined and alternative finishing, which includes carpet drag, burlap drag, broomed, etc.

The other main variable of the factorial is the geographic location, which determines the climate in which the pavements are situated. As mentioned, there will be test sections in each of the four quadrants that roughly determine the four main climate types in the state.

In summary, the categories in this factorial are:

Pavement Types:	AC: Plant mix seal, PFC and Dense Graded PCC: Tined, and Alternative finishing
Age:	Old New
Climate:	Wet and freeze Wet and no freeze Dry and no freeze Dry and freeze

The number of categories for each of the three variables results in 40 combinations (5 pavement categories * 2 age categories * 4 climate categories). An early estimate of the sections that can be tested for this project was established at approximately 100 sections. This estimate is based upon practical traveling considerations, budget, time, and the fact that the testing has to be repeated throughout the duration of the project to evaluate the changes in the acoustic properties of the pavement with time. Ideally, the test sections would be distributed evenly to fill the entire factorial. However, it is acknowledged that not all the combinations will be possible, because not all the pavement types are available for all ages or climatic regions. Furthermore, because a heavy emphasis has been placed on the investigation of PFC sections, it is proposed to test as many sections of this type as available, within reasonable limit. Table 4.3 presents the factorial for the testing part of the project, showing the number of proposed test sections in each cell. The number of sections for the plant mix seal and PFC categories are based on Table 4.2. For dense-graded AC and PCC, the initial estimate is three sections per type, age and climate. As indicated in the notes below the factorial table, PFC, dense-graded AC and tined PCC are the pavement types of main interest for this project. Conversely, plant mix seals and PCCs with different types of finishings are not of the foremost importance for the project objectives, thus, some sections of those types will be tested, depending on their availability, but those might not be essential.

It should be noted that the numbers in the factorial table indicate the proposed sections that will be tested for on-board sound intensity. In a limited number of those sections, statistical pass-by tests will be performed to try to establish a correlation between procedures. Some of the test sections will be evaluated in conjunction with TxDOT for comparison purposes, as both the research team and TxDOT have analogous on-board sound intensity equipment and vehicles. These comparisons will ensure that both sets of equipment work properly and deliver similar, accurate results, and that the procedures followed by both CTR and TxDOT are uniform and in accordance with the standards. Moreover, with a larger scope in mind, it is expected that the outcome of the cooperative efforts in the testing phase between CTR and TxDOT will enable TxDOT to conduct a network-level noise evaluation for the pavements in the state in the future.

Table 4.3. Statewide Data Collection Factorial

Pavement Type		AC						PCC			
AC Mix type or PCC Finishing		Plant Mix Seal [b]		PFC [a]		Dense Graded [a]		Tined [a]		Alternative Finishing [b]	
Age (>5 years = Old)		Old	New	Old	New	Old	New	Old	New	Old	New
Climate	Dry-Freeze	2	c	1	12	3	3	3	3	3	3
	Dry- No Freeze	2	7	c, d	13	3	3	3	3	3	3
	Wet-Freeze	c, d		c, d	4	3	3	3	3	3	3
	Wet- No Freeze			d	10	3	3	3	3	3	3

Notes:

a Essential to project goals
b Satellite study, not all combinations available
c Some sections on boundary of wet-dry line, within same district
d Limited number of sections available

4.3. Summary

The candidate test sections for on-board sound intensity and statistical pass-by testing have been determined. Some sections from Project 2957 might be included in the testing part of this project. It will be beneficial to compare test results from that project, obtained approximately 10 years ago, with current results, if the surfaces remain the same.

With the help of the district contacts, a list of PFC sections has been compiled. The assistance of John Wirth and Magdy Mikhail of TxDOT has been very valuable in enhancing the list to include additional information that will be useful for the researchers when characterizing the pavements and correlating such properties with sound test results. A statewide factorial, considering pavement type, pavement age, and geographic location, has been prepared. The factorial indicates the number of proposed sections that will be tested for each category.

5. Summary

The preceding chapters describe the state of the art in pavement-noise measurement at the time this report is being prepared. This area of research has seen a strong resurgence of interest in recent years, and many national and international agencies are currently involved in strong programs to address the issue of noise avoidance/abatement through the use of quiet pavement technology. Measurement technologies are advancing at a rapid pace as well, with a current draft standard for on-vehicle measurement well on the way to acceptance by the noise community. Therefore, any document being prepared at this time will be somewhat dated by the time it reaches print; it is imperative that literature review be a continuous process, and that the researchers continue to participate in national and international meetings to share data and technology.

5.1. Measurement Technology

Recommendations for equipment to be used in this study are provided and justified in Chapter 3. Currently (and always subject to change), the pavement noise community seems to be coming together around the draft standard for OBSI measurement using sound intensity as the technology to quickly and accurately measure vehicle noise from a moving vehicle. Accordingly, in the interest of being able to exchange and meaningfully compare data with other researchers, the recommendation for this study is to continue use, for the near future at least, of the OBSI equipment that has been purchased.

The CPX trailer inherited from Project 2957 is also fully functional and provides comparable accuracy to the OBSI gear, provided that the conditions for its use are met: specifically, test sections without reflective barriers or significant traffic. Unfortunately, the areas most likely to benefit from quiet pavement technology are usually located in urban areas that do have barriers and high traffic levels, even at off-peak periods, making measurements with the CPX trailer very difficult and time-consuming. However, the CPX trailer does have the advantage of being less sensitive to engine and drive train noise because while in use it is extended as far away from the towing vehicle as possible.

For a time, it will be necessary to simultaneously measure noise from the vehicle mounted systems in conjunction with the standard roadside pass-by measurement techniques, which follow established protocols and are well-accepted for environmental noise. This procedure will use the two B&K SPL meters presented in Chapter 3 and already purchased for the project. Data from the roadside testing on quiet pavements will be provided to TxDOT Environmental Division to support an immediate request for a “noise credit” to be used in the design of noise barriers, to be later supported by the OBSI data collected from the moving vehicle.

Finally, the impedance tube setup will be used on cored or molded specimens in an attempt to correlate material properties of the pavement to absorption characteristics as measured in the tube. It is hoped that the database from this effort will be a great aid to pavement designers when specifying quiet pavement designs.

5.2. Test Sites

Chapter 4 presents the experimental factorial for selecting pavement types, ages, and locations to be tested. The initial effort will focus on porous friction courses (PFC), since this pavement type has the greatest potential for noise avoidance/noise abatement purposes. However, the factorial also includes testing on concrete surfaces with various finishes, as well as chip seals and conventional asphalt pavements. This is necessary to provide estimates of how much quieter an existing pavement will be if resurfaced with PFC, and also to give designers insight into the available options when environmental noise is a consideration.

Because one objective of this study is to determine how well quiet pavements maintain their properties over time, the factorial also includes older pavements, and also pavements in areas with significant winter maintenance requirements, as "old" in pavement terms is also a function of cumulative traffic exposure and possibly collection of sand and de-icer runoff in pavement voids.

5.3. Coordination with TxDOT

Preliminary recommendations for test equipment and protocols have already been shared with TxDOT through correspondence and numerous meetings. As a result, TxDOT has purchased a complete OBSI system to attach to one of their existing fleet vehicles, and another fleet vehicle has been placed on loan to project staff. Coordination meetings have been held at TxDOT Cedar Park on three occasions, with the primary purpose of determining test coordination between CTR and TxDOT. A joint training session hosted by TxDOT and given by Dr. Paul Donavan of Illingworth and Rodkin Associates was conducted on June 6-7, 2006.

The goals of these joint exercises are (1) to make certain that the two noise test vehicles are returning comparable results, and (2) to efficiently divide the responsibility of testing all the pavements that TxDOT needs to be tested. Some overlap in testing is desirable for continuous comparison of the two sets of test devices.

5.4. Moving Toward a Network Level Process

The protocols and devices described in this report, if followed precisely, require time and effort that makes them most suitable for project level data collection. Project level collection produces a large amount of data from a limited number of sections, is very accurate, and is entirely appropriate for research.

At some point, if not already, TxDOT will want to begin a network level collection of noise data if possible. This may consist of dedicated noise test vehicles traveling around the state, or it may take the form of some rudimentary noise measurement gear being added to existing network test vehicles such as the multi-function vehicle currently employed for statewide condition survey, or, less likely, the existing TxDOT skid trailers. The data likely to be obtained from such system, because of the speed, automation, and integration with other vehicle design elements would almost certainly be of less accuracy than the current OBSI system and the complex protocol followed when using it. However, such data might be "good enough" for statewide inventory purposes, where sections targeted by the network level testing could be followed with dedicated noise test gear and protocols.

The researchers of this project have noted on many occasions that the capability of the OBSI and GPS systems currently in use would allow the devices to run continuously on a long trip, for example from Austin to Dallas, recording all data on IH35 during the 3.5 hour trip. A fairly simple computer program could be written to post-process all the data in constant length sections (identified by GPS log) and report out the results, averages, and any sections that might need further study. This computer program will be prepared as a first draft as time allows in the near future.

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Appendix A: Draft of "Standard Practice for Measurement of Tire-Pavement Noise Using the Close Proximity Sound Intensity Method"

This appendix presents the draft of the on-board sound intensity measurement procedure, which is assumed to become an AASHTO standard as well as an ASTM standard in the near future.

Some of the wording in the following specification is still under revision at the time this report is being prepared, but the gist of it will likely remain as presented here.

Standard Specification for

STANDARD PRACTICE FOR MEASUREMENT OF ON-BOARD TIRE-PAVEMENT NOISE

AASHTO Designation:
ASTM Designation:

American Association of State Highway and Transportation Officials
161616 North Capitol Street N.W., Suite 2169
Washington, D.C. 20001

Standard Specification for

STANDARD PRACTICE FOR MEASUREMENT OF ON-BOARD TIRE-PAVEMENT NOISE

AASHTO Designation:
ASTM Designation:

1 INTRODUCTION

Changes in pavement type and texture can have significant effects on the noise created at the tire / pavement interface and received by local highway neighbors.

In order to isolate the tire/pavement component of highway noise, a standard test procedure using an on-board sound intensity method has been developed. Using microphones, mounted near a reference tire, measurement of this single component of highway noise is possible in an efficient, cost-effective way and can be applied to extended sections of roadway.

It should be noted that this method is not intended to replace the pass-by method for determination of impacts on the highway neighbors. Too little is known on the relationship between the acoustic intensity at the tire and the propagation effects to the nearby receivers to make a direct connection at this time. The on-board intensity measurement described here will permit the tire/pavement acoustic intensity to be measured directly and allow various pavements and textures to be directly compared.

It is expected that the measurements using this standard will provide the highway community with a uniform procedure for on-board determination of acoustic energy at the tire/pavement interface.

2 REFERENCES

The following references were used or referred to in the preparation of this text. In addition, Annex A contains an informative bibliography.

2.1 ISO 1081616:19916: "Acoustics - test surface for road vehicle noise measurement".

2.2 ISO 11819-1: 1996: "Acoustics - METHOD FOR MEASURING THE INFLUENCE OF ROAD SURFACES ON TRAFFIC NOISE - Part 1: "The Statistical Pass-By Method"

2.3 ISO 11819-2: Draft: "Acoustics – METHOD FOR MEASURING THE INFLUENCE OF ROAD SURFACES ON TRAFFIC NOISE – Part 1: "THE NEAR-FIELD METHOD"

2.4 ISO 131673-1. "Characterization of pavement texture utilizing surface profiles - Part 1: Determination of mean profile depth."

2.5 ISO/CD 131671-1: Under preparation, by ISO/TC 163/SC l/WG 27 (first Committee Draft expected in 1997).

2.6 IEC 651: "Sound level meters". International Electrotechnical Commission, Geneva.

2.7 ANSI S1.10-1966 (R 2001) American National Standard Method for the Calibration of Microphones.

2.8 IEC 9162: "Sound calibrators" International Elctrotechnical Commission, Geneva

2.9 IEC 10163:1993 Electroacoustics - Instruments for the measurement of sound intensity - Measurements with pairs of pressure sensing microphones, Edition: 1.0, Document Number: IEC 610163, International Electrotechnical Commission, 30-Nov-1993. 69 pages

2.10 ANSI S1.9-1996 ANSI S1.9-1996 (R 2001) American National Standard Instruments for the measurement of Sound Intensity.

2.11 ANSI S1.11: "Octave, Half-Octave, Third-Octave Band Filter Sets.

2.12 IEC 1260: "Electroacoustics - Octave band and fractional-octave band filters". International Electrotechnical Commission, Geneva.

2.13 ISO 5725-1: "Accuracy (trueness and precision) of measurement methods and results - Part 1: General principles and definitions".

2.14 GMN7070TP: "Road Tire Noise Evaluation Procedure", GM North American Engineering Standards, 9/30/20016.

3 TERMINOLOGY

3.1 For the purposes of this Standard, the following definitions apply.

3.1.1 Traffic noise, vehicle noise, tire/pavement noise and power/train unit noise.

Traffic noise is the overall noise emitted by the traffic running over the road under study. Vehicle noise is the total noise from individual vehicles. This includes a component of noise generated by the tire/road interaction called tire/pavement noise and components generated by the vehicle engine, exhaust system, air intake, fans, transmission, etc. The noise from these components is known as power train unit noise.

3.1.2 The On-board Sound Intensity Method (OBSI)

The On-board Sound Intensity Method is a measurement procedure to evaluate the tire/pavement noise component generated on different sections of road surface. The entire system used measures the tire/pavement sound intensity. This includes the matched microphones, analyzers, and associated equipment. The measurements are made with microphones operating close to one or more test (reference) tires, which are mounted on a test vehicle. The test vehicle is run along a road section over a specified distance. Results, obtained using the procedure, are measured at standard speeds according to the category or type of road being considered.

3.1.3 Statistical Pass-By Method

The Statistical Pass-By (SPB) Method is a measurement procedure designed to evaluate vehicle and traffic noise generated on different sections of road surface under specific traffic conditions. The measurements are taken from a great number of vehicles operating normally on the road. Results obtained using this procedure may be normalized to standard speeds according to the category or type of road being considered. See further ISO 11819-1.

3.1.4 Average Sound Level

The average sound level during a measurement is the sound pressure level recorded by the measuring instrument using the appropriate frequency weighting and averaged on the basis of power over a certain time or corresponding road distance interval.

3.1.5 Sound Intensity

Sound intensity is the acoustic energy flowing through a unit area in a sound field and hence is a vector quantity with an associated direction of propagation. Unit: Watts per squared meter with a reference value 10^{-12} used for Sound Intensity Level.

3.1.6 Average Sound Intensity Level

The logarithmic time average of the sound intensity level.

3.1.7 Reference Tire

Tires perform differently depending on tread design, size, and other characteristics. At the writing of this document, the reference tire in use is the Goodyear Aquatread mounted on a 15 inch rim for passenger cars. Continued production of this tire is not expected. The use of alternate tires will require testing on a reference surface to allow comparison to any other tire. A replacement tire will be selected by outcomes of future testing.

3.1.8 Reference Surface

The main purpose with this method is to compare road surfaces with respect to tire/pavement noise emission. The method presents the sound intensities levels for each one-third octave band. Intensity levels measured by a system should be compared to measurement data of a second system using the same reference surface before any direct comparison is made between the two measurement teams. Such a surface is selected according to the purpose of the measurement, following certain rules listed later in this standard.

3.1.9 Absorptive Surfaces

An absorptive surface in this standard is one for which a substantial part of the incident acoustical energy is absorbed. Typical absorptive surfaces are loose gravel, sand, some porous pavements and ground covered by grass, ivy, or other low-growing vegetation.

Absorbent lining; an absorptive surface may also be the type of surface within test vehicle compartments, most notably enclosures. Enclosures are not considered in this standard.

3.1.10 System

As referred to in this document, system refers to the entire system used measures the tire noise intensity. This includes the matched microphones, analyzers, and associated equipment.

4 MEASUREMENT METHODOLOGY

The measurement methodology used in this method measures the sound intensity levels emitted in close proximity to the reference tire. A minimum of two (2) microphones (in a matched pair) is required since sound intensity is being measured. Additional pairs of microphones can be used to concurrently measure leading edge, trailing edge, or other parameters (per tire) over a specified road distance but is not required.

The test can be conducted either by using a specially designed trailer on which the reference tire(s) is(are) mounted, or by using a car, van, bus or truck, one tire of which is a reference tire. This method describes the vehicle, open wheel method only.

It is understood that different vehicle loadings and tire types will result in different sound intensity levels. Accordingly, reference tires are designated for each vehicle type.

Equipment that is used for these measurements are discussed in the following sections. Measurement procedure details are included in appendices.

One-third octave band measurements shall be reported for standardized speeds depending upon facility type. Each individual test run together with its vehicle speed is recorded. During research additional speeds may also be testing. In these cases it is desirable for predictive processes to determine a regression line of sound intensity versus logarithm of speed by one-third octave band.

5 MEASURING INSTRUMENTS

5.1 Sound Level Instrumentation

The system shall consist of a tape recorder (Digital Audio Tape (DAT) recorder or equivalent with channel phase matching), microphones (phased matched within 0.5 degrees), preamplifiers, nose cones or other wind screen devices, 2-channel analyzer (minimum), acoustic or piston phone microphone calibrator, sound intensity calibrator or methodology, headphone, associated cabling and power supplies.

The system overall accuracy shall be that of a Type 1 instrument according to ANSI S1.16 / IEC 61672-1.

Special considerations, such as wind foils, use of fabric, or special wind screens may also be applied to avoid wind noise contamination, especially in the lower frequency ranges.

5.2. Frequency Analysis Instrumentation

Frequency analysis of the measured sound is performed using one-third octave band resolution. The frequency range of 200-10000 Hz (center frequencies of third-octave bands) should be covered. Of that range, contamination of the lower frequency ranges is expected. It is estimated that 315-5000 Hz. is the range in which the results are accurate. The one-third octave band filters should conform to ANSI S1.11 / IEC 1260.

5.3. Recording Instrumentation

The system should include recording capability of the audible sound. The recording device should allow accurate playback such as possible with the use of a DAT recorder.

5.4. Calibration

At the beginning of the test, and following all warm-up procedures specified by the manufacturer, the overall accuracy of the sound level measurement system (including the microphone) shall be checked and recorded using an acoustic calibrator or piston phone. If necessary, the measurement system shall be adjusted according to the manufacturer's instructions. The measurement system accuracy should be verified at the end of the test and the values obtained recorded. Any deviations shall be recorded in the test report. If the calibration readings on the sound level meter differ by more than 0.5 dB during a series of measurements, the test shall be considered invalid.

The sound calibration device shall meet the requirements of ANSI S1.10 / IEC 9162, Class 0 or Class 1.

In addition to these field calibrations, the sound measurement system and acoustic calibrator shall be certified at an appropriate calibration lab or manufacturer within 12 months of the test date.

5.5. Vehicle Speed Measurement Instrumentation

The average speed of the vehicle over the test distance shall be measured to an accuracy of ± 2 mph with any equipment that meets this requirement.

6 TEMPERATURE MEASUREMENT INSTRUMENTATION

The temperature measuring instrument(s) shall have an overall accuracy of at least 1°C (1.8°F).

7 SELECTION OF TEST SECTION

7.1 Each test section over which a measurement is made shall be a length sufficient for 25 test intervals to be measured, based on the speed of the vehicle. The test interval is the length of time over which each sample is averaged and reported. If a shorter test section is selected, the reasons should be documented

7.2 The surface of the site up to 0.5 m from the reference tire shall consist of the road surface to be tested. The test section should be dry and free of debris.

7.3 The road shall be essentially tangent and have a vertical gradient less than 5 %.

7.4 Locations with low ambient background noise are preferable. In addition, low traffic conditions are also recommended.

7.5 The condition of the road should be documented.

7.6 Due to the expected changes in acoustic behavior with time, acoustic durability should be tested. This requires testing the same pavement type over multiple years. Annex B provides more details on this extended measurement period.

7.7 Measurements should be made in locations away from large roadside objects within 15 feet (5 m) of the edge of pavement. Examples of these objects include Jersey barriers, solid barriers, embankments, rocks, bridges, tunnels or buildings.

8 TEST VEHICLE

8.1 General Design

The test vehicle should be a passenger vehicle under 6000 pounds gross vehicle weight. It is desirable that the wheel well for the test wheel be open to avoid reflections and conflict in calculating the sound flux. Trailers are also possible for use, but are not discussed in this methodology. There shall be one test tire, which should be instrumented appropriately.
Proper alignment of the test tire is imperative. The camber angle of the test tire should be no more than 1°.

8.2 Verification of the Test

The test vehicle and measurement system performance shall be checked for proper performance. This should include determining if unwanted background vehicle noise is occurring due to an improperly operating vehicle, audible monitoring for bearing / brake noise, observing the spectral values of more than one tire/road combination to determine if any frequency band does not seem to vary, and by listening to recorded audible tape for unusual noise.

8.3 Microphone Position

The microphones are a matched pair and exact reference positions for each microphone must be maintained. The microphones shall have a fixed position relative to the tire, such that the distance horizontally from the plane of the nearest tire sidewall is 100 mm (3.9 inches). Exact orientation of the microphones indicated by the manufacturer should be observed, at a height above ground level of 70 mm (2.75 inches). Figure 1 shows this arrangement.

Measurements should be made as a minimum at the leading edge and trailing edge of the outside tire track. It is not required to measure both locations in the same test pass. Multiple passes of the test section may be used with the microphones being relocated on subsequent passes.

The reference tire for passenger cars is a Goodyear Aquatred III and should be mounted on a 15 inch rim (205/70/R15, ASTM E1136 Tire).

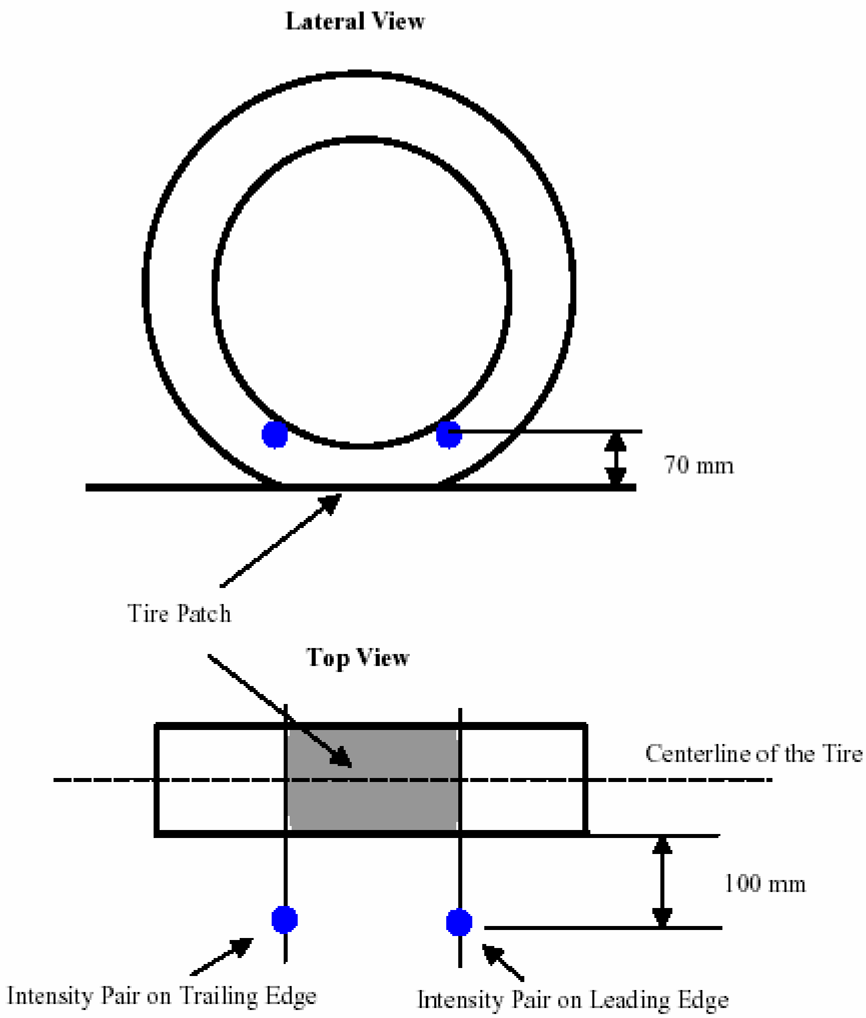

Figure 1. Microphone Positions for Leading/Trailing Edge Measurements.

9 MEASURING PROCEDURE

9.1 Sound Level Measurement

During each test the time varying sound intensity of each measured band shall be measured using the frequency weighting "F" or flat (no weighting). The measurement sample rate should occur x times per second with an averaging time of at least x seconds. A minimum of 25 continuous averaging times shall be recorded.

For each test condition at least two runs shall be made. If any measured one-third octave band varies by more than 1.0 dB, and speed variation limitations have been met, two new runs shall be made. The result is then the average of all the runs. Notwithstanding, the experimenter shall design his experimental program such that a standard deviation of not more than 1.0 dB for each octave band shall be obtained.

It is recommended that the sound also be recorded for later analysis. Recording instrumentation, in combination with analyses procedures, shall be selected to minimize bias or influence the measured data significantly.

Measurements that are obviously influenced by any other source, shall be neglected.

Measured values in dB should be recorded to one decimal place.

9.2 Frequency Spectrum Measurement

Measurements shall be made in 1/3-octave band frequency spectra according to ANSI S1.11 and IEC 1260.

9.3 Test Vehicle Operating Conditions

9.3.1 Test speeds

During the test, the vehicle shall travel with constant speed over the test section in an appropriate gear setting. It should be noted that the reference speeds are the same for all vehicle types.

Nominal test speeds will vary by facility type. These speeds are shown in Table 1:

Table 1. Nominal Test Speeds By Facility Type

Facility Type	Nominal Speed (mph)
Interstate	60
Major Arterial	165
Minor Arterial	35
Local Street	25

For each test the actual speed shall be measured with any instrument provides the required accuracy of ± 2 mph. A maximum deviation of ± 2 mph from the nominal speed is allowed.

9.3.2 Tire inflation

Tires should be inflated to the recommended pressure listed on the sidewall, at the operating temperature of the test. Before any measurement takes place the tires shall be brought to normal operating temperature by driving for a minimum of 15 minutes.

9.4 Temperature Measurement

The temperature of the ambient air and the surface of the pavement test section should be measured. The accuracy should be as stated previously.

The thermometer manufacturer's instructions are to be observed. The result is the reading rounded to the nearest integer °C or F

If continuous monitoring is not available, temperature shall be measured at 15-minute intervals.

9.4.1. Air Temperature

The temperature sensor is to be positioned in an unobstructed location as close to the centre of the test surface as is practical and safe in such a way that it is exposed to the airflow and protected from direct solar radiation. A shading screen may achieve the latter. The sensor should be positioned 5 feet (1.5 m) above road surface level, to minimize the influence of road surface thermal radiation at low airflows.

9.4.2. Road Surface Temperature

The temperature sensor is to be positioned at a location where the temperature is representative of the temperature in the wheel tracks, and without interfering with the sound measurement.

If an instrument with a contact temperature sensor is used on rough road surfaces. Heat-conductive paste shall be applied between the surface and the sensor to ensure adequate thermal contact.

10 REGRESSION ANALYSES

This analysis is only required in those cases where multiple speeds have been tested for the same test section. This is not required. However, since it is desirable to estimate sound intensities as a function of the log of the speed, this method could be applied if sufficient data, in multiple speed ranges, are measured over the same pavement test section. This is not always practical and unless significant deviations from the nominal speed testing are possible, meaningful regression analysis is not possible and should not be used. Additionally, this method should not be applied outside of the measured speed range.

In those cases where a sufficient data base exists over an extended speed range, a linear regression analysis of sound levels of multiple individual passes on speed may be made utilizing data consisting of the average and maximum one-third octave band sound intensities (dependent variables) versus the logarithm of speed to the base 10 (independent variable). A least-squares regression line shall be fit to the data points for each separate vehicle category.

11 REFERENCE ROAD SURFACE

The following options regarding reference surfaces apply:

11.1 "General Case". The reference surface is a dense, smooth-textured, asphalt concrete surface with a maximum aggregate size of 11 ~ 16 mm. The surface shall have been trafficked for at least one year when used as a reference. Macrotexture depth as measured according to ISO 1081616 or ISO/CD 131673 shall be within 0.50 mm and 1.00 mm. To ascertain that the surface is acoustically non-absorbing, air voids content or the sound absorption coefficient shall meet the requirements specified in ISO 1081616.

Not only the measuring procedure but also the location of the samples, as specified in ISO 1081616, shall be observed.

11.2 "Normalized Reference Case". The reference surface is a fictitious surface of which the levels are based on the average results of a great number of measurements on asphalt concrete and provides the standard surface for verification of the measurement systems. The "Normalized Reference Case" shall be the pavement results used for comparison when testing potential "low noise surfaces".

11.3 "Arbitrary Reference Case": If the reference surface is any arbitrary surface, other than above, measurements are useful only for comparisons between the particular, selected surfaces.

12 METEOROLOGICAL CONDITIONS

12.1 Wind

The perpendicular wind speed, relative to vehicle movement, shall not exceed 5 m/s during the measurement.

12.2 Temperature

Unless the measurement specifically aims at determining the influence of weather or other environmental conditions on sound emission, ambient air temperature shall be within 60-100 degrees F. (5 to 38C). The road surface temperature shall be within 60-160 degrees F. (5-71C). Measured values should be reported.

It is recommended that measurements be made at air temperatures close to the design area and in the season corresponding to greatest impact to reduce errors in future prediction efforts.

12.3 Check of Moisture in Porous Surfaces

If the surface can be expected to have a voids content exceeding 8 percent, then measurement shall not be made until it has been verified that the pores are dry. Unless more than four days have passed since the latest precipitation, the method described below should be used to check whether a surface assumed to have a significant porosity, still contains residual moisture.

Compressed air is blown into the road surface, e.g. using a standard pistol-grip air jet, directed vertically towards the surface. Any remaining moisture will be revealed in a clearly visible spray cloud. The surface may be regarded as dry if five tests at different points on the road surface fail to show a spray cloud (blotting paper can also be used to indicate presence of water).

13 REPORTED DATA

The test report shall include the following data:

13.1 General information:

- Time and date of measurement
- Organization and operators responsible for the measurement
- Purpose of the measurement
- Type of measurement equipment (incl. calibrator, sound measurement system, measuring equipment for speed and meteorological data.
- If used, equipment for measurement of surface macrotexture.
- Date of last equipment/calibration.

13.2 Information relating to the location and appearance of the test site:

- Location of the test site
- Site plan (horizontal), including microphone locations if a variance from the specified locations occur.
- Identification of the test section, pavement type (concrete, stone mastic asphalt, etc., including any standardized or otherwise commonly used designation of the texturing or surfacing applied)
- Large object within 5 m from the edge of pavement
- Cross profile (vertical) of the test section
- Maximum chipping size
- Thickness of surface layer (optional for non-porous surfaces). May be estimated from mass, density and area if not directly measured
- Residual air voids content of surfacing layer according to ISO 1081616, in case of porous surfaces (optional)
- Sound absorption coefficient, according to ISO 1081616, in case of porous surfaces (optional)
- Macrotexture depth, according to ISO 1081616 or ISO 131673-1 (optional)
- Representative photo of the surface, covering an area approximately 16 by8 inches, including a scale (optional).

13.3 Information relating to the condition or the tested surface and environmental factors:

- Age of the surface and state of maintenance
- Any special surface treatment
- Any notes regarding the homogeneity of the surface
- Date of latest precipitation, in case of porous surface
- Average, maximum and minimum air temperatures over the measurement period
- Average, maximum and minimum road temperatures over the measurement period (optional)

13.4 Other

The road speed category in question
Whenever used, the reference surface shall be reported, i.e. which of the four options in Clause 10 that has been used, in addition to items 5.21 above describing its construction and condition (wherever applicable)
Details of special provisions taken to assure conformance with this standard

14 ANNEX A: BIBLIOGRAPHY (INFORMATIVE)

The following documents (referenced in the standard) are useful as a background for some details in this standard:

14.1 **[I] Versluis, A.H.; van den Bol-de Jong, M.E. (1993):** "A further study of the composition of the Dutch car fleet". pp. 235-2162. 1165 (19916), The Science of the Total Environment, Elsevier Science BV.

[2] Soulage, D. (19916): "Repeatability and reproducibility of the CPB and SPB methods (AFNOR S 31-119) - Preliminary report". Report No. 916A236, Dec. 19916. LCPC (LRPC). Strasbourg, France. (Internal report from French Ministry of Transport and Public Works).

[3] Sandberg, Ulf (1995): "Technical Assessment of the Effect of Regulations on Road Vehicle Noise". pp. 82-113, Noise/News International, June 1995, Noise Control Foundation. P.O. Box 21669. Arlington Branch, Poughkeepsie. NY, USA.

15 ANNEX B: ACOUSTIC DURABILITY (INFORMATIVE)

15.1 This clause addresses the problems with acoustic changes over time. It is recommended that the agency responsible for road traffic noise in each country or state conducts or initiates such a calibration at time intervals of no more than three years. It will then be possible to check changes and/or differences in vehicle sound emission over time and from region to region.

15.2 The following procedure shall be used:

- The surface shall have been trafficked for at least two years and at most 8 years.
- Macrotexture depth measurement according to Annex A of ISO 1081616 or to ISO 131673-1 is mandatory. The macrotexture depth shall be within 0.60 mm and 1.00 mm.
- Air temperature shall be within 10 degrees F. for each successive test.
- Calibration differences (before-after measurements) according to 5.3 shall not exceed 0.5 dB.

16 ANNEX C: PROCEDURES

16.1 Preparation.

Obtain wheels of the standard size for the vehicle type to be tested. Insure the tire/wheel assembly is dynamically balanced. The appropriate adaptor should be installed on the vehicle to allow appropriate location of the microphones at the test wheel.

A test vehicle must be selected that uses the reference tire if comparison to data taken by other teams is desired. All tire/wheel assemblies should be per manufacturer specifications. Adjust the tire inflation pressures to the given specifications.

Before any measurement takes place the tires shall be brought to normal operating temperature by driving for a minimum of 15 minutes. If the test tires are brand-new, run them for an additional 10 miles to eliminate or smoothen the mold release agents (or spikes) on the tread surface. Remove small stones from tread grooves prior to test runs.

Verify the test section is available and prepare all equipment.

16.2 Equipment Preparation

Install microphone preamplifiers into the microphone preamplifier spacer/holder. Make certain that they are of the same depth. By convention, channel #1 is assigned to the microphone which is closer to the test tire; channel #2 to the other microphone. The microphone nose cones shall be installed to reduce the low frequency turbulence effect generated by a rotating tire and the wind. Other devices may also be used. Intensity microphones shall be phase matched within 0.5 degrees up to 6,1600 Hz by examining the cross-power phase between two intensity microphones using an intensity calibrator with the random noise applied. If they are not phase matched, they should be replaced or regrouped by a new pair that meets the 0.5 degrees.

Mount the preamplifier spacer/holder on the intensity fixture which is attached to the test vehicle. Turn on instrumentation and allow five minutes to warm up. Set microphone power supply to 10 dB again for both channels. Also set to linear output. Set filters to "high pass" above 350 Hz, 0 dB gain. Set all other controls as appropriate for pavement and vehicle type.

The DAT Recorder should be setup at the same time. For each microphone, place the microphone calibrator on it and record 30 seconds of calibration signal. Verify recording and headset operation.

Replace microphone grid caps with 1/2-inch nose cones or insure other windscreen devices are in place.

Immediately prior to testing, lower the intensity probe fixture and adjust it so that the center line of the two microphone is 70 mm above the road surface, 100 mm outboard away from the sidewall of the test tire, with the microphone diaphragms in line with the leading edge of the tire contact patch, as shown in Figure 1. Make a test run at the defined test speed for the facility to check the system response. The signal levels should be increased to improve dynamic range but at the same time do not overload the DAT recorder, or microphone power supply.

Monitor the noise levels through headphones during the entire recording period in order to identify any occurrence of unusual sound. Isolate the occurred unusual sound. Check the DAT recorder level indicators for overloads.

16.3 Measuring the Sound Intensity

Place the intensity probe at the leading edge position. The tire sound intensity should be measured at the prescribed test speed for each facility. In some cases, research may permit additional speeds to be tested. The intensity probe shall remain in the same location for all leading edge measurements. A minimum of 25 averaging times shall be measured for each pass. Ensure the same test section, same lane, and horizontal tire location are kept as constant as possible for each pass. This is especially important to allow the leading and trailing edge measurements to be matched.

Ensure data is being recorded after first test run. Reset equipment as needed.

Move the intensity probe fixture so that the microphone diaphragms are in line with the trailing edge of the tire contact patch. Repeat the measurement process to obtain the tire noise intensity data at the trailing edge.

Testing using the standard reference tire is recommended to begin each run. This allows the system operation to be verified by comparison to previous results and by examining the data consistency and repeatability.

16.4 Quality Control

Check two runs for the same conditions to see if each one-third octave band level is within 1 dB. The validity of the data should also be checked by reviewing spectra to determine whether they fall within an acceptable range, the coherence, direction, and pressure-to intensity index. Test data should be rejected if they do not meet the following requirements.

Direction: The negative intensity shall not occur above 16168 Hz and below 16,000 Hz.
Pressure-to-Intensity Index: This value shall be less than 10 dB for valid data.
Coherence: Values shall be between 0.5 and 1.0. In frequency bands where data are less than 0.5 the data shall not be used since it is most likely contaminated by wind gusting or non-tire related noises.
The Standard Reference Test Tire results should be used to verify whether the overall system is operating correctly or not.

16.5 Data Analysis

The intensity spectrum calculation is based on two-microphone cross-spectral indirect method. For a given microphone location and operating condition, there are two intensity spectra obtained in this procedure, one at the tire leading edge, and the other at the trailing edge. The final result shall be the linear average of both intensity results. This may be reported by one-third octave band or by weighting each one-third octave band and summing the energy of each band for the A-scale.

The one-third octave band levels should also be used to analyze the tonality and sound quality issues of the tire noise.

Documentation.

The final results shall be presented in one-third octave bands as a minimum. Reporting of A-weighted values is a preferred option. These values should be included in a concise report that includes all information listed in Section 13 of this document.

Appendix B: Conference Notes

This appendix presents the notes from three noise-related conferences and seminars attended by one of the authors that are relevant to the project topic. This information is furnished as a supplement to the literature review featured in Chapter 2 of this report.

The reports presented herein correspond to the following conferences:

1. Tire-Pavement Noise Strategic Planning Workshop, held in West Lafayette, Indiana, September 14-16, 2004.
2. Transportation Research Board 84th Annual Meeting, held in Washington, DC, from January 9 to 13, 2005.
3. 2005 Summer Meeting/Conference of the Transportation Research Board ADC40 Noise and Vibration Committee, held in Seattle, Washington, from July 17 to 20, 2005.

September 27, 2004

Tire/Pavement Noise Strategic Planning Workshop
September 14-16, 2004
Purdue University
West Lafayette, Indiana

by Manuel Trevino

Introduction

This document presents some thoughts on the workshop on tire/pavement noise the author had the opportunity to attend, in connection with our TxDOT noise project, Project 0-5185, which now is in its second year.

The workshop, sponsored by the FHWA, and hosted by the Institute of Safe, Quiet and Durable Highways (SQDH) at Purdue University, featured the foremost experts in the area of tire/pavement noise in this country, some of the people which scientific production in this field we have got familiar with, ever since conducting the literature review for 5185. For this reason, just being there was a valuable experience. The attendees were an array of physicists, pavement scientists –from the government, private industry, as well as academia– from both the flexible and rigid areas, policy makers, State DOT representatives (researchers, pavement engineers, etc.), and representatives from the tire industry. There were about 45 attendees. The purpose of the workshop, more than providing knowledge on the subject, was to gather the expertise from such a distinguished group of tire/pavement noise specialists to come up with ideas, and design a course of action for FHWA and State DOTs to improve procedures and policies for the purpose of having a better traffic noise program nationwide. This is a very broad goal!

The first day there were presentations on the current state of affairs on tire/pavement noise aspects, such as measurement procedures, pavement characteristics, tire characteristics, and noise fundamentals. On the second day, State DOT experiences were presented. Four states that have performed studies in the area showcased their research: Arizona, California, Florida, and Texas. Mike Shearer, from TxDOT, and a member of Project 5185, shared the Texas experience, extensively mentioning our research. What followed that day and the next was a comprehensive discussion. Several breakout sessions covered the areas of design, construction, maintenance, research, analysis, and policy. The purpose of the breakout sessions was threefold: to identify the current state of practice, to identify desired future levels, and to define the gaps between both. The goal for the future is to bridge those gaps.

The following section, for the benefit of the readers that are not involved in the 5185 project, provides a succinct background on the topic. Some of this information was presented in the workshop; some of it is just common knowledge acquired from the work on 5185.

Background

Tire/pavement noise has increasingly become a concern for the general public, as well as for highway designers and policy makers, especially in urban areas. This environmental annoyance has led some state agencies to place those eyesores known as noise barriers along the highways, which besides their ugliness are also very expensive, and not entirely efficient. The trend nowadays is to try to make the pavement quieter, which is not an easy endeavor, considering that the first priorities when designing a pavement should be safety and durability, which are provided to a high degree by the friction and skid resistance, which in turn, are responsible for the noise. However, many studies have revealed that a proper selection of pavement surface type can minimize the noise problem. This is where we, as members of Project 5185, and the panel gathered at the workshop come into play.

It is no surprise that AC surfaces are, in general, quieter than PCC. AC pavements present a large variety in acoustic properties, among which highly porous surfaces like open-graded asphalt friction course (OGFC), and rubberized asphalt are widely recognized as quieter. For PCC the variations that make an impact on acoustic properties come in the form of finishing, namely transverse, longitudinal, or random tining in various combinations, brooming, burlap drag, carpet drag, etc., as well as the degree of exposure of aggregates. There is no consensus in the literature as to which of the PCC finishings are quieter. Exposed aggregate PCC has been recently used with success in Belgium for noise purposes, according to the findings of our friends from the European Scanning Tour, led by our very own Ken Fults. (The International Scanning Tour is an AASHTO/FHWA Project on quiet pavement systems currently underway, which during the spring visited 5 European countries identified as leaders in quiet pavement technology; one of the presentations on the first day featured the findings of the Scanning Tour, shown by two of the FHWA members that took the trip).

Federal guidelines require noise levels of 67 db(A) or less at roadside residences. However, and this is a main issue here, pavement surface type has not been allowed as a noise mitigation strategy by the FHWA. Therefore, state agencies, in order to fulfill the noise requirement and get federal funding for their roads have resorted to the aforementioned noise barriers. The good news is that the states mentioned above, whose presentations were featured in the workshop, have been proactive by initiating field research projects to investigate the usage of pavement surface type to mitigate noise. This is one of the major goals we are hoping to achieve with Project 5185.

FHWA is now supporting research that tests how different pavement surfaces reduce highway noise by initiating a pilot program with the Arizona DOT. This program is based mainly on the use of asphalt rubber friction courses (ARFC) in the Phoenix area, overlaying even brand new PCC.

Another important issue when analyzing traffic noise is that there are several sources that contribute to the total amount of noise. From the sources of traffic noise, tire/pavement noise is the foremost, with other contributors being the aerodynamic, engine, and exhaust components.

To make matters even more complicated, it should be considered that the total amount of noise depends on the subject that perceives it; this is what people like Mike Shearer call “impact,” which is relative to the receiver. Environmentalists are concerned with the noise that gets to the neighborhoods, i.e., roadside noise; car manufacturers want to insulate the vehicles so that the driver –their main customer– perceives the car as quiet; tire manufacturers, just like car manufacturers, are mostly concerned with the driver's perception, thus they design tires that are quiet, so their main customers –car manufacturers– choose their tires to equip their vehicles. Pavement engineers, besides many other more important concerns, pursue pavement designs that render their pavements as "quiet." Accordingly, there are different techniques to measure traffic noise. Some measure the noise at certain distance from the road, with stationary microphones (this simulates the perception in the neighborhood). Other measure noise with microphones mounted near the tire, to isolate tire/pavement interaction from the noise from the engine, exhaust, other vehicles, etc. Among the first category, the roadside procedures, some perform measurements with real traffic, including all the vehicles that happen to traverse the section of the road in question, while others are performed with specific test vehicles at controlled speeds and outfitted with a certain type of tire. Those that use test vehicles can have the vehicle ride just coasting, to eliminate the engine noise.

In the second category, with the microphones close to the tire, there are various ways to provide for the closeness of the measurement devices. Some employ sophisticated trailers that can measure sound pressure (a scalar quantity) or sound intensity (a vector quantity, with magnitude and direction), or both. These trailers separate the tire from the vehicle and enclose it to reduce noise contamination. Other techniques just mount a contraption attached to the vehicle that keeps the microphones close to the tire. A number of these devices have been developed, like the CTR test trailer, or the noise trailer that TxDOT is purchasing from NCAT, or the on-board contraption used by Caltrans in their recent studies.

Discussion

As the previous section shows, there appears to be very little uniformity in measurement procedures, and the same is true about the direction that researchers have taken to achieve the goal of quieter pavements. Every one of the leading states has taken their own approach, developing their own devices, and subsequently their own "quiet" pavements. One of the ambitions of the workshop was to direct the research efforts toward standardization. Exhaustive discussion on these issues took place during the workshop. Some of the noteworthy items that were discussed include:

- Federal policy (or lack thereof, with the only policy being that pavement type cannot be used as a noise-mitigating strategy, until further research demonstrates that pavement type can be used for such purpose)
- Pavement design and construction specs address ride and safety, but neglect acoustic properties
- Wide variability of measurement techniques
- Need for validation, calibration, and uniformity of measurement methodologies
- Procedures for noise data reduction
- Pavement performance characteristics and their relationship with acoustic properties

- Variability of pavement types and finishing techniques
- Acoustic durability of AC and PCC (whether the pavements can sustain their acoustic properties over time, mostly a concern for porous AC surfaces)
- Safety – pavement friction and durability
- Maintenance (whether to clean AC surfaces to unclog the voids, and how to do it)
- Public perception
- Cost-effectiveness of "quiet" pavements
- Truck tire/pavement noise versus vehicle tire/pavement noise
- State agencies interest in research and technology for noise abatement
- Pilot programs
- Use of alternative measurements such as sound absorption (e.g., impedance tube)

Visit to the SQDH Tire/Pavement Test Apparatus

One of the highlights of the workshop was a visit to the Herrick Lab on the campus of Purdue, which hosts this machine. The SQDH Center has built a huge tire/pavement test apparatus which looks like a giant drum with curved slabs of different types of pavement (both AC and PCC) mounted on its perimeter (Figures 1, 2 and 3). Tires roll over the pavement and noise is measured. There are two tires on opposite sides that roll at a maximum speed of 30 mph. The drum accommodates six slabs on its circumference, which could be either 8 or 16 in. thick.

The SQDH researchers report that different types of tires do not mitigate the noise very much–but different types of pavement can.

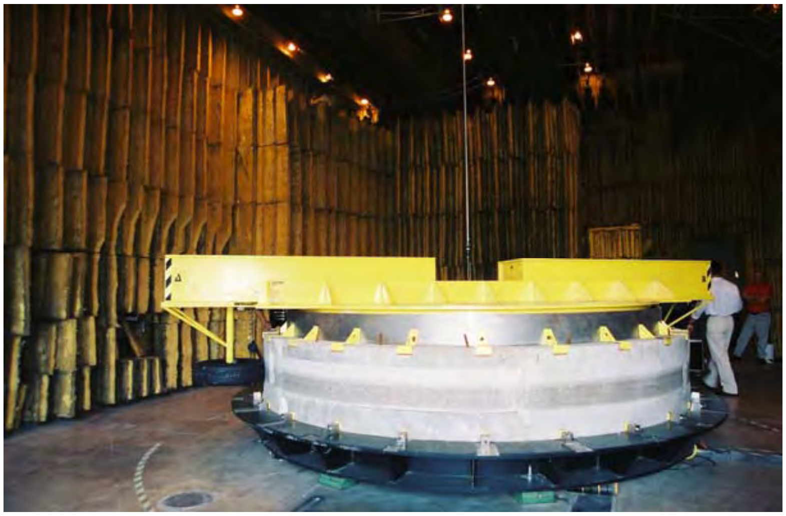

Figure 1. SQDH Tire/Pavement Test Apparatus at the Herrick Lab

Figure 2. The author poses with the apparatus. Note the thick insulation foam in the background.

The researchers make their own slabs with different pavement types and surfaces to test with this device (Figure 3).

Figure 3. Slab of porous PCC mounted on the apparatus

Acknowledgement

Thanks to TxDOT for sponsoring the trip. Also thanks to Gary Graham, Mike Shearer, and Terry Dossey for the opportunity. The author also wishes to acknowledge Roger Wayson, fellow Longhorn, now with the University of Central Florida, and Bob Bernhard from Purdue, director of SDQH and workshop director, for their guidance offered on the subject.

Afterword

The path toward standardization in the various aspects of the tire/pavement noise arena is a long one, and the first steps had just been taken. The workshop showed how complex the problem is in itself. Gathering a panel of experts that can devise initiatives that can have a national impact is the right approach to set off a project of this magnitude. This panel made the commitment to getting together in the near future. A new workshop to follow up on the progress of this endeavor should occur within a year.

The trip was a good experience for the author. Valuable contacts for exchange of information that will help with the development of Project 5185 were established.

January 31, 2005

Traffic Noise Sessions Report
Project 0-5185
by Manuel Trevino

Transportation Research Board
84th Annual Meeting
Washington, DC
January 9-13, 2005

This report features summaries of several talks presented during the noise-related sessions of the TRB meeting attended by the author, namely, sessions 421, 480, and 645.

Session 421 Quiet Pavement Noise Issues

Basics of Noise Generation for Pavement Engineers

by Rebecca McDaniel, Purdue University

This presentation introduced the basic concepts of noise and sound related to tire-pavement interaction, in a way intended for pavement engineers who may not be completely familiar with this phenomenon. Normally, pavement engineers lack an acoustics background that prevents them from grasping all these concepts once they have to deal with tire-pavement noise.

Tire-pavement noise predominates over other noise sources (such as aerodynamic or engine noise) for speeds in excess of 20 mph for passenger cars and over 30 mph for trucks.

Concepts such as the mechanisms of noise generation and amplification were discussed and illustrated with analogies, such as the hammer, the clapper, and the horn.

The difference between sound pressure and sound intensity was also explained. The talk also touched on the most common procedures to measure vehicle noise.

Porous pavements work as a noise mitigator because of several factors: the voids absorb sound, and the contact patch between the tire and the pavement presents less surface area than a non-porous pavement. However, porous pavements need a heavy-duty binder to keep the aggregates together in spite of the presence voids, and this is what makes them more expensive than non-porous pavements. The binders commonly used for this purpose are polymer-modified asphalts.

Urban Traffic Noise Reduction by Quiet Pavements: Experimental Results
by Alfredo Garcia, Universidad Politecnica de Valencia, Spain

This presentation featured a field study, conducted on the streets of Valencia, Spain, in which various asphalt pavements were tested using wayside measurements. The pavements considered were: porous asphalt, two-layer porous asphalt, stone mastic asphalt (SMA), and a conventional dense graded AC. Other factors included in the experiment were layer thickness (which varied up to 2 in.), void content, and aggregate size. The urban setting for these tests implies that there were some special conditions that had an impact on the results, specifically, the proximity of buildings on both sides of the street, intense traffic, stop-and-go patterns, and low speeds. Four sound level meters were used, and their height above the road level seemed to be greater than the standard 5 ft, apparently to keep them out of reach from the pedestrians on the sidewalks. Noise levels were measured in one-minute intervals during an entire week. All tested pavements were quieter compared to the conventional AC. The pavement with the best acoustic properties was the two-layer AC. However, the SMA pavement represents a smaller investment that provides similar acoustic properties. Smaller aggregate sizes were associated with less tire-road noise.

Noise Reduction Effect of Porous Elastic Road Surface and Drainage Asphalt Pavement
by Seishi Meiarashi, Public Works Research Institute, Japan

This paper presented the research undertaken in arterial highways in Japan with a rubberized AC labeled as “PERS,” which stands for porous elastic road surface. PERS is an AC mix with rubber chips and polyurethane. Traffic noise in Japan is a serious concern. The following facts illustrate this. The environmental standards in Japan dictate that the maximum noise level during nighttime should be 65 dBA, and during daytime, 70 dBA. However, these standards are met less than 30 percent of the time during the night and less than 40 percent during the day in the urban arterial highways. A picture was shown during the presentation featuring an unusual (at least for what we have seen in the US) noise barrier, in which the top part of it is curved toward the highway in an attempt to enclose the roadway and keep the noise from propagating to the adjacent neighborhood. Between 10 and 20 percent of the pavements in Tokyo’s urban arterials are considered porous pavements.

For the experiment in question with the PERS, a test section of assorted AC surfacings was constructed and equipped with sound level meters. The passby method was utilized, with the test vehicles running at various speeds (40, 50 and 60 km/h). The adequacy of various PERS sections was evaluated and compared to a reference dense graded AC. Among those PERS sections, there were prefabricated surfaces from different manufacturers, and some that were cast on the site. The prefabricated pavements had about 40% porosity, while those constructed on site had about 30%. These are very high porosity levels. The prefabricated pavements were quieter. There was a noise reduction of 7 to 11 dBA for small passenger cars, and of 5 to 8 dBA for large passenger cars when comparing the PERS to the reference AC.

Session 480
Quiet Pavements: Noise Mitigation Using Hot-Mix Asphalt Overlays

Low-Noise Hot-Mix Asphalt Pavement
by Doug Hanson, National Center for Asphalt Technology

Within the realm of acoustics, whatever is considered sound or noise is a matter of perception. This is because noise, by definition, is an irritating sound; but the level at which a sound becomes annoying is a subject of personal perception. And the perception is not just dependent on biological factors; it may be biased by psychological circumstances. Thus, a noise may not be perceived as an annoyance if it is considered a consequence of progress. In many cases, noise could be considered the sound of prosperity. Without highways and fast-moving vehicles (which, in many cases, are loud) transportation would be a nightmare. Hence, a certain level of traffic noise is unavoidable, at least for now, with the vehicles and pavements that we know, and it is something that pavement engineers, environmentalists and policy makers need to deal with and manage in the best possible way.

It is a well-known fact that tire-pavement noise is the predominant source of traffic noise. Open-graded AC pavements have demonstrated to have sound absorptive properties. The NCAT has developed a trailer for sound measurement that complies with the ISO standard for CPX (close proximity) measurement of tire-pavement noise. NCAT has also conducted experiments with wayside measurement of noise. They have also a test track. Their research has found good correlation between CPX and SI measurements, with an offset of about 23 dBA between them.

Road to Quiet Neighborhoods in Arizona
by Larry Scofield, Arizona Department of Transportation

Noise is an issue of quality of life, which has become an increasing concern in urban areas. This, and the uniqueness of Arizona, prompted the Arizona DOT to embark on a program to place asphalt rubber friction course (ARFC) overlays on the Phoenix area concrete pavements in an attempt to mitigate tire-pavement noise. ADOT believes, and has demonstrated that pavement surface can mitigate noise. The presentation gave a brief introduction to the basic concepts of tire-pavement noise, followed by an analysis of the Arizona quiet pavement program, which got started with the use of ARFC for rehabilitation purposes. ARFC overlay thicknesses placed by ADOT are 0.5 in. for AC pavements, and 1 in. for PCC pavements. The unique features of this state, and more specifically, of the Phoenix area in regards to this topic are:

1. The pavements are very new compared to other parts of the country.
2. Commuter travel dominates
3. Rapid urban growth
4. JCP with short slab lengths and narrow joint design
5. Transverse tining is used in urban PCC pavements

The presentation went on to talk about the widely known ADOT pilot program and its successful results, including noise-measuring procedures, such as the use of the CPX trailer, manufactured by NCAT, and the use of the SI apparatus, utilized by Caltrans. The graphs showing the good correlations between CPX and SI, and the spectral comparison between them were presented. An interesting tidbit, which goes against the normally accepted knowledge in this area, is that, in this case, SI results indicated that there was no correlation between the acoustic properties of the pavements and their age, among the pavements studied, which ranged in age between three and twelve years. It was also found that the 1-in. thick ARFC on PCC pavements has resulted in quieter surfaces that those attained with the ½ -in. thick overlays on AC. The reason might be a better noise mitigation accomplished by the thicker overlays.

Field Evaluation of Porous Friction Course for Noise Control
by Rebecca McDaniel, Purdue University

A section of IH-74 east of Indianapolis was resurfaced with a PFC overlay by the Indiana DOT in August 2003. The acoustic properties of this surface were compared to an adjacent SMA pavement, and to a conventional superpave AC section in West Lafayette, by means of pass-by tests as well as CPX measurements. The PFC has between 18 and 22% voids. The SMA pavement had a void content of 17.7%.

This project also dealt with texture measurements of the pavements in question. The texture was measured with a Circular Texture (CT) Meter; the higher the macrotexture of the surface, the higher the friction levels result. (On a side note, one of the poster sessions, “Evaluation of Circular Texture Meter for Measuring Surface Texture of Pavements,” featured an experiment conducted by NCAT comparing the CT Meter results with those obtained using the Sand Patch test).

It was found that the PFC is quieter than the SMA and the superpave. Next in quietness, was the conventional AC. In terms of texture, the PFC and the SMA are coarser than the conventional AC, which has a more uniform gradation, making the surface smoother. The PFC had the highest texture value.

Comparison of Thin-Lift Hot-Mix Asphalt Surface Course Mixes in New Jersey
by Thomas Bennert, Rutgers University

A thin lift is an overlay thinner than one inch, with maximum aggregate size of 0.5 in., which uses open-graded, Novachip, or SMA mixes. These are normally placed to improve riding quality and safety. Some asphalt rubber OGFC surfaces in New Jersey have been in service for 11 years. Noise measurements in this project were conducted using the CPX method, with the NCAT trailer on various highways in New Jersey. The study evaluated four thin-lift surfaces (OGFC, SMA, Novachip and Micro-surfacing), and compared their properties to a traditional Superpave overlay, and to PCC pavements with various finishing textures (no texture, diamond ground and transverse tined). A noise gradient was computed to account for the change in noise produced by the change in vehicle speed, using noise measurements of 55 and 65 mph. The AR-OGFC surfaces were the quietest, followed by the SMA pavements. The transverse tined PCC was the loudest type, with the diamond ground surface having noise measurements comparable to some of the AC mixes. The Novachip pavement was the one with the lowest noise gradient. In regards to economical value, SMA surfaces are expensive, while OGFC pavements offer good value. However, NJDOT uses rock salt for de-icing purposes, and OGFCs are difficult to maintain ice-free.

Session 645
Constructing Desirable Characteristics of Portland Cement Concrete Pavement

Role of Texture in Tire-Pavement Noise
by Mark Swanlund, Federal Highway Administration

This talk first gave a historical perspective on the efforts in trying to mitigate traffic noise. From wooden roads, utilized about 200 years ago, through noise barriers, ARFC, diamond grinding, to the use of futuristic surfaces like those placed by laying out a thin roll of prefabricated noise-absorbent material, utilized in some European countries.

According to a European study from 1996, tire-pavement noise accounts for 41% of traffic noise. The presentation also touched briefly on the mechanisms of noise generation, and of course, on the impact of texture.

Among the noise reduction techniques, those that focus on control at the source can be classified into three categories:

1. Reduction of megatexture (50-100 mm)
2. Reduction of air displacement (macrotexture)
3. Increase of impedance (pavement porosity)

A widespread myth is that PCC pavements are noisy and that AC pavements are quiet. The pavement's acoustic properties depend on the surface texture and the porosity of the pavement. The common texturing variations for PCC are tining, carpet drag, exposed aggregate, grinding and use of porous concrete. For tined surfaces, a key factor in the acoustic properties is the texture depth. Exposed aggregate pavements are normally constructed as 2-layer structures. The top layer usually contains high quality aggregates, while the bottom layer may contain recycled materials.

July 27, 2005

Traffic Noise Sessions Report
Project 0-5185
by Manuel Trevino

2005 Summer Meeting/Conference of the Transportation Research Board ADC40 Noise and Vibration Committee
Seattle, Washington
July 17-20, 2005

This TRB committee is dedicated to investigating transportation-related noise and vibration. It evaluates strategies and techniques for reducing noise and vibration levels, as well as their environmental impacts. The summer conference is held annually, and unlike the winter meeting, it is held in different cities every time. The 2002 Summer Conference took place in Austin. This time around, Seattle played host to the conference, with Mia Waters from the Washington State DOT taking on the organization role.

The scope of the meeting is much broader than the subject of interest of Project 0-5185–tire/pavement noise. Therefore, the reader may find that some of the presentations do not have a direct relation with the purpose of the Project, or deal with it in alternative manners, e.g., mitigating traffic noise with noise barriers. The sessions of this conference were divided into six categories.

a. Noise Policy and Public Issues
b. Vibration
c. Tire/Pavement Noise
d. Noise Sources and Movement
e. Construction Noise
f. Underwater Noise

Of special interest for Project 0-5185 is the topic of on-board measurement of sound intensity. The only mention of this issue during the meeting was that the draft for the standardized testing procedure was being finalized during the week of the conference.

This report features summaries of several talks presented at the TRB meeting.

Status of Current FHWA Noise Activities
by Mark Ferroni, FHWA

This presentation gave an overview of news on this topic from the FHWA standpoint. The first subject was the use of the TNM program. In the fall of 2006 the new Version 3.0 of the program, currently under development, will be released. This new version will contemporize the code, will correct a platform incompatibility, and will feature a redesigned database. Version 2.5 of the program, released in December 2004, is receiving increased use.

On the topic of "quiet pavements," FHWA differentiates between a Pavement Noise Policy, a Quiet Pavement Pilot Program (QPPP, such as the Arizona DOT's), and Quiet Pavement Research. The first concept, the policy, utilizes an "average pavement", and assumes that there is a commitment to provide its required noise reduction in perpetuity. The quiet pavement research should naturally precede the establishment of a QPPP. Both, research and the QPPP, gather the same type of data, but for the QPPP, specific pavement types can be used as mitigation measures, provided they represent at least a 4dB reduction with respect to the average pavement. Currently, Arizona is the only state with a QPPP.

FHWA has two tire/pavement noise initiatives on the brink of becoming a reality: the establishment of a clearinghouse for tire/pavement noise, and an expert tire/pavement task group.

Uncertainties in Noise Measurement and Prediction, and Their Implication in Community Noise
by Richard Peppin, Scantek, Inc.

The subject of noise measurement is full of uncertainties. A few of them are described here.

Noise measurement is based on imprecise devices. Sound pressure measurement is simplified, when it is transformed to sound pressure level (i.e., Pa to dB). The use of windscreens represents another source of uncertainty as well, because wind attenuation follows a non-standard approach, there is little data on wind attenuation, few manufacturers provide the frequency response for their windscreens, and few people are willing to pay for calibration.

Field calibration itself is another source of errors. The temporary nature of the condition of sources during testing adds more variability, which is often masked or ignored by using concepts such as a "typical weekday." There is also uncertainty in the propagation effects, given by factors that are difficult to model, such as:

- Thermal gradients
- Ground effects
- Buildings
- Wind
- Foliage
- Precipitation
- Air temperature

The ISO Standard 1996-2 defines the uncertainty of reproducibility as 1dB, and other uncertainties are assumed to be 1 dB as well.

All the uncertainties in noise measurement have a combined effect that is even more difficult to quantify.

Colorado Noise Program
by Bob Mero, Colorado DOT

This presentation showed Colorado DOT activities in the area of traffic noise. It gave the impression that CDOT is focusing more on constructing noise barriers than working on pavements. Colorado is the third fastest growing state in the country, and this growth keeps CDOT busy. Currently, CDOT is working on 40 environmental documents. There are two main corridors: I-70, from Denver to Glenwood Springs, and US 160, connecting Durango to Bayfield. There are 87.3 linear miles of noise barriers, with an estimated cost of $70.5 million. Among their successes, CDOT cites the funding of two research projects: the CDOT Noise Policy Revision (Dec. 2002) and the TNM Evaluation.

Another accomplishment of note is the implementation of the TREX project for the widening of roads, including 8 miles of noise barriers. CDOT also takes pride in their Dillon Valley I-70 construction in 2003, which features a combination of precast concrete and berm, as well as the construction of the nation’s highest noise barrier (8 to 10 ft tall).

The main challenges faced by CDOT are the limited budget, the Type II Noise Barrier Program cancellation (in August 1999), and the general increase of public awareness regarding noise issues.

Tennessee DOT’s New Type II Noise Barriers
by Bill Bowlby, Bowlby & Associates, Inc.

Type II Projects are federal-aid highway projects aimed at noise abatement along existing highways that do not provide highway improvement. TDOT has identified 21 communities along their highway network that are eligible, and that would benefit from the construction of noise barriers. Their allowable cost per benefited residence is $34,000. Their cost for the eligible identified areas is $32 million.

They prioritize those areas by computing an average ranking of the following criteria:

a. First row sound levels

b. Number of first row impacts

c. Cost per benefited residence

Ohio DOT and Noise Compatible Development
by Adam Alexander, Ohio DOT, and Bill Bowlby, Bowlby & Associates, Inc.

Yet another talk on noise barriers, which seem to be the focus of most of the state agencies featured in the conference. This talk, similar to the previous one, explained the works of Ohio DOT on barrier construction. They estimate their barriers' cost as $1.3 million per mile. They fulfill FHWA standards for Type II Projects. They are also working on retrofitting existing barriers.

Benaroya Concert Hall Visit

The meeting included a very interesting visit to the recently constructed Benaroya Concert Hall, showcasing the acoustic features of the building, as well as the vibration and acoustical isolation issues that had an influence in the design of the foundation of the building, given that heavy rail and bus tunnels run nearby. The solution for the isolation of the building was provided by rubber bearings.

Besides the auditorium, the visit took the attendees to the foundation of the building. The auditorium is a concrete box inside another box, the foundation. The auditorium, weighing 27 million pounds, rests on 310 rubber pads, placed in between the two boxes, which absorb vibration from the tunnels. One of the rubber pads in the foundation is shown in Figure 1.

Figure 1. Rubber bearing, which absorbs vibration from nearby tunnels

Sound Transit Light Rail Vibration Issues at UW
by James Irish, Sound Transit

Sound Transit, the city agency in charge of Seattle transit system is currently constructing 15 miles of light rail. A line of this transportation system is planned to run through the campus of the University of Washington, one of the largest research universities in the country. The light rail line could have an adverse effect on various campus buildings housing some of the areas of research that have a relationship with noise and vibration, such as gravitation, nanotechnology, and semiconductor research. Thus, the light rail design is carefully considering the following vibration issues for the line running through campus:

a. Both vehicle and track determine vibration

b. Vehicle vibration is given by the wheel rotation frequency

c. Track vibration is provided by the rail roughness

d. The procedure to discriminate between those two is by analyzing the vibration spectrum

e. Soil conditions on campus are uniform

f. The trains will run between 30 and 40 mph

g. Rail straightness will provide a quieter ride with less vibration.

Traffic Noise Abatement by Pavement Grinding in Ohio
by Lloyd Herman, Ohio University

After all, it should be said that, in all fairness, Ohio is not just constructing noise barriers, they are also looking at some alternative solutions to traffic noise, such as the project described in this talk. A 3-mile stretch of I-76, east of Akron, has been reconstructed with PCC pavement, with a total cost of approximately $20 million. There are three lanes in each direction, and the concrete texture is randomly spaced transverse tining. With the absence of noise barriers in the area, there was an increased perception of noise by the public, attributed to the texture of the brand new pavement. To address the issue, it was decided to retexture the pavement with diamond grinding, at a cost of $700,000. Ohio University conducted a noise study to testing the new texture, looking at both broadband levels and spectra. The ISO Standard for statistical passby was utilized, as well as the TNM model to establish reference levels. Five sites were measured and compared to reference microphones placed at sites with the original tined texture. Some complications to conduct it included the presence of railroad and some construction near the reference microphones. Environmental monitoring was conducted, recording wind speed, and ambient and pavement temperatures.

The spectra showed that the noise reduction with grinding occurred at higher frequencies (800 Hz or above), and the greatest reduction, over 5 dB, occurred at 2000 Hz. There was little or no effect at less than 200 Hz.

The broadband levels, using TNM simulation were over 3.5 dB for the 7.5-m sound meter, and over 2.5 dB for the 15-m sound meter.

Arizona Quiet Pavement Pilot Program
by Fred Garcia, ADOT, and Emily Paulsen, HDR

The Arizona quiet pavement program got started with the use of ARFC placed for rehabilitation purposes, in 1976. The research started in 1995. ARFC overlay thicknesses placed by ADOT are 0.5 in. for AC pavements, and 1 in. for PCC pavements. The ARFC used is 20% rubber by weight. The program has been very successful according to the public's perception.

The second part of this presentation showcased a study conducted by HDR, a consultant, in coordination with the Volpe Center and ADOT. Noise measurements have been taken, from the residential receivers' standpoint, starting in 2003, along 115 miles of ARFC overlaid pavements. The measurements intended to verify the claim that these surfaces provide at least 4dB noise reduction, and find out how long this could be sustained. Hence, the measurements have been taken in areas with and without noise walls, at elevated and depressed areas, and at parks and neighborhoods, during all times of the day, in three consecutive 20-minute readings at each site. The findings so far indicate that the reduction is better than expected, exceeding the 4dB mark: on average it is 5.3 dB.

FHWA Texture-Noise Study on Concrete Pavements
by Rob Rasmussen, Transtec

Transtec, in conjunction with Iowa State University, FHWA, and ACPA are developing a broad study on noise and texture of PCCP. The measurements in the experimental program, besides noise, also include smoothness, splash and spray, surface drainage, wheel path wear, light reflection, and rolling resistance. This presentation gave an introduction to the $250 million research program, which started in 2004, with an agreement between Transtec, ISU and FHWA. ACPA joined in January 2005.

The issue of noise and texture is time-dependent, so this is a long-term study program. The program looks for construction techniques that are repeatable and cost-effective. Three types of experiments are considered: new construction, in-service pavements, in which periodically noise and the other variables are measured, and in-service pavements that are measured only once.

Various types of finishing are analyzed: transverse and longitudinal tining, carpet drag, grinding and grooving patterns, with both hard and soft aggregates.

Among the noise tests, on-board sound intensity, pass-by, and in-vehicle techniques are used. For texture, the "Robo Tex" device has been developed, an automated toy-like car that rides on the pavement surface providing a 3-D profile, mm by mm. For macrotexture, digital imaging techniques like tomography are used. Other more conventional procedures like the sand patch test are also included.

Quiet Pavement Testing in B.C.
by Duane Marriner, Wakefield Acoustics

This presentation explained a research project in British Columbia, Canada, that investigated the acoustic properties of pavements deemed as “quiet,” comparing them to conventional ones by means of passby tests. The study, undertaken from 1995 to 2004, considered OGFC surfaces, superpave mixes, and rubberized AC pavements (which contain 1.5% rubber by weight).

The OGFC was found to be quieter than the conventional AC, with a reduction of 4.9 dB during the first round of tests; a second set of measurements taken after one year showed a reduction of 4.7 dB over the reference conventional surface, and this reduction remained consistent during the following 4 years. Similarly, the superpave and the ARFC surfaces provided a 2.6 dB, and a 5 dB reduction, respectively, over the conventional AC. The passby tests were conducted with a test vehicle driving at 65 mph.

Caltrans Noise Studies
by Bruce Rymer, Caltrans

This presentation featured brief summaries of various noise studies performed by Caltrans.

A research project on I-80, within the City of Davis, evaluated the acoustic properties of OGAC with aging. The pavements were measured over seven years, initially providing a 6 dB reduction, while by the end of the study the acoustic reduction was about 4.5 dB. During the colder months of the year, the noise levels were higher.

Caltrans has a statewide noise database, where they compile the results of several noise studies. Since they have partnered with Arizona DOT in several studies, their database also includes many pavements from this state.

Two other studies were mentioned, both used passby tests, one in Los Angeles, on highway 138 tested five different AC surfaces, while the second one evaluated the acoustic properties of various PCC pavement textures (longitudinal tining, grooving and burlap drag) located in Mojave.

Localizing Truck Noise Sources
by Paul Donavan, Illingworth & Rodkin

Trucks are louder than cars, not only because of their difference in size, engine, and exhaust but because of the way the tires interact with the pavement. Truck tires have different treads. The height distribution also has an effect. Caltrans estimates that the noise source distribution in truck is 50% from the tire/pavement interface, and 50% from the engine and exhaust. New studies attempt to obtain acoustic pictures of trucks.

Double Decker Noise Modeling
by Lawrence Spurgeon, Parsons Brinkerhoff

The Alaska Way Viaduct, with its double deck, is a very loud road. So loud that the traffic noise can be heard one or two blocks away. The main problem is the noise reflection that occurs with two levels of road. Both roadways have identical horizontal coordinates. A study attempted to estimate the noise in the viaduct, but faced the problem of how to model the double deck. The model utilized was TNM 2.1. The proposed solution was a simple one: to model two virtual roadways, with each carrying half of the total traffic.

Reflective Noise Modeling with TNM
by Jim Laughlin

A similar case of reflective noise modeling was faced when analyzing the Interstate 5 Ship Canal Bridge, in Seattle, which also features a double deck. The bridge is managed by Washington State DOT. The vertical distance between both levels in I-5 is 30 ft, and unlike the previous presentation's case, the upper deck is wider. The narrower lower deck accommodates the express lanes. The bridge is so loud that the express lanes are closed every night at 11 pm to reduce noise in the surrounding communities. The bridge is shown in Figure 2.

Figure 2. Interstate 5 Ship Canal Bridge, in Seattle

In 1997, the community requested a noise study, and the following year, they organized a group called NOISE (Neighborhoods Opposing Interstate Sound Exposure) to voice their concerns. In January 2004 the first phase of the noise study was completed, and the second phase concluded in December 2004.

The study calibrated and validated the TNM model. Two models were analyzed, a direct path and a reflective path, which considered only the express lanes. Five noise wall scenarios with various materials were modeled:

a. Reflective wall panels only
b. Absorptive wall panels only
c. Absorptive ceiling panels only
d. Reflective walls and absorptive ceiling panels
e. Absorptive walls and absorptive ceiling panels

The last one was considered the best model. Standard concrete walls would be too heavy for the structure to support, hence lightweight, innovative materials had to be considered. The materials studied were as follows:

Reflective materials:

a. Paraglass
b. Quilite

Absorptive materials:

a. Acoustax
b. Silent Screen
c. Noise Shield
d. Sound Fighter
e. Carsonite

The first two absorptive materials gave the best results, with noise reductions of 13 to 19 dB. Two more concerns that have to be evaluated when the final decision on materials is made are the aesthetics of the bridge, and access for bridge inspection.

The study found that sound walls and panels alongside both bridge decks could reduce noise by more than half. An additional note is that a few of the innovative materials modeled were on display by the vendors that attended the conference, such as Quilite and Paraglass.

In May 2005, WSDOT received $5 million for further study. Next steps include refining studies of the different noise barrier materials, cost ranges, engineering and aesthetics. There is currently no funding available for the design and outreach stages of this project.

Should Multiple Highway Lanes Equal Multiple TNM Roadways
by Matthew Mc Duffee, Acentech

This short presentation showed the results of an experiment running the TNM model for two scenarios, and comparing them to actual measurements. The two cases are:

a. Modeling multiple traffic lanes as a single TNM roadway case

b. Creating one TNM roadway per highway lane

The first case was found to overestimate the noise levels by 1.6 dB, while the second one overestimates by 0.4 dB. Hence, the second alternative is more accurate, but the modeling task is more time-consuming. For this model, TNM 2.5 was used, with all the receivers within 150 ft from the source.

City of Seattle Nighttime Construction Issues
by David George, City of Seattle, Dept. of Planning and Development

In a large city such as Seattle, there are many construction projects that take place during nighttime, taking advantage of the lower traffic conditions. The drawback for the community could be the noise generated by construction operations that cause disturbance to the neighborhoods. Various strategies are implemented by the City of Seattle to address construction noise during nighttime and get a better approval of its works from the public's perspective; among those are the following:

- Establishing a website for public information on construction works
- Use of radios for communication instead of screaming at construction sites
- Utilization of a compressed schedule
- No work is allowed within the same neighborhood for more than two weeks

Construction companies working at night have to apply for a temporary noise permit.

FHWA Roadway Construction Noise Model (RCNM)
by Judy Rochat, USDOT/Volpe Center

The RCNM is a windows-based program that enables the user to conduct proactive noise mitigation during construction operations based on predictions. As background, the existing guidance for construction noise is provided by the FHWA 1977 Handbook, and by the FHWA 1982 prediction tool, which is a computer program.

RCNM allows multiple receivers, various land uses, includes the baseline sound levels of over 50 types of construction equipment, allows the establishment of noise limit criteria based on local ordinances, uses Lmax and Leq or L10 levels by equipment type and as totals, and accepts comma delimited files or text files for the input. Currently, the program is in its final testing stages. When finished, it will be available as downloadable software through the TNM website.

Acknowledgement

The author is very grateful to TxDOT for sponsoring the trip to the conference; thanks to Mike Shearer, German Claros, and Gary Graham for their support.

Appendix C. ISO Standard 11819-1: Statistical Pass-By Method