NCAT Report 04-02

TIRE/PAVEMENT NOISE STUDY

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August 2004

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ABSTRACT

In today's society, traffic noise is a serious problem. The term "noise" should not be confused with the term sound. Noise is the generation of sounds that are unwanted. With respect to traffic, noise would be the generation of sounds that affect the quality of life for persons near roadways. Therefore, traffic noise can be considered an environmental pollution because it lowers the standard of living. Research in Europe and in the United States has indicated that it is possible to build pavement surfaces that will reduce the level of noise generated on roadways. Use of hot mix asphalt to reduce noise levels could potentially save millions of dollars by reducing the number or height of noise wall barriers alongside highways. For this reason, in January of 2002 the National Center for Asphalt Technology initiated a research study with the objective to develop safe, quiet and durable asphalt pavement surfaces. This paper provides a basic understanding of the nature of noise, how it is measured, and how the vehicle and the pavement affect noise. The paper recommends that research be done to refine the correlation between near-field noise measurements (such as close-proximity noise testing) and roadside noise measurements, that a better understanding of the nature of the absorptive characteristics of noise be developed, and that field test sections be built to evaluate various methods for designing and building low noise pavements.

Pavement/Tire Noise Study

Douglas I. Hanson, Robert S. James, and Chris NeSmith

INTRODUCTION

Background

Research in Europe and in the United States has indicated that it is possible to build pavement surfaces that will provide low noise roadways. The National Center for Asphalt Technology (NCAT) has initiated a study to develop a pavement selection guide or design manual for use by the DOTs and others to design low noise Hot Mix Asphalt (HMA) pavement wearing courses. The first phase of this study focused on the review of the technical literature and the development of a data base on the noise characteristics of HMA surface types by conducting testing throughout the United States.

Throughout the world, sound caused by transportation systems is the number one noise complaint. Highway noise is one of the prime offenders. Engine (power train), exhaust, aerodynamic and pavement/tire noise all contribute to traffic noise.

In the United States, the Federal Highway Administration has published the noise standards for highway projects as 23CFR772 *(1)*. The FHWA Noise Abatement Criteria states that noise mitigation must be considered for residential areas when the A-weighted sound pressure levels approach or exceed 67 dB (A). To accomplish this, many areas in the United States are building large sound barrier walls at a cost of one to five million dollars per roadway mile. Noise barriers are the most common abatement strategy. The FHWA reports that the DOTs through 2002 have spent over 2.6 billion dollars on walls for noise control *(1)*. The average cost of those walls is $20 per square foot. Thus, a ten foot high wall one mile long would cost about 2.1 million dollars. Other strategies such as alterations of horizontal/ vertical alignment, traffic controls, greenbelts and insulation of structures are used to reduce noise. Each of these noise reduction measures will add significant cost to a project. In addition, each is limited in the amount of noise reduction that is possible and in many cases cannot be used for practical reasons. For example, noise barriers cannot be used if driveways are present.

It has been shown that modification of pavement surface type and/or texture can result in significant tire/pavement noise reductions. European highway agencies have found that the proper selection of the pavement surface can be an appropriate noise abatement procedure. Specifically, they have identified that a low noise road surface can be built at the same time considering safety, durability and cost using one of the following approaches *(2):*

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.

Purpose and Scope

The purpose of this paper is to present the results of the first Phase of the NCAT study of tire/pavement noise and procedures that can be used to build low-noise HMA pavement surfaces. This is to be accomplished while achieving a balance between noise, safety (friction, hydroplaning, splash and spray), smoothness and durability (longevity). The paper describes the results of a review of the technical literature and an analysis of the results of testing conducted by NCAT during the period June 2003 to April 2004. The paper will present recommendations about procedures for testing of pavement surfaces, recommendations of what steps can be taken to construct low noise surfaces and recommendations for future research.

NATURE OF NOISE

Noise is defined as "unwanted sound." Different people have different perceptions of what sound they like and what sound they don't like. The roar of the crowd at a baseball game or the laughter of children would commonly be considered pleasant sounds while the sound of a lawnmower or garbage truck would be considered noise or unwanted sound *(3).*

Noise like all other sounds is a form of acoustic energy. It differs from pleasant sounds only in the fact that it often disturbs us and has the characteristics of an uninvited guest. Understanding noise or sound requires a knowledge of the physics of sound and how humans respond to it.

Sound is fluctuation of air in a wave-like motion. Associated with this motion is acoustic or sound pressure that is measured in decibels. The decibel combines the magnitude of sound with how humans hear. Since human hearing covers such a large range of sounds, it does not lend itself to be measured with a linear scale. If a linear scale was used to measure all sounds that could be heard by the human ear, most sounds (assuming a linear scale of 0 to 1) occurring in daily life would be recorded between 0.0 and 0.01. Thus, it would be difficult to discriminate between sound levels in our daily lives on a linear scale.

Instead of a linear scale, a logarithmic scale is used to represent sound levels and the unit is called a decibel or dB. For environmental noises, the sound pressure levels are typically A-weighted. The term dB(A) is used when referring to the sound levels that have been A-weighted. The curve that describes the A-weighting roughly corresponds to the response of the human ear to sound. Studies have shown that when people make judgments about how noisy a source is that their judgments correspond quite well to the A-scale sound levels. A-weighting was determined such that the sound level at any one frequency would be judged equally loud as any other frequency. It, in effect, is a dB corrected to account for human hearing. The ear has its own filtering mechanisms and the inclusion of the A after dB indicates that the scale has been adjusted or "fine tuned" to hear like a human. Thus, a noise level of 85 dB(A) from a noise source would be judged louder or more annoying than a noise level of 82 dB(A). The decibel scale ranges from 0 dBA, the threshold of human hearing, to 140 dB(A) where serious hearing damage can occur. Table 1 *(3)* represents this scale and some of the levels associated with various daily activities.

Table 1. Noise Levels Associated with Common Activities (*3*)

Activity	Noise Level (dB(A)
Lawnmower	95
Loud Shout	90
Motorcycle passing 50 feet away	85
Blender at 3 feet	85
Car traveling 60 mph passing 50 feet away	80
Normal conversation	60
Quiet Living room	40

A serene farm setting might have a decibel level of 30 dB(A) while a peaceful subdivision might be at 40 to 50 dB(A). Alongside a freeway the sound level (i.e. noise) might be in the range of 70 to 80 dB(A). The transition from a peaceful environment to a noisy environment is around 50 to 70 dB(A). As a general rule of thumb, one can differentiate between two levels of similar sound that are at least 3 dB(A) different in level.

In addition to sound level, people hear over a range of frequencies (and this is the reason for the A weighting described earlier). A person with good hearing can typically hear frequencies between 20 Hertz (Hz where 1 Hz is one oscillation per second) and 20,000 Hz. An older person, however, may not be able to hear frequencies above 5,000 Hz. So this indicates, to some extent, some of the reasons why different people hear things somewhat differently.

Addition of Noise Levels

Noise levels are measured on a logarithmic scale. Therefore, when combining the effect of multiple sources this must be considered. The formula used to combine multiple sources of sound is *(3):*

$$dB(A)_t = 10 * \log\left[10^{\frac{\{dB(A)_1\}}{10}} + 10^{\frac{\{dB(A)_2\}}{10}} + ... + 10^{\frac{\{dB(A)_n\}}{10}}\right]$$

where: $dB(A)_t$ – the total noise level
$dB(A)_i$– the noise level of the i^{th} individual source

Figure 1 illustrates the effects of adding additional point source noise levels. If the sound level from one source of sound (a blender) measured at three feet from the blender is 85 dB(A) (from Table 1), then the sound level from two blenders would be 88 dB(A) and the sound level from three blenders would be 89.8 dB(A). Therefore, doubling the sound emissions would result in a 3 dB(A) increase in noise levels, which can be differentiated by the human ear. This can be determined for any number of sound sources by using the above equation. For roadway surfaces this means that if the number of vehicles in the traffic flow is doubled, the sound level will increase by 3 dB(A) (*3*).

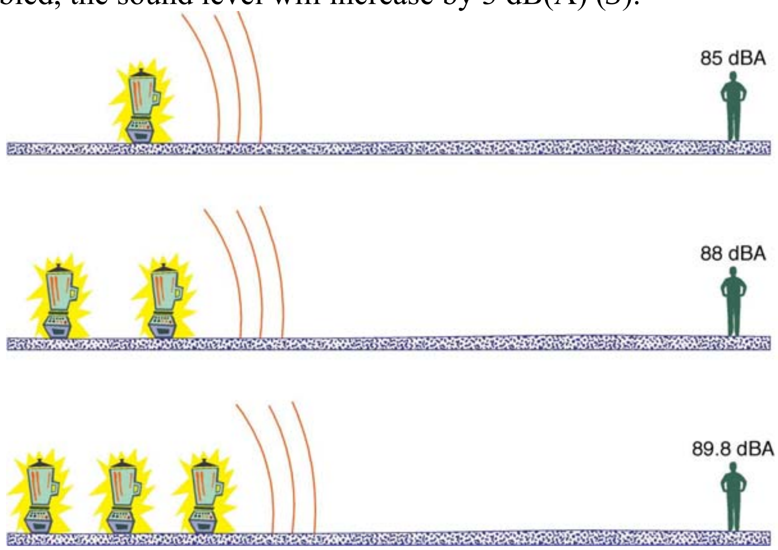

Figure 1. Effect of Adding Noise Sources

Propagation of Noise from a Point Source

An important mitigating factor with regard to noise is the distance between the source and the receiver. Sound levels from an ideal point source decrease in accordance to the inverse-square law. This law is a fundamental law of acoustics – it states that the sound level varies inversely as the square of the distance. As the distance increases, the noise levels decrease. For a point source, such as a blender the attenuation factor is 6 dB (A) when the distance away from the source is doubled and is 9.5 dB (A) at three times the distance. Thus, again if you have a blender that has a sound level of 85 dB (A) at three feet then when you move six feet away from the blender the noise level would be 79 dB (A) and if you move three times the distance (9 feet) away from the blender the noise level would be 75.5 dB (A). This is illustrated in Figure 2.

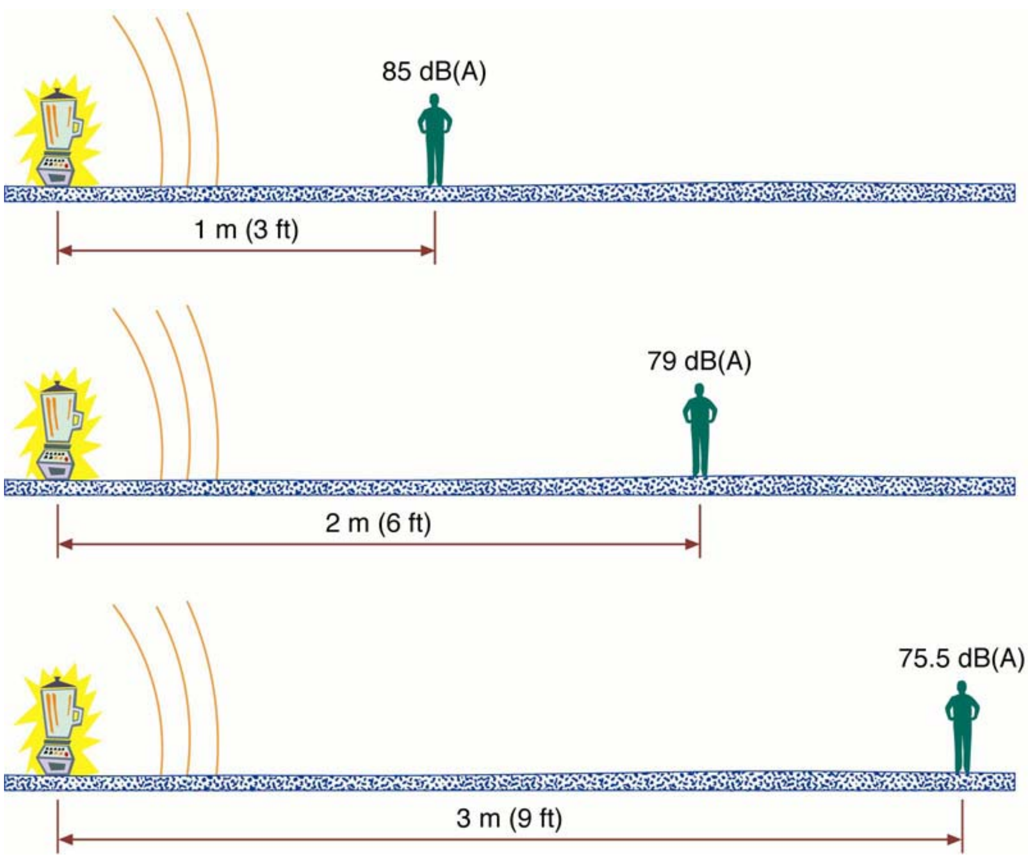

Figure 2. Effect of Distance on a Point Noise Source

Propagation of Traffic Noise

Roadway noise acts in a different manner. Roadway noise is classified as a line source since noise is transmitted along the entire length of the roadway *(3)*. As a vehicle passes by a point, the noise reaches the point from all along the roadway, or from each point where the vehicle was. As the distance from the source increases, the noise level decreases at a lower rate than from a single point noise source. For paved surfaces, the doubling of the distance ideally results in a 3 dB (A) reduction in the noise level. Thus, if a point 16 feet from the center of the noise source (the center of the lane) of the roadway has a noise level of 85 dB (A), then a point 32 feet from the edge of the roadway would have a noise level of 82 dB (A). This is illustrated in Figure 3.

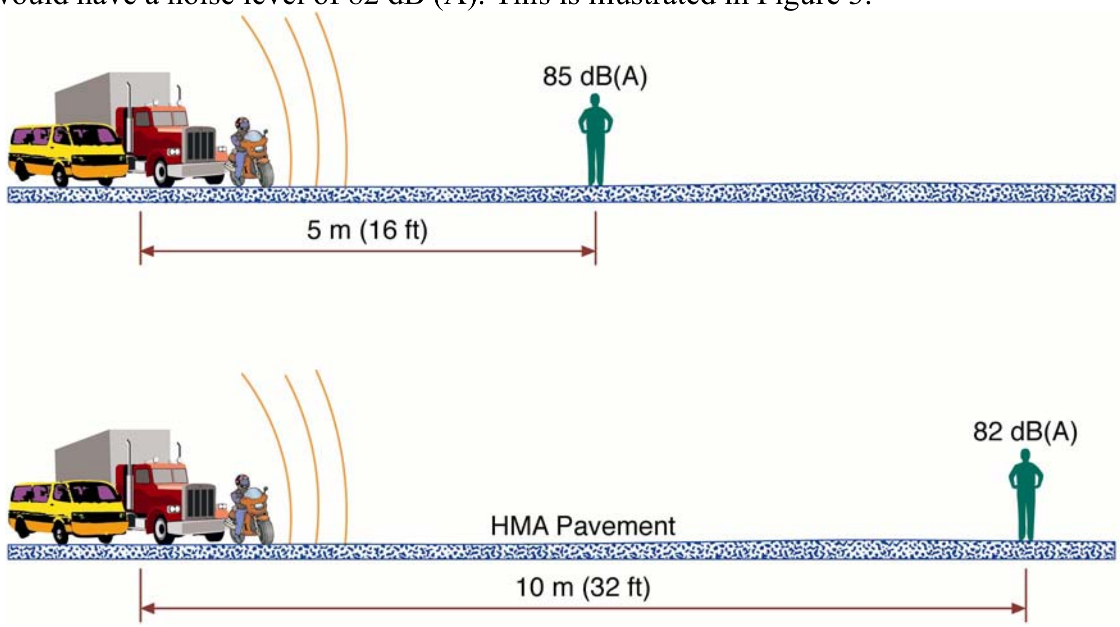

Figure 3. Effect of Distance on a Line Noise Source Over a Paved Surface

The noise level near the road not only depends on the noise being generated by the traffic but, also the characteristics of the ground adjacent to the road. The Traffic Noise Model used by the Federal Highway Administration *(3)* to predict noise levels along side the roadway uses the following equation to approximate the drop off:

$$dB(A) = 10 * \log_{10}\left\{\left(\frac{d_1}{d_2}\right)^{1+\alpha}\right\}$$

where: α = attenuation coefficient which is
0.0 for hard ground or pavement
0.5 for soft ground

d_1 = distance from the sound source to the first point of interest
d_2 = distance from the sound source to second point of interest

If the noise level is 85 dB(A) at the edge of pavement which is at 16 feet (d_1) (1/2 of a 12 foot lane plus a ten foot shoulder) from the center of the noise source. Then the noise level at a house 200 feet (d_2) from the roadway edge with soft ground between the roadway edge and the house would have a predicted noise level of 68.5 dB(A). This is illustrated in Figure 4.

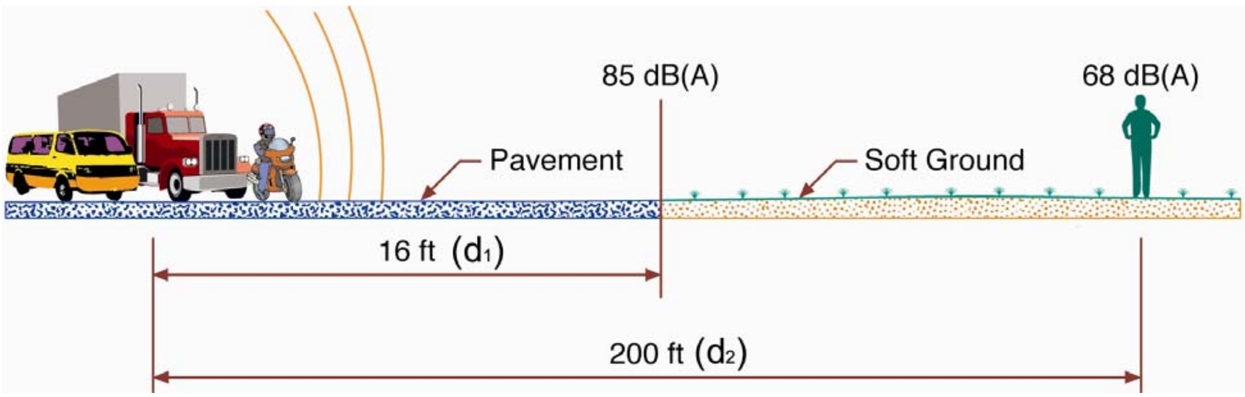

Figure 4. Effect of Distance on a Line Noise Source Sound Traveling Over Soft Ground

THE EFFECT OF THE VEHICLE ON TRAFFIC NOISE

The noise generated by the vehicle can be classified into three general categories: the power unit noise (engine, fan, exhaust and the transmission, etc.), the aerodynamic noise, which is related to the turbulent airflow around the vehicle, and the tire/pavement noise. The power unit noise and the tire/pavement noise are the important sources of noise levels for roadside noise. At low speeds the power unit noise dominates the roadside noise levels and at high speeds the tire/pavement interaction dominates the roadside noise levels. Table 2 provides an estimate of the crossover speeds. Cruising is a constant speed, such as found on a high-speed urban or rural highway. Acceleration is an indication of an average driver pulling away from a stop.

Table 2. Approximate Cross-Over Speeds *(2)*

Vehicle Type	Cruising (constant speed)	Accelerating (increasing Speed)
Cars made 1985 to 95	18 to 22 mph (30-35 kph)	25 to 31 mph (40-50 kph)
Cars made after 1996 -	10 to 16 mph (15-25 kph)	18 to 28 mph (30-45 kph)
Heavy Trucks made 1985 to 95	25 to 30 mph (40-50 kph)	31 to 35mph (50-55 kph)
Heavy Trucks made after 1996 -	18 to 22 mph (30-35 kph)	28 to 31 mph (45-50 kph)

The speed of the vehicle also affects the noise level. Figure 5 shows the effect of speed on noise. This figure presents the national average as used in the FHWA's Traffic Noise Model (TNM). (23 CFR, Chapter 1 (4-1-99 Edition) *(3)*

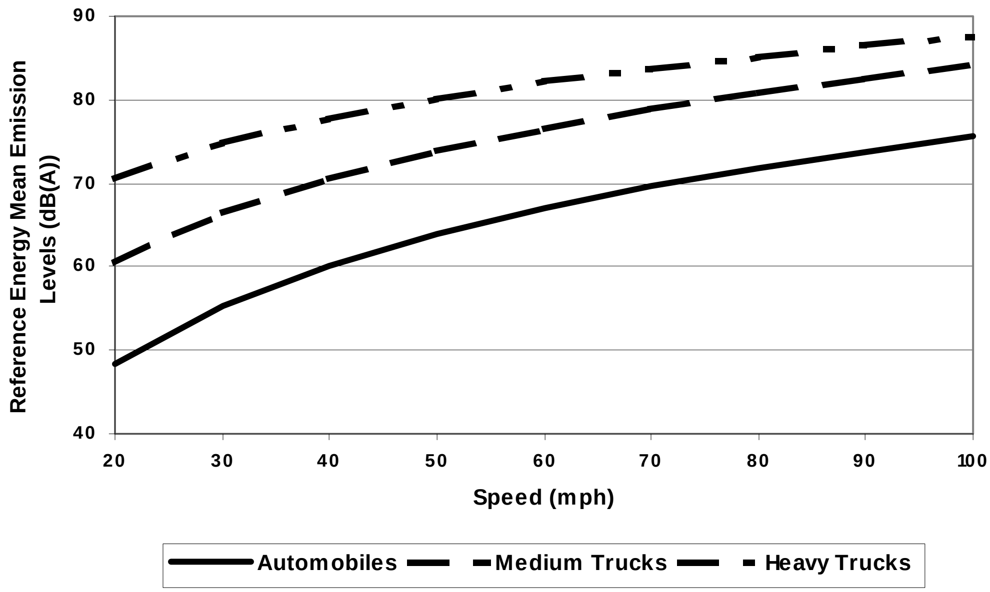

Figure 5. National Reference Energy Mean Emission Levels as a Function of Speed *(3)*

EFFECT OF THE TIRE ON TIRE/PAVEMENT NOISE

To understand how to design a low noise pavement surface, it is necessary to understand the mechanism or the tire/pavement noise phenomenon. There are approximately 16,000 different tire tread patterns used on tires *(2).* Tire tread pattern design is a compromise between safety, noise, ride and tire longevity. Generally it is thought that tire/pavement noise can be described as two mechanisms: the mechanical vibrations of the tire, which includes the tread impact and adhesion mechanisms, and the aerodynamic phenomenon. Sandberg concluded that the tire impact mechanisms controlled the low frequency noise and that the air displacement mechanisms controlled the high frequency noise *(2).*

The aerodynamic phenomenon can be described as: pipe resonance and air pumping. The pipe or tube resonance effect occurs in the circumferential groove of the tire tread. Air pumping can be either pavement or tire related. As a tire rolls over the pavement air is forced out of voids or pockets in the pavement. This rapid exit of air can then lead to sound generation. As the tire rolls out of contact, air is rapidly sucked back into the pavement voids, again creating a rapid displacement of air which can generate sound. Air pumping also occurs when the air is pressed out of the voids in the tire tread pattern. A related effect is the "horn effect." This is an enhancement of the radiation of sound due to the geometry of the circular tire and flat ground forming a horn that can amplify the sound generated by any of the suspected tire noise mechanisms. It is thought that both horn effects and air displacement mechanisms can be reduced by the use of a thick porous pavement.

As a part of its development of the NCAT Close Proximity (CPX) Trailer, work was done at NCAT to evaluate the effect of tires on the noise levels measured with the CPX trailer. The ISO Standard calls for four tires to be used when doing investigative work and two tires for survey work *(4)*. The tires listed in the standard are not tires commonly found in the United States. Therefore, one of the first tasks after delivery of the trailer was a study to evaluate the effect of various tires on pavement/tire noise. To accomplish this task, seven tires were used on the trailer with the sections of the NCAT test track as the test surface. Five of these tires were standard automobile tires and two were ASTM standardized tires (the tires used on the ASTM T274 skid trailer).

Table 3 presents the average tire pavement noise level for each of the tires. The tires are ranked in this table from quietest to the nosiest based on sound pressure. The testing showed that from quietest to noisiest the range in noise levels was 4 dB(A) (91.2 for the ASTM Slick and 95.2 for the Michelin Rain Forest). Recall that the rule of thumb is that one can differentiate between two sound levels when they are different by more than 3dB(A).

Table 3. Tire Test Results: NCAT Test Track *(5)*

Tire Type	CPX Noise Level dB(A)
ASTM Slick	91.2
UniRoyal Tiger Paw	92.4
ASTM 501- Ribbed	93.8
Firestone FR 380	93.9
MasterCraft Glacier Grip	94.7
Goodyear Aquatread	94.9
Michelin Rain Forest	95.2

An analysis of variance (ANOVA) was conducted to compare the pavement/noise characteristics of the tires based on sound pressure. Results of this statistical analysis indicated that tire type significantly affected sound pressure. The slick tire was the quietest, which conforms with information in the literature on tire noise *(2)*. A Duncan's multiple range test was conducted to determine which (if any) tires provided similar results. This analysis showed that the data could be grouped into five groupings:

1. ASTM Slick
2. UniRoyal Tiger Paw
3. ASTM 501-Ribbed Tire and Firestone FR 380
4. MasterCraft Glacier Grip and Goodyear Aquatread
5. Michelin Rain Forest

Based on this testing it was concluded that when conducting noise testing in the field, the type of tire used in the testing needs to be considered. Manufacturers are constantly changing their tire compounds to provide a better longer lasting tire and to meet the competitive requirements of the market place. Also, the elasticity of a tire changes with time. The technical literature clearly indicates that the noise generation of a tire is affected by the elasticity of the tire.

DEVELOPMENT OF NOISE POLICY

For the first several thousand years in the history of transportation, roadways consisted of cobblestone and stone block construction *(6)* this technology dates back to about 4000 BC in Ur in the Middle East. With the decline of the Roman Empire around 450 AD, the art of road building was essentially lost until the late 1700's and early 1800s. Around 1820, a Scotsman named John Macadam developed an improved roadway design called macadam. This roadway design consisted of an eight-inch thick layer of three-inch aggregate followed by a two-inch thick layer of three quarter inch aggregate. For the first time this new design allowed highway speeds (up to 9 mph) to be dictated by the vehicle (wagon) instead of the roadway. This design became popular in the US for rural road construction during the 1830s and 40s.

As US cities became more modernized they used the block and brick street construction similar to what existed in Europe and they began experiencing similar noise problems. This led US cities during the 1870s to start using wooden blocks in lieu of granite blocks for roadway construction. And, similar to what was previously reported by the British Physician in London (who stated "the roar of London by day was almost terrible – a never varying deep rumble that made a background to all other sounds") *(7),* major US communities began experiencing similar noise issues. Although wooden blocks were first used in Russia in the 14th century, their re-emergence provided a welcome relief from the clickety-clank of the wagons and the pounding of the horseshoes. During the late 1800s wooden blocks saw wide spread use in major cities as a quiet pavement strategy.

Just how important the noise issue was during the late1800s is exemplified by the willingness of the communities to accept pavement service lives of half to one fourth of what could be obtained with granite block streets. Wooden blocks were considered to have an expected service life of only 10 years while the granite blocks they were replacing had an expected life of 15-25 years under heavy traffic and 40-50 years under normal traffic.

During this same time period, the use of mastic streets, consisting of native asphalt spread over a prepared base was also becoming common and, like wooden blocks, this design produced quiet pavements. As is true today, each design had its strengths and weaknesses. Although mastic streets proved to be quiet, they had traction issues. In those days, this was related to the number of falls of horses. A study in the 1890s reported typical distances a horse could travel between falls. For sheet or mastic asphalt it was 220 km, for granite blocks 320 km, and for wood blocks, 550 km.

Along with the advent of hot mix asphalt in the early 1900s came the development of motorized travel. So at about the same time that technology was beginning to allow the construction of a smoother, quieter roadway, technology was providing a noisier vehicle. However, instead of tires making the noise as with wagons, engines and exhausts were the new culprits. As the use of motorized vehicles became more common, noise levels increased. As motorized transportation expanded during the 1900s noise problems continued un-abated until the early 1950s when US manufacturers imposed voluntary limitations on exhaust noise. This was followed by California noise legislation in the late 1960s and eventually Federal noise regulations in the early 1970s. The current FHWA noise abatement criterion is shown in Table 4.

Table 4. FHWA Noise Abatement Criteria *(8)*

Hourly A-Weighted Sound Level in Decibels {dB(A)}*			
Activity Category	$L_{eq}(h)$[1]	$L_{10}(h)$[2]	Description of Activity Category
A	57 (Exterior)	60 (Exterior)	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B	67 (Exterior)	70 (Exterior)	Picnic areas, recreation areas, playgrounds, active sports areas, parks, residences, motels, hotels, schools, churches, libraries, and hospitals.
C	72 (Exterior)	75 (Exterior)	Developed lands, properties, or activities not included in Categories A or B above.
D	--	--	Undeveloped lands.
E	52 (Interior)	55 (Interior)	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, and auditoriums.
* Either $L_{eq}(h)$ or $L_{10}(h)$ (but not both) may be used on a project.			

1. $L_{eq}(h)$ is the hourly equivalent sound level
2. $L_{10}(h)$ is the A-weighted sound level that is exceeded 10% of the time over a one-hour time period.

The policy further states that "The plans and specifications will not be approved by the FHWA unless the noise abatement measures which are reasonable and feasible are incorporated into the plans and specifications to reduce or eliminate the noise impact on existing activities …." The policy further states:

> "Pavement is sometimes mentioned as a factor in traffic noise. While it is true that noise levels do vary with changes in pavements and tires, it is not clear that these variations are substantial when compared to the noise from exhausts and engines, especially when there are a large number of trucks on the highway. Additional research is needed to determine to what extent different types of pavements and tires contribute to traffic noise.
>
> It is very difficult to forecast pavement surface condition into the future. Unless definite knowledge is available on the pavement type and condition

> and its noise generating characteristics, no adjustments should be made for pavement type in the prediction of highway traffic noise levels. Studies have shown open-graded asphalt pavement can initially produce a benefit of 2-4 dB(A) reduction in noise levels. However, within a short time period (approximately 6-12 months), the noise reduction benefit is lost when the voids fill up and the aggregate becomes polished. The use of specific pavement types or surface textures must not be considered as a noise abatement measure."

MEASUREMENT OF ROAD NOISE

A standardized method for the measurement of noise is necessary to allow the pavement engineer to characterize the level of the noise from different pavement wearing courses. Considerable work has been done to develop such techniques.

Field Measurements

Two concepts used for measuring of roadway noise in the field are:

1. Far-field measurements where the noise level is measured by microphones that are placed along side the roadway.
    a. The statistical pass-by (SPB) procedures as defined by both International Standards Organization (ISO) Standard 11819-1 *(9)* and the FHWA in their manual Measurement of Highway-Related Noise *(10),*
    b. The controlled pass-by procedures (CPB) using either a single vehicle or multiple selected vehicles *(11).*
2. And the near-field techniques where the noise level is measured by microphones placed near the tire/pavement interface. These procedures are classified as the close proximity methods (CPX). There are two approaches to conducting this type of testing:
    a. The procedures that were developed in Europe and are defined by ISO Standard 11819-2 *(4)*. These procedures measure sound pressure.
    b. The procedure developed by Dr. Paul Donavon which uses sound intensity to measure the noise levels *(12).*

Work has also been conducted to determine the noise levels of different pavement types in the laboratory. *(14)* These procedures are based on the measurement of sound absorption. Sound absorption is the fraction of the sound energy that is absorbed by a material when a sound wave is reflected by its surface. It is a function of both frequency and angle of sound incidence. The most promising of these procedures is the use of the impedance tube to determine the normal absorptive characteristics of the pavement being tested. The basic principle for this technique is that when the lateral dimensions of the tube are small compared to the wavelength of the acoustical signal, only plane waves will propagate. The sample placed at the end of the tube is thus subjected to plane acoustical waves. The amount of absorption can then be determined for different samples of HMA material. A controlling factor is that the frequency of the waves generated in the tube are related to the diameter of the tube.

Statistical Pass-by Methods (SPB)

The statistical pass-by (SPB) method consists of placing microphones at a defined distance from the vehicle path at the side of the roadway. In Europe, the ISO Standard 11819-1 calls for placing microphones 7.5 m (25 ft) from the center of the vehicle lane at a height of 1.2 m (4 ft) above the pavement. It also requires that the noise characteristics and speed of 180 vehicles be obtained (100 automobiles and 80 dual-axle and multi-axle trucks). This data is then analyzed to determine the statistical pass-by index (SPBI) *(9).*

The FHWA procedure developed by the Volpe Transportation Systems Center *(10)* calls for the placement of a microphone or microphones 15 m (50 ft) (instead of 7.5 m (25 ft) from the center of the travel lane and microphone height of 1.5 m (5 ft). The ground surface within the measurement area must be representative of acoustically hard terrain. The site must be located away from known noise surface, and is to exhibit constant-speed roadway traffic operating under cruise conditions. The FHWA procedure does not specifically state the number of vehicles required for a valid sample. It states that the number of samples is somewhat arbitary and is often a function of budgetary limitations. But, the procedure does provide some guidance. For example if the traffic speed is 51 to 60 mph the minimum *number* of samples recommended is 200.

Both of these pass-by methods are time consuming to conduct. The results can vary based on the traffic mix (even if the vehicle types are the same the differences in tires can cause problems). The testing conditions that must be met to conduct these measurements are very restrictive. The roadway must be essentially straight and level, there is a limit on the background noise, no acoustical reflective surfaces can be within 30 m (100 ft) of the microphone position, and the vehicle must be moving at a relatively uniform speed. The passbys are of individual vehicles and must be acoustically separated from all other traffic noise. The result of these restrictions is that a limited number of pavement surfaces can be tested economically.

Controlled Pass-by (CPB) Method

The controlled pass-by methods can be accomplished using either a single vehicle or selected vehicles. In this method, the noise generated from a single car or light truck is measured at a specially designed test site which means certain restrictions. The vehicle approaches the site at a specified speed in a specified gear. There are no national standards for this type of testing. An example of this type of testing is a study conducted by Marquette University for the Wisconsin DOT *(11).* In this study, they used a 1996 Ford Taurus that was operated at 60, 65 and 70 mph in the right lane. They conducted their testing by placing two microphones five feet above the pavement and positioned at

25 feet from the center of the traffic lane. The microphones were placed two hundred feet apart. Three runs were made to collect enough data for each speed.

Another method *(11)* to conduct this testing is to conduct the testing on an accelerating vehicle or vehicles. In this procedure at the entrance to a "trap" section of the test site, the vehicle begins to accelerate at full throttle. A sound level meter is set at a specified distance from the center of the travel path of the vehicle and is used to capture the maximum sound level of the vehicle as it passes through the "trap." This procedure tends to emphasize power train noise since the vehicle is in full acceleration during the test.

Close-Proximity Method (CPX) or Near-field Measurements

Near-field tire/pavement noise consists of measuring the sound levels at or near the tire/pavement interface. There are two approaches for measuring sound levels at the tire/pavement interface: the CPX as developed in Europe and defined by ISO Standard 11819-2 *(4)* and the sound intensity technique developed at General Motors *(13).* In the CPX method, sound pressure is measured using microphones located near the road surface. An alternate procedure for noise measurement is the use of sound intensity procedures. A sound source radiates acoustical power that results in sound pressure. Sound pressure is a measure of the variation in the density of the air caused by the source. This is measured by a standard sound level meter. Recently, it has become possible to measure an additional property of sound, sound intensity. Sound intensity is the rate of energy flow through a unit area. When sound intensity is integrated over the area, you obtain sound power. Sound power is the cause and sound pressure is the effect.

Thus, by measuring sound intensity one can determine a basic parameter of sound. Both sound pressure and sound intensity can be measured using a close-proximity trailer. Also, sound intensity can be measured by mounting the microphones on a standard automobile.

The requirements for the CPX trailer are described in ISO Standard 11819-2 *(10).* This method consists of placing microphones near the tire/pavement interface to directly measure tire/pavement noise levels. In 2002, NCAT built two CPX trailers, one for the Arizona Department of Transportation and one for use by NCAT. A picture of the NCAT trailer is shown in Figure 6. When testing with the NCAT CPX trailer the testing is done with two tires, the Goodyear Aquatred and the UniRoyal TigerPaw. Pictures of the tire tread patterns are shown in Appendix A.

Figure 6. NCAT Close Proximity Trailer

The ISO Standard calls for the measurement of sound pressure and the microphones at eight inches from the center of the tire and four inches above the surface of the pavement. The microphones are mounted outboard from the tire but inside an acoustical chamber to isolate the sound from passing traffic. The acoustical chamber is required because sound pressure microphones will measure the sound from all directions and thus, there is a need to isolate the sound from other traffic. Figure 7 shows the mounting of the microphones and the acoustical chamber.

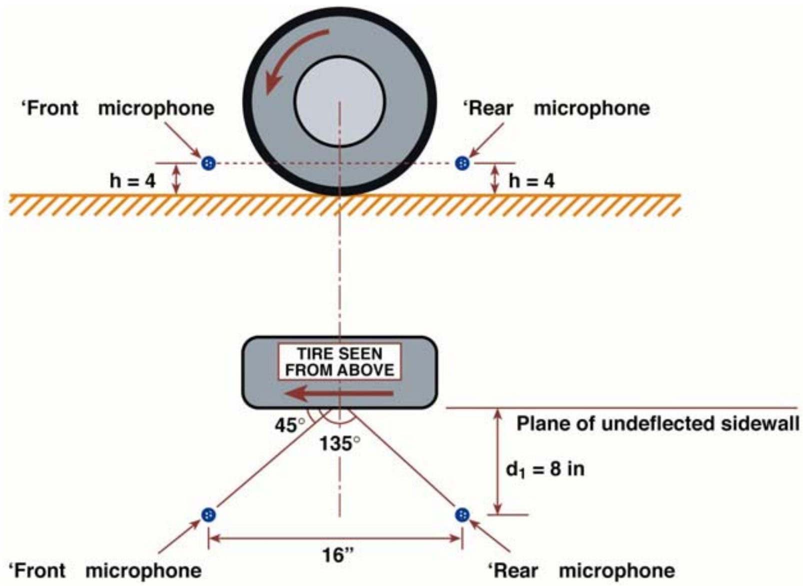

Figure 7. Diagram showing microphone locations in NCAT CPX Trailer

The second approach to measuring noise levels at the tire/pavement interface is the use of the sound intensity. The data is collected using two microphones located as shown in Figure 8 *(12).* The sound intensity probe consists of two ½ inch (12.5 mm) diameter microphones and preamplifiers in a "side-by-side" configuration spaced 5/8 inch (16 mm) apart and protected with a custom foam windscreen. The sound intensity was measured at four inches (100 mm) from the plane of the tire sidewall, within 70 to 80 mm of the pavement surface and opposite the leading and trailing edges of the tire/pavement contact. These data (leading and trailing edge measurements) are averaged together on an energy basis to estimate the sound intensity passing through the plane of the sidewall toward a sideline receiver. Because of the nature of sound intensity, there is no need for an acoustical chamber. Thus, the equipment can be mounted on any wheel of a passenger car.

Figure 8. Mounting Arrangement for Sound-Intensity Microphones *(12)*

Two CPX Noise Trailers have been built by NCAT. There was a need to evaluate the repeatability of the two devices – i.e. to determine if the same results were obtained with the two trailers. A study was done in November 2003 and completed in January 2004. The two trailers were used to test five pavement sections in the Phoenix metropolitan area. Three tires were used. The average difference between the NCAT trailer and the ADOT trailer is about 1.3 dB(A). Of the twelve comparisons, the NCAT trailer had a higher noise level 10 of the 12 times. It appears that the two trailers rated the pavements the same from loudest to quietest. The summary of the results is shown in Table 5. A comparison of the data in the table indicates a correction factor of approximately 1 dB(A) should be applied to the results. Although the difference was larger than desired it does fall within the expected reproducibility of 2 dB stated in the ISO Draft Standard. (The complete study is included as Appendix B to this report.)

Table 5. Comparison of NCAT and ADOT Trailers

Pavement Surface	Aquatred dB(A)		Michelin dB(A)		UniRoyal dB(A)	
	NCAT	ADOT	NCAT	ADOT	NCAT	ADOT
1 - PCCP	101.5	99.9	103.9	104.0	104.0	101.8
2 - ARFC	93.2	93.6	96.4	95.4	96.7	94.6
3 - PEM	96.7	95.9	98.6	97.8	98.2	95.8
4 – SMA	96.8	95.5	99.0	97.2	98.6	96.9
Average	97.0	96.2	99.5	98.6	99.3	97.2

Comparison of Field Measurement Procedures

There is a concern that near-field measurements measure only the tire/pavement noise component of traffic related noise *(2).* The standard method used by the FHWA's Volpe Laboratories for measuring traffic noise for use with the FHWA's traffic noise model is the statistical pass-by method. This method was selected because it includes both the power train and tire/pavement noise and measures what the receiver or listener hears in his/her backyard. Both the power train and tire/pavement noise are strongly related to vehicle speed. At low speeds power train noise dominates while at high speeds tire/pavement noise dominates. As was discussed earlier, work done in Europe has indicated that there is a crossover speed for constant-speed driving of about 25 to 30 mph for cars and about 35 to 45 mph for trucks *(2).* At speeds less than 25 to 30 mph for cars or 35 to 45 mph for trucks, the power train noise dominates; however, at higher speeds the tire/pavement noise is more prevalent. Therefore, it appears that the concept of measuring the noise level of roadways at the tire/pavement interface is valid for roadways having speed limits above 45 mph.

Comparisons between the near field (SPB and CPB) methods and the CPX methods have been done. The measurement of the tire/pavement noise at the interface is commonly used in Europe but it is new technology in the United States. The concern is that it is limited in that it is relevant only in cases where tire/road noise dominates and the power unit noise can be neglected. There is a concern that there is not a direct correlation between the CPX method and the statistical pass-by or controlled vehicle pass-by methods. As noted in Reference 2 Ejsmont found in 1992 found that there appears to be a correlation between these techniques but that the value depends on the type of tire and the nature of the road surface being tested.

The current approach for evaluating highway projects for noise related impact on the environment is the use of the FHWA's Traffic Noise Model. A recent study has been done in Arizona to evaluate this correlation with the single-vehicle pass-by method *(13).* The testing was done on a closed section of SR 202. The testing was done on PCC surfaces. The pass-by sound pressure measurements were done at 25 feet and 50 feet from the centerline of the vehicle travel lane. It was done using a vehicle mix that included heavy and medium trucks, SUV/pickup trucks and passenger vehicles. The testing was done at 60 and 70 mph. The near-field measurements were accomplished using sound intensity measurements. The sound-intensity measurements were conducted using a fixture mounted to the right rear wheel of the test vehicle. Figure 9 shows the results of the testing at 50 feet and Figure 10 shows the results of the testing at 25 feet. The offset (or reduction in noise) between the sound intensity and pass-by for the 25 feet was 23.8 dB(A) and for 50 feet is was 30 dB(A) as determined on 6 different asphalt surfaces and 3 different PCCP surfaces of different surface finishes. This data confirms earlier work done by Dr. Donavan in 1990 where he found that the offset was approximately 25 dB(A) at 25 feet from the centerline of the traffic. This database needs to be expanded and widened to include the CPX method.

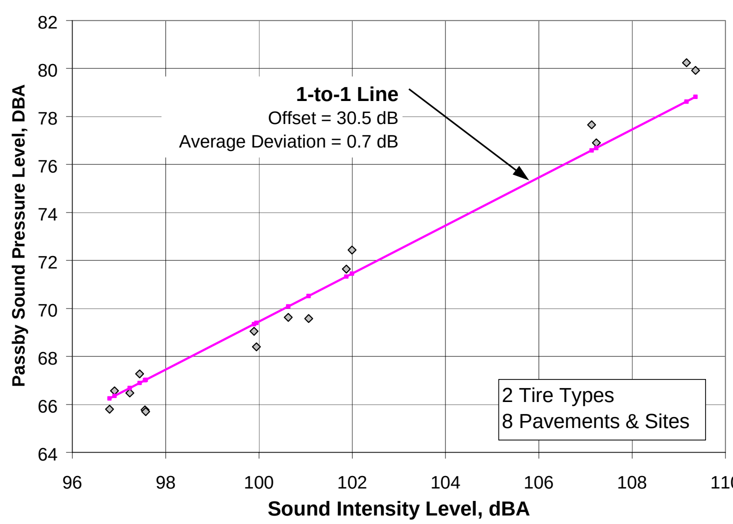

Figure 9. Comparison of Near-field Measurements vs. Pass-By (50 ft) *(13)*

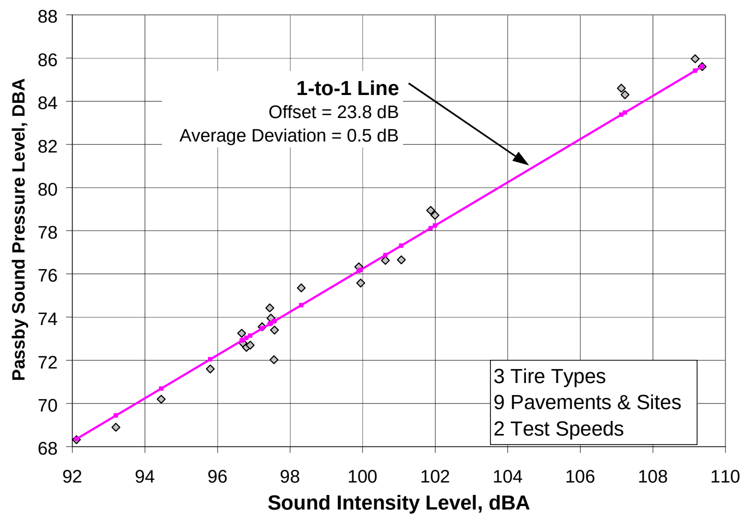

Figure 10. Comparison Near-field Measurements vs. Pass-By (25 feet) *(13)*

A study was conducted by NCAT in cooperation with Purdue University and the North Central Superpave Center on a newly constructed section of Interstate Highway near Indianapolis. The study used the controlled pass-by (CPB) procedure with a Ford Taurus as the test vehicle to determine the noise from the pavement surface. Three pavement surfaces were included in the study: an OGFC, an SMA and a dense graded pavement. The microphones were placed 7.5 meters from the center of the traffic lane. The Ford Taurus and the NCAT CPX trailer both used Uniroyal and Aquatred tires. The test speed (60 mph) was the same for both vehicles. Figure 11 shows the results of the comparison. The offset was approximately 23 dB(A).

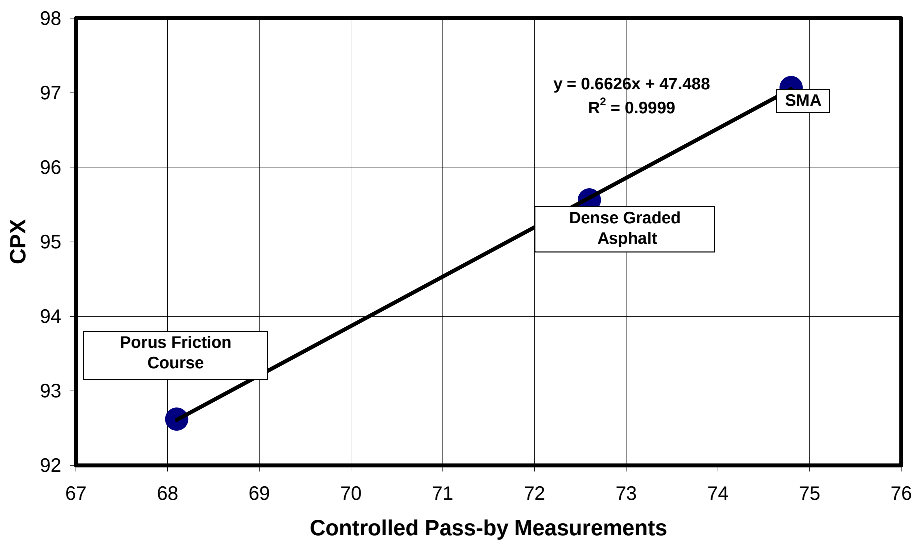

Figure 11. Comparison of CPX vs CPB Measurements

Based on the work done by Dr. Donavan and NCAT there appears to be a strong relationship between far-field (CPB) and near-field (CPX) noise measurements and that at 7.5 m (25 ft) the difference between far-field measurements is about 23 dB(A). Additional work is needed to validate this.

The near-field test (CPX) procedure offers several advantages:

1. The ability to determine the noise characteristics of the road surface at almost any arbitrary site such as depressed freeway sections, or where the topography of the area is such that it does not meet the acoustical requirements for roadside measurements..
2. The potential to evaluate the noise characteristics of a DOT's pavement system and to input the results into the DOT's pavement management program.
3. It is much more portable than the SPB or CPB methods, requiring less setup prior to use.

Laboratory Measurements - Sound Absorption

Sound is absorbed when the sound energy is converted into heat energy in the pores of the material. The absorption coefficient depends on the frequency and the angle of incidence of the sound waves on the material. For materials used in building construction the manufacturers of those materials provide the absorption coefficients of the material. The concept of absorption in pavement surfaces is shown in Figure 12. A higher absorption coefficient will mean that more sound will be absorbed by the pavement surface.

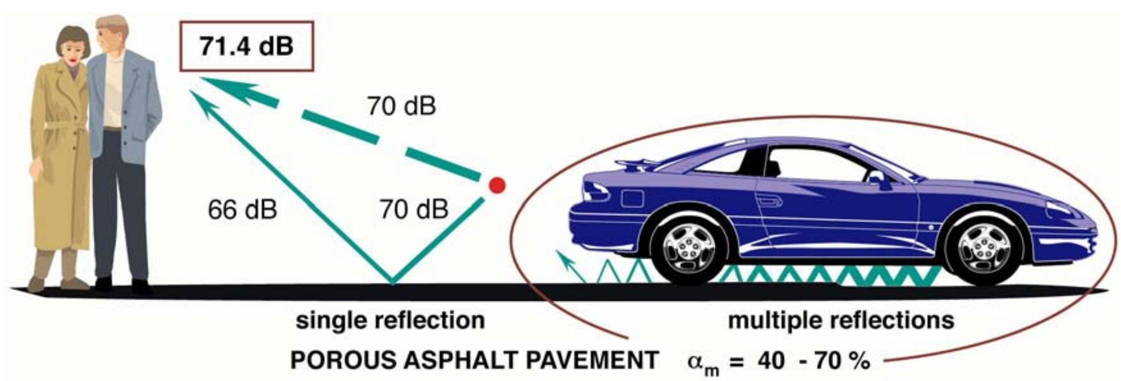

Figure 12. Sound Absorption into a Porous Asphalt Pavement *(2)*

The sound absorption (Ω) of porous road pavement surfaces is affected by the thickness of the porous layer, the air voids (Va) and the interconnectivity of the air voids. For most common dense asphalt mixes with air voids in the 4 to 8% range, the absorption coefficient will be 0.1 to 0.2 and for open-graded mixes with an air void content Va of about 15% the absorption coefficient is typically about 0.4 to 0.7 depending on frequency. The absorption coefficient also is affected by the interconnectability of the air voids. The more interconnected the voids – or the higher the air and water permeability of the layer – the higher the absorption coefficient.

A standard method *(14)* for evaluating the noise absorption characteristics of materials used in many fields is the use of the impedance tube or standing wave method. This technique has been standardized by the International Standards Organization (ISO) to determine the acoustical properties of road surface materials. The results of these measurements have been used by automobile companies for the evaluation of the noise characteristics of road surfaces and the acoustical interactions with the tires of an automobile.

An impedance tube can be used to measure the sound absorption of a roadway core sample by mounting it at the end of a specially designed impedance tube. A loudspeaker mounted at the end of the tube emits white noise. (White noise is a type of noise that is produced by combining sounds of all different frequencies together. If you took all of the imaginable tones that a human can hear and combined them together, you would have white noise.) The sound waves produced by the loudspeaker propagate along the tube and are reflected or absorbed by the sample. Two microphones that are flush mounted in the impedance tube wall measure the resulting sound field in the tube. The signals from the microphones, after suitable processing by standard software now readily available, are used to calculate the sound absorption coefficient of the roadway core sample. Figure 13 is a schematic of the impedance tube built by NCAT for NCAT's noise studies. Early work with this tube indicates the use of the equipment has promise *(14).* This technique can provide the materials engineer with the capability to evaluate different materials and mix designs in the laboratory to optimize their noise reduction capability.

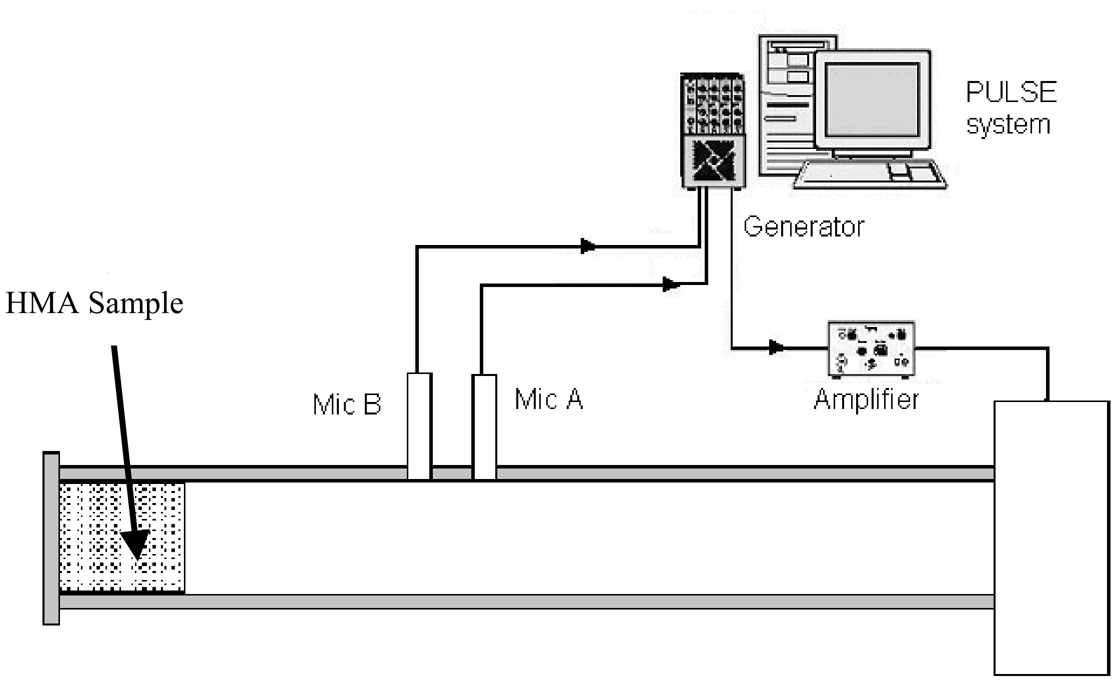

Figure 13. Experimental Setup of Sound Absorption of HMA Samples (*14*)

NOISE CHARACTERISTICS OF HMA MIXTURE TYPES

The Europeans have found that the proper selection of the pavement surface can be an appropriate noise abatement procedure and recommend that when designing a low noise surface, the goal is to *(2):*

1. Maximize the sound absorption at 1000 Hz for high-speed roads and 600 Hz for low speed roads.
2. Minimize the airflow resistance to reduce the aerodynamic influences (or horn effect from the tires) by providing an open pavement surface.
3. Maximize the smoothness of the surface that is in contact with the tire to reduce the impact of the pavement texture on mechanical vibrations of the tire.

Specifically, the recommendation is that a low noise road surface can be built at the same time considering safety, durability and cost using one or more of the following approaches:

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

In reference 2 Sandberg and Ejsmont *(2)* further defined what a "low noise road surface" is. It is "a road surface which, when interacting with a rolling tyre, influences the vehicle noise in such a way as to cause at least a 3 dB(A) lower vehicle noise than that obtained on conventional and 'most common' road surfaces" *(2).*

Three types of HMA mixes are used for surfacing of high volume highways: Open Graded Friction Courses (OGFC), Dense Graded HMA Mixes (DGA), and Stone Matrix Asphalt (SMA) mixes. The following discussion will include information obtained from the technical literature on tire/pavement noise and the results of testing conducted using the NCAT CPX trailer during the period July 2003 to April 2004.

Open Graded Friction Courses or Porous Mixtures

The technical literature *(2)* indicates that OGFC surfaces or porous pavements will have lower noise levels than DGA surfaces. Studies have shown that an OGFC can reduce the noise level 3 to 5 dB (A) when compared to non-porous HMA pavements. This is accomplished because the air voids in a pavement provide a means for air trapped between the tire and the pavement surface to escape (thus, reducing the horn effect) and they provide for increased sound absorption *(2).* To achieve this improved noise performance, the pores need to be interconnected. The added advantage of these surfaces is that they also provide a reduction of splash and spray and an increase in frictional and hydroplaning resistance of HMA wearing courses. The noise level from an OGFC surface is dependent on four factors: the interconnected air voids or permeability of the surface, the thickness of the OGFC layer, the gradation (the maximum size of the aggregate) of the OGFC and the quantity of the binder used in the OGFC mixture [state of the art].

An OGFC can provide significant reduction in the noise level of a wearing course. In reference 2 Sandberg and Ejsmont *(2)* state that the optimum surface for noise reduction is a porous surface with more than 15 % air voids. They provide the following definitions:

Dense surface:	< 10 % air voids
Semi-porous surface:	10 to 15 % air voids
Porous surface:	> 15 % air voids

Thus, the OGFC must have air voids in excess of 15%. The French, Dutch and Italian specifications require that the total air voids content must be in excess of 20% *(18).* The increased air voids results in improved absorption characteristics of the pavement surface. But, the increased absorption is related not only to air voids but also to the thickness of the paved pavement layer. Studies conducted in Belgium have shown that variations in noise levels relate to both layer thickness and to air voids *(18).* The layer thicknesses used in the study varied from 20 to 40 mm (0.78 to 1.57 inch) and the air voids varied between 15 and 25%. This work was confirmed by similar studies in Sweden *(2).* They developed an equation that relates the influence of these two variables which is:

$$\Delta L = 0.005\ e * v$$

Where: ΔL = noise level (dB(A)
e = thickness of surfacing layer (mm)
v = air voids (expressed as a whole number)

Thus, for an OGFC wearing surface with 20% air voids, the increase of 25.4 mm (1 inch) in thickness would result in approximately 2.5 dB(A) noise reduction (0.005*25.4*20). The design of a low noise pavement must consider not only air voids but also the thickness of the layer and that they should not be considered independent of each other.

Tire vibrations are responsible for the low frequencies of the noise spectrum (< 1000 Hz). The noise level increases as the amplitude of the megatexture is increased. When transmitted by the suspension, these vibrations elicit resonances which are coupled to some degree both to the walls of the passenger compartment and the volume of air, that it contains. As a result, noise inside vehicles is determined mainly by the amplitude of the megatexture of the road surface *(2).*

NCAT has conducted tests on OGFC surfaces in Alabama (both on Alabama roads and at the NCAT test track), Nevada, Arizona, Texas and in Colorado. This testing has shown that OGFC surfaces can provide a low noise pavement. But, the range in noise levels for OGFC pavements as a generic type varies considerably. Values have ranged from 91.5 dB(A) in Arizona to 98.6 dB(A) in Alabama. The data presented in this report must be considered preliminary. Additional research must be accomplished to validate the results presented below.

The thickness of these OGFC sections ranged from about 19 mm (¾ in) to 25 mm (1 in) in depth. Therefore, there was little data obtained with regard to the effect of thickness on noise levels. On nine sections all with similar gradations cores were obtained and the air voids of the pavement were determined. The noise levels as measured with the CPX trailer, the gradation data, and the air voids is shown in Table 6.

Table 6. OGFC Pavement Data

	Texas Site 2-1	Alabama Site 1-7	Alabama Site 1-8	Alabama Site 1-9	Alabama Site 1-10	Alabama Site 1-11	Colorado
19 mm	100	100	100	100	100	100	100
12.5 mm	93	89	96	96	94	92	98
9.5 mm	61	56	67	60	65	68	64
No. 4	18	14	13	15	16	16	11
No. 8	13	14	13	15	16	16	11
No.16	10	9	9	12	10	10	8
No. 30	8	6	6	9	6	6	6
No. 50	7	4	4	5	4	4	4
No. 100	6	3	3	4	3	3	4
No. 200	4.5	3.2	4.2	3.5	3.1	3.8	3.3
Air Voids	18.8	17.1	14.7	16.6	16.9	13.2	20.2
Noise Level dB(A)	95.2	97.1	98.5	95.5	97.1	97.6	95.1

Figure 14 shows a plot of noise level versus air void content. As can be seen from this data as the air void content increases the noise level decreases. This is very preliminary data. Much of the testing on OGFC surfaces has been done on roadways with very high traffic volumes that could not be closed to obtain cores to determine the air voids.

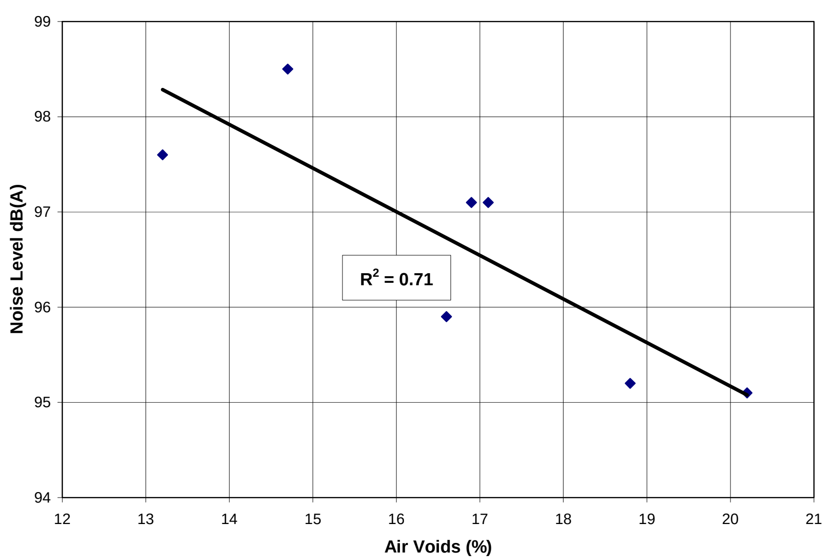

Figure 14. Effect of Air Voids on Tire/pavement Noise

From the literature *(2)* there is an indication that the gradation of the mix will affect the noise level of the OGFC and that as discussed above the coarser the gradation the higher the noise level at low frequencies. To provide a preliminary evaluation of this concept a frequency spectrum analysis was conducted. For traffic noise it is important to consider not only the magnitude of the noise but also the frequency of the noise. Sound at low frequencies is generally less attenuated by distance than sound at high frequencies and thus propagates further away from the road. The sound wave files collected in this study were analyzed using a Fourier Transform technique to produce a frequency spectrum plot. To evaluate the noise characteristics of pavements from throughout the United States – four pavements were chosen for comparison. To fully understand the effect of gradation on noise level considerable additional testing will need to be done. But, this provides a preliminary look at the effect of gradation of an OGFC on the noise frequency spectrum. Table 7 presents the gradations for the four surfaces evaluated. Where it is known the air voids for each of the pavements is also included. Figure 15 presents the frequency spectrum (noise (dB) versus frequency (Hz)) for the HMA surfaces tested. The curves show the site number, the noise level in dB(A) and the year that the pavement was built. It can be seen from this Figure 15 that for OGFC surfaces the noise generated is primarily in the low frequency range (about 600 Hz) and as the gradation became coarser the noise increased due an increase in the low frequency noise.

Table 7. Gradations of OGFC Surfaces Tested

Gradation	Arizona[1]	Nevada[1]	Colorado[2]	AL 1 – 7[2]
Nominal Max Size	4.75 mm	9.5 mm	12.5 mm	12.5 mm
¾ inch	-	-	100	100
½ inch	-	100	98	89
3/8 inch	100	95	64	56
No. 4	38	45	11	14
No. 8	6	-	8	9
No. 16	-	11	6	-
No. 200	1.2	2	3.3	3.2
Fineness Modulus	5.42	5.00	6.00	6.14
Air Voids	-	-	21 %	17 %
Noise Level	91.5	93.8	95.1	98.6

Notes: 1. from specification ranges
2. from cores

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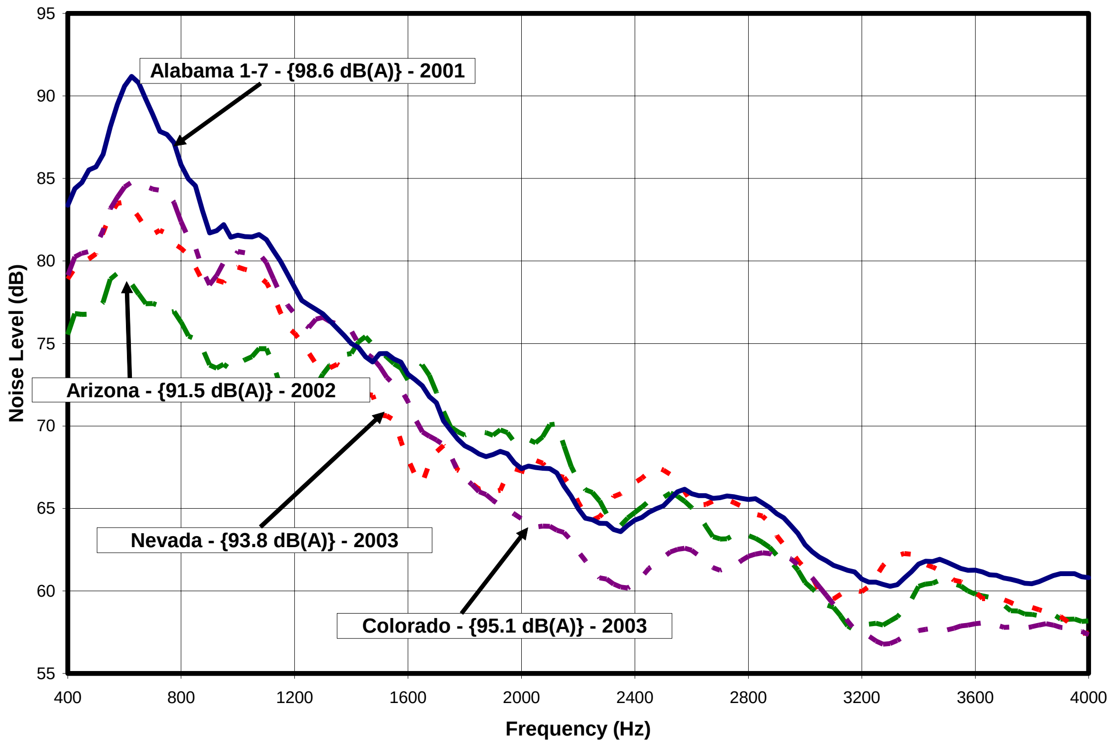


Figure 15. Noise Spectrum for Different OGFC Gradations

One of the concerns with OGFC wearing surfaces is the clogging of the surface with dirt and dust from the environment and from snow removal operations. The result of this clogging can be a reduction in the acoustical absorption of the pavement surface and an increase in the noise level of the surface. Europe has recently been experimenting with a two-layer drainage pavement. Figure 16 shows a diagram of this concept.

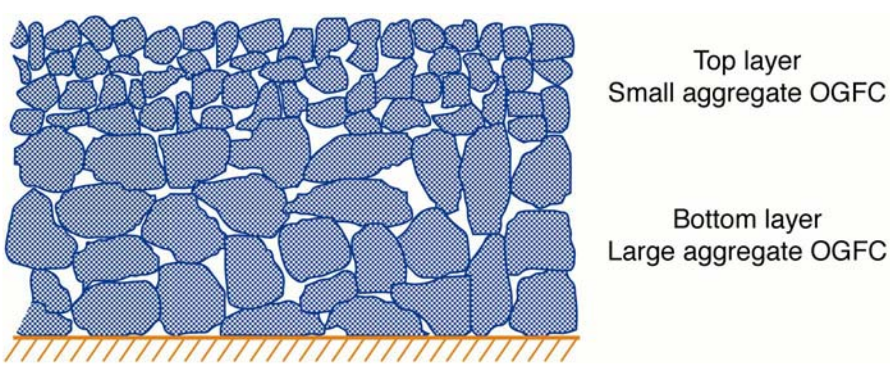


Figure 16. Two-Layer System (*16*)

French contractors have developed pavements that reduce the tire/pavement noise level by 3 to 5 dB(A). Their solution is to place porous mixes with a residual porosity (or air voids) of between 10 and 20% with a modified asphalt binder. They also had good longitudinal friction with these mixes. They have also experimented with double-layered porous asphalt. The principle is to lay an initial, thick layer (about 80 mm (3 ½ in)) of a highly porous mix (with roughly 15.6 mm (5/8 in) top size aggregate) for acoustic absorption, and to cover it with 30 mm (1.2 inch) or 40 mm (1.6 inch) of a fine (with roughly ¼ inch top size aggregate) porous mix. One of the principal functions of this course is to filter out those elements that usually cause clogging *(15)*.

The Danes constructed four test pavements in Copenhagen in 1999 *(16)*. Three sections had a two-layer drainage pavement. The top layer had a maximum of 5 (0.2 in) or 8-mm (0.32 in) chippings. The total layer thickness was 55 mm (2.1 inch), 70 mm (2.8 inch), and 90 mm (3.5 inch). They reported that the small-grained top surface ensures an even surface and has small pores that keeps out some of the dirt and ensures that dirt and water penetrating the surface is washed away without clogging the pores.

Dense Graded Mixes

There is little information in the literature on the noise levels of dense graded HMA mixes. The NCAT Test Track contains 46 different pavement surfaces. The majority of these surfaces are dense graded HMA mixtures. Thus, the test track provides an excellent tool to evaluate the properties of dense graded mixtures on pavement noise levels. An analysis was conducted where the tire/pavement noise from each of the seven tires tested (discussed above) was averaged and the average noise level from these seven tires was used to evaluate what properties of a dense graded HMA pavement will affect noise levels. The noise testing on the track was done at 45 mph due to safety considerations. The following pavement properties were evaluated: surface texture as measured with the Circular Texture Meter (CTM), the composite gradation properties of the mixtures as measured by the fineness modulus and the air voids of the mixes.

Conventional wisdom is that if a pavement surface has increased surface texture in a wearing course it is generally thought to result in increased skid resistance and, as a result of that increased surface texture, the noise level will increase. This increase in noise level would result from tire impact noise on the tips of the rocks in the roadway. The research has shown that there is a good relationship between interior noise, noise inside the vehicle, and the texture of the roadway as measured by mean particle depth. Figure 17 shows that based on the testing of the 46 sections at the test track that there is not a good correlation between mean particle depth and tire/pavement noise.

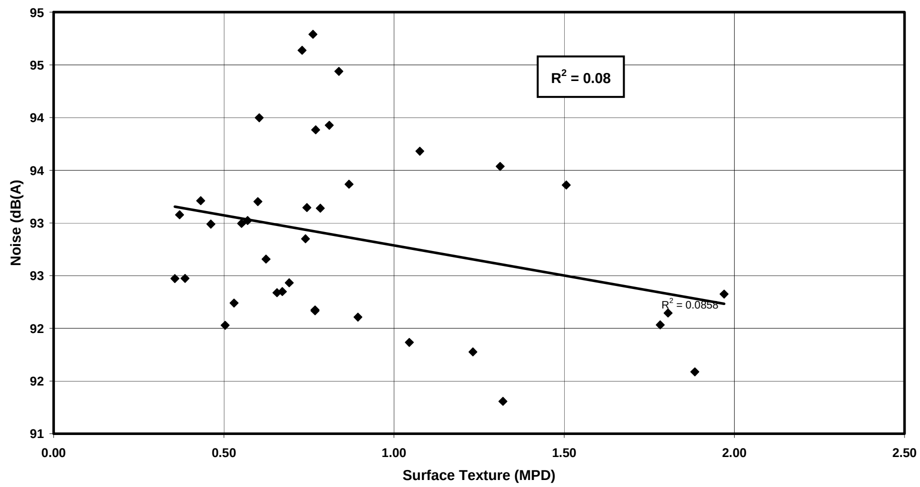


Figure 17. Mean Particle Depth vs Noise Level

Another method for evaluating the effect of the aggregate properties on noise levels is the use of fineness modulus. Fineness modulus is used in the design of portland cement concrete mixtures to describe a weighted average for the aggregate being analyzed. The fineness modulus is the sum of the percentages in the sieve analysis expressed as total percentages (by weight) coarser than the square mesh sizes in the Tyler or US series. A higher fineness modulus represents a coarser mixture (a higher percentage of coarse materials), also a higher fineness modulus may represent a more uniform mixture. This technique was chosen to provide a representation of the cumulative effects of gradation It is defined as the cumulative percentages retained on each sieve divided by 100. An aggregate gradation with a higher percentage of coarse aggregate will have a higher fineness modulus. Table 8 presents the average fineness modulus for the HMA mixtures used on the NCAT test track.

Table 8. Fineness Modulus for Different Types of Mixes at the NCAT Track

Type of Mix		Fineness Modulus
SMA		5.06
Dense Graded HMA	Above the RZ[1]	4.07
	Through the RZ	4.46
	Below the RZ	4.61

1. RZ = restricted zone

Figure 18 presents the correlation of fineness modulus versus noise level. Again there is a clear trend with an R^2 of 0.51.

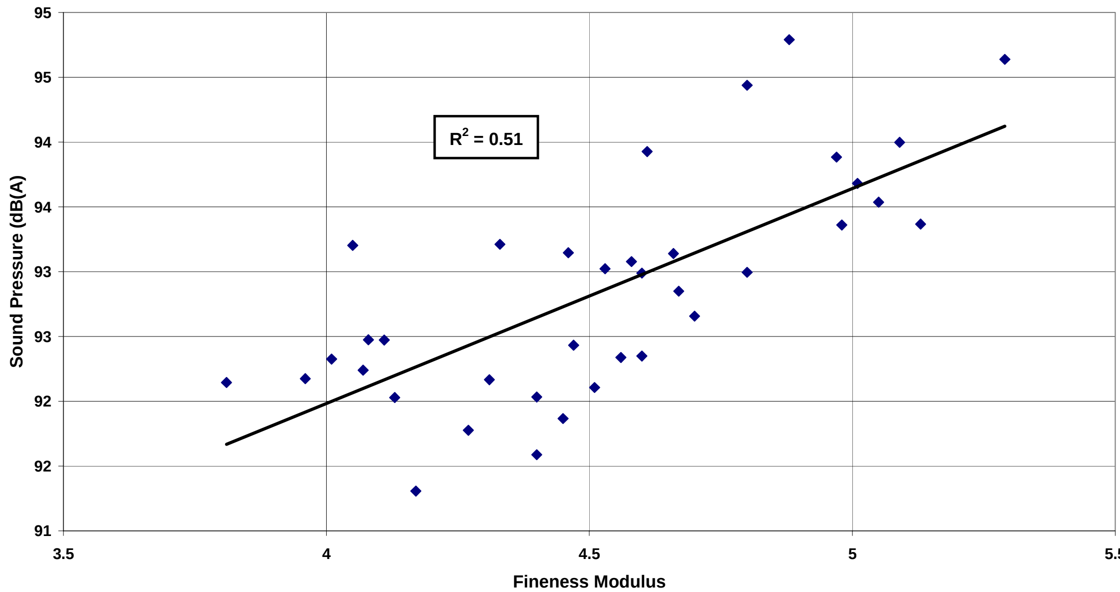


Figure 18. Fineness Modulus vs Noise Level

As discussed above there is a relationship between air voids and noise levels for OGFC mixes. Nothing was found in the literature that identified a relationship between air voids and tire/pavement noise for dense graded HMA mixes. Therefore, the air void and tire/pavement noise data as measured by the CPX trailer from the test track was used to determine if there is a relationship between air voids and noise level for dense graded HMA. Figure 19 presents the results of that analysis. Unlike OGFC the data indicates that there is very little relationship between air voids and tire/pavement noise for dense graded HMA.

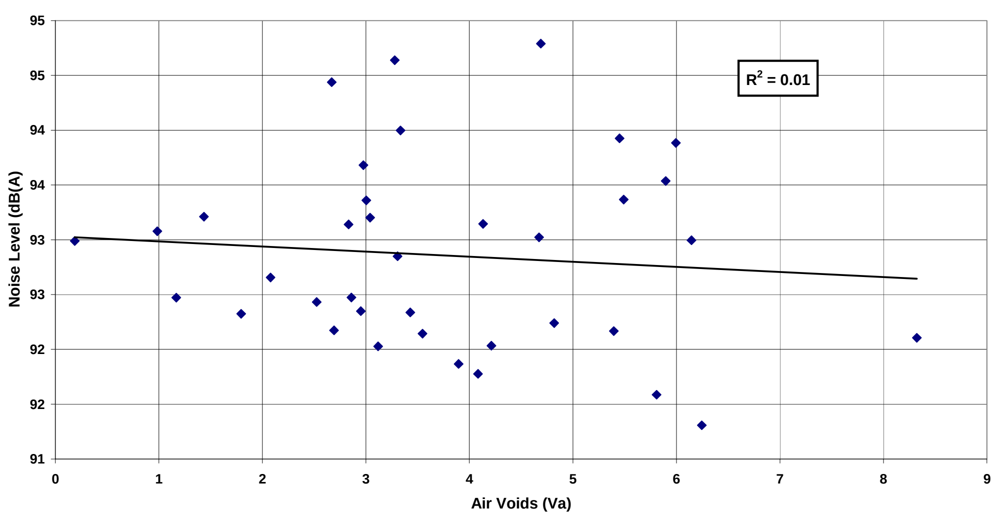


Figure 19. Effect of Air Voids in a Dense Graded HMA Mix on Tire/pavement Noise

It was postulated that there might be a relationship between tire/pavement noise level and air voids and fineness modulus combined. Therefore a multiple regression equation was developed where it was determined that:

$$L = 93.4 - 2.56 * \text{Air Voids} + 0.53 * \text{Fineness Modulus} * \text{Air Voids}$$

This equation was used to calculate the noise level for each of the dense graded test sections on the test track. The calculated value was then plotted against the actual value. As can be seen from Figure 20 the developed equation does seem to provide some explanation about the properties of a dense graded HMA mix and noise level.

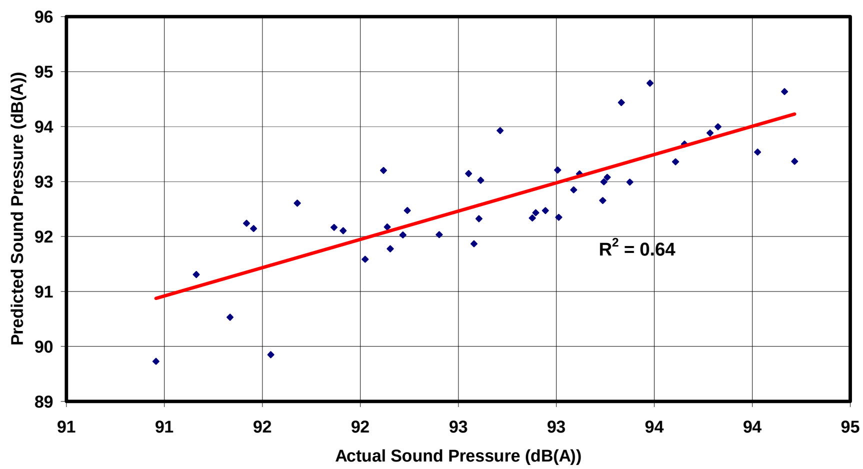


Figure 20. Comparison of Predicted Noise Level Against Actual Noise Level

In conclusion there appears to be a relationship between noise and the aggregate particle size and gradation used in a HMA wearing course. But, it is not totally explained by either fineness modulus or surface texture. Research has been done using a spectral analysis of the surface texture profile. Additional work to evaluate that approach may produce a method of quantifying surface texture with regard to noise levels

Stone Matrix Asphalt Mixes

Stone matrix asphalt mixes are seeing increased use in the United States to reduce the rutting or permanent deformation of HMA mixes. They were originally developed in Europe. Research in Europe has shown that these surfaces can have a noise level of 96.3 to 100.6 dB(A) *(2)* when measured with a CPX trailer. The noise level increases as the maximum sized aggregate increases. The lowest noise level occurred with a surface having a top size aggregate of 4-8 mm (0.15 to 0.30 inch) and the highest noise level had a top size of 12-16 mm (1/2 to 5/8 inch).

Testing done by NCAT on SMA surfaces has shown that an SMA surface can provide a noise level in the range of 95.9 dB(A) to 100.0 dB(A) with an average noise level of 97.2 dB(A). Table 9 shows the results of testing conducted on SMA pavements in Maryland, Colorado, New Jersey, and Virginia. The average noise level for the 9.5 mm SMA mixes is 96.8 dB(A), for the 12.5 SMA mixes is 98.7 dB(A) and for the 19 mm SMA mixes is 98.2 dB(A).

Table 9. Noise Levels for SMA Mixes Tested

Route	State	Noise Level dB(A)	Mix	Date Placed
US 1	NJ	100.5	19 mm	-
MD 50	MD	95.5	9.5 mm	2002
I – 270	MD	97.7	12.5 mm	2003
I - 495	MD	98.9	12.5 mm	2003
I - 83	MD	99.0	19 mm	1994
US 50	CO	96.2	12.5 mm	2002
I – 70 W	CO	96.3	19 mm	2003
I – 225 N	CO	96.9	19 mm	2002
I – 81 N	VA	100.0	12.5 mm	2003
7	VA	99.6	12.5 mm	2003
8	VA	98.8	12.5 mm	2003
12	VA	97.6	9.5 mm	2003
14	VA	97.4	9.5 mm	2003
15	VA	98.4	12.5 mm	2003
16	VA	99.4	12,5 mm	2003
17	VA	99.6	12.5 mm	2000
20	VA	98.8	12.5 mm	2003

VARIABILITY OF NOISE LEVELS WITHIN A PAVEMENT SECTION

To adequately predict the noise level at a point along a roadway (e.g. a person's backyard or a swimming pool), it is not only necessary to have an understanding of the total magnitude of noise that emits from traffic on a paved surface but also the variability of the noise along the pavement surface. The standard data collection process used for this study was to determine the average noise level over approximately one mile of paved surface. The test sections were approximately 1.61 km (one mile) long and the testing was done at 60 miles per hour; therefore, each section represents approximately 60 seconds of data. Each test section was broken into two second segments (or sections of 53 m (176 feet)). Each of these segments was analyzed to determine the noise level in dB(A) for that two second section. The objective of this analysis was to determine the approximate level of variation that could be expected. Also, this analysis is very time consuming. Therefore, the analysis was conducted on selected sites chosen to provide a range of noise level and pavement type.

Table 10 shows the results of that analysis for selected sites in Nevada, New Jersey and Colorado and Virginia. As can be seen the typical range is about 2.8 dB(A). There does not appear to be a clear trend for the different types of mixes. This indicates that if far-field or sideline measurements are to be used to evaluate the noise characteristics of an pavement type it must be done with care. A visual inspection was conducted of the New Jersey sites to attempt to understand why the variability existed. The high and low values could be attributed to physical properties of pavement surface. The implication of the data shown in Table 10 is that if the objective of sideline measurements is to evaluate the noise characteristics of a pavement type that more than one location needs to be tested and the values averaged.

Table 10. Longitudinal Variability of Noise Data

Route & Direction	State	Mix Type of Surface	Average dB(A)	Range dB(A)
IR 15 S	NV	9.5 mm OGFC	94	3.3
US 160 W	NV	9.5 mm OGFC	99	2.9
US 95 N	NV	9.5 mm OGFC	94	2.5
US 95 N	NV	9.5 mm OGFC	94	2.8
IR 215 Interim Frontage Road W	NV	12.5 mm DGA	98	3.3
I – 195 E	NJ	12.5 mm OGFC	98	3.8
I – 78 E	NJ	19 mm DGA	97	2.3
US – 9	NJ	12.5 mmOGFC (9 yrs old)	97	5.8
SR 58	CO	NovaChip	95	5.4
I – 225 N	CO	DGA	101	2.8
I -70 W	CO	19 mm SMA	96	2.9
I – 81	VA	12.5 mm SMA	100	1.2
US 460	VA	12.5 mm DGA	98	0.7
US 29 N	VA	9.5 mm DGA	99	2.0
US 29 S	VA	9.5 mm SMA	98	1.0

EFFECT OF AGE ON PAVEMENT NOISE

A detailed study needs to be done to evaluate the effect of pavement age and traffic on noise. Traffic levels and region of the country need to be included as variables in that study. The testing NCAT did in Colorado provides a preliminary understanding of the nature of pavement age on noise level. Ten dense graded HMA pavements in Colorado were tested by NCAT. Figure 21 shows the results of noise level plotted versus age of pavement. As expected the older the pavement, the higher the noise level. A study is being conducted using the NCAT test track to monitor the noise level of the 45 sections on the track versus noise. Measurements are being made at 1 million ESAL intervals throughout the 10 million ESAL test regime.

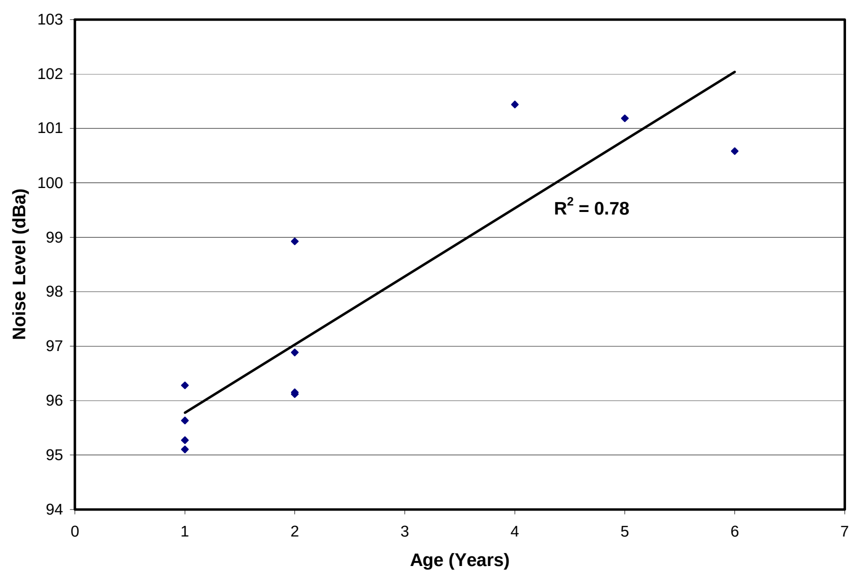


Figure 21. Effect of Age of Pavement on Noise (Colorado data)

SUGGESTED RESEARCH PROGRAM

Based on the information gathered for this paper, it is recommended that a three studies be conducted. The studies outlined below can be conducted independently of each other.

Study I

The objective of this study would be to develop a correlation between noise levels determined with near-field (close-proximity and/or sound intensity) measurements and roadside measurements. A study needs to be done to determine if the correlation varies with pavement type. The study as a minimum should include the following. It would be beneficial (but, may be cost prohibitive) to include replicates.

1. Two PCCP pavements with different textures (for example – transverse tined and longitudinally tined).
2. Two different OGFC sections (for example – fine graded and coarse graded gradations.)
3. Two different SMA sections (for example - a 9.5 mm and a 12.5 mm).
4. Two different dense graded (DGA) sections (for example – a 4.75 mm, 9.5 mm and 12.5 mm)

Study II

The objective of this study would be to utilize the current state of knowledge with regard to tire/pavement noise to construct test sections that would evaluate various open-graded concepts, two-layer systems, thicker layers, and different maximum size aggregates. Figure 22 presents a possible test matrix for this study. This would allow the evaluation a direct comparison of the coarse and fine graded OGFC mixes along with the two layer system. This could also be used to do a direct evaluation of different binders.

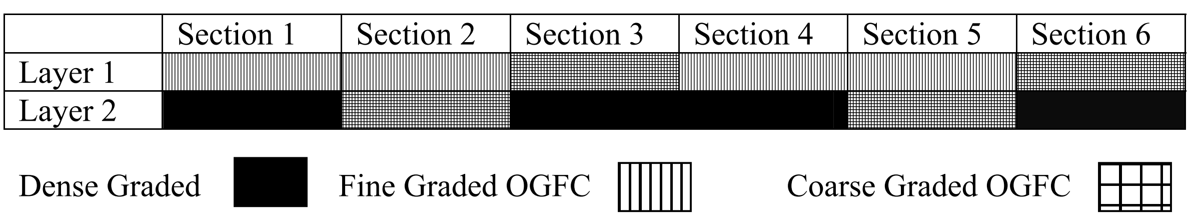


Figure 22. Possible Test Matrix for Quiet Pavement Field Study

Study III

The objective of this study would be to evaluate the absorptive characteristics of various HMA pavement types. By conducting this research in the laboratory the effect of binder, air voids, and gradation on absorption can be evaluated relatively inexpensively as compared to field studies. This laboratory research would be validated by also conducting tests at field sites and on field cores taken from sites where CPX testing was accomplished. The pavements tested in Study II and III outlined above would be included in this study.

CONCLUSIONS AND RECOMMENDATIONS

Based on the information gathered for this paper, the following conclusions are made:

1. The CPX Noise Trailer developed by NCAT can be used to evaluate the noise characteristics of pavement surfaces. This is a tool that could be used by a DOT to evaluate the noise characteristics of their pavements on a system wide basis. The next step in this process is for a company that manufactures pavement test equipment to evaluate the feasibility of producing a commercially available CPX Noise Trailer.
2. Based on the testing done by NCAT with the CPX Noise Trailer the typical noise level for
   a. Open-graded (coarse gradation) mixes is approximately 97 dB(A).
   b. Open-graded (fine gradation) mixes is approximately 93 bB(A)
   c. Dense graded HMA is approximately 95 dB(A).
   d. Stone Matrix Asphalt Mixes is approximately 96 dB(A).
3. It is possible to build low noise HMA pavements.
4. It appears that it will be possible to develop a correlation between noise levels determined with near-field (close-proximity and/or sound intensity) measurements and roadside measurements.

REFERENCES

(1) Highway Traffic Noise in the United States – Problem and Response, Federal Highway Administration, US Department of Transportation, April 2000.

(2) Sandberg, Ulf and Jerzy A Easement, Tyre/Road Noise Reference Book, Informex, 2002.

(3) Highway Noise Fundamentals, Noise Fundamentals Training Document., Federal Highway Administration, US Department of Transportation, September 1980.

(4) International Organization for Standardization, Measurement of the Influence of Road Surfaces on Traffic Noise- Part 2, Close-Proximity Method ISO Standard 11819-2, 1997.

(5) Hanson, D., R. James, N. Christopher, "Development of Close-Proximity Trailer for Measurement of Tire/Pavement Noise," Submitted to the Transportation Research Board for the January 2004 Meeting.

(6) Crocker, Malcolm J, Noise Control, Van Norstrand Reinhold Co, Inc., New York, 1984.

(7) "Sound Barriers & Noise Control," Arizona Milepost, Vol. 3, No. 2, Spring 2002.

(8) Highway Traffic Noise Analysis and Abatement Policy and Guidance, U.S. Department of Transportation, FHWA, Office of Environment and Planning, Washington, D.C., June 1995.

(9) International Organization for Standardization, Measurement of the Influence of Road Surfaces on Traffic Noise- Part 1, Statistical Pass-by Method 11819-1, 1997.

(10) Lee, Cynthia S.Y., and Gregg G. Fleming, Measurement of Highway-Related Noise, FHWA-PD-96-046, May 1996.

(11) Kuemmel, D. A., R. C. Sonntag, James Crovetti, Y. Becker, "Noise and Texture on PCC Pavements – Results of a Multi-state Study," Wisconsin Report SPR 08-99, June 2000.

(12) "Tire Testing Using Acoustical Intensity," General Motors North American Operational Center, Noise and Vibration Center, Undated.

(13) Donavan, P.R., and Larry Scofield, "An Evaluation of the Effects of Different Portland Cement Concrete Texturing on Tire/Pavement Noise," Noise-Con 2003.

(14) Crocker, M., D. Hanson, "Measurement of the Acoustical and Mechanical Properties of Porous Road Surfaces and Their Relationship to Tire/Road Noise," Submitted to the Transportation Research Board for the January 2004 Meeting.

(15) Descornet, G, B. Faure, J-F Hamet, X Kestemont, M. Luminari, L. Quaresma, D. Sandulli, "Traffic Noise and Road Surfaces: State of the Art," Belgian Road Research Centre, Brussels, March 2000.

(16) Bendtsen, H., L. E. Larsen, "Two-Layer Porous Pavements and Noise Reductions in Denmark," Internoise 2001.

(17) Scofield, Larry, "Preliminary Noise Research Reports," Arizona Department of Transportation, December 2002.

APPENDIX A

TIRES USED ON NCAT TEST TRAILER

TIRES USED FOR STUDY

Figure A-1. Goodyear Aquatred

Figure A-2. Uniroyal TigerPaw

APPENDIX B

COMPARISON STUDY BETWEEN NCAT DESIGNED CLOSE PROXIMITY NOISE TRAILERS

COMPARISON STUDY BETWEEN NCAT DESIGNED CLOSE PROXIMITY NOISE TRAILERS

BACKGROUND

When test equipment is designed and built it is desirable for the next generations of the equipment to be able to reproduce the data that was collected by the first. In the case of the National Center for Asphalt Technology (NCAT) Close Proximity Noise trailer (hereafter referred to as a sound trailer), the first trailer was designed and built and subsequently sold to the Arizona Department of Transportation. The second sound trailer was of the same design with slight modifications for NCAT's own use. In order to be valuable to the industry the close proximity noise trailer must be reproducible. Both trailers were built according to International Standard Organization specification 11819-2. Using these specifications it is believed that the trailers will provide consistent data between themselves.

OBJECTIVES

The objective of the comparison study is to prove that the two close proximity trailers are, in fact, able to provide comparable data.

TEST PLAN

Testing was accomplished on four different asphalt sections and one concrete section. The different sections were used to provide a range of decibel levels recorded to rule out the possible hypothesis that the trailers may provide consistent data on loud pavements but not on soft pavements. The asphalt sections included a Stone Matrix Asphalt (SMA), a Porous European Mix asphalt (PEM) and two different sections of Asphalt Rubber Friction Course (ARFC). The concrete section tested was a longitudinally tined Portland Cement Concrete Pavement (PCCP). Three of the asphalt sections (SMA, PEM and ARFC) are located south of Phoenix, AZ on I-10. The other asphalt section (ARFC) and the concrete section are located on State Road 202 in Phoenix, AZ.

Three different types of tires were used in the comparison testing, Goodyear Aquatred, Michelin Rainforce and Uniroyal Tiger-Paw. Again, the different tires were used to provide some range in the decibel level of the tire noise generation.

At the start of each day of testing all microphones in the trailers were calibrated using a Larson Davis tone generating calibrator. The desired set of tires was mounted on the trailer and microphone locations in reference to the tire were adjusted per ISO 11819-2. For each of the three tire types used, the same set of tires was used on each sound trailer. For example, the Uniroyal Tiger-Paw tire was tested on the AZDOT trailer, when testing was complete on the AZDOT trailer the Uniroyal Tiger Paw tires were removed and placed on the NCAT trailer for its round of testing.

Three passes were made over each pavement with each tire, (except that the Uniroyal Tiger Paw and the Michelin Rain Force were not run on the ARFC pavement on SR 202) resulting in a total of thirty-nine passes for thirteen tests. Each run was done at sixty miles per hour and at approximately the same time using the AZDOT standard of five seconds of recording time. Those three runs were then averaged to give an overall decibel level. This is the number typically reported.

TEST RESULTS

The Data collected is displayed in Table B-1. Three runs were accomplished for each test. The overall average is usually reported for sound investigations. The average standard deviation for each tire/ pavement combination calculating from both the individual runs and the overall value was 0.9 dB(A). The results of t-tests run on the overall data are shown in Table B-2. Paired t-tests were run on each of the individual tire sets (e.g. Aquatred, Michelin, and Uniroyal) and on the data as a whole pairing each of the tests. The last column is the interpretation of the P-value indicating whether or not the runs done by a particular tire on a particular pavement are significantly different. As shown in Table B-2 the calculated P-values do not imply significant differences in the test values.

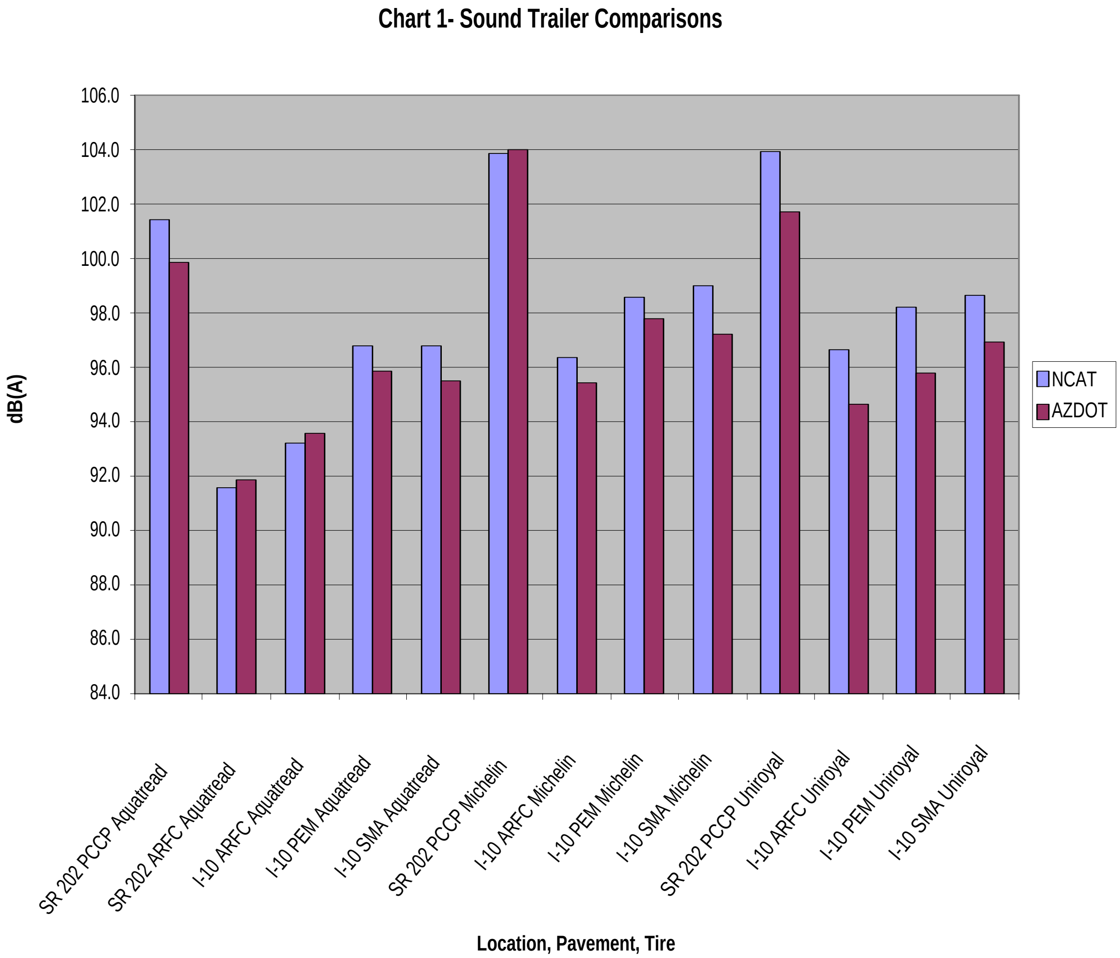
Table B-1.

Site	NCAT				AZDOT			
	Run 1	Run 2	Run 3	Overall	Run 1	Run 2	Run 3	Overall
SR 202 PCCP Aquatred	101.8	101.2	101.5	101.5	99.4	100.4	99.9	99.9
SR 202 ARFC Aquatred	91.3	92.1	91.3	91.6	91.0	90.5	94.2	91.9
I-10 ARFC Aquatred	93.2	93.3	93.2	93.2	93.6	94.0	93.2	93.6
I-10 PEM Aquatred	96.7	96.8	96.7	96.8	95.7	95.1	96.9	95.9
I-10 SMA Aquatred	96.7	96.9	96.8	96.8	95.5	96.2	94.8	95.5
SR 202 PCCP Michelin	104.4	103.1	104.1	103.9	104.7	104.5	102.8	104.0
I-10 ARFC Michelin	96.4	96.4	96.3	96.4	94.9	96.1	95.3	95.4
I-10 PEM Michelin	98.5	99.1	98.2	98.6	98.2	97.2	98.0	97.8
I-10 SMA Michelin	99.7	98.7	98.5	99.0	97.5	97.0	97.1	97.2
SR 202 PCCP Uniroyal	104.0	104.0	103.9	104.0	100.7	102.6	102.0	101.8
I-10 ARFC Uniroyal	96.4	96.7	96.9	96.7	94.3	94.0	95.5	94.6
I-10 PEM Uniroyal	98.0	98.6	98.0	98.2	96.2	95.5	95.7	95.8
I-10 SMA Uniroyal	99.1	98.4	98.3	98.6	96.5	97.1	97.1	96.9

Table B-2.

Sample tested	P Value	Significantly Different?
Goodyear Aquatred - All Pavements	0.393	No
Michelin Rain Force - All Pavements	0.372	No
Uniroyal Tiger Paw - All Pavements	0.193	No
All Tires - All Pavements	0.205	No

Chart 1 shows the relationships between the same tire/pavement combination and the NCAT and AZDOT trailers. The largest difference is 2.4 dB(A), given by the Uniroyal



tire on the PEM pavement. The Uniroyal tire tended to give the highest differences overall. The highest difference not generated by the Uniroyal tire is 1.8 dB(A) by the Michelin on an SMA pavement. If the Uniroyal tire is removed from the standard deviation averages the average standard deviation for the individual runs and for the overall levels drops to 0.8 dB(A) and 0.6 dB(A) respectively.

While the statistical tests show insignificant differences between the two trailers, there is some difference. The differences between the trailers are on the same order as those differences observed in multiple passes of a single test. Some reasons for those differences in readings could include: weather changes through the course of testing, normal vehicle wander leading not testing exactly the same strip of pavement or vehicle wander caused by passing traffic. In addition, the trailers, although they were designed to be the same, do have some differences. There were improvements made to the design from the first generation to the second generation and AZDOT trailer has received some modifications since it was purchased. It is difficult to determine precisely what differences in the trailers cause inconsistencies between the two trailer's data. But, for the purposes of highway noise testing the differences appear to be insignificant. These differences are usually overcome by sampling a one mile section of pavement when possible. This longer section reduces variability and minimizes the effect of inconsistencies by taking a larger sample than the five second samples taken in this study.

RECOMMENDATIONS

Because of differences in trailers from one generation to the next and complicated mechanisms, each new trailer should always endure a comparison study with an existing trailer before important testing is undertaken. However, there should be some changes made to the study. Each recording analyzer should have the exact same setup to avoid confusion. Namely, the recording frequency spectrum should be set from 0-20,000 Hz. This will avoid the procedure of exporting the sound to digital audio tape and them importing it back into the analyzer at the selected frequencies. Also, the recording time needs to be adjusted. The 5 second intervals, while providing valuable data, did not provide the best indication of how the variability can be reduced with a longer test section. The recording time should be at least 20 seconds if not 60 seconds.

CONCLUSIONS

Two NCAT Close Proximity Noise trailers have been designed and built by the National Center for Asphalt Technology. Both sound trailers were built using guidelines set forth in ISO 11819-2. Comparable data from the two trailers is crucial for this type of experimentation to be of value to the rest of the industry. Prior to this experiment, it was just assumed that the two trailers, having been built by the same standard, would provide comparable data. Given the data collected, the trailers do provide comparable numbers. Of course, it will always be critical that the trailers are setup, calibrated and driven properly to continue the free flow of data from one trailer to the next especially as further trailers are built and sold around the country.