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16. Abstract

This report provides guidelines for the selection and design of quieter pavement surfaces. The focus is on reducing noise at the tire-pavement interface, although the use of quieter pavement surfaces in conjunction with other noise abatement options, such as noise barriers, is also addressed as a case study. A comprehensive literature review is included that outlines the current state of the art in designing quieter pavements and all relevant contributing factors in terms of surface macrotexture, porosity, and resilience. An extensive pavement-noise database was compiled containing a large number and variety of different pavement surfaces used in Texas. In the effort to develop laboratory procedures for designing quieter surfaces, this database was analyzed to identify all relevant design parameters influencing noise. A laboratory test and design procedure to measure and evaluate noise was developed and correlated against design parameters for asphalt and concrete surfaces. Field testing of different asphalt and concrete surfaces was completed, including noise measurements using the on-board sound intensity test method as well as field measurements of surface macrotexture and permeability. The case study documents the design and use of a noise barrier in conjunction with low-noise surfaces to address noise complaints from residents residing along a busy stretch of IH30 near Dallas. Products of this research include detailed laboratory test procedures for measuring noise generated by surface materials and a set of guidelines developed to provide the Districts with recommendations to assist in selecting appropriate candidate projects for low-noise surfaces and for designing surfaces to provide long-term noise reductions.

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Selection and Design of Quiet Pavement Surfaces

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Disclaimers

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Products

One product of this research (0-6819-P1) is detailed laboratory test procedures for measuring noise generated by surface materials, included in Appendix A of this report. Guidelines were also developed to provide the Districts with recommendations to assist in selecting appropriate candidate projects for low-noise surfaces and for designing surfaces to provide long-term noise reductions. These guidelines are the final product (0-6819-P2) of the research study and are included in Appendix B of the report.

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List of Acronyms & Terms

AC	asphalt content
BPT	British pendulum test
CPB	controlled pass-by
CPX	close proximity
CRCP	continuously reinforced concrete pavement
CTIM	Continuous Flow Traffic Time Integrated Method
CTM	circular texture meter
DGA	dense-graded HMA
DGAC	dense-graded asphaltic concrete
EAC	exposed aggregate concrete
ETD	estimated texture depth
FHWA	Federal Highway Administration
FM	fineness modulus
GDYR	Goodyear Aquatread
HMA	hot-mix asphalt
LDS	laser displacement sensor
L_{eq}	equivalent continuous sound level
L_{veh}	measured vehicle sound level
LTS	laser texture scanner
MPD	mean profile depth
MTD	mean texture depth
NAC	noise abatement criteria
NCAT	National Center for Asphalt Technology
NGCS	next-generation concrete surface
OBSI	on-board sound intensity
PCC	portland cement concrete
PCC	Portland cement concrete
PERS	Porous Elastic Road Surface
PFC	permeable or porous friction course
PGH	high temperature binder grades

RMS	root mean square
SILVIA	Sustainable Road Surfaces for Traffic Noise Control
SIP	statistical isolated pass-by
SMA	stone matrix asphalt
SPB	statistical pass-by
SPL	sound pressure level
SRTT	standard reference test tire
STC	Sound Transmission Class
Stdev	standard deviation
TNM	Traffic Noise Model
TOM	thin overlay mixture
TTI	Texas Transportation Institute
TxDOT	Texas Department of Transportation
UNIR	Uniroyal Tigerpaw
VMA	voids in the mineral aggregate
WisDOT	Wisconsin Department of Transportation

Chapter 1. Introduction

1.1 Problem statement

Traffic noise is increasingly becoming a serious problem, particularly in dense urban areas. The term "noise" should not be confused with the term sound. Noise is the generation of unwanted sounds. With respect to traffic, noise would be the generation of sounds that affect the quality of life for persons living or working near or along heavily trafficked roadways. As such it can be considered an environmental pollution that affects the health and well-being of these people. This report provides a basic understanding of the nature of noise, how it is measured, and how the vehicle and the pavement affect noise. It provides procedures to design quieter pavement surfaces and guidelines for noise abatement strategies.

Pavement noise research in the United States and abroad (Sandberg and Ejsmont, 1998) has indicated that it is possible to design and build pavement surfaces that will provide low noise roadways, so-called quieter pavements. It has been shown that modification of pavement surface type and/or texture can result in significant tire-pavement noise reductions. Highway agencies around the world 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 or more of the following fundamental approaches:

1. A surface with a smooth surface texture using small maximum size aggregate.
2. A porous surface with a high air void content.
3. A pavement-wearing surface with an inherent low stiffness at the tire/pavement interface.

These approaches are fundamental to the understanding of tire-pavement noise and are a recurring theme throughout the report.

1.2 History of noise studies in Texas

Noise studies in Texas date back to the 1970s (Woods and Young, 1971). These initial studies did not consider the effect of the pavement surface on noise and focused more on far-field measurements to map noise levels alongside roadways in urban environments. The University of Texas at Austin started to evaluate road noise in the mid 1990s (Klingner et al., 1995). These early studies focused on noise barriers to reduce road noise levels and the development of a noise abatement policy/program for Texas (Landsberger et al., 2000). At that time, the Federal Highway Administration's (FHWA) Traffic Noise Model (TNM) did not consider the pavement surface as a factor in noise abatement and this is reflected in the Texas Department of Transportation (TxDOT) policy on noise abatement at the time (TxDOT, 1996). The following two reasons are cited for not considering pavement for noise abatement:

1. Traffic noise levels do vary with changes in pavement; however, additional research is needed to determine if these variations are substantial when compared to the noise from a vehicle's exhaust and/or engine.

2. It is very difficult to forecast the deterioration of pavement over time and any associated effects on traffic noise levels. Therefore, unless very definitive, verifiable data is available on a particular type of pavement, including its condition and noise generating characteristics, no adjustments for pavement type can be made.

It was not until the year 2000, that TxDOT started to consider the effect of pavement on noise. Initial studies at the University of Texas at Austin investigated this influence for porous and dense-graded hot-mix asphalt (HMA) mixtures as well as jointed and continuously reinforced concrete pavements (CRCP) with and without tining (DeMoss et al., 1999), (McNerney et al., 2000) and (McNerney et al., 2001). These studies coincide with the introduction of pavement models in the FHWA's TNM and are the first reported studies of the use of near-field or close-proximity measurements of pavement-tire noise in Texas using sound pressure technology.

The University of Texas at Austin continues to evaluate pavement-tire noise and was instrumental in the development of the onboard sound intensity (OBSI) method for close-proximity tire-pavement noise measurement (Trevino and Dossey, 2009a), (Trevino and Dossey, 2009b) that is now standardized as AASHTO TP 76-13: *Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method* and was used in the current study as well.

1.3 Study objectives

The primary objective of this project was to develop specifications for the design of roadway surfaces to meet specific noise requirements. These specifications include laboratory and field test procedures and limits to evaluate compliance. To achieve this goal, the following list of technical objectives are addressed:

1. Develop a fundamental understanding of what is required to design and construct a long-lasting, low-noise pavement surface.
2. Identify the mix design options available to ensure low noise generation, specifically for materials, pavements and conditions in Texas, towards identifying appropriate best practices.
3. Develop laboratory procedures to measure noise generated by surfacing materials.
4. Conduct validation studies to demonstrate that laboratory noise readings match values measured in the field. Monitor noise performance with both OBSI and wayside measurements.
5. Develop guidelines for District use on selecting candidate projects and for designing the appropriate surface to provide long-term noise reductions.

6. Document the roles and relative importance of roadway surface characteristics, roadway geometry, other structural features, and cross section to noise generation/propagation.

1.4 Scope of the study

This study investigated the noise properties of a variety of different asphaltic and concrete pavement surfaces. Results of noise testing on a range of different dense- and open-graded asphalt mixtures consistently indicated the noise reducing benefits of mixtures with low surface macrotexture and/or high porosity. This prompted the research team to focus testing on these types of asphalt surfaces in the field trials.

Furthermore, the noise on concrete pavements is predominantly influenced by the surface tining. The majority of CRCP in Texas is constructed using transverse tining that is generally noisier than CRCP with longitudinal tining. One experimental section of CRCP with longitudinal tining was located at the Texas Transportation Institute (TTI) Test Track and included in the study. The benefits of diamond grinding to reduce noise on CRCP is well reported and the results of noise testing of a diamond-ground section on IH35W near Fort Worth is included in the report as well.

1.5 Report outline

The report starts by documenting a literature review done to determine the state-of-the-art in designing quieter pavements and to identify contributing factors significantly influencing road noise.

A comprehensive pavement-noise database of noise records from tests on a large number and variety of pavement surfaces used in Texas was compiled and analyzed. Chapter 3 expands on the database and findings from the statistical evaluation of the noise data towards identifying all relevant surface and mixture design parameters influencing noise.

Chapter 4 of the report discusses the development of a laboratory test and associated design procedures for quieter surfaces. This chapter introduces a simple yet practical procedure that can be used for the laboratory design of quieter pavement surfaces that can also be used in the field. A product of this research is detailed laboratory test procedures for measuring noise generated by surface materials that is included in Appendix A of this report.

Field testing including OBSI, macrotexture and permeability measurements on a variety of asphalt and concrete surfaces is then addressed in Chapter 5, that includes evaluation of both new and existing asphalt and concrete pavements.

Chapter 6 documents a case study that outlines strategies for addressing noise complaints in an urban setting. It discusses the design and use of low noise pavement surfaces and other noise abatement options such as sound barriers to reduce road noise in a residential neighborhood along IH30 near Dallas.

Finally, conclusions and recommendations based on the study findings are documented. From these, a set of guidelines were developed to provide the Districts with recommendations to assist in selecting appropriate candidate projects for low-noise surfaces and for designing surfaces to provide long-term noise reductions. These guidelines are the final product of the research study and are included in Appendix B of the report.

Chapter 2. Literature review

2.1 Introduction

The disturbance caused by noise pollution is one of the most important environmental health consequences. Road traffic noise has been identified as the greatest noise pollutant in the industrialized world with the tire-pavement interaction being the major contributor at higher vehicle speeds. This is well documented and researchers such as van Keulen and Duškov (2005) discuss how road noise for both light and heavy vehicles becomes the dominant noise source for vehicles at highways speeds. Figure 2.1 shows how tire-pavement or rolling noise is dominant over propulsion (engine) noise for speeds of 35 and 50 km/h (20 and 30 mph) or higher for light vehicle (straight line) and heavy vehicles (dashed line), respectively. The contribution of propulsion noise in total traffic noise decreases with the speed while the share of pavement-tire noise continuously increases. At a speed of more than 80 km/h (50 mph) for light vehicles propulsion noise is negligible. However, in the case of heavy vehicles the contribution of propulsion noise cannot be neglected even at higher speeds.

Low-noise pavements are a cost-effective option to reduce traffic noise. Based on cost-benefit analysis it can be shown that a low noise asphalt pavement can reduce investments in noise abatement measures by up to 80 percent compared to noise barriers. While efforts are underway to produce quieter tires by randomizing tread patterns to avoid the creation of tonal components, for example, tire manufacturers are more concerned with the safety aspects of tires and pavement influences are generally not considered.

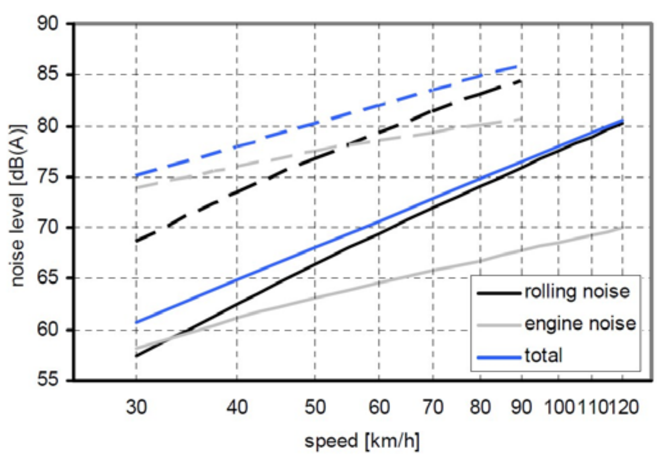


Figure 2.1: Vehicle engine and road noise with speed (van Keulen and Duškov, 2005)

The most influential set of parameters affecting pavement-tire noise apart from the influence of vehicle speed is that associated with the road surface. In particular, whilst tire design and vehicle operation affect the levels of noise generated, the design and construction of the road surface can affect both the generation and propagation of noise. The principal factors are the roughness or texture of the surface, the texture pattern and the degree of porosity of the surface structure. The mechanical impedance (stiffness) of the surface may also be relevant. It must be emphasized, however, that any measure taken to design quieter road surfaces must be weighed against the influence on safety, particularly skid resistance.

A vast amount of literature and information is available on tire-pavement noise studies, both locally and abroad. To narrow the scope of the literature review undertaken as part of the current study, the search was focused on specific literature related to material influences on tire-pavement noise. In this regard, emphasis was placed on gathering information on the impact of the three primary material-related factors influencing road noise, i.e., surface texture, porosity and stiffness. The literature review expands on the underlying tire-pavement interaction mechanisms causing noise and how these may be addressed in terms of texture, porosity and stiffness to reduce noise towards achieving the primary objective of this study, i.e., the development of design procedures for quieter pavements.

Noise is defined as unwanted sound. An overview of the literature on road noise indicates general agreement on the noise generating mechanisms, which are discussed below. Researchers consistently point out a peak in road noise frequency spectra in the region of 1 kHz. This is significant since although the human ear can detect frequencies from 20 Hz to 20 kHz, we are particularly sensitive to frequencies in the 1 kHz range. Figure 2.2 shows a map of equal loudness contours derived from experiments on the subjective ratings of loudness as expressed by humans. Results from attitude surveys have shown that the frequency response described by the 40 phon[1] contour shown in this figure is reasonably good at rating the subjective loudness of traffic noise and describes the A-weighting filter response used in sound level meters for assessing the environmental impact of road traffic noise. At a loudness level of 40 phons, it can be deduced that the 40-decibel noise at a frequency of 1 kHz is "equal" to a 50-decibel noise level at a frequency of 100 Hz. A-weighting of road noise levels as shown in Figure 2.3 is applied to emphasize the sensitivity of the human ear to frequencies in the 500 Hz to 6 kHz region and is expressed in units dbA. This figure shows other weighting sets of values—B, C, and D, which are not used to assess traffic noise but are used for other applications. For example, the D-weighting is applied to high-level aircraft noise to reflect the fact that humans hear random noise differently from pure tones, an effect that is particularly pronounced around 6 kHz. There is even an R-weighting which provides better estimation for rat hearing sensitivity.

Another interesting aspect defining noise is how the human brain distinguishes between pleasant and unpleasant sounds. This is very subjective but in general humans prefer sounds that have equal levels across the frequency spectrum, i.e., random white or pink noise, and are annoyed by sounds that are concentrated at a particular frequency—so-called *tonal noise*. Tonal road noise is generated, for example, by equally spaced transversely tined concrete pavements. By randomizing the spacing between the tines, the frequency range of the noise is extended thereby reducing the annoyance effect (Wayson, 1998). Tonal noise alerts the brain and peaks interest whereas random noise appears to fade and blend into the background. This phenomenon is known as "masking" where random sounds are more easily ignored, since our brains find no patterns in them.

[1] a unit of subjective loudness.

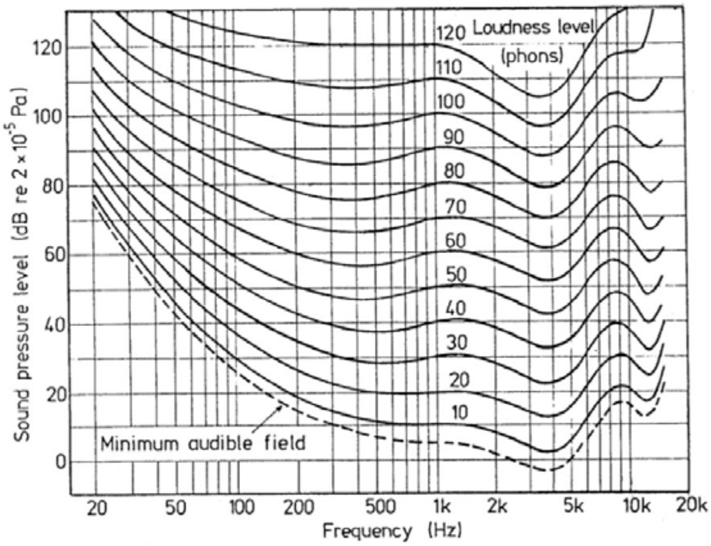


Figure 2.2: Equal loudness contours

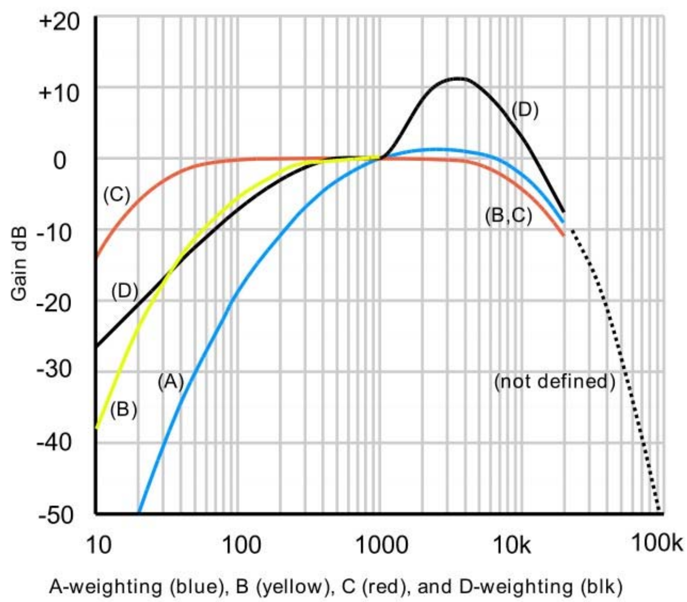


Figure 2.3: A-, B-, C- and D-weightings across the frequency range 10 Hz -20 kHz

2.2 Tire-pavement noise influences

This section discusses the primary mechanisms responsible for noise generation at the tire-pavement interface and other aspects of road noise to consider as part of the study.

2.2.1 Noise generating mechanisms

The Forum of European National Highway Research Laboratories, as part of their Sustainable Road Surfaces for Traffic Noise Control (SILVIA) initiative, provided guidelines (Morgan, 2006) outlining in detail the various tire-pavement mechanisms influencing road noise generation and amplification. These may be categorized into three distinct classes of mechanism in order of significance:

1. Impacts and shocks caused by the variation of the interaction forces between the tire tread and the road including the vibrational response of the tire carcass;
2. Aerodynamic processes between, and within, the tire tread and road surface;
3. Adhesion and micro-movement effects of tread rubber on the road surface.

Figure 2.4 shows how impacts and shocks with contact of the tire on the road surface at high speed result in excitation of the tire tread elements causing vibrational response of the tire carcass, which radiates sound. This is pronounced when the tire knocks surface irregularities at high speed. The figure also shows how air is compressed within the tread of the tire that will lead to air pumping as shown in Figure 2.5. Air pumping results as the compressed air trapped within the tire tread decompresses as the tire moves over the surface leading to resonance in the longitudinal tire grooves. In addition, frictional forces acting on the tire result in the "slip-stick" effect, where the tread blocks grip the surface. These deflected blocks will snap-out, causing tire vibration that coincides with the release of compressed air as shown in Figure 2.6. Noise generated through these mechanisms is amplified by the geometry of the tire and the road surface at both the leading and trailing edges of the tire due to the "horn-effect" as illustrated in Figure 2.7.
The horn effect is more pronounced for wider tires.

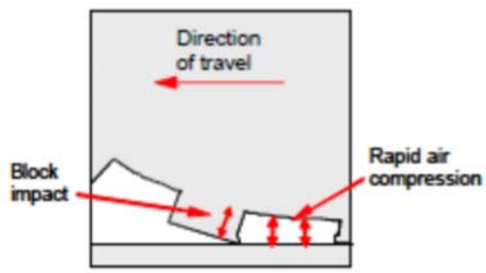


Figure 2.4: Impacts and shocks noise generating mechanism

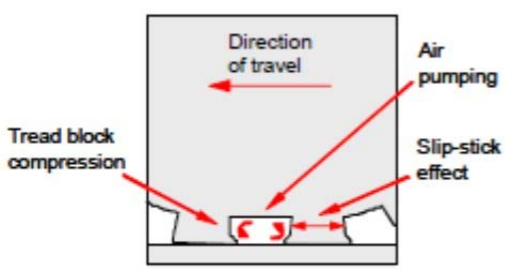


Figure 2.5: Air pumping noise generating mechanism

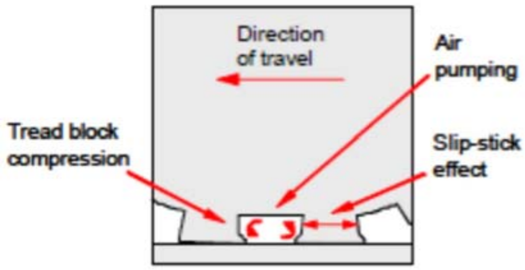


Figure 2.6: Slip-stick effect noise generating mechanism

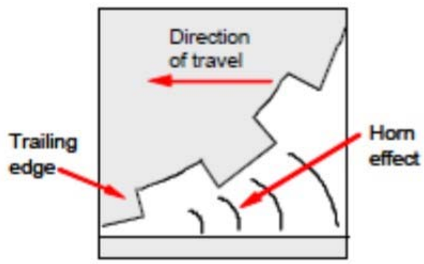


Figure 2.7: Horn-effect amplification mechanism

Noise that is generated by the tire as a result of vibrations caused by impacts and "snap out" effects tends to occur towards the lower end of the frequency range below about 1 kHz. In this frequency range it is known that the amplitude of the longer texture wavelengths in the road texture profile have an important role in controlling noise emissions. This is addressed in more detail in the following section. Differences in the structure of car and truck tires will lead to differences in the frequency response caused by vibration of these respective tires, which is typically lower for truck tires. Tire vibration is exacerbated by positive or aggressive surface macrotexture but will be impeded by surfaces which are more flexible or less stiff. In contrast, the air pumping mechanism is typically emphasized on non-porous and relatively smooth surfaces and leads to noise with frequencies typically in the range from 1 to 2 kHz. Surfaces with sufficient macrotexture will provide air-paths to dissipate air trapped in the tire tread grooves and prevent the occurrence of air pumping. Porous surfaces also serve to negate the "horn effect" amplification of sound. The challenge in designing quieter pavements is to consider these contrasting effects, i.e., proving sufficient surface macrotexture to reduce high frequency noise but not too much so as to raise the low frequency noise.

2.2.2 Fundamental noise aspects

There are a number of different aspects to consider when evaluating road noise such as layer thickness and distance of the receiver from the source since these may serve to attenuate noise levels. Smit (2008) reports that layer thickness appears to have a significant influence on noise levels, particularly for coarser open-graded mixtures and its influence on noise reduction should be considered when designing porous mixtures as low-noise alternatives. Hanson et al. (2004) provide an excellent overview on some fundamental aspects concerning road noise. Noise levels are measured on a logarithmic scale. Figure 2.8

illustrates the effects of adding two point source noise levels. If the sound level from one source of sound (a blender) measured at three feet from the blender is 85 dBA, then the sound level from two blenders would be 88 dBA and the sound level from three blenders would 89.8 dBA. Therefore, doubling the sound emissions would result in a 3 dBA increase in noise levels. For roadway surfaces this means that if the number of vehicles in the traffic flow is doubled, the sound level will increase by 3 dBA.

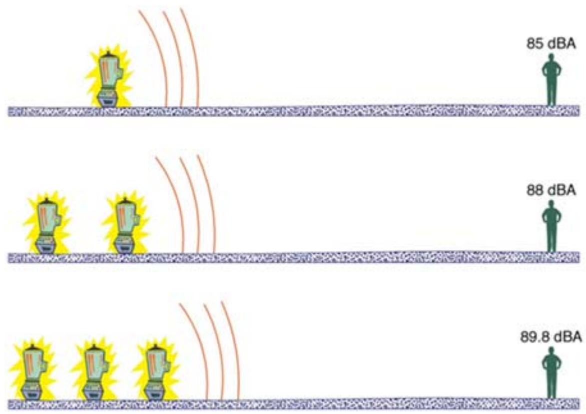


Figure 2.8: Effect of adding noise sources (Hanson et al., 2004)

An important mitigating factor with regard to noise is the distance between the source and the receiver. Sound levels decrease in accordance to the inverse-square law. This law is a fundamental law of acoustics, which states that the sound 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 dBA when the distance away from the source is doubled and is 9.5 dBA at three times the distance. Thus, again if you have a blender that has a sound level of 85 dBA at three feet, then when you move six feet away from the blender the noise level would be 79 dBA and if you move three times the distance (9 feet) away from the blender the noise level would be 75.5 dBA. This is illustrated in Figure 2.9.

Roadway noise acts differently than a simple point source and is classified as a line source since noise is transmitted along the entire length of the roadway. As a vehicle passes by a point, the noise is reaching 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 would result in a 3-dBA 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 dBA, then a point 32 feet from the edge of the roadway would have a noise level of 82 dBA. This is illustrated in Figure 2.10.

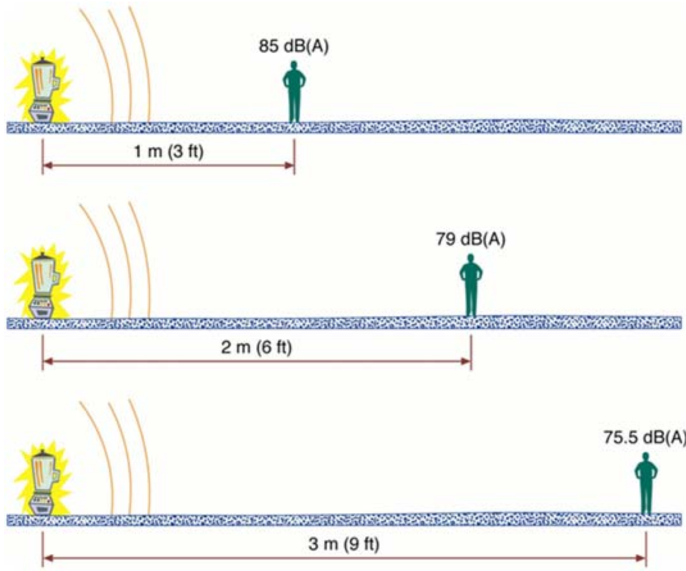


Figure 2.9: Effect of distance on a point noise source (Hanson et al., 2004)

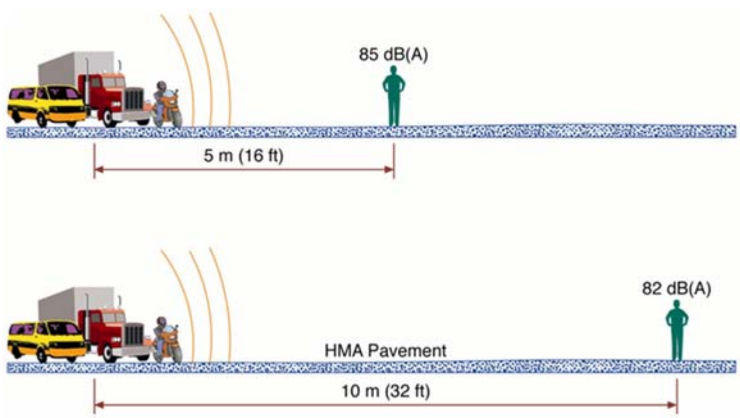


Figure 2.10: Effect of distance on a line noise source over a paved surface (Hanson et al., 2004)

The noise level near the road not only depends on the noise being generated by the traffic but also on the characteristics of the ground adjacent to the road. The TNM used by the FHWA (1980) to predict noise levels alongside the roadway uses the following equation to approximate the drop off:

$$P = 10 \cdot \log_{10}\left\{\left(\frac{d_1}{d_2}\right)^{1+\alpha}\right\} \tag{2.1}$$

where:

P = sound pressure level, dBA

α = attenuation coefficient:

= 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

Thus, if the noise level is 85 dBA at the edge of pavement which is at 16 feet (1/2 of a 12-foot lane plus a 10-foot shoulder) from the center of the noise source and the house is 200 feet from the roadway edge with soft ground between the roadway edge and the house this equation would predict that the noise level would be 68 dBA at the house. This is illustrated in Figure 2.11. In a rural situation, where the ground between the roadway edge and the receiver is soft and covered with vegetation the noise level would be further reduced due to absorption of the sound into the ground.

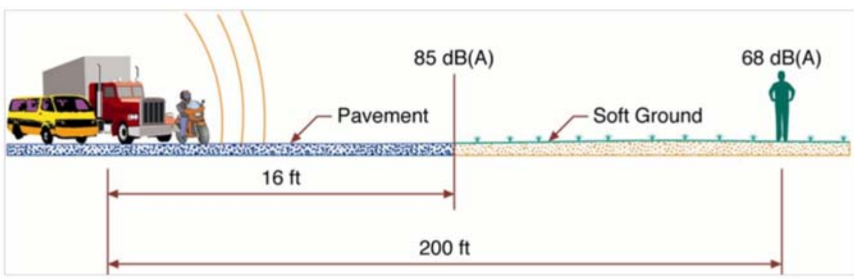


Figure 2.11: Effect of distance on a line noise source over soft ground (Hanson et al., 2004)

Vehicle effects on noise must also be considered, especially speed and tire type. Noise levels increase with vehicle speed and the effect is more pronounced for truck tires. The influence of vehicle tire on road noise is emphasized in the literature. Figure 2.12 shows, for example, differences in sound intensity measured on various open-graded mixtures at the National Center for Asphalt Technology (NCAT) test track using three different tires tested at the same speed. The tires referred to in this figure are the Goodyear Aquatread, the Uniroyal TigerPaw, and the standard reference test tire (SRTT). Given the significant influence of test tire, the SRTT tire (ASTM E1136) is routinely specified for road noise testing. Tires age and stiffen over time, which may negatively influence noise measurements, particularly if it is necessary to compare measurement levels over time.

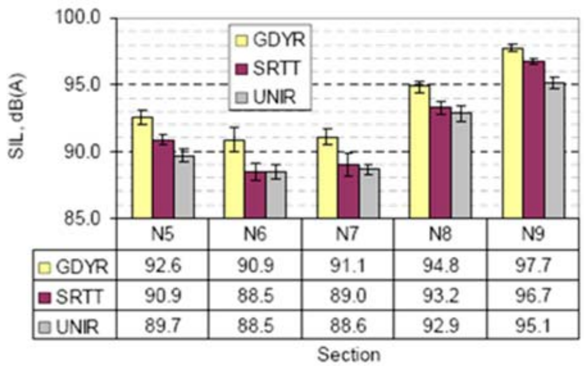


Figure 2.12: Effect of tire type on sound levels (Smit and Waller, 2007a)

The temperature influence on noise should also be considered. The rule of thumb typically applied is a decrease of 1 dB for every 10 ˚C increase in temperature. Smit and Waller (2007b) investigated the influence of temperature on close proximity noise measurements on a variety of different HMA surfaces at the NCAT test track with average air temperatures ranging from 50 to 85 ˚F. An analysis of the sound level data collected at varying temperatures indicated differences due to temperature that could be related to differences in sound levels with frequency. The temperature-frequency dependency of the sound levels differed for measurements above and below a selected reference temperature of 66 ˚F (19 ˚C). It was found that in general, for sound level measurements below the reference temperature, the sound levels were higher at lower frequencies and lower at higher frequencies than corresponding sound levels at the reference temperature. The opposite was true for sound level measurements taken at temperatures above the reference temperature, i.e., lower at lower frequencies and higher at higher frequencies. It was illustrated how these variations in sound pressure level (SPL) with frequency and temperature could be better defined by relating the sound levels in terms of wavelength calculated based on estimated sound wave speeds as influenced by test temperature. Overall, the influence of temperature on measured SPLs was found to be practically negligible. It is concluded therefore, that temperature correction of measured sound levels is generally not necessary when testing is done at temperatures ranging from 50 to 85 ˚F.

2.3 Surface macrotexture

Surface texture has a pronounced influence on tire-pavement noise and is generally considered the primary tire-pavement noise generator, particularly for dense-graded HMA and concrete pavements. The literature indicates that both the wavelength and amplitude of the surface profile affects noise generation and this appears to be different for light and heavy vehicles.

2.3.1 Overview of macrotexture influences

Fujikawa et al. (2006) showed that the effects of macrotexture on tire vibration are larger for truck tires than for passenger car tires because of the higher inflation pressure of truck tires. Their research indicated that measurements of sound pressure in a lateral tire groove showed that the resonance is decreased by a larger amplitude of macrotexture. They concluded that a small height unevenness and a short spacing of road asperities are important for reducing truck tire noise and that a large amplitude of macrotexture is also important for reducing noise from the wide lateral grooves of truck tires.

Smit (2008) evaluated the noise response of a variety of different HMA surfaces at the NCAT test track including dense-graded, stone matrix asphalt (SMA) and permeable friction course (PFC) mixtures with varying macrotexture. He reports an interesting noise response found when comparing sound intensity measurements of passenger and truck tires on surfaces with very low surface macrotexture. When truck tires were used, the pavements with very low surface macrotexture were relatively quieter than the other surfaces tested. This finding was contrary to the results when passenger vehicle tires were used. It is believed that this is as a result of the wider and deeper tire treads on the truck tires that would alleviate or reduce air pumping beneath these tires. This suggests an interaction between the macrotexture and air-pumping noise generating mechanisms. The findings of the NCAT study indicated that while too low a surface macrotexture led to increases in noise levels for passenger vehicle tires, a reduction in macrotexture did decrease the noise levels for the open-graded mixtures when comparing the sound levels measured on the finer PFC relative to coarser PFC.

The texture of road surfaces may be categorized in terms of wavelength. Surface macrotexture is defined in the wavelength band between 0.5 to 50 mm (0.02 to 2 in.) as shown in Figure 2.13. Tire-pavement noise is known to be influenced by both surface macrotexture and megatexture as shown in the figure although some researchers argue that even the microtexture of the surface influences the friction thereof, which in turn may contribute to the slip-stick effect at the tire-pavement interface as discussed previously.

This research focuses on the noise influence of surface macrotexture since this property may be manipulated as part of a) mixture design in the case of HMA and b) tining construction in the case of Portland cement concrete (PCC) pavements. The macrotexture of HMA will be influenced by the gradation of the mix and the degree of compaction applied. Dense-graded asphalt mixtures may present a positive texture, while SMA mixtures, for example, present negative textures. The macrotexture of PCC pavements will vary depending on the tining depth and pattern applied and may also present a positive or negative texture depending on the method applied, for example raking may result in a positive texture while burlap drag finishes may present negative textures. A positive macrotexture exhibits protrusions above the plane of the surface and a negative texture exhibits depressions. To quantify this asymmetry, one may apply an analysis of the statistical skewness of the surface profile. Figure 2.14 shows the clear difference between positive and negative surface texture in relation to a passenger car tire.

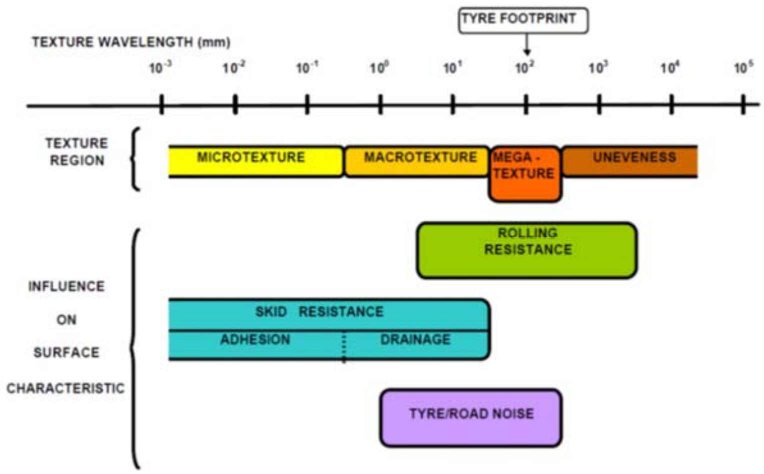


Figure 2.13: Influence of texture on surface characterization

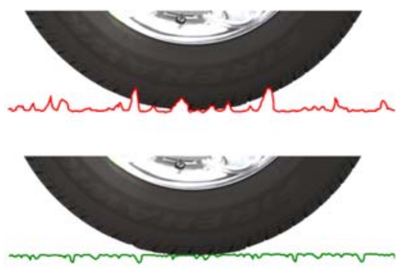


Figure 2.14: Positive (top) and negative (bottom) texture

Numerous research studies have attempted to establish relationships between surface macrotexture and noise generated at the tire-pavement interface. These relationships are based on various parameters used to quantify macrotexture. The surface macrotexture of a pavement may be measured using the volumetric sand-patch method (ASTM E965) or the circular texture meter (CTM, ASTM E2157), the latter being preferred for surfaces with high porosity such as PFC. The CTM uses a laser to measure the surface profile of a circle 284 mm (11 in.) in diameter. The profile is divided into eight segments of 111.5 mm (4.4 in.). The average mean profile depth (MPD) is determined for each of the segments of the circle and the reported MPD is the average of all eight segment depths. Macrotexture measured using the CTM is quantified in terms of MPD calculated based on ASTM E1845. Figure 2.15 shows the definition of mean segment depth, which is determined over a baseline length of 100 mm. MPD is the average value of the mean segment depths for all segments of the measured profile. MPD may be transformed to an estimated texture depth (ETD) using the equation below, which provides a good estimate for mean texture depth (MTD) measured using the sand patch method:

$$ETD = 0.2 + 0.8 \cdot MPD \qquad (2.2)$$

Hanson and Prowell (2004) compared various macrotexture measurements. They found an excellent correlation between sand patch and CTM measurements on dense-graded mixtures and report the following relationship based on CTM and sand patch testing at the NCAT test track:

$$\text{MTD} = 1.0094 \cdot \text{MPD} - 0.0056 \tag{2.3}$$

Research as part of NCHRP 441 (Stroup-Gardiner and Brown, 2000) produced the following prediction equation for ETD based on aggregate size and distribution. This model was reported to have an $R^2 = 0.65$:

$$\text{ETD} = 0.01980 \cdot \text{MAS} - 0.004984 \cdot \text{P4.75} + 0.1038 \cdot C_c + 0.004861 \cdot C_u \tag{2.4}$$

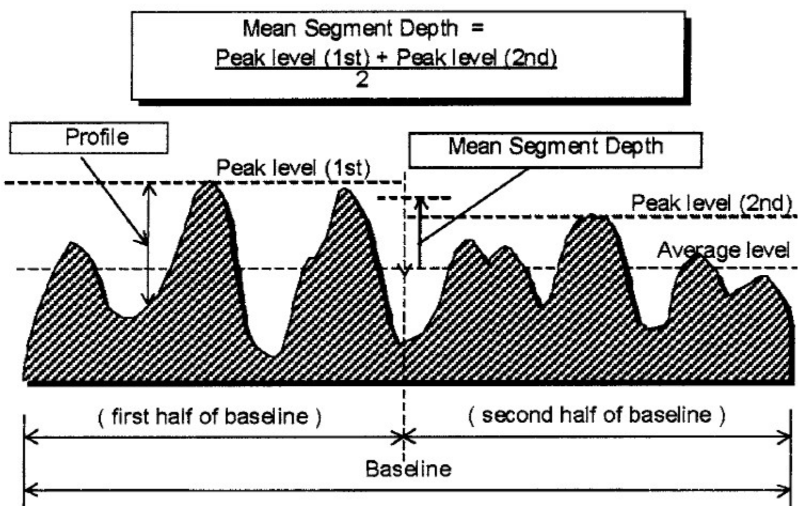


Figure 2.15: Computation of mean segment depth [after ASTM E1845]

where:

ETD = estimated MTD (mm),

MAS = maximum aggregate size of the mixture (mm),

P4.75 = percentage passing the 4.75 mm sieve,

C_c = coefficient of curvature = $(D_{30})^2/(D_{10} \cdot D_{60})$

C_u = coefficient of uniformity = D_{60}/D_{10}

D_{10} = the sieve size associated with 10 percent passing (mm),

D_{30} = the sieve size associated with 30 percent passing (mm),

D_{60} = the sieve size associated with 60 percent passing (mm).

In an attempt to relate mixture gradation to macrotexture, Hanson and Prowell (2004) established the following relationship between MTD and fineness modulus (FM) calculated by summing the cumulative percentages retained on the 0.15, 0.30, 0.60, 1.18, 2.36, 4.75, 9.5, 19.0, 37.5, 75, and 150 mm sieves and dividing by 100 (ASTM C125). This equation produced an $R^2 = 0.93$ with a root mean squared error of 0.136 mm.

$$\text{MTD} = 0.2421 \cdot \text{FM}^2 - 1.576 \cdot \text{FM} + 2.727 \tag{2.5}$$

While it is clear from the literature that macrotexture is related to tire/pavement noise, no strong correlation is evident suggesting other influence factors and interactions masking individual effects. Consider, for example, Figure 2.16 which compares noise measurements to macrotexture measurements taken on various HMA sections at the NCAT test track. In this case, the macrotexture (MPD) of the HMA surfaces was measured using the ultralight inertial profiler. While a slight increasing trend is evident in this figure, clearly no strong correlation was found.

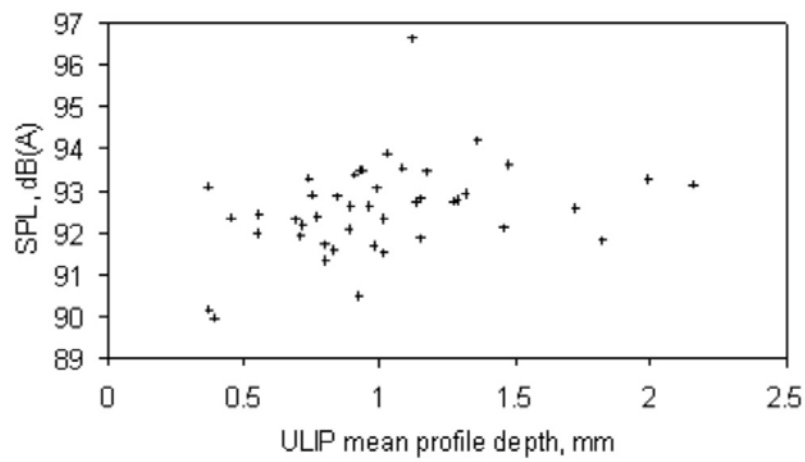


Figure 2.16: Relating road noise level to surface macrotexture

2.3.2 Surface texture profiles

To better assess the influence of macrotexture on tire-pavement noise, researchers have looked at various parameters of the surface profile. A popular approach in this regard is deriving parameters based on texture spectra. The concept of a texture spectrum is explained in ISO 13473-2. This is the spectrum obtained when a surface profile curve has been analyzed by filtering techniques to determine the magnitude of its spectral components at different wavelengths or spatial frequencies. Wavelength is a concept commonly used and accepted in signal-processing vocabularies. The profile can be considered as a stationary, random function of the distance along the surface. By means of a Fourier analysis, such a function can be mathematically represented as an infinite series of sinusoidal components of various frequencies, each having a given amplitude and initial phase. For typical and continuous surface profiles, a profile analyzed by its Fourier components contains a continuous distribution of wavelengths. Texture wavelength is the inverse of the spatial frequency, with unit 1/m or cycles/m. Figure 2.17 outlines a flow chart indicating the steps necessary to calculate the amplitude texture levels starting from a measured profile, such as that obtained from the CTM.

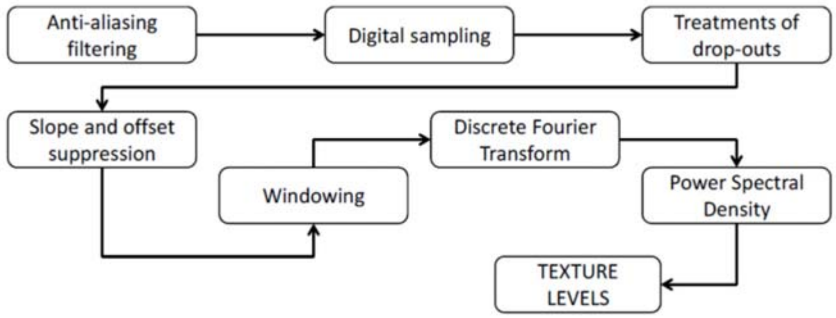


Figure 2.17: Calculation of texture spectrum

Sandberg and Descornet (1980) has shown that increasing texture amplitudes at wavelengths in the range 0.5 to 10 mm (0.02 to 0.4 in.) may reduce noise generation particularly at high frequencies generally above 1 kHz. Texture wavelengths in this range accord with dimensions associated with the small asperities in the surface which are thought to have an influence on the aerodynamic mechanism of tire-pavement generation, particularly air pumping. Increasing texture amplitudes at wavelengths in the range 0.5 to 10 mm (0.02 to 0.4 in.) reduces the air resonating in the grooves of the tread pattern of the tire and the surface of the road as the tire passes through the contact patch. The increase in texture allows the air trapped between the tire and the road surface to be released less suddenly and therefore generates less noise. In addition to this high frequency noise effect there is a low frequency component which behaves differently. Increasing texture amplitudes at wavelengths in the range 10 to 500 mm (0.4 to 20 in.) causes noise levels to increase, particularly at frequencies generally below 1 kHz. The tire mechanism affected by texture amplitudes in the 10 to 500 mm (0.4 to 20 in.) wavelength range is thought to be associated with tire tread impacts with the road surface. As the texture increases, the vibration levels set up in the tire carcass due to the tread impact increases causing higher levels of noise to be generated, particularly at frequencies below 1 kHz. Sandberg and Descornet (1980) defined two special measures derived from the texture spectrum to describe noise relevant characteristics of road surfaces. These are L4 and L63 as shown in Figure 2.18, the texture profile levels for the one-third octave band having center wavelengths of 4 and 63 mm (0.16 and 2.5 in.) respectively. They emphasize that, in general, quieter pavements are those with higher L4 levels and lower L63 levels.

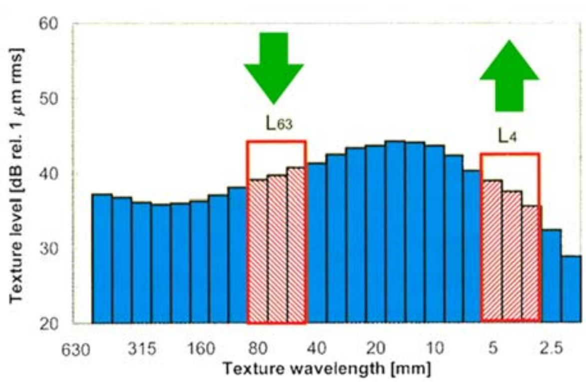


Figure 2.18: Texture spectra parameters

Sandberg (1992) correlated noise levels at each acoustic frequency against the road texture levels at each texture wavelength. The best correlation between noise and road texture was obtained for certain frequencies of the noise and certain spatial frequencies or wavelengths of the macrotexture. It was concluded that there are (at least) two major generation mechanisms which are uncorrelated with each other; one in the low-frequency range (below 1 kHz) with a positive correlation with road macrotexture and another in the high-frequency range (above 1 kHz) with a negative correlation with macrotexture. The low frequency mechanism is related to the tire radial vibration noise mechanism and the high frequency to the air resonant and adhesion mechanisms. Some researchers report very strong correlations between noise and texture spectrum amplitudes at specific wavelengths as shown in Figure 2.19.

Anfosso-Lédée and Do (2002) used an alternative approach to derive surface profile parameters related to tire-pavement noise. Their approach focused on asperities called "indenters," which are in contact with the tire. Profile indenters were defined as being composed of a profile peak and its two neighboring left-right valleys as shown in Figure 2.20. The indenter shape was defined locally as the cotangent of its summit semi-angle (α). In order to take into account the relative positions of the indenters, the indenter relief was defined locally as the angle (θ) between the segment connecting the summits of two consecutive indenters and the horizontal.

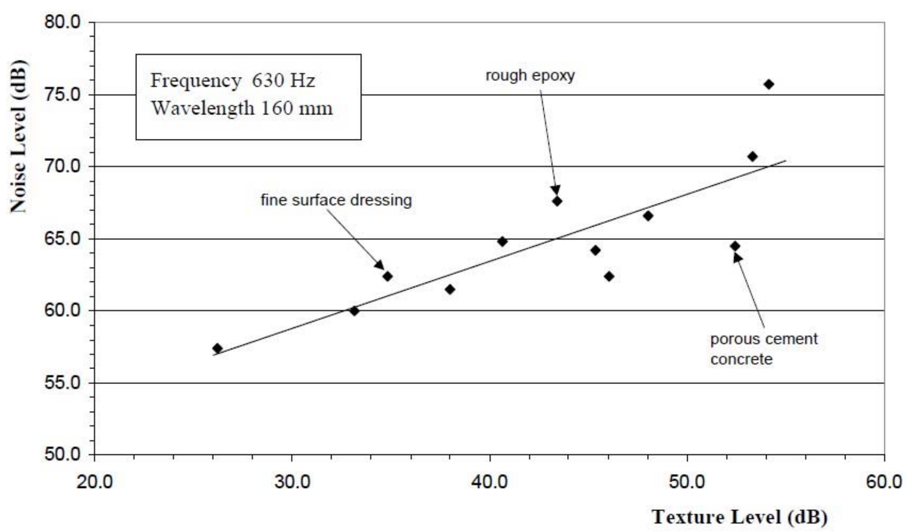


Figure 2.19: Correlation between noise and texture third band octave bands (Anfosso-Lédée and Do, 2002)

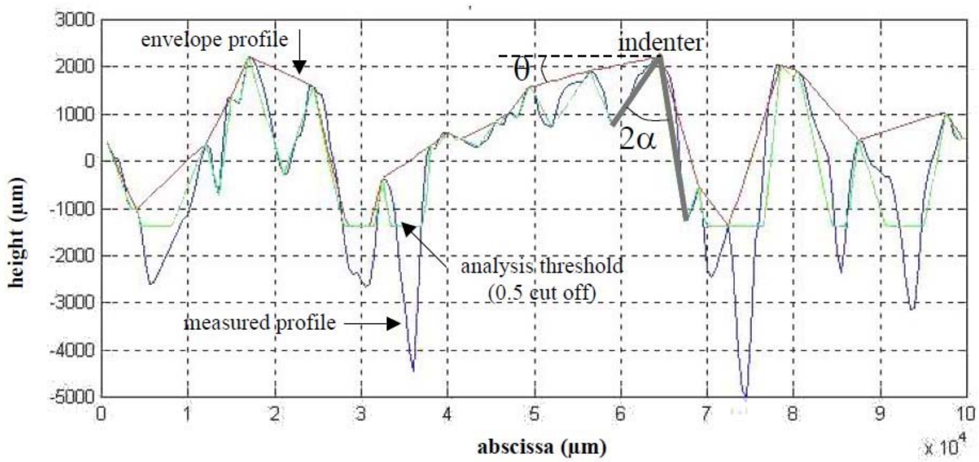


Figure 2.20: Definition of geometric parameters (Anfosso-L´ed´ee and Do, 2002)

Beside the angular parameters, Anfosso-Lédée and Do (2002) defined an indenter density as being the number of indenters per unit length. Peaks and valleys were defined as points respectively higher and lower than their neighboring left and right points. They report reasonable correlations between these parameters and noise measured on dense-graded mixtures but attenuation corrections were necessary to improve this correlation for porous mixtures. Equations for calculating the shape and relief were as follows:

$$\theta = \tan^{-1}\left|\frac{z_{p+1} - z_p}{x_{p+1} - x_p}\right| \tag{2.6}$$

where:

z_p = height of the pth peak,
x_p = abscissa of the pth peak.

$$\alpha = \frac{1}{2}\cdot\left[\tan^{-1}\left|\frac{x_e - x_{e-1}}{z_e - z_{e-1}}\right| + \tan^{-1}\left|\frac{x_{e+1} - x_e}{z_{e+1} - z_e}\right|\right] \tag{2.7}$$

where:

z_e = height of the eth extremum,
x_e = abscissa of the eth extremum.

An interesting application of surface texture spectra is the estimation of pass-by noise levels of a surface relative to a reference surface based on texture level variations. This method is described by Klein and Hamet (2005) and included in ISO 10844 standard. The estimated pass-by noise level (E) is given by the following relation:

$$\mathrm{E} = 10\cdot\log\frac{\sum_i 10^{\left(L_{m_i} + b_i \Delta L_{eT_i}\right)/10}}{\sum_i 10^{L_{m_i}/10}} \tag{2.8}$$

where:

L_{mi} = the third octave noise level of the reference surface,
ΔL_{eTi} = the third octave texture level difference,
b_i = the regression slope (see Table 2.1)

Table 2.1: The coefficients b_i

f (Hz)	b_i	f (Hz)	b_i
250	0.90	1,250	0.00
315	0.85	1,600	0.00
400	0.80	2,000	0.00
500	0.75	2,500	0.00
630	0.70	3,150	0.00
800	0.65	4,000	0.00
1,000	0.40		

This approach allows an estimation of the pass-by noise levels of any surface relative to a reference surface with known surface texture and on which noise has been measured. This approach has not been applied to close proximity measurements using the OBSI method, but given the excellent correlation between OBSI and pass-by noise measurements as discussed by Donavan and Lodico (2009) and shown in Figure 2.21, Equation 2.8 should be valid for OBSI measurements as well. This is emphasized since this approach allows a rapid assessment of the influence of changes in surface texture on road noise, an aspect that should be investigated further as part of the current study. A step-by-step guide of this procedure together with a practical example for application thereof is outlined in the ISO 10844 standard.

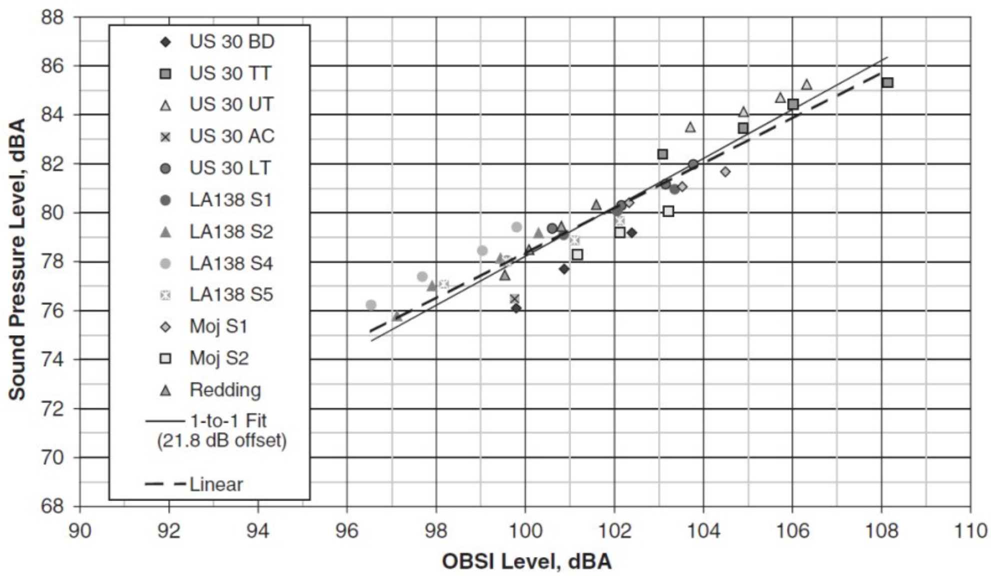


Figure 2.21: Light vehicle pass-by levels at 25 ft versus OBSI for SRTT (Donavan and Lodico, 2009)

2.3.3 Surface profile envelopes

A problem with applying texture profiles as outlined in the previous section is that the surface profile as measured does not provide an accurate outline of the actual tire contact profile. When a tire runs on a textured road surface, it does not necessarily make contact with all points on the surface in its wheel path. This is particularly the case for porous mixtures or mixtures with pronounced macrotexture, where the tires will bridge depressions or valleys in the profile. The tire is said to be “enveloping” the part of the surface with which it is in contact. To better addresses actual tire contact with the surface profile, various enveloping procedures have been developed. A popular enveloping procedure was developed and is reported by von Meier et al. (1992). Their procedure is empirically based on the idea of limiting the second order derivative of the surface profile to a given tire stiffness ($d^* = 0.054$ mm^{-1}) using an iterative procedure as defined by:

$$\frac{y_i - \frac{y_{i-1}+y_{i+1}}{2}}{dx^2} \le d^* \tag{2.9}$$

Figure 2.22 shows the influence of tire stiffness selected for enveloping, allowing varying degrees of penetration into the surface depressions. As can be seen in Figure 2.23, the influence of enveloping is very significant, providing a different texture spectrum from the original profile by suppressing amplitudes at the shorter texture wavelengths due to a “smoothening” effect.

Klein and Hamet (2004) report another profile enveloping procedure, which is based on a physical contact model that was originally developed by Clapp (1984). Their procedure is used by the European SILVIA project and comprises complex mathematics to calculate the tire pressure distribution along the profile contact zone. It is uncertain whether the results from the complex model are better than those from the empirical model since no evidence has been reported. It is clear, however, that profile enveloping will allow a better correlation of texture and noise spectra and allow for a more realistic evaluation of the profiles of porous pavements.

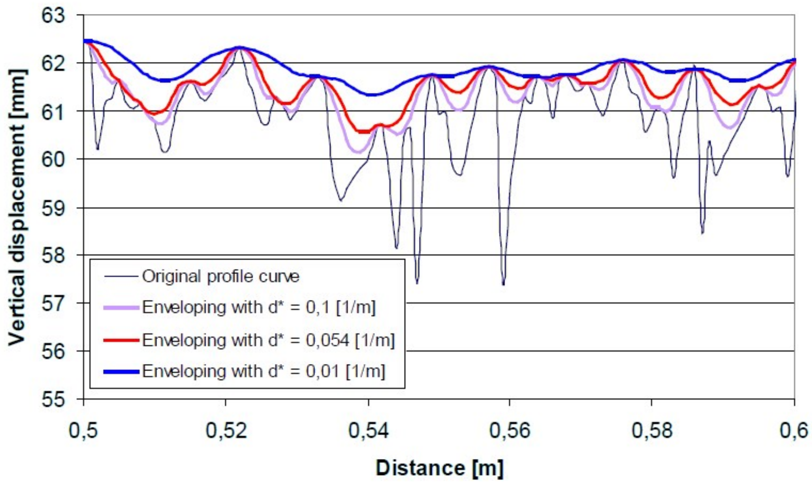


Figure 2.22: Profile envelopes with varying stiffness (Sandberg et al., 2011)

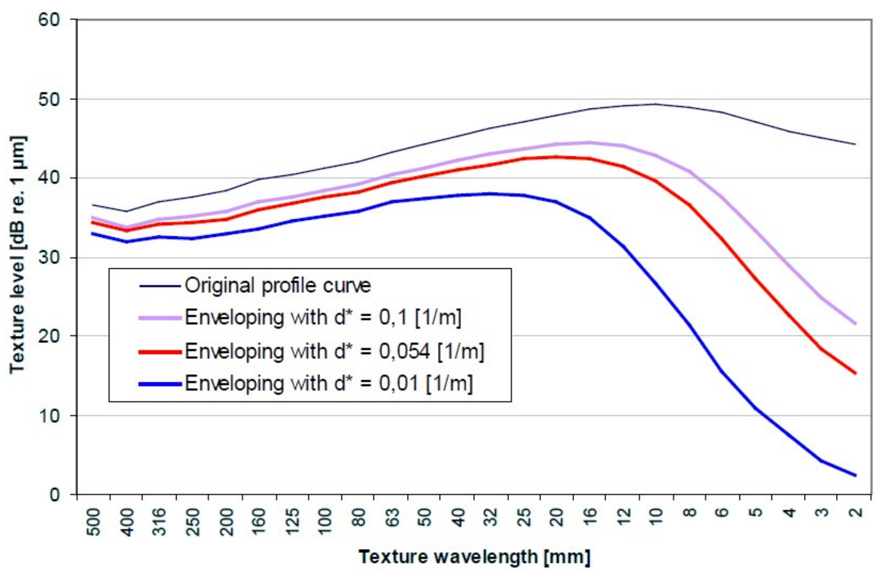


Figure 2.23: Third octave band texture spectra (Sandberg et al., 2011)

2.4 Surface porosity

Porous surfaces serve to reduce road noise by propagation and sound absorption. The porosity of the surface is a measure of the voids in the surface mix that are open to the air. All asphalt mixtures contain air voids but these are not necessarily interconnected and the structure cannot necessarily be defined as open unless the volume of voids in the mix exceed about 18 percent. As outlined previously, increasing the porosity of the surface reduces the compression and expansion of air trapped in the tire treads, reducing the noise generated by aerodynamic mechanisms. Porosity is also important in sound absorption and increasing the porosity generally increases the acoustic absorption and, by consequence, reduces the horn effect.

The literature indicates that the porosity of the surface interacts with other mechanisms to reduce noise:

- Thickness of the porous layer which influences where the maximum absorption occurs in the frequency spectrum. Increasing layer thickness lowers the fundamental frequency of maximum absorption together with its harmonics;
- Air flow resistance is important in governing the air flow in the pores of the surface. A high air flow resistance is favorable to sound energy dissipation, but a too high air flow resistance prevents the acoustic waves to penetrate into the layer. The optimum range of the air flow resistance depends on the thickness of the layer. It can be shown that the shape of the absorption curve in the frequency domain depends on the total air flow resistance of the layer, i.e., on the product of the specific air flow resistance of the porous medium by the thickness of the layer (Hamet et al., 1990);
- Tortuosity is a measure of the curved or meandering nature of the air path through the surface layer. In practice the air path through the layer will be dependent upon the shape of the interconnecting voids. The more tortuous the air path, the lower the fundamental frequency of maximum absorption. The fundamental frequency is therefore governed by both the tortuosity and the layer thickness (Hamet and Berengier, 1993).

Results from a number of different sources when combined, indicate that the noise reduction of porous surfaces is statistically highly correlated with the product of residual air voids and layer depth (Wd). As the product Wd increases the noise also increases in a roughly linear fashion. The relationship appears to hold for values of Wd <30 mm (1.2 in.), when W is expressed as a fraction. By taking into account the size of the aggregate, improvements in the correlation are obtained, i.e., surface with similar Wd but with smaller aggregates provide greater noise reductions. For values of Wd above about 30 mm (1.2 in.) there was found to be no significant increase in noise reduction (Sandberg and Ejsmont, 2002).

Porous surfaces provide three major properties of importance to vehicle noise reduction:

1. Surface porosity will eliminate the compression and expansion of air entrapped at the tire-pavement interface when tires are rolling over the surface. Air pumping and air resonant tire noise will then be reduced.
2. Surface porosity will also reduce the amplifying effect of the acoustical horn existing in the space between the curved tire tread and the plane road surface.
3. Finally, the porosity will give the surface an acoustical absorption, which will influence the reflection and propagation of the noise. This will influence not only tire-pavement noise but also other types of vehicle noise.

It is emphasized that to be able to dampen the noise successfully, the voids in a porous surface need to be interconnected (Sandberg and Ejsmont, 2002). Brown and Heitzman (2013) point out that for finer open-graded mixtures (4.75 mm) there are many small air voids but these do not tend to be interconnected as is the case for coarser mixes. Finer porous mixtures also reportedly clog more rapidly than coarser mixes. This may be due to the self-cleansing nature of coarser surfaces, such as the suction action produced by high speed vehicles and sufficient drainage paths that facilitate the removal of dirt and debris from coarser surfaces. von Meier et al. (1990) indicate that porous surfaces designed for noise, which provide optimal flow resistance as well as short wavelength texture, are often in conflict with surfaces designed for good drainage. The smaller aggregates used in low noise mixtures provide poorer drainage and carry the risk of clogging over time. They propose, therefore, the use of double layer porous surfaces comprising a coarser porous mix that ensure adequate drainage beneath a finer porous surface that provides low macrotexture. They outline a design procedure based on the following equations:

$$\alpha = 1 - \left| \frac{W - \rho \cdot c}{W + \rho \cdot c} \right|^2 \tag{2.10}$$

$$W = -j \cdot \frac{\rho \cdot c}{\sigma} \sqrt{\left(1 - j \cdot \frac{\Xi \cdot \sigma}{\omega \cdot \rho \cdot c}\right) \cdot \chi} \cdot \cot\left[d \cdot \frac{\omega}{c} \sqrt{\left(1 - j \cdot \frac{\Xi \cdot \sigma}{\omega \cdot \rho \cdot \chi}\right) \cdot \chi}\right] \tag{2.11}$$

where:

σ = porosity

ρ = density of air

Ξ = specific flow resistance of the porous material d = thickness of the layer
χ = configuration (structure) factor of the porous material ω = wavelength = $2 \cdot \pi \cdot f$

Using these equations, the specification for the design of a noise optimized porous road surface can be derived. This leads to the following basic requirements:

- choose the layer thickness d and the configuration factor Ξ so that the first maximum of α occurs at a frequency f of 1 kHz.
- choose the porosity σ as high as possible.
- choose the flow resistance χ to be within its optimum range.

This can be realized in the following way:

- the layer thickness to be chosen is dependent on the configuration factor of the material which typically ranges from 3 to 7. The corresponding layer thickness then varies from about 32 to 50 mm (1.25 to 2 in.) if the absorption maximum is to be placed at 1 kHz. The value of Ξ can be determined from absorption measurements on cores using an impedance tube,

- the porosity can be maximized by using a gap-graded mixture,
- the optimal flow resistance is a function of aggregate diameter k and porosity, approximated by the following equation:

$$\chi = \frac{10^{-2}}{1.7 \cdot k^2 \cdot \sigma^2 \cdot d} \mathrm{Nsm}^{-4} \quad (2.12)$$

This leads to the requirement that for layers of about 40 mm (1.6 in.) thickness the aggregate size should preferably be below about 10 mm (0.4 in.). von Meier and Heerkens (1986) indicate that with regards mixture gradation, it can be said that the finer the aggregates in the mixture, the greater the flow resistance. An aggregate consisting of irregular stones with sharp angles has a high structure factor. Taking account of this, the appropriate frequency for the first absorption maximum can be obtained with a thinner surface course.

An aspect to consider in this approach is the report shift apparent between peaks in maximum absorption and noise reduction curves as illustrated in Figure 2.24 as reported by (Peeters et al., 2010) and others (Mingliang, 2013). As shown, for a 50 mm (2 in.) thick layer, generally the sound absorption under normal incidence at a frequency of 0.8 kHz is found at a higher frequency of 1 kHz in the attenuation curve of the propagation measurements. In this regard, sound absorption is more effective in the frequency range between 0.8 and 1.6 kHz, where the horn effect is significant.

The design approach discussed above was also applied by Masondo et al. (2002) for the design of double layer porous layers. They discuss the design of 7 different double layer structures with variations in layer thickness and porosity. Masondo et al. (2002) provide information including gradations of these double layer porous asphalt mixtures as used in the Netherlands. The top layer is constructed to a thickness of 25 mm (1 in.) and the bottom to a thickness of 45 mm (2 in.). The mixtures reported comprise SBS modified and asphalt rubber binders. They indicate that the use of bitumen rubber as a binder will offer a higher absorption coefficient as opposed to conventional binder. The mechanical impedance of these mixtures also has an influence on the amplitude (loudness) in the production of tire-pavement noise. The mechanical impedance (or relative stiffness) of bitumen rubber generates a relatively lower noise as opposed to conventional densely graded asphalt. This is discussed in more detail in the following section.

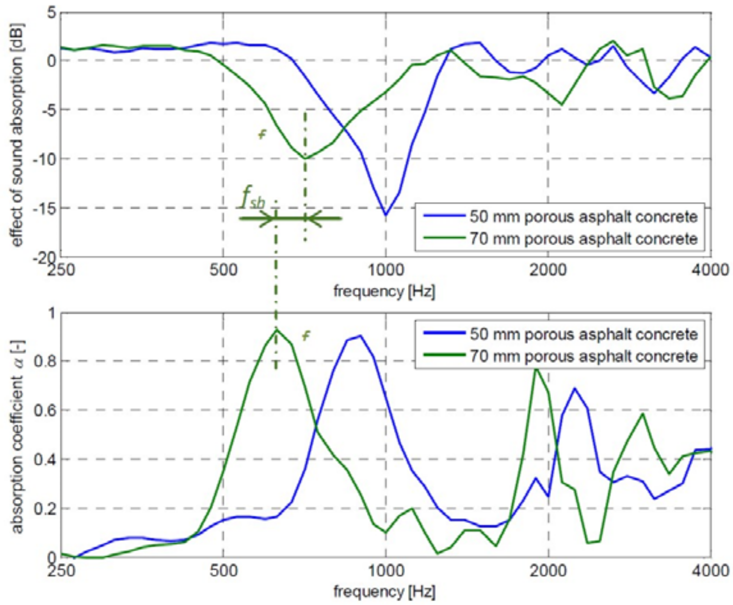


Figure 2.24: Sound absorption effect on noise reduction (Peeters et al., 2010)

2.5 Surface stiffness

The property of the pavement surface referred to as the stiffness or mechanical impedance of the surface has also been associated with noise generation relating to tire impact mechanisms. Generally the mechanical impedance of the road surfaces is several orders of magnitude higher than that of the rubber in the tire tread. Lowering the road mechanical impedance will tend to reduce the tread block impact forces transmitted into a tire which in turn will reduce tire vibration levels and hence noise generation. There are mixed reviews on the potential benefits of reducing the mechanical impedance of pavement surfaces, particularly with regards conventional dense- or open-graded surface layers.

Mingliang (2013) indicate that based on mechanical impedance tests on various HMA surfaces, cores from road sections have comparable mechanical impedance independent on the type of asphalt mixtures used. When comparing two materials, the difference in mechanical impedance of materials is only significant when they have a great difference in stiffness. A relationship between the mechanical impedance and stiffness was developed. It was shown that the mechanical impedance is linearly related to the logarithm of the resilient modulus. From the relationship, it is learned that an effective way to reduce the mechanical impedance is by using low stiffness materials, such as poro-elastic materials. They conclude that it will *not* be possible to produce low mechanical impedance layers using standard asphalt concrete mixtures. Kocak (2011) investigated the relationship between basic HMA material characteristics including volumetric and viscoelastic properties including dynamic modulus and phase angle of various HMA mixes. They found that the individual material characteristics do not have an appreciable influence on sound absorption but interaction of these characteristics provide better correlations with tire-pavement noise. Biligiri and Kaloush (2007) hypothesized that materials with more viscous behavior would provide a greater noise dampening effect, leading to less tire-pavement surface noise. Based on the noise data analysis of about 200 HMA mixtures, about 50 of which included open- and gap-graded mixtures with asphalt rubber binder, they conclude that viscosity phase angle is a potential pavement noise discriminating parameter.

Unconventional surfaces or so called “euphonic” pavements are specifically designed for low noise. These surfaces consist of a thin wearing course of porous asphalt laid on a continuously reinforced concrete slab that includes Helmholtz resonators each of about 500 cm^3. The resonators set in the subbase will absorb acoustic energy at their resonant frequencies. Two examples of third generation low noise road surfaces are reported in the literature. The Japanese Public Works Research Institute developed a new type of low-noise pavement named “Porous Elastic Road Surface” (PERS). It has a porous structure composed of granular rubber made from recycled tires as aggregate and polyurethane resin as binder. The porosity of the surface is approximately 40 percent. The thickness thereof is 30 to 40 mm. PERS can either be produced on site or prefabricated as a carpet which is glued with epoxy resin onto the underlying sub layer. PERS generally shows high noise reductions, typically 10 up to 12 dBA compared to conventional HMA surfaces. However, problems arise in terms of insufficient binding to the underlying sublayer, damage by snow ploughs and low skid resistance. Roll-Pave is another new generation surface developed in the Netherlands. The layer is made by mixing polyurethane resin, rubber and quartz. The air voids content is around 30 percent. It is prefabricated in the factory and the slab has a length of 50–60 m with a width of 3.5 m. The thickness is 30 mm. For transportation, each pave is rolled onto a drum which is transported to the site. During construction, the rubber surface is unrolled. A special type of glue is sprayed between the Roll-Pave and the underlying asphalt layer surface. Then a roller is used to flatten the mat and glue the Roll-Pave onto the underlying surface. The noise reduction of this surface is in the order of 8 dBA compared to conventional HMA surfaces. These surfaces are cost prohibitive and more experimental in nature than for practical applications.

2.6 Concrete pavements

Texture depth, orientation and acoustic absorption are key pavement surface characteristics that influence tire-pavement noise. However, in regards to concrete pavements, the quest for quietness has focused on the use of alternative methods of finishing the concrete using textures that produce less tire noise. The texture of PCC pavement surfaces directly influences friction and noise, as well as safety characteristics.

Pavement surface texture consists of the deviation of the pavement surface from a true planar surface, with a wavelength less than 0.5 m (19.7 in.) (Sandberg and Ejsmont, 2002). A hypothetical true flat surface would not be safe, as it would not provide any traction for the tires of the vehicles. Depending on the scale of such deviations, the texture can be classified into three categories: microtexture, macrotexture, and megatexture. Microtexture is defined as the deviation of a road surface from a true planar surface with the characteristic dimensions along the surface of less than 0.5 mm, corresponding to texture wavelengths with one-third octave bands with up to 0.5 mm of center wavelengths. Similarly, macrotexture is the deviation of a road surface from a true planar surface with characteristic dimensions of 0.5 to 50 mm (0.02 to 2 in.), corresponding to texture wavelengths with one-third octave bands in the range of 0.63 to 50 mm (0.025 to 2 in.) of center wavelengths. Megatexture is the deviation of a road surface from a true planar surface with characteristic dimensions of 50 to 500 mm (2 to 20 in.), corresponding to texture wavelengths with one-third octave bands in the range of 63 to 500 mm (2.5 to 20 in.) of center wavelengths (Sandberg and Ejsmont, 2002).

Microtexture is regarded as a function of the aggregate properties of the concrete pavement, while macrotexture is defined by the method of finishing and texturing (e.g., carpet dragging, tining, grooving, etc.), and by the depth, width, spacing, and direction of such texturing procedure. Megatexture is largely defined by the distresses and defects on the pavement in question (Hall et al., 2009).

Traditionally, in Texas, as well as in many other states, PCC pavements are finished with transverse tining, a technique that is effective in reducing hydroplaning under wet conditions, but that also results in high noise levels, especially near the 1 kHz frequency at highway speeds due to the spacing between tines (about 1 in.), which gives these pavements a characteristic "whine." Tining generally is performed to enhance pavement-surface frictional properties and reduce potential for hydroplaning, skidding, and wet-weather crashes.

The concept of tining PCC pavements originated in San Antonio during the late 1950s (Hilgers and McCullough, 1963). The depressed section of IH 35 through downtown, constructed with limestone fines, had worn under traffic, eventually developing a surface resembling polished glass. Because of this wear, an excessive accident rate was being experienced each time rainfall occurred. A large percentage of the accidents were from cars fishtailing out of control. The condition was so severe and predictable that television stations would frequently send crews to film the accidents whenever rain was forecast.

As a corrective action, longitudinal grooves were cut using spaced concrete saw blades; a 100 percent coverage from the Concut bump cutter employed would have resulted in a rough texture and unnecessary expense. As a cost compromise, the end result was a series of longitudinal grooves spaced at approximately 0.5 inch intervals. Transverse grooves were desired but the cost would have been excessive. Ironically, only a small increase in skid number was attained; however, the underlying but unsuspected mechanism, hydroplaning, was entirely eliminated, greatly reducing the accident rate.

An article published by Hilgers and McCullough (1963), along with promotional activities undertaken by the Concut Company, resulted in the technique being adopted as a "corrective action" across the United States and in other countries. The aforementioned article showed positive results in terms of stopping distance before and after sawing, for a subsection selected for testing from the IH35 section in question, measuring the stopping distance from an initial speed of 30 mph and measuring friction coefficients. For wet conditions, the stopping distance was reduced from 94 ft. before sawing to 72 ft after sawing. Under dry conditions, stopping distances were approximately the same before and after sawing. Before sawing, the coefficient of friction ranged from 0.7 for the dry pavement to 0.32 for the wet pavement. After sawing, the coefficient ranged from 0.7 on the dry pavement to 0.42 on the wet pavement. A coefficient of 0.4 is deemed as a minimum allowable for safe driving conditions.

In the 1970s, the American Concrete Paving Association, with FHWA support, developed a recommendation to tine surfaces (instead of grooving) to prevent hydroplaning. This practice soon found its way into all state DOT specifications. But Texas had introduced grooving as a remedy for fine aggregates susceptible to polishing existing pavements; unfortunately, the Texas "preventive step" of eliminating limestone fines was lost in the move toward tining. As of this date, very little quantitative data has been collected comparing the effect of tining to broom or carpet drag on pavements constructed with silica-based fines.

Tining, in spite of being the most commonly utilized texturing finishing, has the drawback of originating noise with the vehicular tires. The FHWA, concerned with the tire-pavement noise generation on some PCC pavements, created a Technical Working Group in 1993 to investigate the problem by conducting a review of previous research and by evaluating the results of ongoing research in the United States. The objective of this technical group was to make recommendations on PCC pavement surface texturing that could reduce the noise frequencies without compromising safety. The group produced a comprehensive report (Hibbs and Larson, 1996).

The group performed a thorough literature review on the issue, taking into account past research, ongoing investigations, experiences of state agencies, and international efforts on the issue. It was determined that PCC surfaces constructed for speeds under 50 mph (80 km/h) need only a good microtexture for wet-weather stopping. For speeds of 50 mph (80 km/hr) or greater, a macrotexture is also needed to reduce water film thickness to and prevent hydroplaning. The exposed-aggregate-surfaced PCC pavements and the open-graded asphalt friction course pavements combine for the quietest and safest rides where premium textures are desired.

The researchers reported the following regarding the tining issue and tire/pavement noise, based on studies from Colorado, Michigan, Minnesota, North Dakota, and Wisconsin:

- Uniformly spaced transverse tines, particularly those spaced over 1 in. (25 mm), produce the most irritating tire/pavement noise.
- Using transverse and longitudinal tining together (cross-hatching) produces consistently higher total noise based on Wisconsin's study results and on Virginia's experience.
- Colorado's variable transversely tined texture was the loudest, but it also had the greatest average texture depth. However, Wisconsin found a transversely tined section whose tines had greater randomized spacing that reduced objectionable noise output significantly when compared to the state standard transversely tined texture. The specified randomness of the spacing and the construction quality are initial factors in determining the generated noise characteristics and, ultimately, the resulting level of annoyance to the human ear. The document concludes that while transversely tined PCC pavements with a hard fine aggregate provide excellent skid resistance through a combination of microtexture and macrotexture, the transverse tined surfaces are also the ones that present the most annoying tire-pavement effect.
- The friction properties will generally be present for the life of the pavement (up to 30 years). But friction can also be reduced if the surface is tined too deep or the tines are too closely spaced, causing spalling of the surface under traffic.
- On the tire-pavement noise issue, research has determined that the spacing and width of the tined texture will determine the extent of noise. Tines spaced too far apart 1 in. (25 mm) or greater may cause an annoying whine inside the vehicle that may carry up to 2 to 3 miles outside the vehicle to nearby properties. Tines

uniformly spaced too close together 0.5 in. (13 mm) and closer may result in excessive wear and poor durability of the pavement surface. Random spacing of the tines reduces the probability of objectionable tonal noises. The depth of tining should be between 0.12 to 0.24 in. (3 to 6 mm). Greater depth often causes tearing of the aggregate particles from the pavement surface, which results in more surface roughness (poorer ride) and higher noise levels. Tining, besides any acoustical considerations, may be detrimental to the long-term performance of the pavement, because tining operations delay curing, causing additional water losses from the pavement surface during its early-age.

Research project 7-3925 (McCullough et al., 1998), developed for TxDOT by CTR, found that the effect of evaporation on the early age of concrete (especially during the first 72 hours after placement) plays a fundamental role on the crack development and on the spalling mechanism. When high evaporation occurs at the time the concrete sets, the evaporation occurring from placement to the time the tining operation is performed could increase the risk of strength loss on the concrete surface, creating cracking and spalling, and thus reducing the life of the pavement.

A similar subsequent CTR study confirmed the research findings of a negative impact of tining on long-term pavement performance owing to its effect on the curing operation (Rochefort et al., 2000). The additional time required for tining results in evaporation of surface moisture and in the creation of uneven surfaces, which the curing compound does not completely cover, increasing the evaporation during the early age of the pavement. However, the study also compared the cost of different surface treatments aimed to increase skid resistance, finding that tining was the most economical option. As the practice of tining PCCP has become common across the country, several states have conducted research on this issue to quantitatively determine the benefits of tining versus alternative techniques and to investigate the various detrimental effects that each operation can have on pavement performance, e.g., ride quality, noise, and other issues such as accident incidence. Other studies that constitute valuable background information for this project deal with accidents occurrence as a result of slick pavements and the development of techniques to evaluate surface friction. Some of these studies are summarized in the following paragraphs.

However, there are other alternatives for texturing concrete pavements that are able to provide good wet-weather performance, as well as provide some environmental benefits. An early alternative to transverse tining was the longitudinal tining specified by California starting in 1978 (Neal et al., 1978). This study analyzed several texturing procedures, which were tried on ongoing projects. The methods were aggregate broadcast on pavement surface; transverse texture using a steel-ribbed grooving plate, a nylon bristle broom, and several steel tine devices with various spacings and tine lengths; and longitudinal texture with steel tines. As a result of the tests, longitudinal texturing with steel tines was adopted as a standard procedure at the time.

Other options are random transverse tining, which may reduce or eliminate the whine associated with uniform transverse tining; and the skewed transverse tine that was shown to eliminate whine and reduce overall noise (Kuemmel et al., 2000). A related study sponsored by the Wisconsin Department of Transportation (WisDOT) measured and analyzed the noise and texture parameters of 57 test sites in Colorado, Iowa, Michigan, Minnesota, North Dakota, and Wisconsin (Jaeckel et al., 2000); it was found that both uniform and random transverse tining produce higher noise levels than skewed or longitudinally tined PCC pavements. Also, the study showed that test sections with the greatest tining width and texture depth were among the noisiest, reinforcing the hypothesis that as width and texture depth increase, so does the generated noise.

Research efforts sponsored by the concrete industry have resulted in the development of diamond grinding as a rehabilitation method for existing pavements. Diamond grinding originated in the early 1950s, when a California engineer introduced a machine that improved concrete pavement ride by grinding away localized high spots. The machine consisted of a large number of diamond saw blades mounted closely together on a single rotating shaft (Snyder, 2006). This machine, called the "Bump Cutter," was first used in 1965 on an existing concrete pavement on the San Bernardino Freeway, east of Los Angeles. Its success led to the widespread acceptance of diamond grinding as a concrete surface rehabilitation technique in the 1970s. Today, the technique is recognized not only as a feasible rehabilitation option for deteriorated concrete pavements, capable of improving profile and ride quality and restoring surface friction, but as a treatment for the reduction of tire/pavement noise. The procedure removes a thin layer of the hardened concrete pavement surface (between 0.1 and 0.8 in.), with a typical production of 50 to 60 saw grooves per foot width of pavement. In the U.S., typical diamond grinding costs range between $2 and $5 per square yard. (Snyder, 2006). Grinding effectively reduces the impulses generated at pavement joints, including both the "tire slap" noise that is radiated externally by the tire and the interior noise that is carried through the vehicle structure. It provides an irregular surface texture that reduces the generation and propagation of other sources of tire/pavement contact noise.

Diamond-ground surfaces in the WisDOT study showed no predominant frequency that may cause any objectionable whine.

The diamond grinding technique has produced the quietest concrete pavements measured in Texas [(Trevino and Dossey, 2009a) and (Buddhavarapu et al., 2013)].

A recent study conducted for TxDOT (Project 5-9046) demonstrated significant reductions in noise levels and other benefits in terms of improved friction, riding quality, and cost savings apparent when using diamond grinding on concrete pavements (Buddhavarapu et al., 2013). The primary objective of this rehabilitation was to improve the friction characteristics of the old pavement. Various PCC sections, aged 20 to 40 years old, on a stretch of about 9 miles on IH 35W outside of Fort Worth, were subjected to these treatments. The original texturing of the sections, prior to the diamond grinding, consisted of carpet drag, burlap drag, and transverse tining. Noise measurements were conducted by means of the OBSI method, before and after the diamond grinding took place.

The grinding operation reduced the average overall noise level by 3.2 dBA, which represents a considerable reduction. The noise reduction achieved by diamond grinding is comparable to, and even greater than that of a PFC overlay on a dense-graded asphalt pavement. The maximum noise reduction of 5.6 dB was achieved at the 1.6 kHz frequency band irrespective of any pre-existing condition. The study team noticed a maximum reduction in the region of frequencies spanning 1 to 2.5 kHz.

Another recent study (Rasmussen et al., 2004), using roadside measurements, concluded that longitudinally ground pavements were 2 to 5 dBA quieter than transversely tined pavements.

Taking diamond grinding a step further, the concrete industry has recently experimented with next-generation concrete surface (NGCS) in other states. This new texturing technique has delivered the quietest texture yet developed for non-porous concrete pavements. The texture can be applied on newly constructed pavements as well as existing pavements. It uses conventional diamond grinding equipment and blades but in a different head configuration. At the time of construction, the NGCS is typically 99 dBA in noise level and has a range up to 101 dBA over time. Although the NGCS has only been in service 3 years, it is under evaluation at 17 locations in 10 states (Scofield, 2012).

Other concrete texturing methods that have delivered reductions in noise levels over transverse tining are carpet drag, grooving, and longitudinal tining. Grooving has certain advantages over tining, especially with respect to controlling the depth of the grooves, flexibility in the time to perform the operation, and an increase in drainage. Also, by eliminating the delay in the application of curing compound, the pavement is subjected to less moisture loss, leading to increased strength and long-term performance.

Other innovative and recent methods include longitudinal grooving, exposed aggregate concrete (EAC), porous PCC, and shot-abraded PCC (Hall et al., 2009).

EAC pavements are commonly used in European countries, but the technique has not been routinely used in the United States. The exposed aggregate surface is commonly constructed by applying a set-retarding agent to the newly placed concrete pavement. After a period of time has passed (typically 24 hours), the surface mortar is then brushed and/or washed away from the top of the pavement, exposing a surface of durable aggregates. When designed and constructed correctly, EAC pavements have been reported to reduce noise, improve friction, and provide durability equal to that of conventional concrete pavements (Sandberg and Ejsmont, 2002).

EAC pavements can have friction qualities close or equivalent to transversely tined pavements. This surface texture is more durable than most other PCC types when exposed to studded tire wear. According to European experience, the surface will have a lower initial friction quality, which will steadily increase as the sand grit and mortar are worn away by traffic, thereby exposing the larger (4 to 8 mm) aggregate and increasing the average surface texture depth. European contractors had a learning curve experience when constructing this surface, with the initial surface friction quality growing after each project. This surface generally has a lower total noise level than other currently used PCC textures and is not known to have resulted in either a higher pitched tire whining or a lower frequency rumble (Hibbs and Larson, 1996).

A European demonstration project built an exposed aggregate experimental section on IH 75 in Detroit, Michigan (Smiley, 1995), which had similar total noise and frequency characteristics as the adjacent standard transversely tined section, but initially had lower skid resistance. It is likely that the use of 0 to 4 mm rather than 0 to 1 mm size sand particles contributed to the lower friction resistance. These deficiencies could be easily corrected in future projects.

Porous concrete is a material that is designed to have a large void content, similar to the PFC concept. The void content for the porous PCC is in the range of 15 to 20 percent by volume of concrete (Sandberg and Ejsmont, 2002). The void structure is typically created by using a gap-graded concrete mix with a sand-to-total-aggregate ratio of only 5 to 10 percent, as opposed to 40 percent in typical concrete mixes (Snyder, 2006). The resulting surface's permeability allows water and air to flow through the material, which in turn helps to absorb noise energy. Also, the porous surface results in a decreased tire/pavement contact area, which reduces the noise generation through the slip-stick and slap mechanisms. Generated sound is partially absorbed by the porous surface, which also reduces the "horn effect" by which tire/pavement noise is amplified and directed. Porous concrete is mainly used as a surface for low-volume facilities such as parking lots, but it can also be used as a quieter pavement through both single-layer and overlays over a conventional PCC pavement. Strength and durability of these surfaces are accomplished by means of the underlying conventional dense concrete layer, or by the increased thickness of the single-layer system [(Sandberg and Ejsmont, 2002) and (Rasmussen et al., 2004)]. The preferred usage for porous PCC as a quieter pavement has been through the use of thin bonded porous concrete overlays (Rasmussen et al., 2004). According to a study developed by Purdue University (Olek et al., 2003), decreasing aggregate size improves the sound absorption characteristics of porous PCC.

The National Concrete Pavement Technology Center (NCPTC, 2006) provide the following summary of various concrete pavement texture options:

- **Artificial turf drag:** Produced by dragging an inverted section of artificial turf from a device that allows control of the time and rate of texturing, usually a construction bridge that spans the pavement; typically produces 1/16 to 1/8 in. deep striations. Artificial turf drag textures have been shown to provide sufficient friction characteristics for many roadways, as well as reduced noise relative to many transversely tined pavements. Minnesota has used this type of texturing as a cost-effective method to reduce tire-pavement noise on high-speed roadways.
- **Burlap drag:** Produced by dragging moistened coarse burlap from a device that allows control of the time and rate of texturing, usually a construction bridge that spans the pavement; typically produces 1/16 to 1/8 in. deep striations. Burlap drag textures have been shown to provide sufficient friction characteristics for many roadways, especially those with speeds less than 45 mph, as well as reduced noise relative to many transversely tined pavements. Germany has used this type of texture on its high-speed Autobahn system.
- **Transverse tining:** Achieved by a mechanical device equipped with a tining head that moves across the width of the paving surface laterally or on a skew. It is important to maintain a consistent concrete mixture and move the paving train forward constantly at a uniform rate of speed for consistent tining depth. Most agencies precede with an artificial turf or burlap drag texture. For tined pavements, texture depth and groove width are important parameters in tire-pavement noise generation. Pavements with uniformly spaced transverse tining generally, but not always, exhibit undesirable "wheel whine" noise.
- **Longitudinal tining:** Achieved by a mechanical device equipped with a tining head (metal rake) pulled in a line parallel to the pavement centerline. It is important to maintain a consistent concrete mixture and move the paving train forward constantly at a uniform rate of speed for consistent tining depth. Most agencies precede with an artificial turf or burlap drag texture. Tined texture depth and groove width are important parameters in tire-pavement noise generation. Longitudinal tining is more often quieter than transverse tining. Narrower tine

spacings might be used to reduce vehicle tracking and possibly reduce noise even further. Lateral stability of narrow-tired vehicles may also benefit from this.

- **Diamond grinding:** Longitudinal, corduroy-like texture made by equipment using diamond saw blades gang-mounted on a cutting head. The cutting head generally produces 50–60 grooves/ft and can remove 1/8 to 3/4 in. from the pavement surface. Although diamond grinding has traditionally been used to restore pavement smoothness, this method has also been shown to reduce tire-pavement noise and improve friction in the short term. Diamond-ground pavements do not affect vehicle tracking as much as widely spaced longitudinally tined pavements.
- **EAC pavement:** European practice includes applying a set retarder to the new concrete pavement and then brushing or washing away mortar to expose durable aggregates. Other techniques involve the uniform application of aggregates to the fresh concrete. EAC pavement surfaces are regarded as an effective method for reducing tire-pavement noise while providing adequate friction. Smaller aggregate sizes have been reported to provide larger noise reductions, while aggregates with a high polished stone value increase durability. Only one large-scale EAC pavement has been built in the United States.
- **Pervious concrete pavement:** When used in highway applications, pervious concrete is typically used as a top layer (wearing course), providing both low noise emission and good drainage capacity. The pervious concrete typically overlays a conventional (dense) concrete pavement using a "wet-on-wet" process. Sound absorption levels for pervious concrete pavements have been shown to increase with higher porosity levels. Quieter pervious concrete also results from smaller aggregate sizes. Use of pervious concrete pavements for high-volume, high-speed facilities is still in its infancy and will likely require years of experimentation before the requisite confidence can be gained in this application. Regular maintenance and cleaning may be needed to prevent clogged pores and to preserve the pavement's acoustical performance. Research on durability is ongoing in wet, hard-freeze areas.

2.7 Wayside measurements

Wayside noise measurements, also known as roadside measurements, are SPL measurements normally conducted by setting a sound meter mounted on a tripod on the side of the road. The SPL meter is illustrated in Figure 2.25. These measurements capture all the noise from all sources: tire-pavement noise, aerodynamic noise, propulsion and engine noise, exhaust noise, reflections, and even other sources of noise not related to the vehicle. Figure 2.26 shows a meter on a tripod during a wayside test.

While close-proximity test methods (such as OBSI) are able to provide noise measurements at the source (tire-pavement interface), they cannot provide an indication of the influence of roadway features such as geometry, other structural features, and cross section on noise generation and propagation. In some cases, roadway features may increase road noise levels through reflection and propagation, while in other cases embankments and slopes may serve to absorb and attenuate noise levels. Far-field measurements provide this technique of investigating roadway features and also allow time-dependent noise mapping in urban areas. Wayside measurements are the most basic (and still the most accurate and common) method of measuring traffic noise. All other methods used to measure road noise are simply more convenient, faster ways to approximate the wayside noise via correlation.

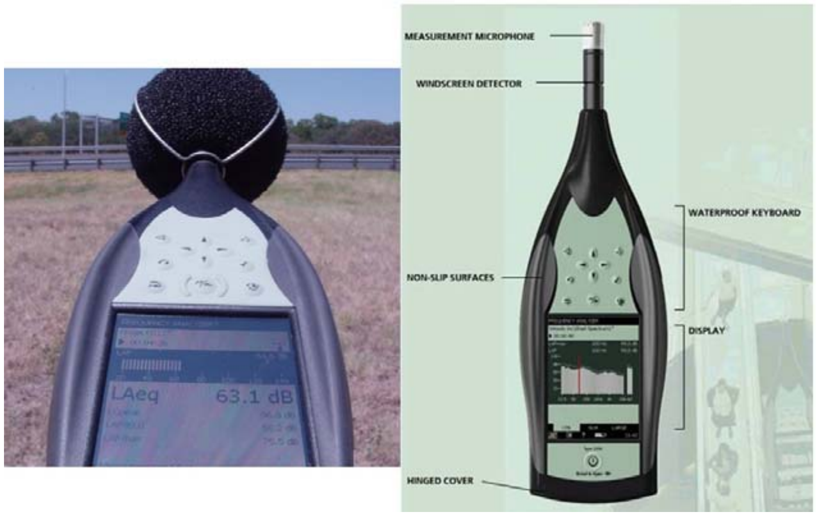


Figure 2.25: Sound pressure level meter

Figure 2.26: SPL meter on a tripod during wayside test

Wayside measurements can be categorized into two main types: pass-by methods and time-averaged methods. There are a few variations among the pass-by methods. Statistical pass-by involves measuring the maximum noise levels at the roadside from a statistical significant number of vehicles. Controlled pass-by makes use of a single test vehicle while no other vehicles are on the road. Sometimes the conditions for a pass-by test are too difficult to satisfy, in which case the most preferred way of performing roadside tests is time-averaged: a sound pressure meter measures the noise level over a specified time period, and the average noise level over that time period is the result of the test. The time-averaged value of the SPL during the test interval, i.e., the “equivalent continuous sound level” (L_{eq}) is used. L_{eq} is defined as the equivalent steady-state sound level that, in a given time period, contains the same acoustic energy as a time-varying sound level during the same period (Figure 2.27). L_{eq} is used for all traffic noise analyses for TxDOT highway projects. Normally, the measurements take place over 15 minute periods, or until the readings stabilize.

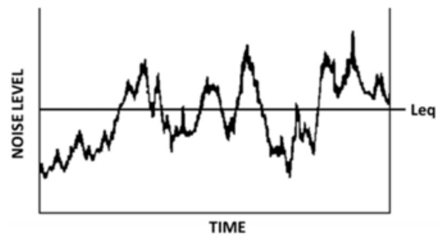


Figure 2.27: L_{eq}: average noise level over a period of time

2.7.1 Pass-by methods

The Statistical Pass-by Method (SPB), ISO 11819-1: *Measurement of the Influence of Road Surfaces on Traffic Noise*, is a measurement procedure designed to evaluate vehicle and traffic noise generated on different sections of road surface under specific traffic conditions. The maximum A-weighted SPLs of a statistically significant number of individual vehicle pass-bys are measured at a specified roadside location together with the vehicle speeds. The measurements are taken from a great number of vehicles operating normally on the road. Results obtained using this procedure are normalized to standard speeds according to the category or type of road being considered.

As specified by the SPB standard, the SPL meter is mounted on a tripod located at 7.5 m (25 ft) from the center of the travel lane, with the measurement microphone elevated 1.2 meters (4 ft) above the plane of the roadway. The standard establishes that measurements are not possible during windy conditions or when the roadway is wet. The standard classifies each vehicle into one of three vehicle categories: passenger cars, dual-axle heavy vehicles, and multi-axle heavy vehicles. A minimum number of vehicles is specified for each category.

Each individual pass-by is recorded along with its corresponding vehicle speed, and a regression line of the maximum A-weighted SPL versus the logarithm of speed is calculated for each vehicle category. From this line, the average maximum A-weighted SPL is determined at the reference speed. This level is called the Vehicle Sound Level. A single index, called the Statistical Pass-by Index, is calculated by adding on a power basis the vehicle sound levels for each vehicle category, assuming certain proportions of these vehicle categories. Among its disadvantages, the method is not suitable for determining actual traffic noise levels. Another disadvantage is that measurements shall only be taken on individual pass-bys that are clearly distinguished from other traffic on the road, and this can be a considerable difficulty on busy roads. Achieving the specified number of vehicles can be considered as another important drawback of the method.

An alternative method, an FHWA procedure developed by the Volpe Transportation Systems Center (Lee and Fleming, 1996) calls for the placement of a microphone or microphones 15 m (50 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 arbitrary and is often a function of budgetary limitations. However, 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.

Another alternative method that overcomes the SPB method's disadvantage of not being suitable of determining actual traffic noise levels is the Statistical Isolated Pass-By Method (SIP) based on AASHTO TP 98-11: *Determining the Influence of Road Surfaces on Vehicle Noise Using the Statistical Isolated Pass-By Method (SIP)*. This test method is a procedure for measuring the influence of road surfaces on highway traffic noise. The test provides a quantitative measure of the SPL at locations adjacent to a roadway. The SIP method allows for the comparison of vehicle noise on roadways of varying surfaces and across studies by comparing measured sound levels to a reference noise curve. Measurements capture the SPL from isolated vehicles in existing traffic. The SIP method is to be applied on roadways where measuring sound levels from single vehicle pass-by events is possible without contamination from sound from other vehicles.

Each measured vehicle is classified into one of five categories: automobiles, medium trucks, heavy trucks, buses, and motorcycles. At a minimum, the automobile and heavy truck categories should be evaluated in order to determine the influence of each roadway surface; the other categories are optional.

Each individual pass-by level, together with its vehicle speed, is recorded, and a linear regression of the maximum A-weighted SPL versus the logarithm of the speed is calculated for each vehicle category. From this regression line, the maximum A-weighted SPL and regression uncertainty are determined at the designated speed. The measured sound level is called the Measured Vehicle Sound Level, L_{veh}. For each roadway surface or pavement type, the L_{veh} is calculated for each vehicle category. The L_{veh} value is compared to the Reference Vehicle Sound Level, $L_{veh,ref}$, using the Reference Surface. The difference between the two regression lines at the designated speed is calculated and reported as the Statistical Isolated Pass-by Index. The Reference Surface is defined as the average pavement type from the FHWA TNM (FHWA, 2004) measured in the Reference Energy Mean Emission Level (REMEL) study (FHWA, 1995). All results shall be compared to the Reference Noise Curve based on the average pavement, a dense-graded asphaltic concrete (DGAC), and PCC combined, found in the TNM vehicle noise emission level database (FHWA, 1995).

The controlled pass-by (CPB) method 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. The vehicle approaches the site at a specified speed in a specified gear. There are no national standards for this type of testing (Hanson and Prowell, 2004). An example of the CPB method is the aforementioned study conducted by Marquette University for WisDOT (Kuemmel et al., 2000). In this study, a 1996 Ford Taurus was operated at 60, 65, and 70 mph in the right lane to perform the tests. The testing was conducted by placing two microphones 5 feet above the pavement and positioned at 25 ft from the center of the traffic lane. The microphones were placed 200 feet apart. Three runs were made to collect enough data for each speed. Another way to conduct the testing is also described in Kuemmel et al., 2000: the testing is conducted on an accelerating vehicle or vehicles; 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.

2.7.2 Time-averaged methods

Among the time-averaged methods, the Continuous Flow Traffic Time Integrated Method (CTIM) based on AASHTO TP 99-12: *Standard Method of Test for Determining the Influence of Road Surfaces on Traffic Noise Using the Continuous Flow Traffic Time Integrated Method (CTIM)* is a procedure for measuring the influence of road surfaces on highway traffic noise at a specific site. CTIM is to be applied on roadways where measuring single vehicle pass-by events would be difficult due to continuously flowing, relatively dense traffic. The CTIM provides a quantitative measure of the SPL at locations adjacent to a roadway. Measurements capture the sound from existing traffic for all vehicles on all roadway lanes. Measurements also include propagation effects over the roadway pavement and adjacent terrain to the nearby measurement location. Measurements should be conducted for continuous and freely flowing traffic at a constant speed.

A-weighted time-integrated SPLs, traffic volumes, speeds, vehicle categories, and meteorological data are measured continuously on the side of a roadway for a period of time that captures enough data to properly represent the site.

The preferred measurement location is 50 ft (15 m) from the center of the near travel lane, 12 ft (3.7 m) above the center of the near travel lane, and at least 5 ft (1.5 m) above the elevation of the ground surface. A microphone is set to record all of the traffic noise over a fixed time (commonly 15 minutes) and traffic levels and speeds are simultaneously recorded. An average equivalent sound level over this period is calculated, and is reported as an average of repeated measurements. Traffic volume counts are performed in conjunction with the noise measurements with the use of traffic counters, video cameras, and post-processing systems and procedures. The average vehicle speed for each lane of travel can be determined by means of a radar gun and the video camera. CTIM tests allow for the comparison of data sets collected on different pavements, as the measured sound levels can be normalized for differences due to variations in traffic using the FHWA's TNM (FHWA, 2004).

Therefore, an important application of roadside measurements is to provide measured data for comparison with predicted roadside noise levels using the TNM software.

2.8 Traffic Noise Model program

The TNM program is a fundamental tool in determining noise levels for highway projects. The use of the TNM program (FHWA, 2004) is required on federally funded projects to determine whether a noise barrier is required. TNM can predict the noise level at any location near a roadway, provided very detailed inputs are available, including vehicle counts, roadway geometry, type of surfaces, and vehicle speeds.

TNM computes highway traffic noise at nearby receivers and aids in the design of highway noise barriers. As sources of noise, it includes 1994–1995 noise emission levels (FHWA, 1995) for the following cruise-throttle vehicle types: automobiles, medium trucks, heavy trucks, buses, and motorcycles.

Noise emission levels consist of A-weighted sound levels, one-third octave-band spectra, and subsource-height strengths for the following pavement types:

1. DGAC
2. PCC
3. Open-graded asphaltic concrete
4. A composite pavement type consisting of data for DGAC and PCC combined

In addition, TNM includes full-throttle noise emission levels for vehicles on upgrades and vehicles accelerating away from the following traffic-control devices:

1. Stop signs
2. Toll booths
3. Traffic signals
4. On-ramp start points

TNM combines these full-throttle noise emission levels with its internal speed computations to account for the full effect (noise emissions plus speed) of roadway grades and traffic-control devices. TNM evaluates sound energy propagation, in one-third-octave bands, between highway systems and nearby receivers. Sound propagation takes the following factors into account:

1. Atmospheric absorption
2. Divergence
3. Intervening ground: its acoustical characteristics and its topography
4. Intervening barriers: walls, berms and their combination
5. Intervening rows of buildings
6. Intervening areas of heavy vegetation

The program computes three measures of highway traffic noise:

1. L_{Aeq1h}: hourly A-weighted equivalent sound level
2. L_{dn}: day-night average sound level
3. L_{den}: community noise equivalent level, where "den" stands for day/evening/night

TNM computes these three noise measures at user-defined receiver locations, where it also computes several diagnostics to aid in noise-barrier design. In addition, it computes three types of contours:

1. Sound-level contours
2. Noise reduction, i.e., insertion-loss and contours for noise barriers
3. Level-difference contours between any two noise-barrier designs.

The TNM program predicts noise levels for any receiver locations. Figure 2.2. provides an example of TNM output.

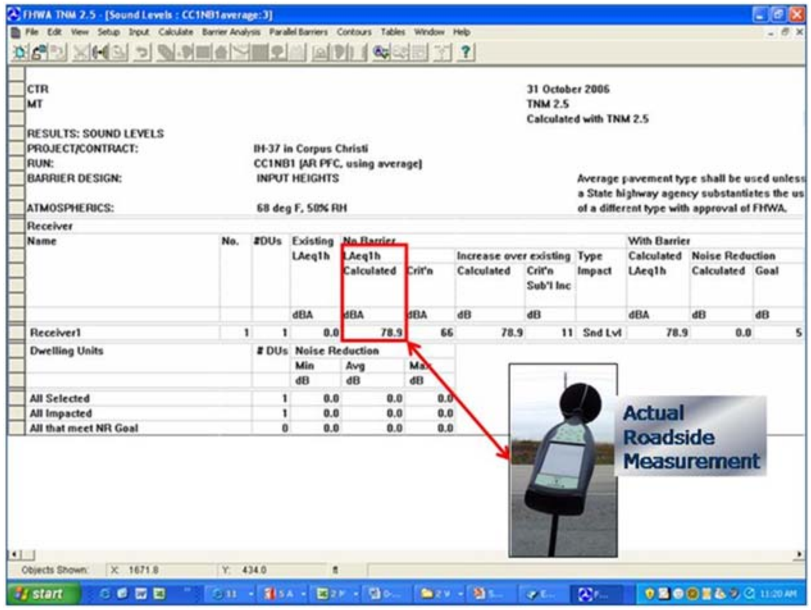


Figure 2.28: Comparison of actual roadside versus predicted noise levels using TNM

2.9 Summary

This chapter discusses various aspects to consider for the design of quieter pavement surfaces and addresses the noise effects of surface macrotexture, porosity and mechanical impedance. It is emphasized that surface texture wavelengths that fall within the megatexture range (50–500 mm) are important for both controlling noise performance and providing sufficient skidding resistance. A balanced ratio between surface macrotexture and microtexture is necessary to achieve low noise surfaces. It is possible to specify the influence:

- At wavelengths ranging between 10 mm and 500 mm (0.4 and 20 in.), the rolling noise increases notably as the amplitude in this range increases. The main noise mechanism is related to tire tread impacts. This tends to give rise to noise at frequencies below 1 kHz. For this reason, the megatexture must have the lowest possible roughness over this range.
- At wavelengths ranging between roughly 0.5 mm and 10 mm (0.02 and 0.4 in.), the rolling noise decreases with the amplitude, particularly at frequencies >1 kHz. In this case the texture provides improved "ventilation" of the tire profile, which helps to reduce the generation of aerodynamic noise. Average texture depths of 0.4 mm to 0.8 mm (0.016 to 0.03 in.) have proven favorable for noise reduction of car tires and at least 1.0 mm (0.04 in.) for heavy vehicle tires. The sound absorption properties of porous pavements can be tuned to the typical spectrum of the traffic operating on the road in question. Increasing the porosity of the surface reduces noise generated by air pumping and increases the acoustic absorption and by consequence, reduces the horn effect. Increasing the layer thickness or the void

volume will tend to reduce the frequency where the main sound-absorbing effects take place.

- A small maximum aggregate size for porous surfaces is favorable for noise reduction, whereas a large maximum size improves the durability and drainage capabilities; hence the benefit of a surface such as double-layer porous asphalt.

Sandberg and Descornet (1980) provide a useful summary of the general guidelines that should be followed to achieve a good quality low-noise surface, the key points of which are:

- For porous surfaces, the wearing course should be constructed with as much a void content as possible from a durability perspective. An initial void content of more than 20 percent is a minimum to achieve good noise reduction, although 20–30 percent is preferable. The thickness of a porous layer should be at least 40 mm, preferably thicker, in order to also achieve sound absorption at relatively low frequencies.
- For porous surfaces, it is essential to increase the porosity in order to prevent clogging by providing wider channels.
- Megatexture should be minimized, especially around wavelengths of 50–100 mm. This can be achieved by, for example, using uniform smaller aggregates that are densely graded.
- Very smooth macrotextures should be avoided. Macrotexture should be maximized at wavelengths around 2 to 6 mm (0.04 to 0.24 in.) for car tires and 4 to 8 mm (0.16 to 0.3 in.) for truck tires.
- The above megatexture and macrotexture requirements are easier to achieve if a small maximum aggregate size is used, ideally in the range 3 to 6 mm (0.1 to 0.2 in.), and if crushed aggregates having sharp edges are used.

Up till now, scenarios for developing a low noise road surface have mainly been based on the following experimental findings (Sandberg, 1996):

1. Surface textures with a wavelength greater than 10 mm (0.4 in.) tend to increase noise excited by the tire vibration
2. Surface textures with a wavelength less than 10 mm (0.4 in.) tend to reduce noise from air pumping
3. Porosity of the pavement helps to reduce aerodynamic effects on noise
4. A stiffer surface generates a higher noise level than a softer one
5. A negative texture is much more favorable for noise reduction than a positive texture.

The primary noise generating mechanisms noise influence noise at varying frequencies as summarized in Figure 2.29.

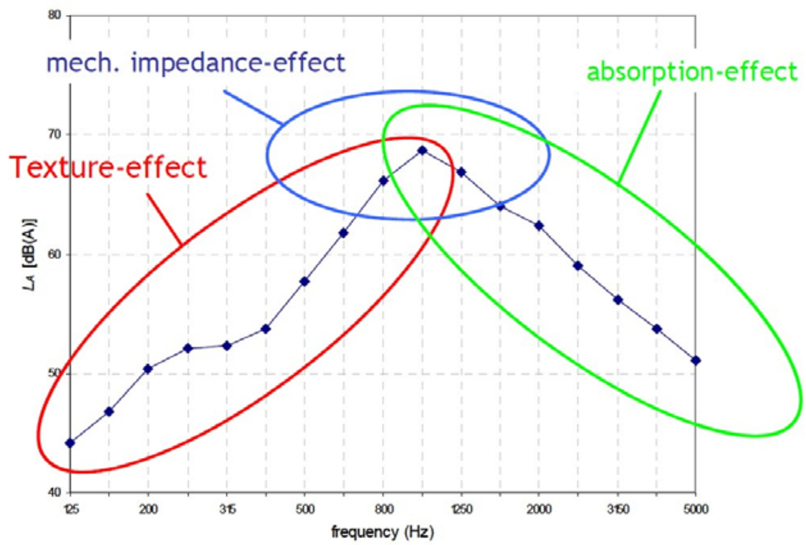


Figure 2.29: Frequency range of road noise influences (Kuijpers and van Blokland, 2005)

Unconventional third-generation surfaces are under development that are designed specifically to reduce road noise. An example of one such surface that addresses each of the three primary noise generating mechanisms is shown in Figure 2.30.

Finally, variations in road noise levels are to be expected for different surface types. Figure 2.31 shows a summary of statistical pass-by noise levels measured for cars traveling at 110 km/h (black), dual-axle trucks traveling at 85 km/h (red) and multi-axle trucks traveling at 85 km/h (blue) on different surfaces. Overall, considering the variations in noise levels measured for the different surfaces shown in the figure, no distinct benefit in one surface type over another can be observed although lower noise levels are expected for porous and thin surface layers. Design procedures for quieter surfaces should therefore aim to reduce the variability of tire-pavement noise associated with these surface types.

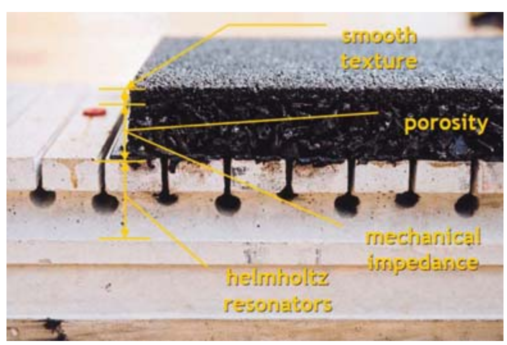
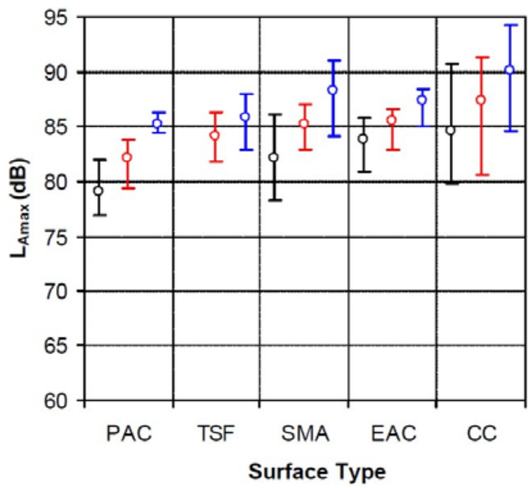


Figure 2.30: Low noise road surface (Kuijpers and van Blokland, 2005)



PAC: porous asphalt concrete; TSF: thin surfacings;
SMA: stone matrix asphalt; EAC: exposed aggregate concrete;
CC: cement concrete

Figure 2.31: Noise measured on various surface types (Morgan, 2006)

Chapter 3. Noise database

3.1 Introduction

The literature review highlighted different mixture-related properties influencing tire-pavement noise and emphasized the effect of surface macrotexture for dense-graded asphalt mixtures and in addition, mixture porosity for open-graded asphalt mixtures. Surface macrotexture and mixture porosity are influenced by the volumetric composition of the mix, primarily aggregate gradation and binder content. The primary objective of this research study is the design of quieter pavement surfaces. This chapter discusses a research task that involved the analysis of a large number of pavement noise tests done on a variety of different asphalt surfaces to better understand how mixture related properties influence noise. The purpose of this task was to identify those properties of a mixture and characteristics of pavement surfaces influencing noise attenuation and generation. The goal therefore was to identify the mix design options available to ensure low noise generation, focusing on materials, pavements, and conditions in Texas, towards identifying appropriate best practices.

This chapter expands on the pavement noise database developed as part of this study. A detailed statistical analysis was done to identify significant influence variables that can be controlled as part of mixture design to produce quieter pavement surfaces. Based on the outcome of this analysis, an experimental plan was developed, outlining laboratory procedures for the design of quieter pavement surfaces and how these should be validated through field testing.

3.2 Database

A noise database was established from data collected on asphalt pavements tested in Texas and at the NCAT test track. The surfaces tested include dense-, gap- and open-graded mixtures with varying maximum aggregate size. Noise testing on these mixtures was done using both the OBSI method as well as close proximity (CPX) sound pressure testing using the NCAT noise trailer. The database includes noise testing done using different tires and at different speeds.

Mixture gradation, asphalt binder type and content as well as paved layer thickness was identified for each of the asphalt surfaces tested. In addition, surface macrotexture measurements using the CTM on each of the different surfaces is included in the database. The macrotexture measurements include MTD as well as the root mean square (RMS) of the surface profiles measured. This section provides an overview of the noise database and a description of the different mixture and surface properties collected for analysis.

3.2.1 Gradation

The asphalt surfaces included in the noise database comprise dense-, gap- and open-graded mixtures as well as a microsurfacing. The dense-graded mixtures include Type C and Type D mixtures used by TxDOT as well as Superpave mixtures. Gap-graded mixtures are SMA. The open-graded mixtures include PFC as used by TxDOT; a porous European mixture used by the Georgia Department of Transportation; and fine-graded open-graded friction course as used in Arizona. These mixtures vary in maximum aggregate size, although all pass the ¾-inch sieve. A total of 93 different asphalt surfaces are included in the noise database, the gradations of which range significantly. Figure 3.1 shows a box plot of the gradations of the database mixtures indicating the variation in percentage passing the respective sieve sizes. The box plot indicates the range of the gradations (minimum and maximum values), the mean and the 25 and 75 percent quantiles of the percentage passing data. The gradations of the mixes in the noise database are all "as-constructed." In the case of the NCAT mixes this comprised a single construction lot but for the TxDOT mixes, the gradation was determined as the mean of a number of lots as extracted from the SiteManager database—these gradations were consistent between lots. The plots of percentage passing the #8 and #200 sieves in Figure 3.1 provide an indication of the fines (sand) and filler content ranges of the mixes in the noise database.

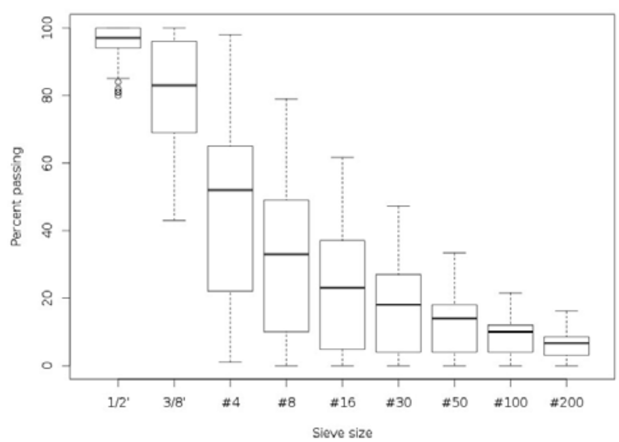


Figure 3.1: Box plot of database gradations

3.2.2 Thickness

Layer thickness is known to influence noise at the tire-pavement interface, particularly for open-graded mixtures. The thicknesses of the different surfaces in the noise database varied from 0.6 to 4 inches. Figure 3.2 shows a histogram of these thicknesses indicating that the majority of the sections had a thickness in the order of 2 inches. When available, as was the case for all of the NCAT sections, the thickness reported in the noise database is the "as-constructed" thickness. If this data was not available, then the design thickness of the section was used.

3.2.3 Binder properties

Although stiffness of the binder, as reported in the literature review, is not a critical parameter influencing the road noise of conventional HMA surfaces, the noise database does indicate the high temperature performance grade (PG) of the asphalt binders used for all of the surface mixes. Figure 3.3 shows the distribution of binder grades of the noise database sections indicating the majority of the mixes used PG 76 binders.

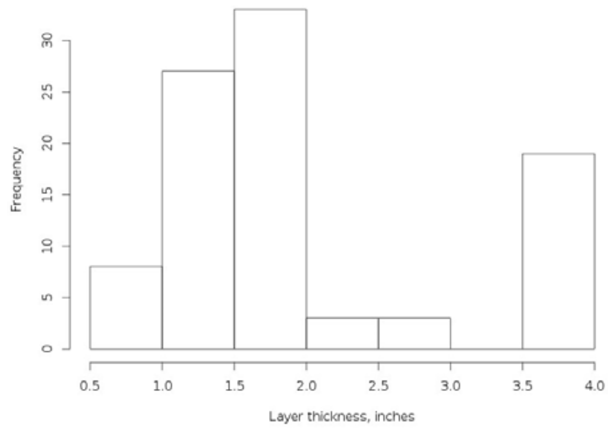


Figure 3.2: Histogram of layer thickness

The "as-constructed" binder contents of the surface mixes are also included in the noise database. These vary quite significantly as expected since the binder content of a mix will vary with gradation and aggregate size. As shown in Figure 3.4, the majority of the mixes in the noise database had binder contents ranging from 5 to 6.5 percent. The dense-graded Superpave mixes had the lowest binder contents (4.0–4.5 percent) while some of the open-graded mixes had the highest binder contents (around 8.0 percent)—specifically those with asphalt rubber binders.

3.2.4 Macrotexture

Surface macrotexture was measured using the CTM on each of the surfaces in the noise database. The NCAT sections used for the noise testing were at least 200 ft in length; the TxDOT sections were in excess of 400 ft in length. Macrotexture testing was done at random locations longitudinally along the sections—at least four locations per section. For each of these, macrotexture measurements were taken on untrafficked regions of the pavement between the wheelpaths. Thus the macrotexture measurements also provide an "as-constructed" snapshot of the pavement profile before trafficking. This is also clear in Figure 3.5 that shows box plots of the surface macrotexture measurements for the database sections. Plot A-H in this figure represents the average macrotexture in each of the circle segments A through H shown in the inset, which illustrates the circular segments that the CTM measures and reports macrotexture at. The arrow in the inset indicates the direction of traffic travel. Plot A+E is the average macrotexture in circle segments A and E, parallel to the direction of traffic travel. Comparing these plots, it is clear that no directional macrotexture is apparent. Plot RMS indicates the RMS of the surface profiles in the noise database, yet another macrotexture parameter that provides an indication of the aggregate orientation on the surface.

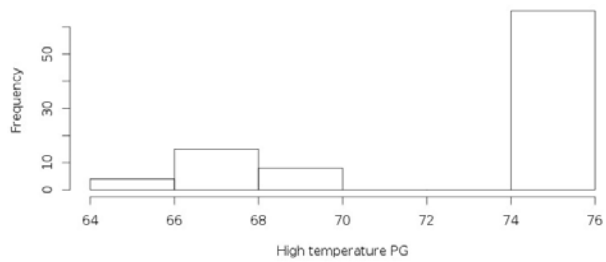


Figure 3.3: Histogram of binder high temperature PG

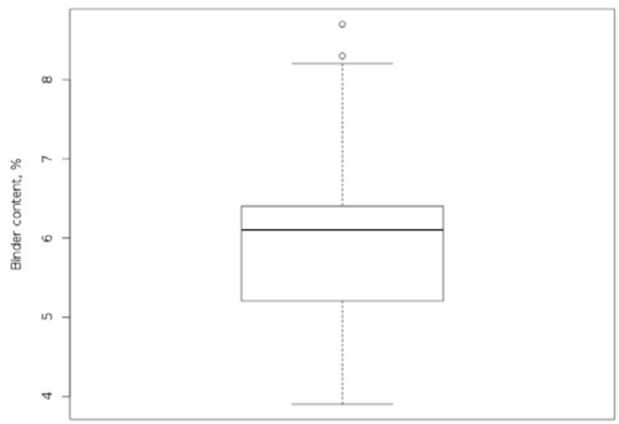


Figure 3.4: Box plot of asphalt binder contents

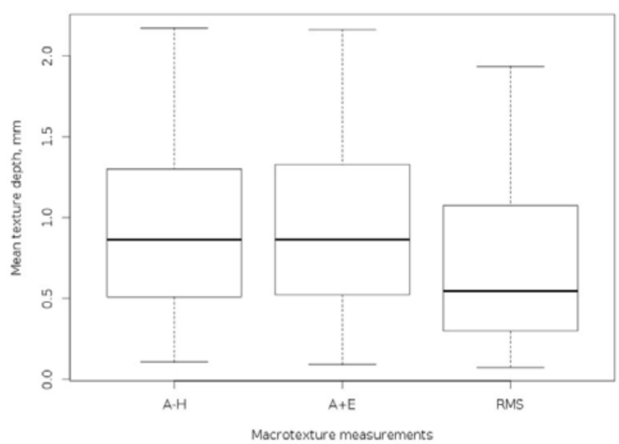


Figure 3.5: Box plot of surface macrotexture

3.2.5 Noise

The noise measurements make up the bulk of the data in the database. A total of 3,596 noise measurements are included that comprise replicated measurements of 533 distinct tests grouped into the following categories depending on the procedure or method used to collect the data:

- Method: SIL and SPL
- Vehicle: Chevy Malibu (CYML) and CPX trailer
- Tire: SRTT, Goodyear Aquatread (GDYR), and Uniroyal Tigerpaw (UNIR)
- Speed: 45 and 60
- Channel: CH1 and CH2

The noise data include both sound intensity levels (SIL) and SPLs. These noise measures differ in that SIL are collected using the OBSI method with phase matched sound intensity microphones whereas SPL were collected using sound pressure microphones within the NCAT noise trailer (the CPX). Hence, SPL measurements were always taken using the CPX trailer but SIL measurements were collected using a passenger vehicle, the CYML, as well as the NCAT CPX trailer with sound intensity microphones mounted to the wheel inside the CPX trailer. Noise testing was done with three different test tires: the SRTT, GDYR, and UNIR. Noise testing was done at two speeds: 45 and 60 mph. Noise data were collected on two channels at the tire-pavement interface, from the leading (CH1) and trailing (CH2) edges. The noise data was split instead of averaging between the channels to provide an indication of the noise in front of and behind the tire contact patch. The data includes a trailing edge measurement for every leading edge measurement.

Noise data in the database are reported at the third-octave band frequencies from 400 to 4,000 Hz to allow the effect of the mixture parameters to be investigated by frequency. TxDOT uses the OBSI method for SIL noise measurements using a passenger vehicle (similar to the CYML) with SRTT tires at 60 mph. It was decided not to restrict the noise database to these specific variables since this would have significantly reduced the number of noise records available for analysis. Including all of the variables as indicated, however, requires normalization of the noise data since the levels measured at different speeds and tires, for example, are obviously different. The statistical procedure used for normalization of the noise data is expanded on later in the report. Figure 3.6 shows a breakdown of the number of distinct noise tests by category. The figure uses a logarithmic scale on the y-axis, but it is clear that the majority of the tests included in the noise database are SIL and SPL measurements using the CPX trailer and SRTT tire at a speed of 45 mph, at the NCAT test track.

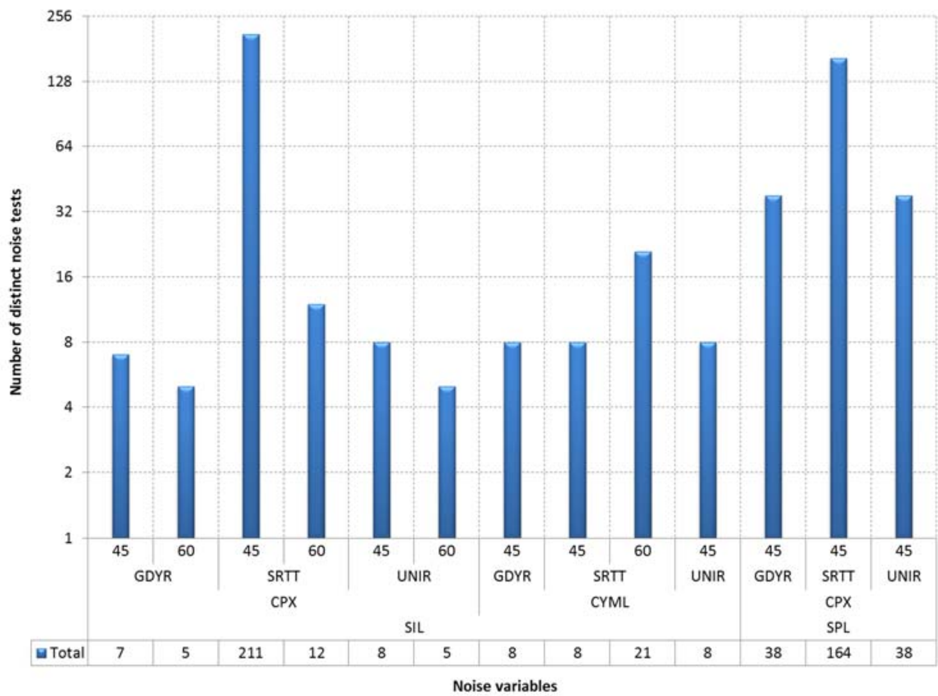


Figure 3.6: Breakdown of noise tests by category

3.3 Analysis

This section expands on various statistical analyses done to identify and investigate mixture-related influence variables impacting road noise. An initial analysis of gradation and macrotexture indicated that the percentage passing a respective sieve size was not a robust parameter to evaluate a mixture's gradation influence on noise. This led to the definition of alternative gradation parameters to better assess its influence.

3.3.1 Gradation influence on macrotexture

The noise database contains a large variety of different asphalt mixtures and as previously shown in Figure 3.1, the different mixtures represent a wide range in the percentages passing the different sieves making up the gradation curve, particularly for the #4 and #8 sieves. The #8 sieve (2.36 mm) is often used to indicate the sand content of the mixture and defines the boundary between the coarser and finer aggregates. Figure 3.7 shows that for the mixes in the noise database, the percentage passing the #8 sieve is strongly correlated with the percentage passing the #4 sieve. The macrotexture measured on the different database surfaces was related to the gradations of the surface mixtures. The best correlation was found between MPD and percentage passing the #4 sieve (4.75 mm). This relationship is shown in Figure 3.8.

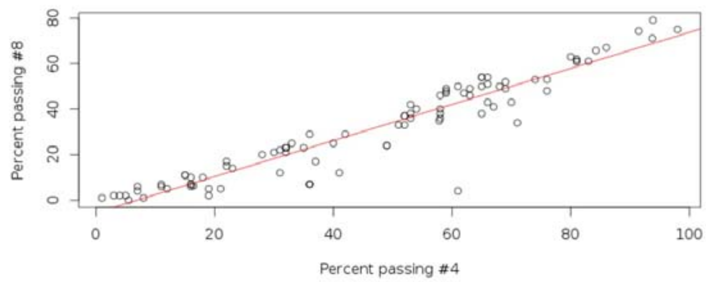


Figure 3.7: Relationship between #4 and #8 percentages

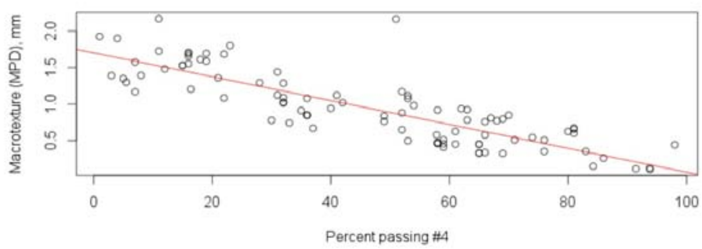


Figure 3.8: Relationship between macrotexture and #4 percentages

3.3.2 Root mean square

The RMS of the surface profile is often used to indicate whether the surface has a positive or negative texture in terms of aggregate orientation. Negative texture is characterized by surfaces with voids without exposed aggregates while positive texture has exposed aggregates protruding for the surface. Therefore, seal coat surfaces would have positive texture but grooved PCC provides negative texture as shown in Figure 3.9. Positive textured surfaces are generally louder. McGhee and Flintsch (2003) defined positive surface textures as those for which the MPD is five percent or more than the RMS value while surfaces for which the RMS value was five percent or more than the MPD were considered to be negatively textured. Using this definition, all of the mixtures in the noise database with the exception of one Superpave dense-graded mixture appear to have positive surfaces textures.

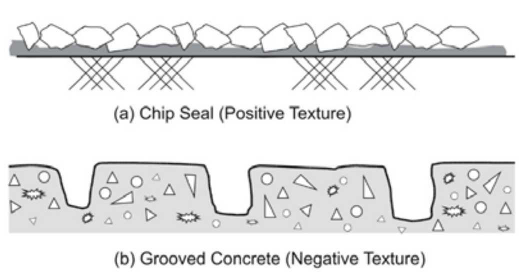


Figure 3.9: Surfaces with positive and negative texture (McGhee and Flintsch, 2003)

3.3.3 Gradation modeling

The aggregate gradation of asphalt mixtures is typically expressed in terms of percentage passing a standard set of sieves with varying sizes. To better understand the relationship between mixture gradation and road noise and to reduce the number of influence parameters, an alternative formulation of mixture gradation using logistic curves was employed. This provides a mathematical measure of mixture gradation using only two parameters. The logistic equation used is shown in Equation 3.1.

$$y = \frac{1}{1 + e^{-\beta_1(x-\beta_2)}} \tag{3.1}$$

Figure 3.10 and Figure 3.11 show the influence of varying parameters β_1 and β_2 respectively. As shown in Figure 3.10, varying β_1 changes the rotation or slope of the gradation curve. Higher β_1 values correspond to gradations with larger slope. Therefore, the slope parameter (β_1) acts as an indicator of the openness of the gradation. As shown in Figure 3.11, varying β_2 changes the horizontal translation of the gradation curve. Higher β_2 values correspond to gradations with larger aggregate sizes. Therefore, the location parameter (β_2) acts as an indicator of the aggregate size of the gradation.

To illustrate the effectiveness of representing gradation using logistic models, consider Figure 3.12, which shows all of the gradations of the mixtures in the noise database. Non-linear regression techniques were utilized to fit logistic curves to each of these gradations. Figure 3.13 shows the fitted gradations using the logistic function in Equation 3.1. As seen in these figures, the logistic curves fit the original gradation curves reasonably well.

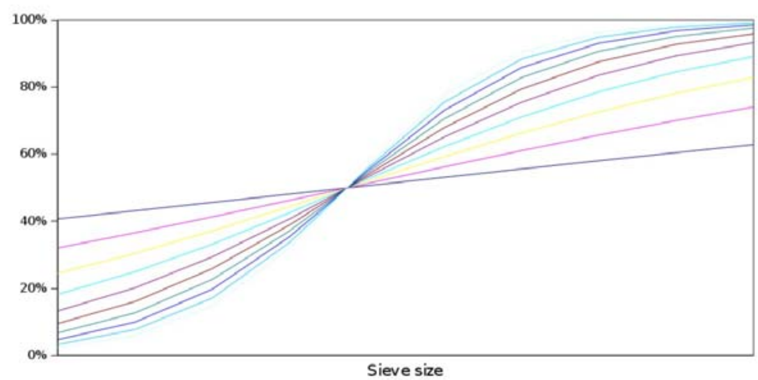


Figure 3.10: Gradations by varying slope

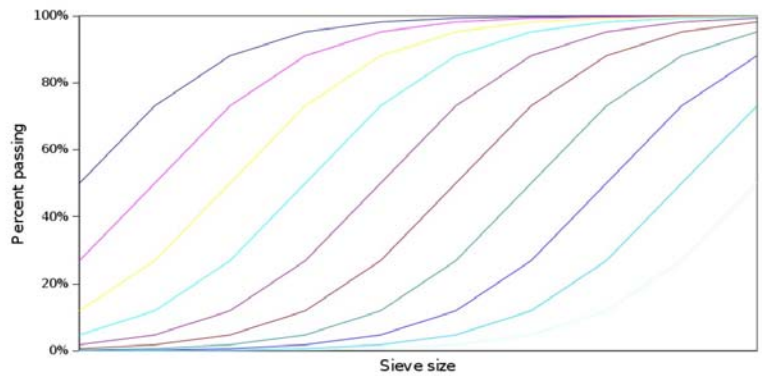


Figure 3.11: Gradations by varying location

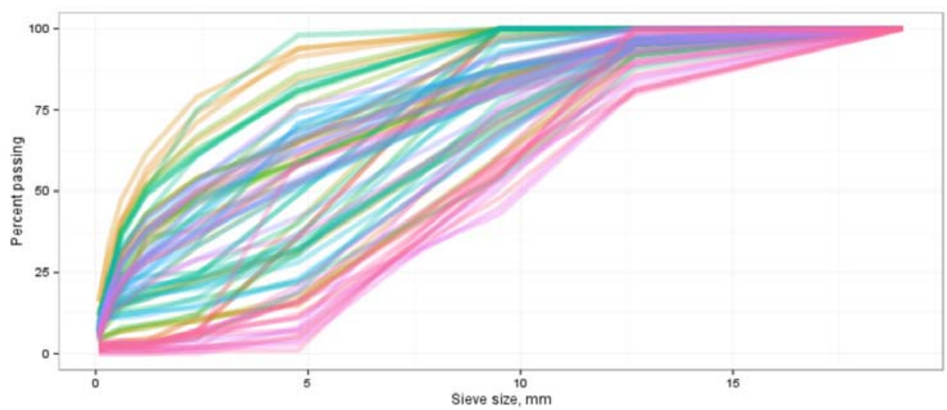


Figure 3.12: Original gradation curves

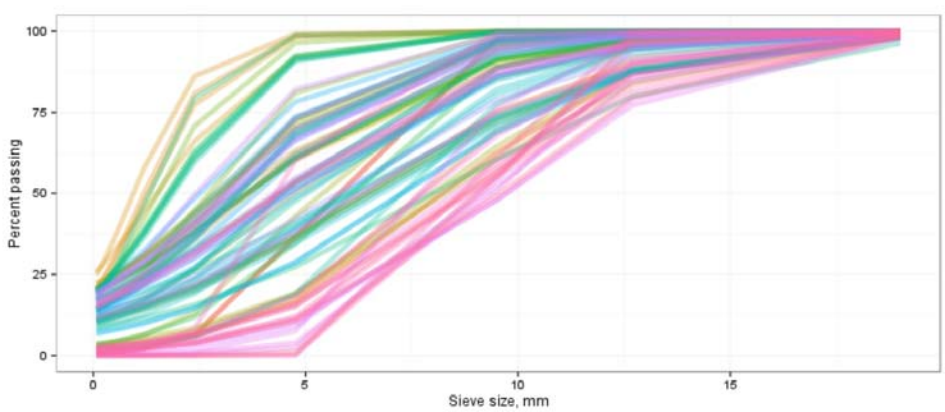


Figure 3.13: Fitted gradation curves

By representing the gradations of the database mixtures using the β_1 slope and β_2 location parameters, some interesting observations are apparent. Figure 3.14 shows a scatter plot distinctly grouping the open-graded and dense-graded mixtures in terms of the slope and location parameters. A nonlinear dividing line is apparent that separates the open-graded and dense-graded mixtures as shown in Figure 3.15. The separator is mathematically represented using by $\beta_1 \cdot \beta_2 = 3$. Thus the product of β_1 and β_2 is another possible parameter to characterize the gradation curve of asphalt mixtures. The product of β_1 and β_2 better represents the "openness" of the gradation. The slope and location parameters provide more robust measures to assess the effect of mixture gradation on road noise. The distribution or range of these parameters for the database mixtures are shown in Figure 3.16 and Figure 3.17 for the slope and location parameters respectively.

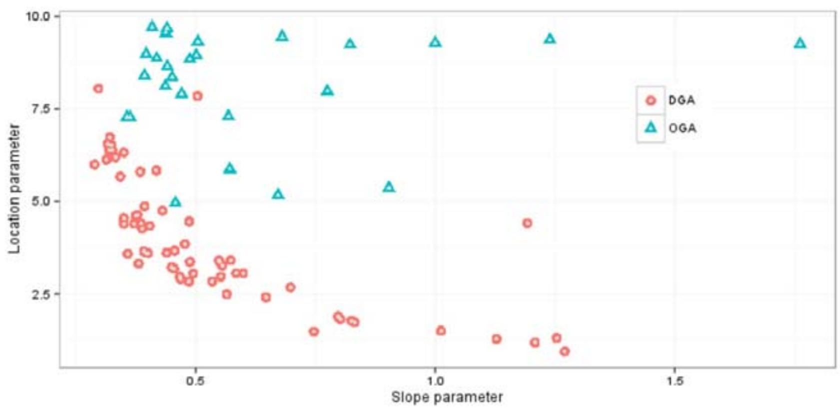


Figure 3.14: Grouping of open- and dense-graded mixtures by parameter

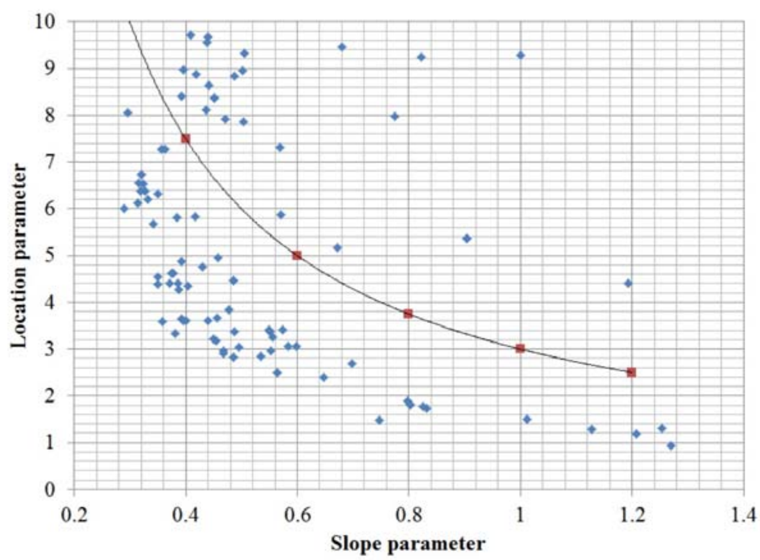


Figure 3.15: Division between open- and dense-graded mixtures

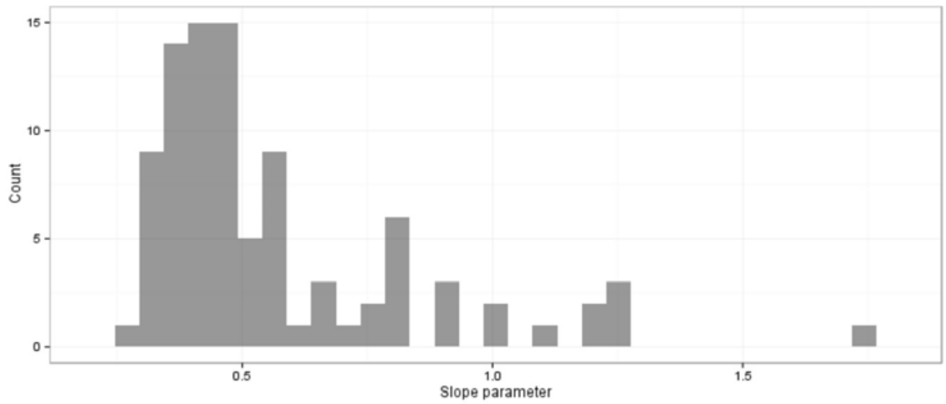


Figure 3.16: Distribution of slope parameter β_1

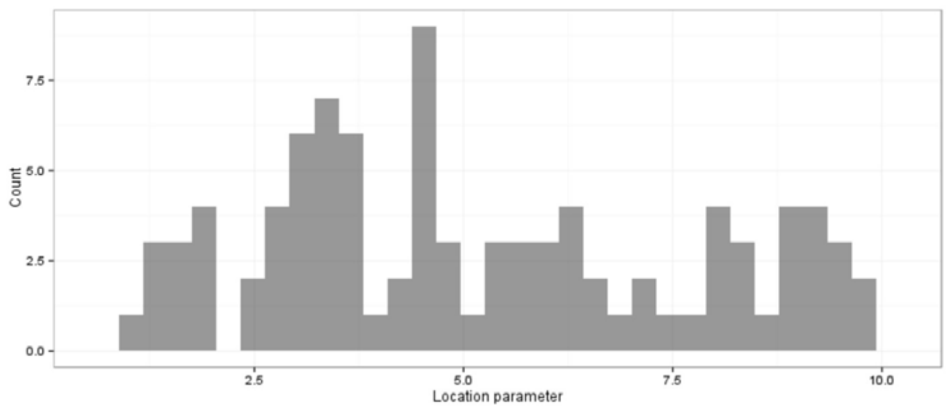


Figure 3.17: Distribution of location parameter β_2

3.3.4 Regression analysis

Apart from the mixture parameters such as gradation slope and location the database also includes different levels of high temperature binder grades (PGH), asphalt contents (AC) and surface layer thicknesses (THK). Pavement noise level is also influenced by several other factors such as the noise measurement parameters (vehicle type, tire type and speed) as well as the macrotexture parameters (MPD and RMS). Mixture-related parameters potentially explain only a part of the variability in the pavement noise levels measured. In addition, mixture parameters are potentially correlated with the macrotexture and other pavement surface properties. Excluding variables that are potentially correlated with the mixture parameters as well as those affecting pavement noise introduces omitted variable bias. Consequently, mixture parameters, noise measurement parameters, and pavement surface characteristics are simultaneously included in the statistical analysis that follows.

Multiple linear regression analysis was used to develop a predictive model for pavement noise. Since pavement noise was measured at different third octave band frequencies, separate linear regression models were estimated for pavement noise level at each of these frequencies; however, a common set of explanatory variables were used for each model. The A-weighted noise levels in the database were unweighted by dividing each with the corresponding weighting factor to ensure that the analysis was not constrained by the A-weighting applied at the respective frequencies evaluated. The linear regression results are shown in Table 3.1 and Table 3.2 for the low and high frequencies respectively.

It is important to note that all of the different noise measurements in the database are included in the analysis regardless of method used, be it sound intensity or sound pressure (SIL or SPL), type of tire (SRTT, GDYR, UNIR), vehicle type (CPX or CYML), or test speed (45 or 60 mph). Therefore, the intercept term as reported is not a true mean noise level but rather a relative noise level at the respective frequencies. Each of the parameters included in the analyses was found to be significant and the coefficients reported (both sign and value) provide an indication of the relative impact on noise levels at the respective frequencies. In the case of categorical parameters, the results are reported with respect to a particular reference variable.

Table 3.1: Noise regression models at low frequencies

Hz	500.0	630.0	800.0	1000.0	1260.0
Intercept	112.9	102.3	96.4	89.7	80.3
CH2	-3.0	-2.0	-0.7	1.5	1.8
SPL	-1.5	-1.8	-3.0	0.7	1.5
SRTT	-3.7	-1.6	1.4	-0.7	-1.2
UNIR	-6.7	-4.2	-3.3	-5.3	-3.1
CYML	2.9	4.1	3.6	1.0	1.2
60 MPH	8.2	5.2	3.6	6.0	3.9
MPD	8.6	5.9	2.1	1.0	-1.3
RMS	-2.0	-0.9	-0.6	-1.5	-1.2
β_2	1.0	0.9	0.6	0.2	0.1
$\beta_1 \cdot \beta_2$	-0.2	-0.5	-0.5	-0.5	-0.1
AC	-0.8	-0.7	-0.6	-0.1	-0.1
PGH67	3.2	2.8	2.1	0.1	0.3
PGH70	1.8	1.3	1.3	0.3	1.1
PGH76	2.2	1.6	0.7	-1.4	-0.9
THK	-0.6	-0.5	0.1	0.3	0.7

Table 3.2: Noise regression models at high frequencies

Hz	1585.0	2000.0	2500.0	3160.0	4000.0
Intercept	76.9	71.0	66.8	64.0	62.4
CH2	0.3	-0.2	0.5	1.7	1.4
SPL	1.2	0.7	1.6	1.6	2.8
SRTT	1.0	2.4	2.4	2.1	0.7
UNIR	-1.5	-1.3	-1.0	-0.6	-2.0
CYML	0.9	1.0	1.3	1.0	1.2
60 MPH	3.6	4.5	4.2	3.7	4.5
MPD	-3.1	-2.2	-1.2	-1.1	-1.6
RMS	-0.9	-1.0	-1.0	-0.7	-0.6
β_2	0.0	-0.1	-0.1	-0.1	0.0
$\beta_1 \cdot \beta_2$	-0.1	-0.2	-0.2	-0.2	-0.2
AC	0.1	0.3	0.2	0.2	0.1
PGH67	-1.6	-1.8	-1.2	-1.2	-0.2
PGH70	-0.8	-1.2	-0.7	-0.6	0.5
PGH76	-2.4	-2.5	-1.8	-1.5	-0.7
THK	0.9	0.8	0.6	0.5	0.5

3.4 Synthesis

This section discusses the analysis results towards the development of laboratory procedures for the design of quieter pavement surfaces.

3.4.1 Mixture gradation

The analysis indicated a strong correlation between surface macrotexture (MPD in mm) and the percentage passing the #4 sieve (P4) as shown in Figure 3.8. The relationship between these parameters is shown in Equation 3.2 and provides a simple estimation of surface macrotexture in terms of mixture gradation and suggests an increase for coarser mixes and a decrease as the fines in the mix increase.

$$\text{MPD} = 1.7 - 0.0164 \cdot \text{P4} \tag{3.2}$$

3.4.2 Pavement noise model

The noise parameters and levels evaluated include:

- Channel: CH1 (leading edge, reference) and CH2 (trailing edge)
- Method: SIL (sound intensity, reference) and SPL (sound pressure)
- Tire: GDYR (reference), SRTT, and UNIR
- Speed 45 mph (reference) and 60 mph
- Macrotexture: MPD and RMS

- Gradation parameters β_1 and β_2
- AC
- High temperature grade: PGH64 (reference), PGH67, PGH70, PGH76
- Layer thickness (THK)

A number of observations can be made from the regression results shown in Table 3.1 and Table 3.2 for the low and high frequencies respectively. The location or aggregate size parameter is positively correlated to the noise level at frequencies lower than 1,585 Hz; it is inversely related to the noise levels at higher frequencies. In other words, pavements that are quieter at higher frequencies are associated with gradations with larger aggregate sizes for a given "openness" level. On the other hand, pavements that are quieter at lower frequencies are associated with smaller aggregate sizes for a given "openness" level. The "openness" parameter is inversely related to the pavement noise level at all frequencies; this indicates that open gradations are generally associated with quieter pavements. Therefore, one may adjust an open gradation by modifying its average aggregate size (translating the gradation curve) to achieve surfaces that are quieter at either lower or higher frequencies.

The data suggest that noise levels at the leading edge microphone are typically higher than the trailing edge at lower frequencies; on the other hand, pavement noise captured by the microphone at the trailing edge is louder at higher frequencies. Pavement noise measured using the SRTT tire was quieter than the GDYR tire at frequencies lower than 1,585 Hz; while the SRTT tire measurements are louder than that of the GDYR tire at higher frequencies. Noise measurements obtained using the UNIR tire were consistently quieter at all frequencies compared to the GDYR tire.

Pavement noise is louder at higher testing speeds, as expected. Pavement surface texture is found to be statistically significantly related to pavement noise. Surfaces with higher MPD values are louder at lower frequencies; however, pavements with higher MPD values are found to be quieter at frequencies higher than 1,250 HZ. The RMS value of macrotexture was found to be negatively correlated with pavement noise at all frequencies. Generally, pavements with stiffer binders were found to be louder at lower frequencies and quieter at higher frequencies. The data shows that thicker pavements were louder at frequencies higher than 794 Hz.

Considering the coefficients of the mixture-related variables in the regression analysis, surface macrotexture clearly has the greatest influence at the different frequency levels and appears to dilute the contribution of the gradation parameters, both in terms of size and mixture porosity or "openness."

The inability of the regression model to accurately reflect the known influence of surface porosity on noise reduction or attenuation is a shortcoming of the test procedures currently used to measure noise at the pavement-tire interface. Noise attenuation in porous pavements would typically occur across a wider span than the distance between the microphone receivers and the tire noise source as used in both the sound pressure SPL and OBSI SIL methods (in the order of 4 inches). Asphalt content appears to have a minimal effect and although the effect of high temperature PG grade is significant, no consistent trends are apparent, probably because the majority of the open-graded mixtures tested use a PG 76-22 binder.

The results of the statistical analysis of the noise data suggest that to reduce pavement-tire noise, the design of quieter pavements should focus more on producing mixtures with reduced macrotexture. Adjusting the gradation of the mixture may have a significant effect on noise production, but the low levels of these coefficients indicate that this effect may not be of practical significance and the effect is minor compared to that of macrotexture. The data also suggest an alternative noise measurement procedure (such as sound absorption or wayside noise measurements) to more effectively evaluate the effect of mixture porosity on tire-pavement noise.

Chapter 4. Laboratory procedures

4.1 Introduction

The primary objective of this study is the design of quieter pavement surfaces. As part of Technical Objective 3 of the study, a standard laboratory procedure was developed and used to measure noise from different laboratory-compacted specimens. This approach was developed specifically to allow the design of quieter pavement surfaces in the laboratory before applying these in the field. This chapter describes the process used to assess noise under laboratory conditions and the results obtained using different mixture designs of thin overlay mixture (TOM) compacted samples.

4.2 Test implementation

The laboratory procedure developed is a modification of the standard ASTM E303 procedure: *Measuring Surface Frictional Properties Using the British Pendulum Tester (BPT)*. In this test, compacted laboratory specimens are tested using the BPT. The noise generated as the rubber slider of the BPT comes into contact with the surface of the specimen is recorded with a SPL meter in a process similar to wayside noise measurements in the field, as shown in Figures 4.1 through 4.4. Unlike the standard BPT test, the implemented test does not use water on the surface and uses a 4-inch diameter specimen held in place in the path of the swinging arm of the BPT. The contact path of the slider is manually adjusted to test an area smaller than 4 inches in order to avoid noise due to impact with the side of the sample. An SPL meter is placed 4 inches from the contact of the rubber slider and the surface, and 3 inches above the surface of the specimen as shown in Figure 4.4. These distances are the same as those used to align the OBSI microphones above the road surface for consistency.

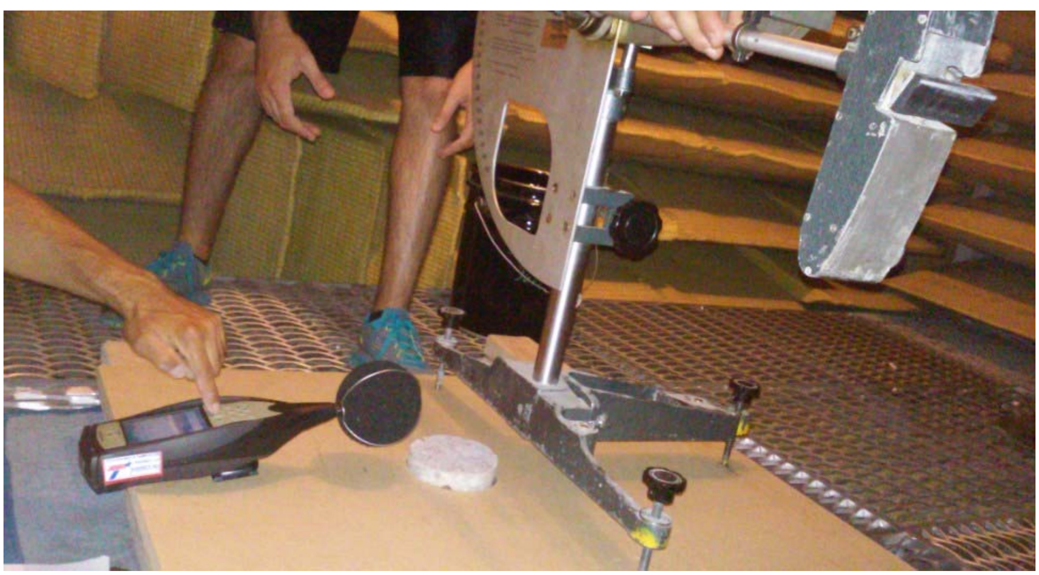


Figure 4.1: BPT noise setup

The SPL meter measurements capture all the noise from all sources in a determined period of time. In this test implementation, a time of two seconds was used in order to capture just the noise due to the rubber slider going over the sample's surface. Instead of reporting the average noise level over this period of time, the noise reported was the maximum measurement during the time period. Additionally, the measurements were made in an anechoic chamber located at the Cockrell School of Engineering building. This was done specifically because of ongoing construction noise at this facility that is dampened in an anechoic chamber.

Preliminary tests were performed to observe the accuracy and sensitivity of the laboratory noise measurements using the proposed procedure. Three samples of different surfaces—including a PCC, PFC, and TOM surface—were tested and the macrotextures of these were measured with the laser texture scanner. The PCC specimen had transverse tining on one face and was smooth on the other face. Results of these preliminary tests are shown in Figure 4.5.

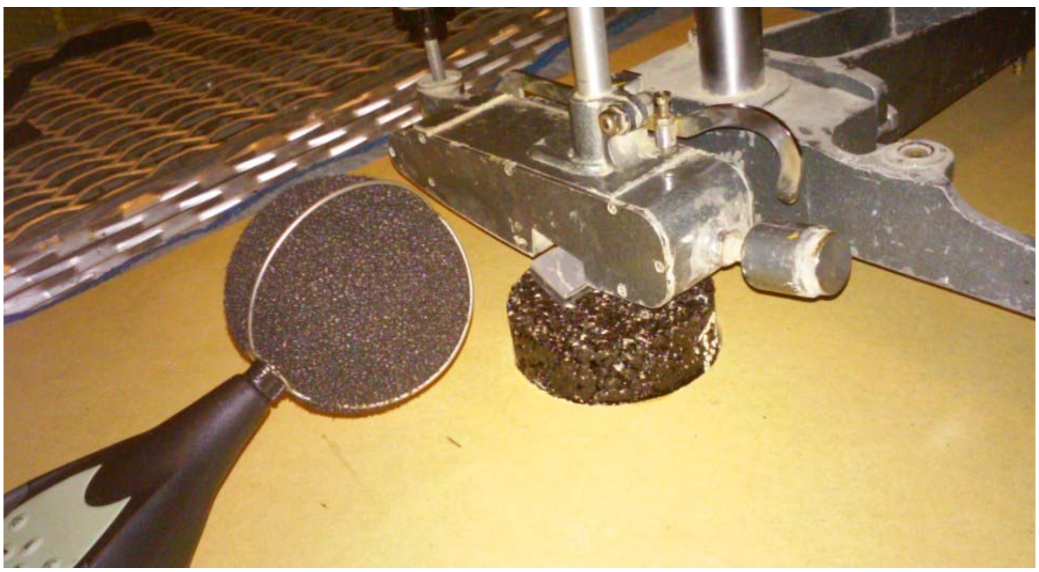


Figure 4.2: BPT testing head in contact with specimen

Figure 4.3: Side view of test setup

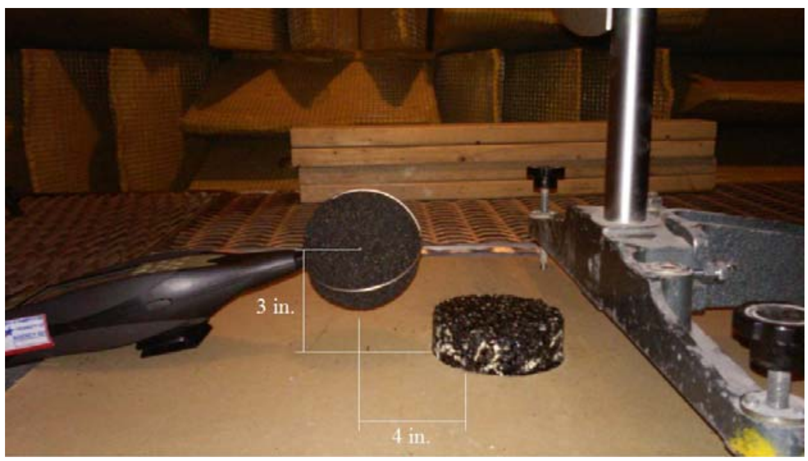


Figure 4.4: Sound meter position

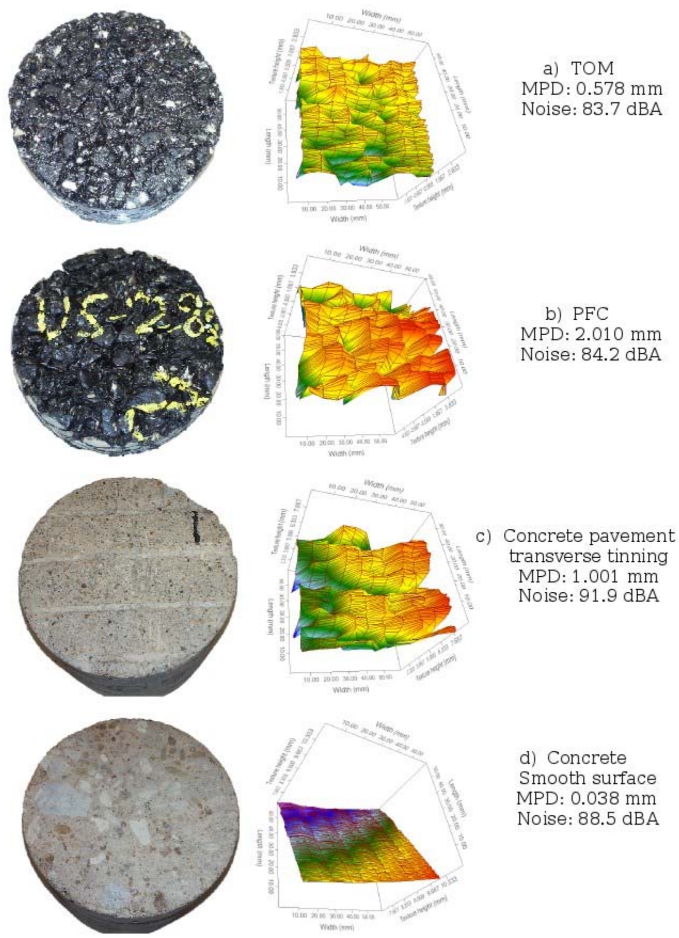


Figure 4.5: Preliminary tests results

As observed, both TOM and PFC obtained similar noise levels, 83.7 dBA and 84.2 dBA respectively. These surfaces are both known as quiet surfaces, unlike transverse tining finishing in PCC pavement. In the present test, the transverse tining finishing presented a noise measurement of 91.9 dBA, higher than the other surfaces tested, as expected from historical noise measurements in the field.

Noise levels on the smooth PCC specimen were at 88.5 dBA, about 4 dBA higher than noise levels on the TOM and PFC specimen. This result was not unexpected and emphasizes the negative impact of too low a surface macrotexture on pavement-noise generation. As outlined in the literature review in Chapter 2, in contrast to an impact noise generating mechanism, surfaces with low macrotexture generate noise through slip-stick and air pumping. There are insufficient air-paths on these surfaces to dissipate the noise and since the rubber is in contact with a greater surface area, higher noise levels can be generated. While low surface macrotexture will reduce impact noise, there is a threshold, however, below which the air pumping and slip-stick noise generating mechanisms will start to increase tire-pavement noise.

This simple laboratory test shows promise in that the results appear to reflect noise conditions as expected in the field and it is both sensitive to surface texture and repeatable in nature. Based on these preliminary findings it was decided to expand the testing program by measuring noise on different TOM laboratory-compacted specimens towards optimizing the mixture design for low noise surfaces.

4.3 Mixture design

A laboratory experiment was designed to assess the noise sensitivity of TOM to variations in gradation and asphalt content. A popular mixture design of TOM was obtained from the Austin district. This TOM mixture comprises three different aggregate sources: a Grade 5 sandstone, a Type F limestone, and limestone screenings. Aggregates were collected from the Bolm Road quarry in Austin and mixtures with these aggregates were manufactured in the laboratory by varying the proportion of Grade 5 rock in the mix at A) 40, B) 60, and C) 80 percent. In each case the screenings were maintained at 20 percent. Figure 4.6 shows the three gradations tested and the TOM gradation specification envelope. Gradation C is the coarser of the gradations tested.

The aggregates were blended with a PG 76-22 asphalt binder at three different asphalt contents: 5.5, 6.5, and 7.5 percent. This experiment provides TOM mixtures that vary quite significantly in terms of composition but which still meet standard TxDOT gradation specifications for TOM. Mixtures for the specimen were manufactured in batches of 10 kg to provide sufficient material to compact three specimens as well as to run Rice's maximum theoretical density and ignition oven tests. Three specimens at each of the aggregate and binder levels were compacted using the Texas gyratory compactor. The results of the laboratory mixture design experiment (Figure 4.7 and Figure 4.8) show the voids in the mineral aggregate (VMA) and density (Gmb) volumetric properties of the mixtures with the three different gradations against AC.

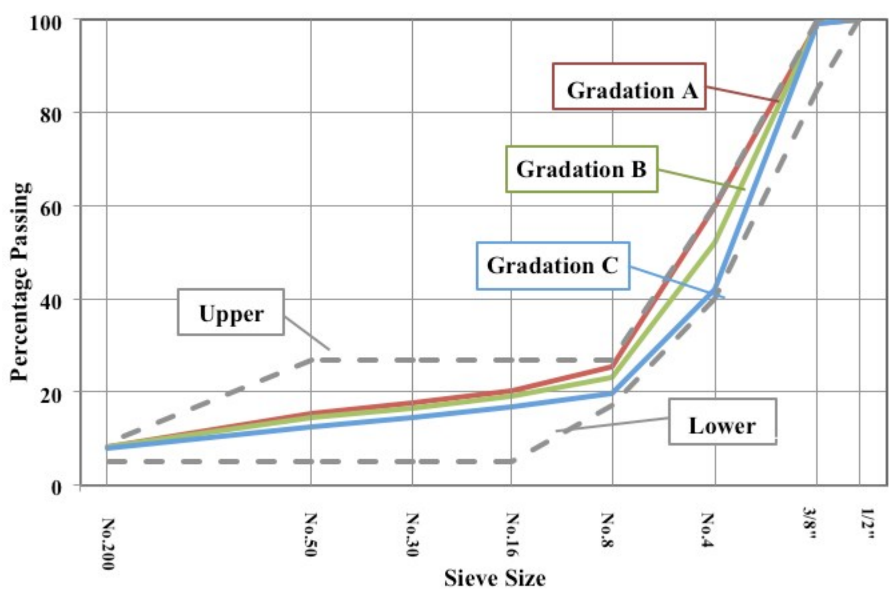


Figure 4.6: TOM gradations

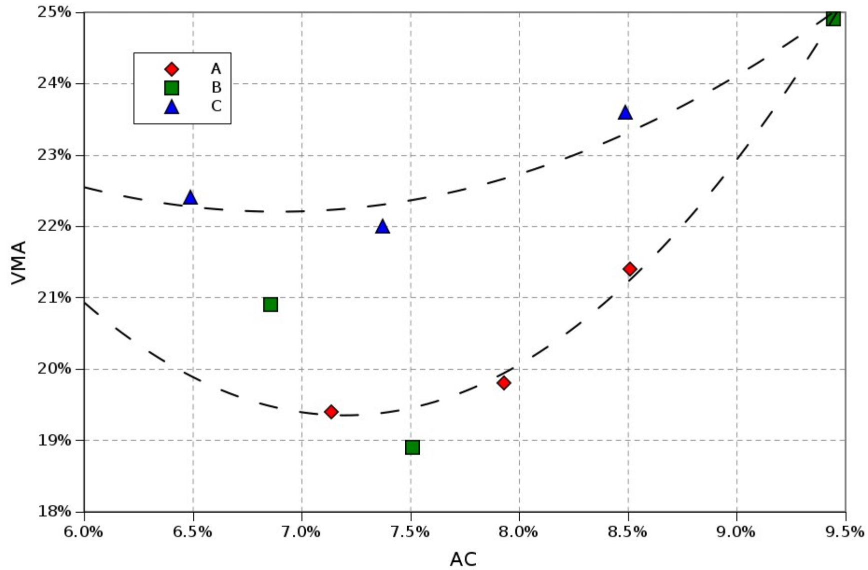


Figure 4.7: TOM VMA properties

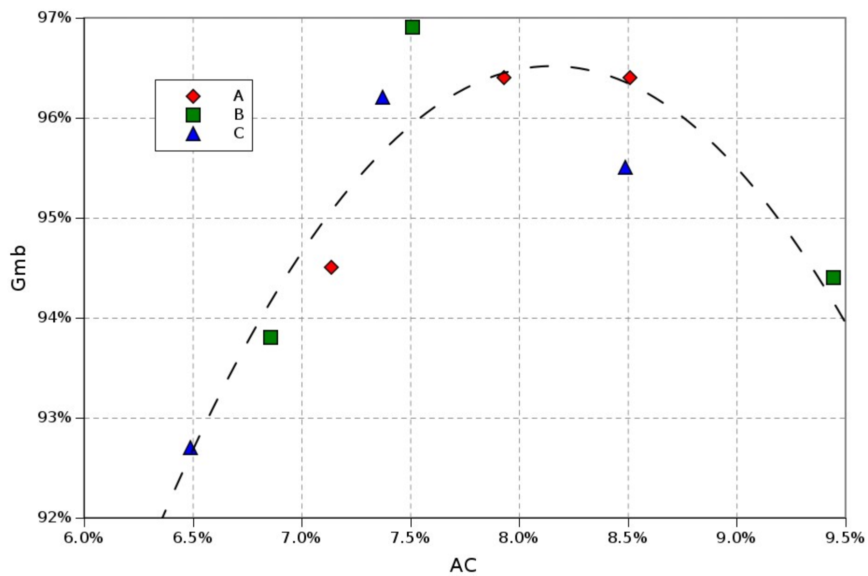


Figure 4.8: TOM density properties

4.3.1 Laboratory noise testing

The TOM laboratory-compacted specimen were tested with the modified BPT as described previously. Results show that the gradation of the TOM mix has an influence on noise generation as shown in Figure 4.9. This figure compares the mean noise levels obtained for the TOM mixtures at the three Grade 5 proportions: A) 40, B) 60, and C) 80 percent.

The standard deviations of the noise measurements are also shown, being less for gradation B. This figure indicates that coarser TOM gradations are relatively noisier although the variation in the noise measurements indicates that these differences are not particularly significant. No significant influence of asphalt content on noise was found, although the data do suggest a slight decrease in noise with an increase in asphalt content.

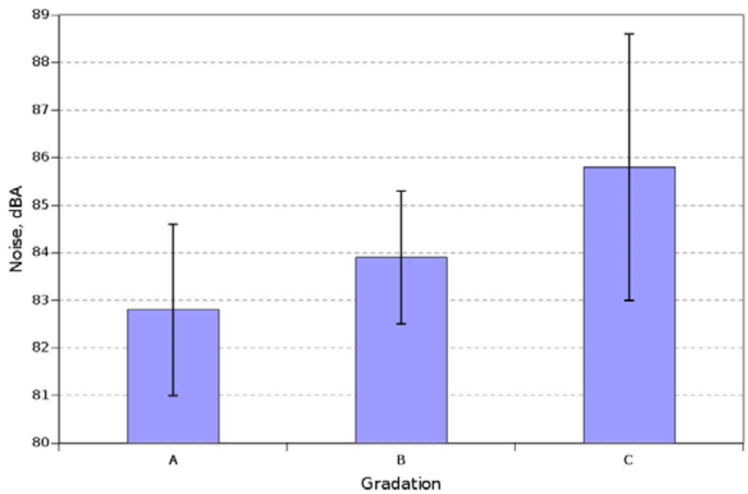


Figure 4.9: Influence of TOM gradation on noise

4.3.2 Design parameters

Various surface measures were investigated as possible design parameters for quieter mixtures. The surface macrotexture of laboratory-compacted specimen were tested using the Ames laser texture scanner (LTS) shown in Figure 4.10 as well as a new 3D laser displacement sensor (LDS) from Keyence. The LTS is a line scanning laser and the LDS provides a very accurate 3D profile of the scanned surface as shown in Figure 4.11, that shows the 3D surface of a TOM laboratory-compacted specimen. A closer view of the TOM surface with gradation A as scanned using the LDS is shown in Figure 4.12. The macrotexture on the surface of the laboratory-compacted specimen were found to be similar to the macrotexture of field compacted specimen.

In contrast to the CTM, these laser profilers provide multiple line measurements to measure surface macrotexture. Therefore, in addition to calculating surface macrotexture parameters such as MPD and the profile's RMS, a measure of the variation of these parameters may be determined.

Figure 4.13 shows a histogram of the distribution of macrotexture measured in terms of MPD on a TOM laboratory-compacted specimen. From this figure it can be seen that the macrotexture on a specimen can vary considerably depending on where the surface profile is scanned. The variability in surface macrotexture is an important noise parameter that can be controlled as part of the mixture design procedure and should be minimized for low-noise surfaces. It is interesting to note that the variation in surface macrotexture as shown is log-normally distributed.

Minimizing the surface macrotexture of compacted laboratory specimen and reducing the variability of this macrotexture provides a simple yet effective procedure to design quieter pavement surfaces. The TOM mixtures tested as part of this study had surface macrotexture in terms of MPD in the order of 0.5 mm with a standard deviation less than 0.2 mm.

The different designs of TOM laboratory-compacted specimen also show that asphalt content does not represent a significant influence factor in noise generation in these mixtures. A wide range of asphalt content were tested and as shown in Figure 4.14 there is not a significant relationship between asphalt content and noise.

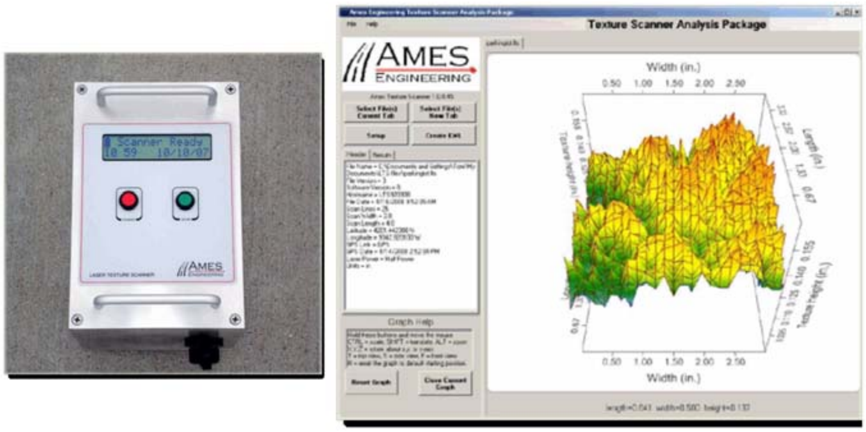


Figure 4.10: Ames laser texture scanner

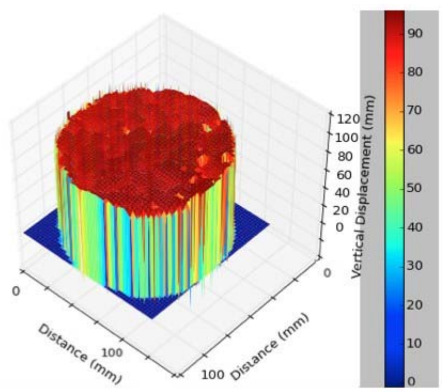


Figure 4.11: LDS-scanned TOM specimen

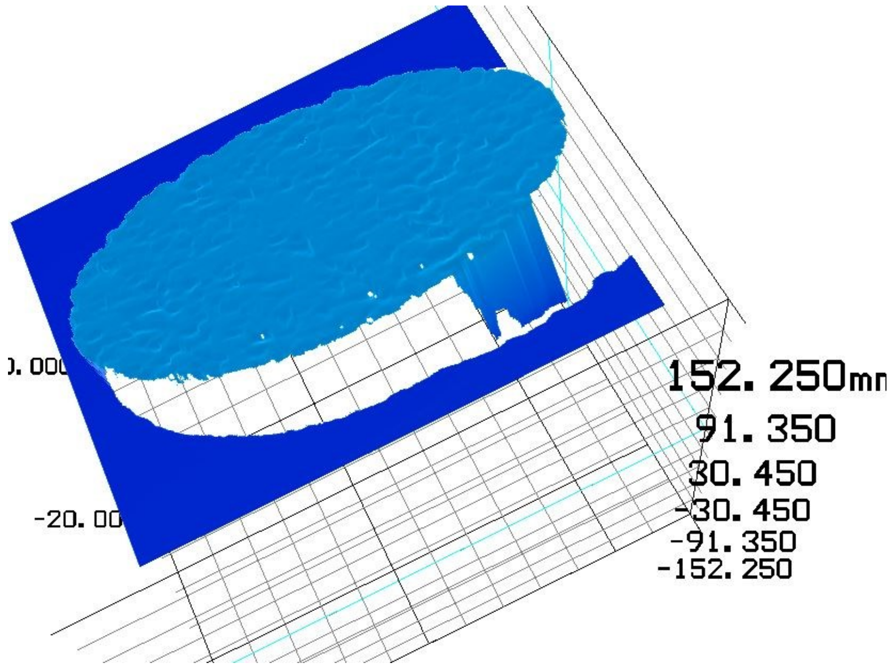


Figure 4.12: LDS scanned TOM surface profile

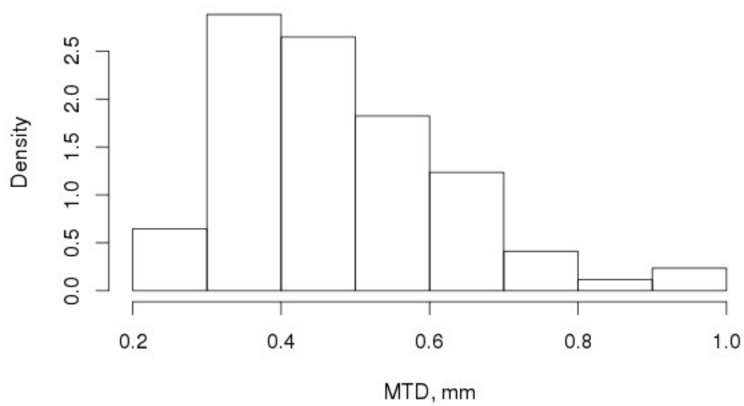


Figure 4.13: Surface macrotexture variability

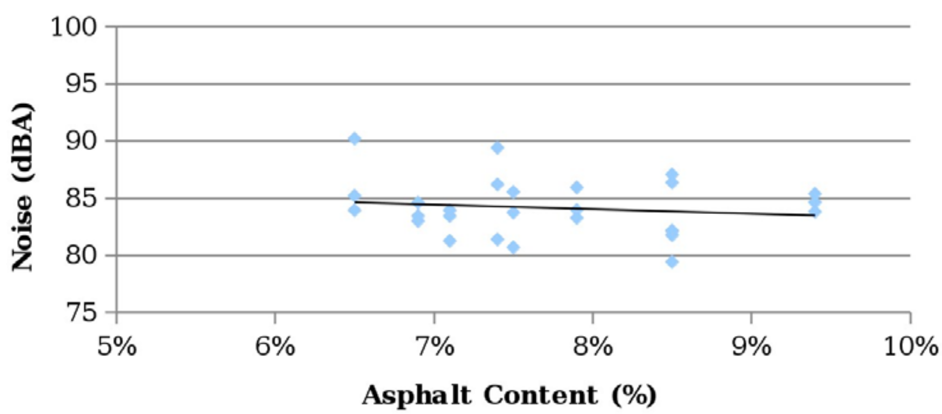


Figure 4.14: Influence of asphalt content on lab noise

Figure 4.15 shows the influence of macrotexture on noise for the TOM mixtures. A slight increase in noise with macrotexture was observed (as expected).

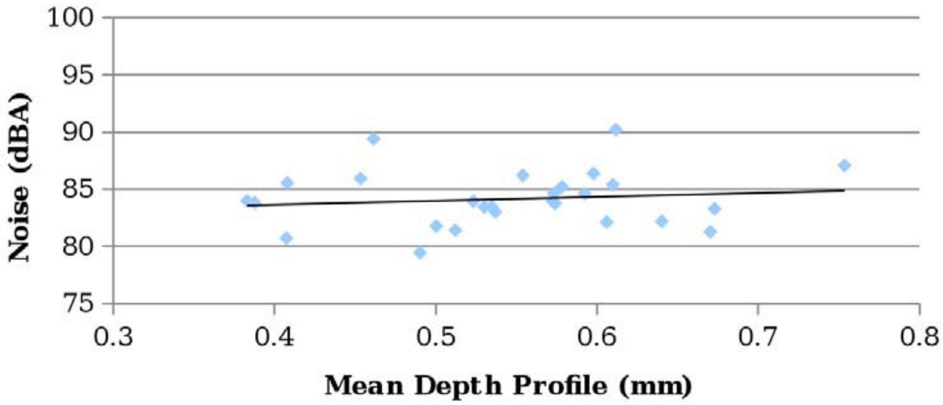


Figure 4.15: Influence of macrotexture on lab noise

4.3.3 Profile envelopes

In an attempt to identify design parameters that more closely relate to noise, enveloping of surface profiles was investigated. Enveloping was introduced in the literature review in Chapter 2 and allows establishing a surface profile that more closely represents the contact profile at the interface between the tire and the pavement. The tire is said to be "enveloping" the surface with which it is in contact. Since this is the source of road noise, it was investigated whether these envelopes would provide better design parameters that correlate with noise produced at the interface.

The von Meier enveloping procedure (von Meier et al., 1992) was applied to determine the tire contact profiles. This procedure is empirically based on the concept of limiting the second order derivative of the surface profile to a fixed value that represents a given tire stiffness using an iterative procedure. Using this procedure, envelopes can be calculated for different surface profiles as illustrated in Figure 4.16 and Figure 4.17 that show envelopes for a TOM and PFC surface respectively. These envelopes effectively bridge over the valleys in the original surface profile to simulate contact with an inflated tire.

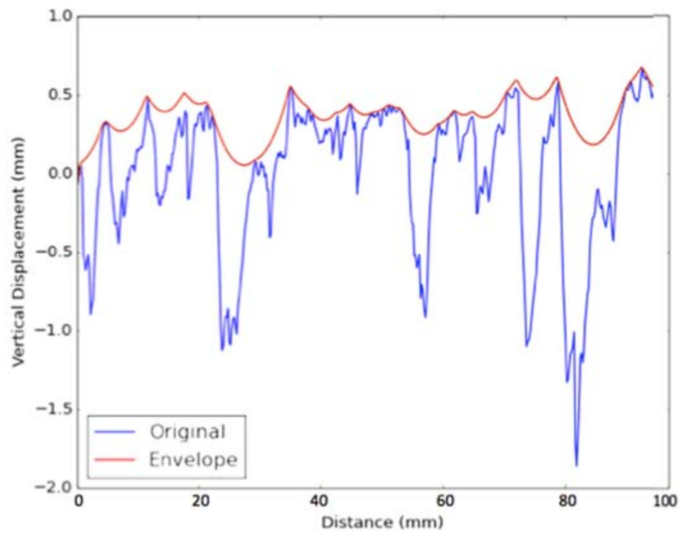


Figure 4.16: Envelope of TOM surface profile

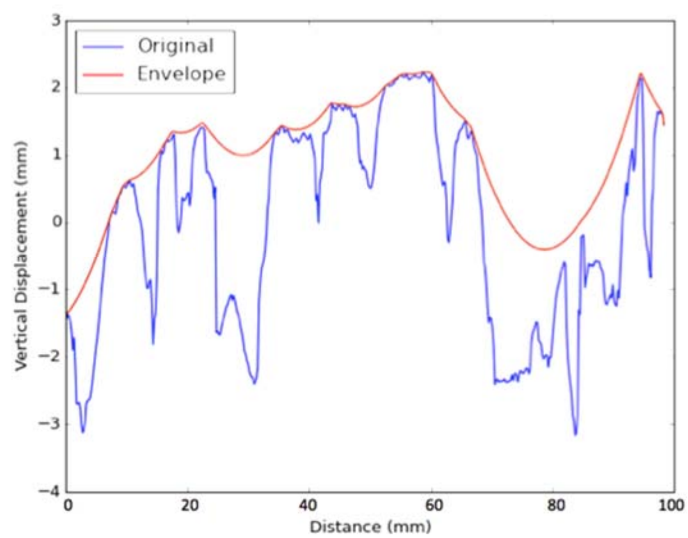


Figure 4.17: Envelope of PFC surface profile

Having calculated surface envelopes, new texture parameters can be determined for the enveloped profile as is typically done for the original profile, such as MTD and RMS, etc. The research team investigated the relationship between these parameters calculated for various surface profiles and found *no* significant improvement in the correlation between the macrotexture parameters calculated for the envelope and noise as measured on the surfaces.

4.4 Summary

With the implementation of the laboratory noise test, it was possible to accurately measure noise in the laboratory on samples of different pavement surfaces. This test shows promise in that it provides repeatable results that appear to accurately reflect noise levels as expected in the field. This allows the laboratory design of quieter pavement surfaces. The test can be run on both laboratory-compacted specimens and field cores and it is proposed that the test be further developed.

The test of the TOM laboratory-compacted specimen with different gradations and asphalt contents shows that the noise generated by these mixtures is not overly sensitive to variations in gradation or asphalt content. This is an important finding that motivates the use of TOM as a quiet pavement surface—in contrast, PFC would show significant changes given the sensitivity of the volumetric properties of PFC mixtures to variations in gradation and asphalt content. Another observation from the laboratory experiment is that the noise on the TOM at the higher asphalt contents was not significantly different from the TOM at lower asphalt contents. With field trafficking, mixtures tend to densify and the voids in the mixture tend to fill with asphalt as the mixture VMA is reduced. The research findings suggest that the noise of TOM will not vary significantly over time as these mixtures are trafficked in the field—a positive aspect when compared to the expected degradation of noise attenuation apparent for PFC mixtures over time.

Enveloping of surface profiles used to measure surface properties did not provide improved measures of macrotexture that correlate with noise measured on these surfaces. While no significant relationship was established between macrotexture parameters measured on various surfaces evaluated as part of the study and corresponding noise levels measured on these surfaces it was found that TOM mixtures with lower surface macrotexture are quieter surfaces.

Based on the laboratory investigation, a product of this research study was developed, i.e., detailed laboratory test procedures for measuring noise generated by surface materials, which is included in Appendix A of this report.

Chapter 5. Field testing

5.1 Introduction

This chapter addresses the field testing done as part of the study. A variety of different asphalt and concrete surfaces were tested. The testing included:

1. **On-board sound intensity.** The OBSI tests were run in accordance with AASHTO TP 76-12 using the dual probe setup that simultaneously collects leading and trailing edge noise data at the tire/pavement interface. This involved testing a lane at a constant speed of 60 mph using an SRTT over subsections that are at least 440 ft long. Tests of such subsections at 60 mph are performed for durations of 5 seconds. In addition to collecting noise, the air and road temperature, humidity and wind speed during OBSI testing is also collected and used in the software that calculates the sound intensity levels.

   The research team uses the same procedures and software as TxDOT for measuring, analyzing, and processing sound intensity data. To validate the OBSI measurements, comparisons of OBSI data collected as part of the study at the TTI test track near College Station were made against data collected by TxDOT on the same sections.

2. **Impedance tube sound absorption.** An impedance tube was used in the field by placing one side of the tube directly on the pavement surface and performing measurements with the tube in an upright position. This technique was used to evaluate the sound absorption properties of pavement surfaces in the field having correlated these measurements to laboratory noise absorption values. The impedance tube uses the two-microphone method described in ASTM E 1050-10. A standing wave field generated in the tube is measured by two microphones aligned along the length of the tube. The advantage of this method is that the absorption coefficient is determined at multiple frequencies from a single measurement.

3. **Macrotexture.** Surface macrotexture was measured using the CTM in accordance with ASTM E 2157 and the Ames LTS previously shown in Figure 4.10. Field test measurements were taken at multiple locations in the wheelpath and untrafficked sections on the road between the wheelpaths.

4. **Permeability or water-flow.** The falling head permeability test shown in Figure 5.1 was used to determine the time required to drain a known volume of water placed on the surface. This test is used by TxDOT to evaluate the permeability of PFC during construction. A flow time of 20 seconds or less is used to indicate acceptable permeability.

Figure 5.1: Falling head permeability test

The intent was to run field tests on each of the sections where OBSI testing was done. Unfortunately, the research team was unable to arrange traffic control on some of the more heavily trafficked sections. Furthermore, although sound absorption testing was done in the field, none of the impedance data collected could be processed or reported due to malfunctioning equipment.

5.2 Field sections

A variety of different field sections were tested. Although the focus of the testing was on evaluating the field noise performance of TOM and PFC, testing was also done on a dense-graded asphalt (DGA) surface that is included as a reference section and different concrete pavement surfaces with transverse and longitudinal tining and diamond-ground sections. The following is a summary of test results from each of the field sections evaluated.

5.2.1 Dense-graded HMA

OBSI testing was done on two dense-graded HMA sections, one along Ronald Reagan Blvd in the Austin district and the other at the TTI test track near College Station also known as TTI Annex. Dense-graded mixtures are typically not used as quiet surfaces but are included in the report for reference purposes against which to compare the relative noise levels of the other TOM and PFC sections tested.

DGA on Ronald Reagan Blvd (Austin district)

Figure 5.2 shows a photograph of the surface on Ronald Reagan Blvd. This surface is a dense-graded Type-C HMA. The research team was unable to arrange traffic control for field testing on Ronald Reagan Blvd.

Six subsections were identified for OBSI tests: three on the eastbound outside lanes (A, B, and C) and three on the westbound outside lanes (D, E, and F). Figure 5.3 summarizes the OBSI noise levels measured on the DGA sections and shows the deviation of all OBSI measurements on the respective sections from the overall average noise level measured. Figure 5.4 shows the spectra of OBSI noise levels with frequency. This figure summarizes the range in average noise levels measured at each of the third-octave band frequencies shown.

The average OBSI noise level on the DGA section tested is 102.2 dBA. This noise level is typical for DGA mixtures in general. The spectra plot indicates that the maximum noise levels occur at the 1 kHz frequency.

Figure 5.2: DGA surface on Ronald Reagan Blvd

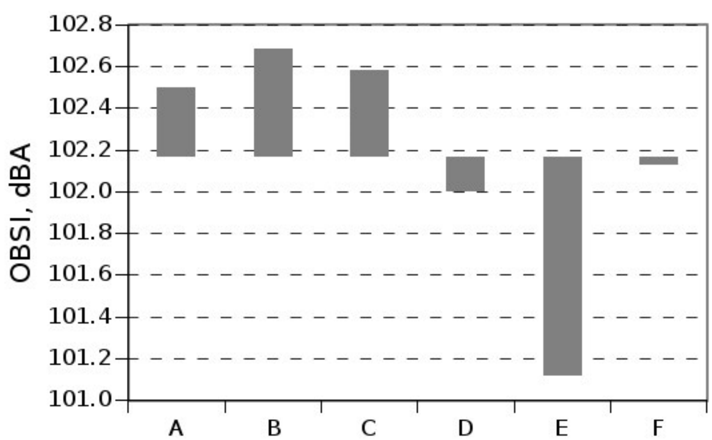


Figure 5.3: OBSI overall levels from DGA on Ronald Reagan Blvd

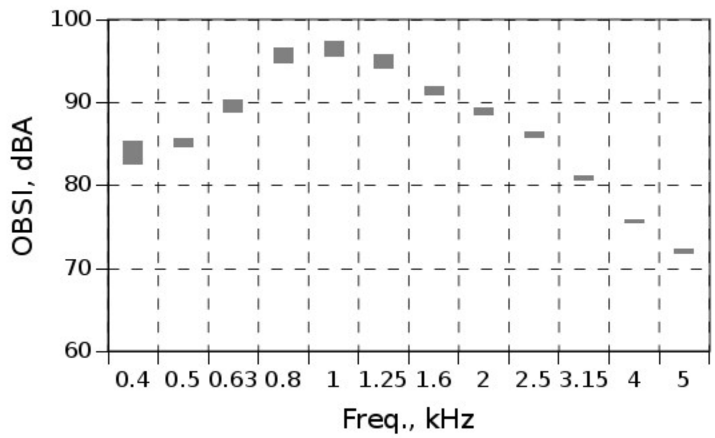


Figure 5.4: OBSI spectra from DGA on Ronald Reagan Blvd

DGA at TTI test track

Figure 5.5 shows a photograph of the DGA surface at the TTI test track. This is a dense-graded Type D mix.

Two subsections were identified for OBSI tests along this short stretch of track. These are TP1 (from station 595 to 1125 going south) and TP2 (from station 0 to 530 going south). Figure 5.6 summarizes the OBSI noise levels measured on the DGA sections and Figure 5.7 shows the spectra of OBSI noise levels with frequency.

Table 5.1 shows the macrotexture measurements in terms of MPD in millimeters for the DGA at the TTI test track. The MPD values are the means and standard deviations of three measurements each in the right wheel path and in the center of the lane.

Table 5.1: Macrotexture from DGA at TTI test track

Direction	Location	Mean MPD, mm	Stdev MPD, mm
TP1	Right	0.45	0.04
TP1	Center	0.53	0.04
TP2	Right	0.64	0.10
TP2	Center	0.57	0.09

TP1 = from station 595 to 1125 going south; TP2 = from station 0 to 530 going south; Stdev = standard deviation

Figure 5.5: DGA surface at TTI test track

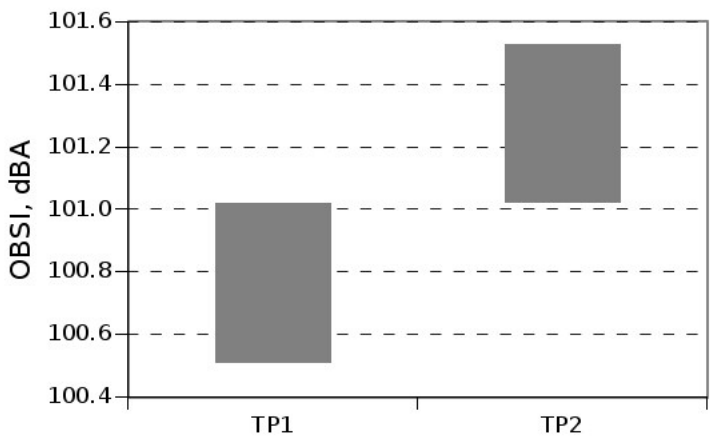


Figure 5.6: OBSI overall levels from DGA at TTI test track

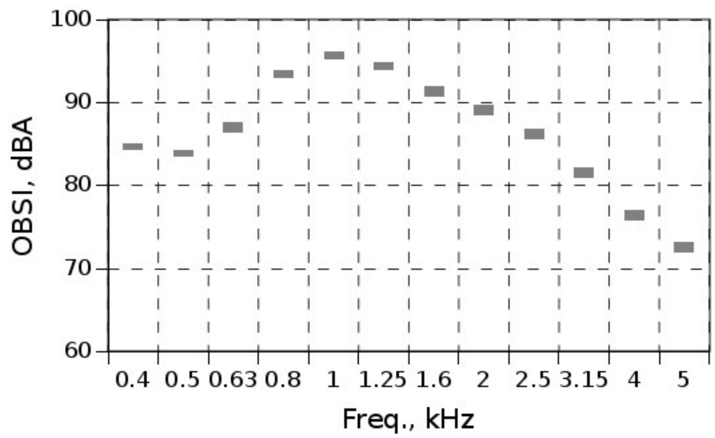


Figure 5.7: OBSI spectra from DGA at TTI test track

The average OBSI noise level on the Type-D DGA section tested at the TTI test track is 101 dBA. This is lower than the noise level measured on the Type-C DGA on Ronald Reagan Blvd and suggests that finer Type-D mixtures with lower macrotexture are quieter than coarser Type-C dense-graded mixtures. The spectra plot indicates that the maximum noise levels occur at the 1 kHz frequency.

5.2.2 Permeable friction course

PFC is a popular surface used on high utility, heavily trafficked roads in Texas specifically to improve safety during wet conditions owing to its high surface friction and ability to rapidly drain rainfall reducing splash and spray. These mixtures are characterized by high surface porosity that serves to significantly attenuate tire-pavement noise and consequently are known as low-noise pavement surfaces. The high porosity of these mixtures, however, promotes oxidation and aging of the asphalt in the mix that can lead to early deterioration and raveling of the surface.

PFC on SH6 (Bryan district)

This is a PFC section, constructed in May of 2009, located north of Calvert in the Bryan District. The project consists of six subsections, three in the northbound (5-1, 5-3, and 5-4) and three in the southbound (5-5, 5-6, and 57) directions, all with the same PFC mixture. Figure 5.8 shows a photograph of the PFC surface texture, and although surface voids are apparent, there also appears to be signs of flushing on the surface that would reduce the noise attenuating benefits typically obtained from the porosity of PFC mixtures.

The figures and tables that follow summarize the results of noise and field tests done on these sections. Figure 5.9 summarizes the OBSI noise levels recently measured on the PFC sections. This figure shows the deviation of all OBSI measurements on the respective sections from the overall average noise level measured. Figure 5.10 shows the spectra of OBSI noise levels with frequency. This figure summarizes the range in average noise levels measured at each of the third-octave band frequencies shown.

Table 5.2 shows the permeability in flow time (seconds) and macrotexture measurements in terms of MPD in millimeters for the PFC on SH6 in the Bryan District.

Measurements on the northbound and southbound lanes are shown. The MPD values are the means and standard deviations of three measurements each in the right wheel path and in the center of the lane.

Table 5.2: Permeability and macrotexture from PFC on SH6

Direction	Location	Flow, s	Mean MPD, mm	Stdev MPD, mm
NB	Right	42	1.82	0.052
NB	Center	21	2.35	0.137
SB	Right	18	1.91	0.079
SB	Center	20	1.98	0.095

NB = northbound; SB = southbound; Stdev = standard deviation

The mean OBSI noise level on this PFC section is high at 104.2 dBA. This is higher than the mean noise level measured on the dense-graded reference section. The frequency spectra also indicate that the noise levels are higher at the lower frequency ranges below 1 kHz. Even though this PFC surface is not very old, it is showing signs of flushing. The porosity of the PFC in the wheelpaths appears to be significantly reduced compared to that between the wheelpaths on the northbound lanes. The surface macrotexture in the wheelpaths is also lower than that between the wheelpaths indicating loss of surface voids and possible consolidation or embedment of the aggregates in the wheelpaths.

Figure 5.8: PFC surface on SH6

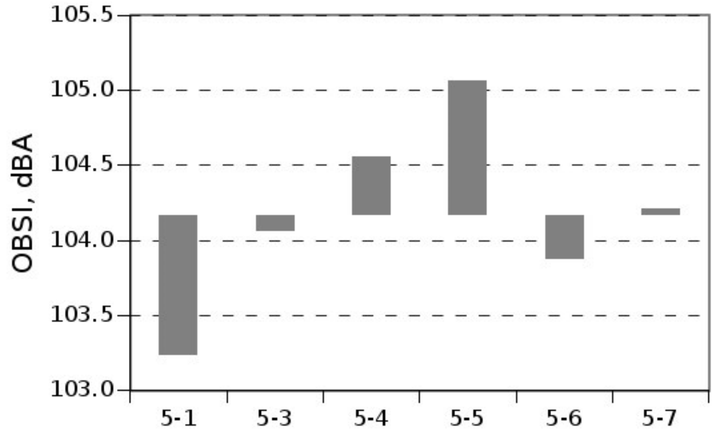


Figure 5.9: OBSI overall levels from PFC on SH6

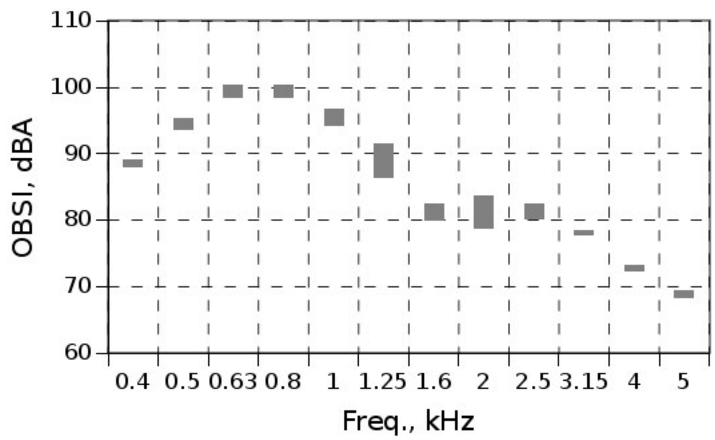


Figure 5.10: OBSI spectra from PFC on SH6

PFC on SH195 (Austin district)

The PFC on SH195 near Florence is a new porous pavement that was tested for OBSI in November 2014, shortly after it had been opened to traffic. Figure 5.11 shows a photograph of the road surface from which it can be seen that the surface was sprayed with a fog seal or rejuvenator after showing signs of early oxidation.

Figure 5.11: PFC surface on SH195

Six subsections were identified for OBSI tests. Figure 5.12 summarizes the OBSI noise levels measured on the PFC sections and Figure 5.13 shows the spectra of OBSI noise levels with frequency.

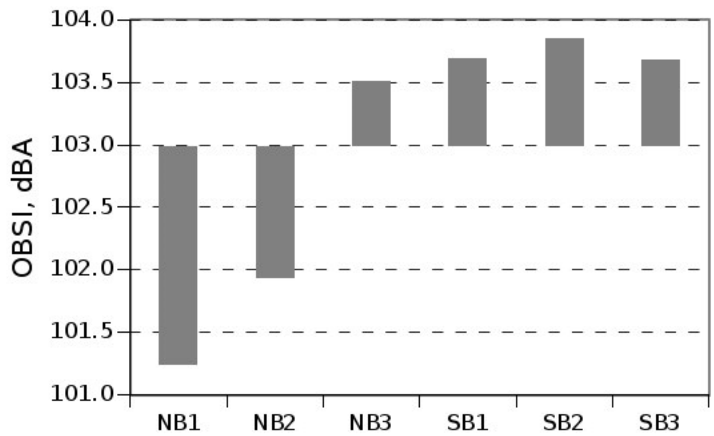


Figure 5.12: OBSI overall levels from PFC on SH195

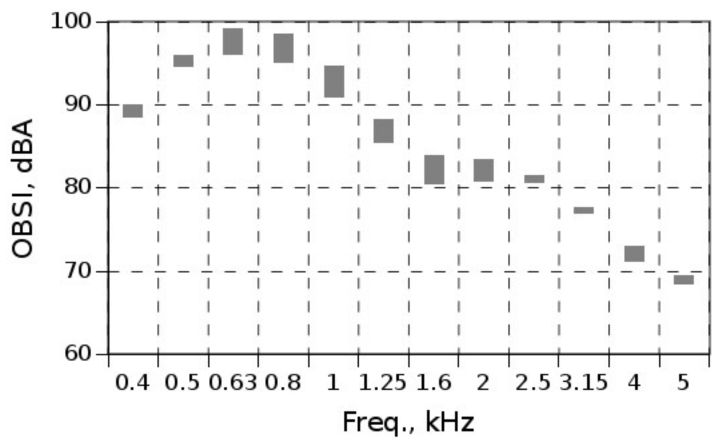


Figure 5.13: OBSI spectra from PFC on SH195

Table 5.3 shows the permeability and macrotexture measurements in terms of MPD in millimeters for the PFC on SH195. Measurements on the northbound and southbound lanes are shown. The MPD values are the means and standard deviations of three measurements each in the right wheel path and in the center of the lane.

Table 5.3: Permeability and macrotexture from PFC on SH195

Direction	Location	Flows	Mean MPD	Stdev MPD
NB	Right	18	1.86	0.20
NB	Center	14	2.04	0.28
SB	Right	12	1.95	0.16
SB	Center	13	2.00	0.24

NB = northbound; SB = southbound; Stdev = standard deviation

The mean OBSI noise level on this PFC section is at 103 dBA, which is surprisingly high given that this is a newly paved PFC. This is higher than the mean noise level measured on the dense-graded reference section. The OBSI noise levels ranged quite considerably from about 101 to 104 dBA. The frequency spectra also indicate that the noise levels are higher at the lower frequency ranges below 1 kHz. The permeability flow times are well below 20 seconds and indicate that this surface has adequate porosity although it was indicated that the fog seal did increase the flow time on the surface by as much as 7 seconds at certain locations.

PFC on US 281 (San Antonio district)

Two different PFC sections were tested on the heavily trafficked US281 in San Antonio. These sections are located north of IH 35 in the vicinity of the San Antonio Zoo between IH 35 and E Basse Rd. The PFC on these sections use asphalt rubber (AR) binder instead of PG76-22 and are among the quieter PFC in the State.

PFC1 is the older of the two sections constructed in 2005. Figure 5.14 shows a photograph of the road surface. Six subsections were tested on this PFC, S3, S4 and S5 on the southbound outside lanes and S12, S13 and S14 on the northbound outside lanes. Figure 5.15 summarizes the OBSI noise levels measured on the PFC sections and Figure 5.16 shows the spectra of OBSI noise levels with frequency.

PFC2 is located north of PFC1 but runs adjacent to it and was constructed in 2006. Figure 5.17 shows a photograph of the road surface. Seven subsections were tested on this PFC—S6, S7, S8, and S17 on the southbound outside lanes and S9, S10, and S11 on the northbound outside lanes. Figure 5.18 summarizes the OBSI noise levels measured on the PFC sections and Figure 5.19 shows the spectra of OBSI noise levels with frequency.

Figure 5.14: PFC1 surface on US281

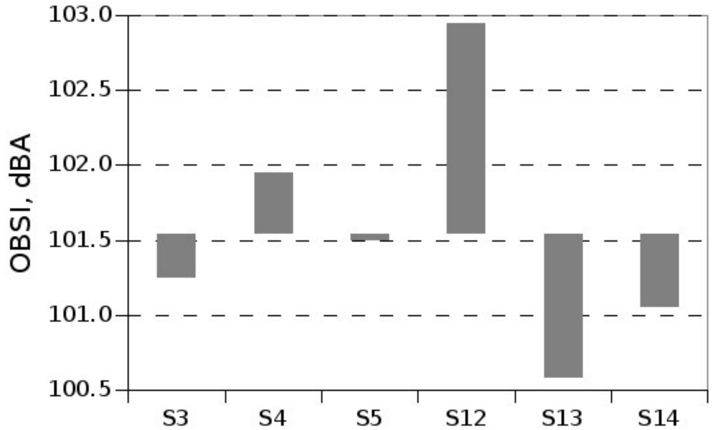


Figure 5.15: OBSI overall levels from PFC1 on US281

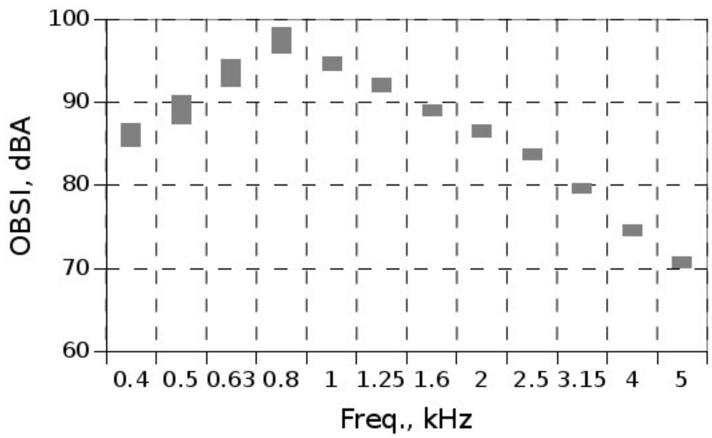


Figure 5.16: OBSI spectra from PFC1 on US281

Figure 5.17: PFC2 surface on US281

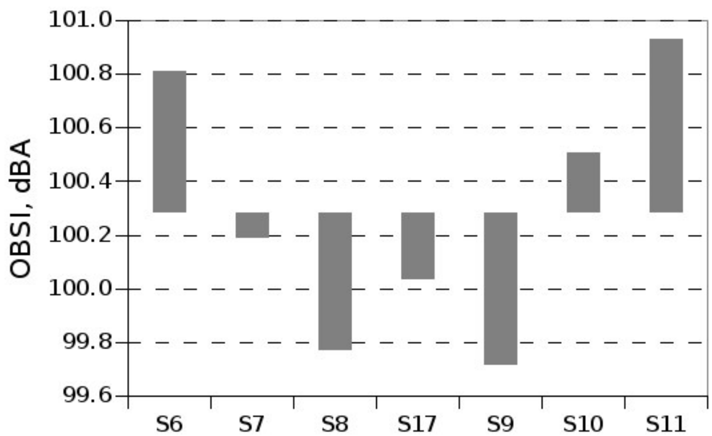


Figure 5.18: OBSI overall levels from PFC2 on US281

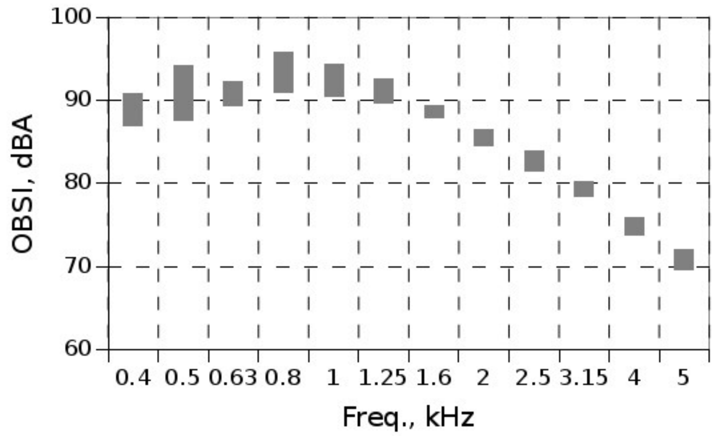


Figure 5.19: OBSI spectra from PFC2 on US281

The research team was unable to arrange traffic control on US281 and were therefore unable to run field tests to measure the macrotexture or permeability of these sections.

From the OBSI test results, these are the quietest PFC sections evaluated as part of the study. The average OBSI levels on PFC1 is at 101.5 dBA and at 100.3 dBA on PFC2. This is lower than the mean noise level measured on the dense-graded reference section.

PFC on FM1431 (Austin district)

OBSI testing was done on the PFC section on FM1431 between Leander and Lago Vista. This PFC section was constructed specifically to address wet weather accidents on this curved stretch of road. The research team was unable to arrange traffic control for field testing on this section.

Figure 5.20 shows a photograph of the road surface. Six subsections were tested on this PFC: three on the eastbound outside lanes (A, B, and C) and three on the westbound outside lanes (D, E, and F). Figure 5.21 summarizes the OBSI noise levels measured on the PFC sections and Figure 5.22 shows the spectra of OBSI noise levels with frequency.

Figure 5.20: PFC surface on FM1431

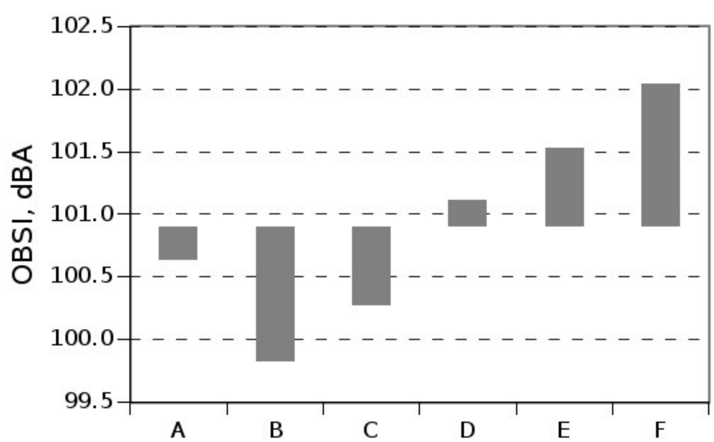


Figure 5.21: OBSI overall levels from PFC on FM1431

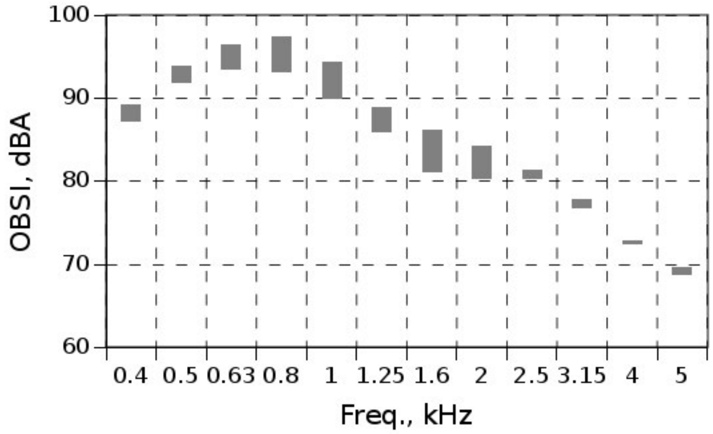


Figure 5.22: OBSI spectra from PFC on FM1431

The average noise level on this PFC section is 101 dBA, which is lower than the average noise levels measured on the DGA reference section. The highest noise levels were recorded at frequency levels below 1 kHz, which appears to be typical for the PFC sections tested as part of this study.

PFC on IH 30 (Dallas district)

Two PFC mixtures on IH 30 just west of IH 35E in the Dallas district were tested as part of the study. The older of these (PFC1) passing under Beckley Avenue was constructed in 2006 and shows signs of ravelling. The second (PFC2), further west from PFC1 was constructed in 2010. Figure 5.23 shows a photograph of the PFC1 road surface and Figure 5.24 that of PFC2. These mixtures were placed to reduce noise along this section of highway that passes through residential and commercial areas, which also includes a noise wall as shown in Figure 5.25. This section of highway is interesting from a highway noise perspective and is addressed as a case study in Chapter 6.

Figure 5.23: PFC1 surface on IH 30

Figure 5.24: PFC2 surface on IH 30

Figure 5.25: Noise wall along IH30 section

OBSI testing was done on both the eastbound and westbound lanes of these two surfaces. Figure 5.26 and Figure 5.27 summarize the OBSI noise levels measured on the PFC1 and PFC2 sections respectively and Figure 5.28 and Figure 5.29 show the spectra of OBSI noise levels with frequency on PFC1 and PFC2 respectively.

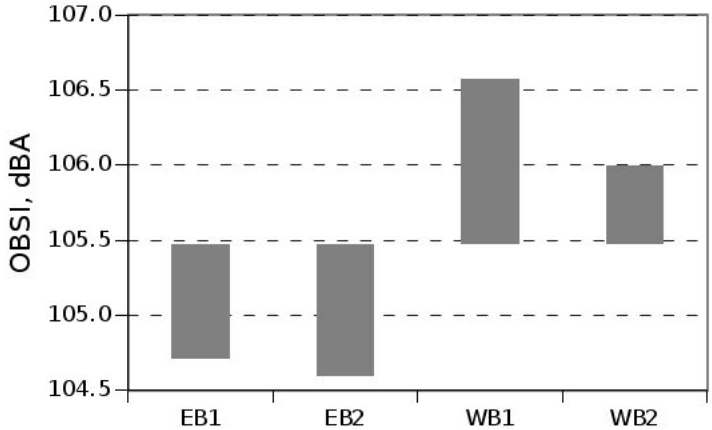


Figure 5.26: OBSI overall levels from PFC1 on IH 30

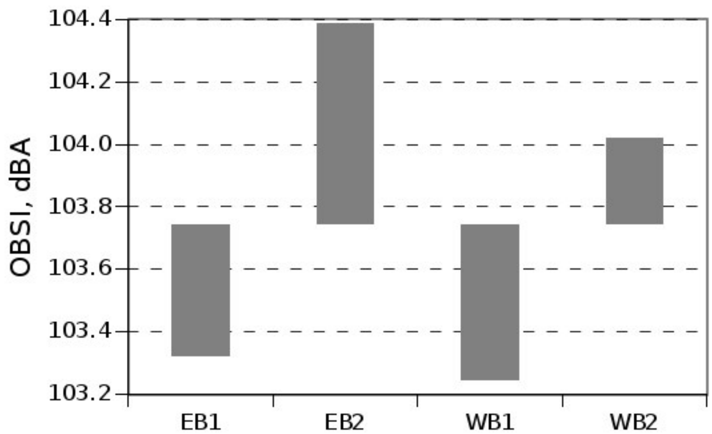


Figure 5.27: OBSI overall levels from PFC2 on IH 30

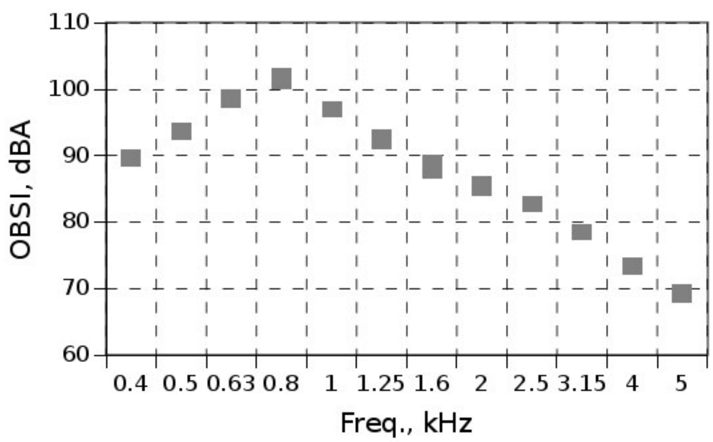


Figure 5.28: OBSI spectra from PFC1 on IH 30

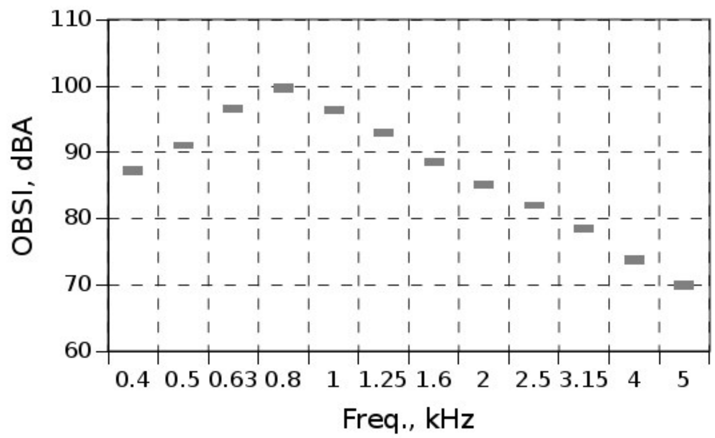


Figure 5.29: OBSI spectra from PFC2 on IH 30

Table 5.4 and Table 5.5 shows the macrotexture measurements in terms of MPD in millimeters for the two PFC surfaces tested on IH 30, i.e., PFC1 and PFC2 respectively. Measurements on the westbound and eastbound lanes are shown. The MPD values are the means and standard deviations of three measurements each in the right wheel path and in the center of the outside lane.

Table 5.4: Macrotexture from PFC1 on IH 30

Direction	Location	Mean MPD	Stdev MPD
WB	Right	1.82	0.20
WB	Center	1.75	0.10
EB	Right	1.36	0.15
EB	Center	1.50	0.28

Table 5.5: Macrotexture from PFC2 on IH 30

Direction	Location	Mean MPD	Stdev MPD
WB	Right	1.52	0.18
WB	Center	1.64	0.16
EB	Right	1.36	0.20
EB	Center	1.55	0.08

WB = westbound; EB = eastbound; Stdev = standard deviation

The mean OBSI noise level on the older PFC1 section is at 105.5 dBA and that on PFC2 at 103.7 dBA. These levels are relatively high considering that these are porous mixtures that were placed for low noise. The macrotexture on PFC1 is on average slightly higher than PFC2 but the increased noise on PFC1 is probably due to raveling of this aged section that is also observed from the increased variation in macrotexture on this surface. Permeability tests were done on all the surfaces and *no* flow was observed with the water standing in the test tube as shown in Figure 5.30 indicating that these “permeable” friction courses were impermeable. Inspection of the surface indicates that the surface voids or pores of these mixtures were fused with binder, sand, debris and aggregates with no paths to drain surface water as shown in Figure 5.31. This surface “fusion” apparent on older PFC surfaces was also observed and reported by the research team evaluating PFC mixtures in Texas as part of a prior TxDOT research project 0-5836 (Arámbula et al., 2013). This effectively negates all the noise reduction benefits from surface porosity and, given the higher macrotetxure on these PFC mixtures, results in a noisier surface.

Figure 5.30: Permeability testing of PFC2 on IH 30

Figure 5.31: Close-up of PFC1 surface texture

5.2.3 Thin overlay mixtures

TOMs are used extensively in the Austin district as a rehabilitation option to overlay structurally sound pavements. These mixtures are paved as thin layers with a minimum lift thickness of 0.5 inches for TOM Type F mixture and 0.75 inches for TOM Type C. The maximum aggregate sizes in these mixtures is restricted to 3/8 inches thus providing surfaces with relatively low macrotexture.

TOM on RM3238 (Austin district)

The RM3238 section is a TOM, west of Austin, that covers an 8-mile stretch, from just north of US 290, between Bee Caves and Dripping Springs. Figure 5.32 shows a photograph of the road surface.

Six subsections were identified (A, B, and C are northbound and D, E and F are southbound). Macrotexture (MPD) was measured on the northbound lanes to be 0.6 mm in the wheelpath and 0.4 mm between the wheelpaths. Permeability testing was done but no water drainage was apparent as shown in Figure 5.33.

Figure 5.34 summarizes the OBSI noise levels measured on the TOM sections and Figure 5.35 shows the spectra of OBSI noise levels with frequency.

The mean OBSI noise level on this TOM section is low at 99.8 dBA. It is quieter than the DGA reference section. The frequency spectra also indicate that the noise levels are highest at a frequency of 1 kHz and the low frequency noise is considerably lower than that observed on the PFC mixtures tested. The low noise levels on this surface are attributed to the low surface macrotexture. The surface appears to be sufficiently rough to provide adequate friction and skid resistance. These mixtures are dense and impermeable with little or no surface porosity.

Figure 5.32: TOM surface on RM3238

Figure 5.33: Permeability testing on RM3238

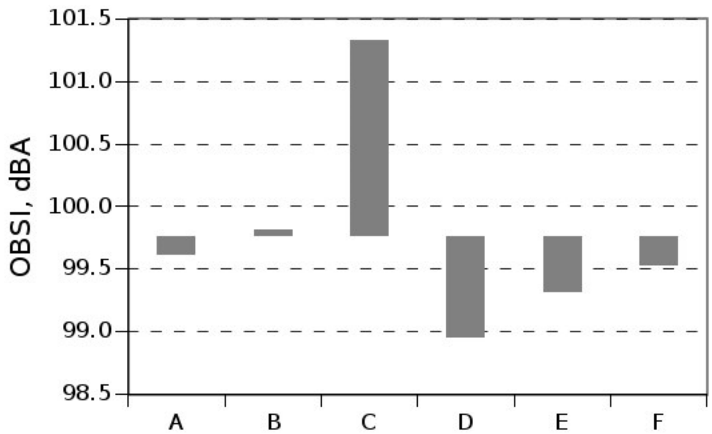


Figure 5.34: OBSI overall levels from TOM on RM3238

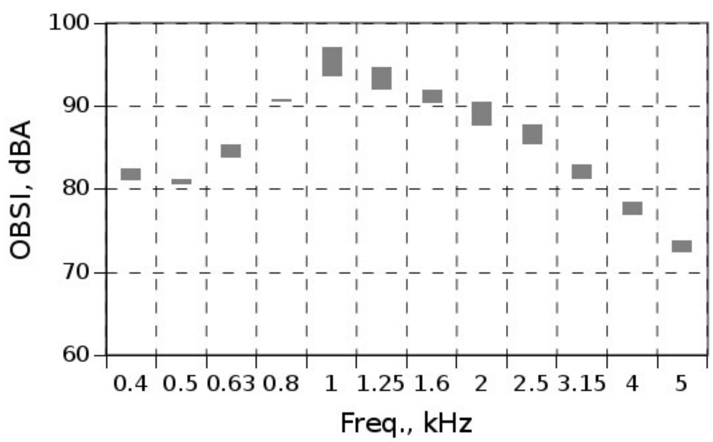


Figure 5.35: OBSI spectra from TOM on RM3238

TOM on RM12 (Austin Dstrict)

RM12 is a rural road, just west of Austin. In this case, the TOM overlay is 0.5 inches thick. This overlay mix is one of the first ultra-thin pavements in the Austin District and extends for 6.21 miles from just south of US290 to the Wimberley city limits. This section was originally resurfaced with a seal coat, but it was so noisy, that shortly thereafter, the district decided to replace it with the ultra-thin pavement. Figure 5.36 shows a photograph of the road surface.

Six subsections were identified for OBSI tests. Figure 5.37 summarizes the OBSI noise levels measured on the TOM sections and Figure 5.38 shows the spectra of OBSI noise levels with frequency.

Table 5.6 shows the macrotexture measurements in terms of MPD in millimeters for the TOM on RM12. Measurements on the northbound and southbound lanes are shown. These MPD values are the means and standard deviations of three measurements each in the right wheel path and in the center of the lane. Permeability testing indicated no drainage of water from the TOM surface.

Table 5.6: Macrotexture from TOM on RM12

Direction	Location	Mean MPD	Stdev MPD
NB	Right	0.36	0.1
NB	Center	0.42	0.1
SB	Right	0.35	0.1
SB	Center	0.52	0.1

NB = northbound; SB = southbound; Stdev = standard deviation

The mean OBSI noise level on this TOM section is very low at 97.4 dBA. It is significantly quieter than the DGA reference section. The frequency spectra also indicate that the noise levels are highest at a frequency of 1 kHz.

TOM on IH 35 near Serenada (Austin District)

OBSI testing was done on the new section of TOM on IH 35 near Serenada. The research team was unable to arrange traffic control for field testing on this section. Figure 5.39 and Figure 5.40 show photographs of the TOM surface on the northbound and southbound lanes respectively.

Figure 5.36: TOM surface on RM12

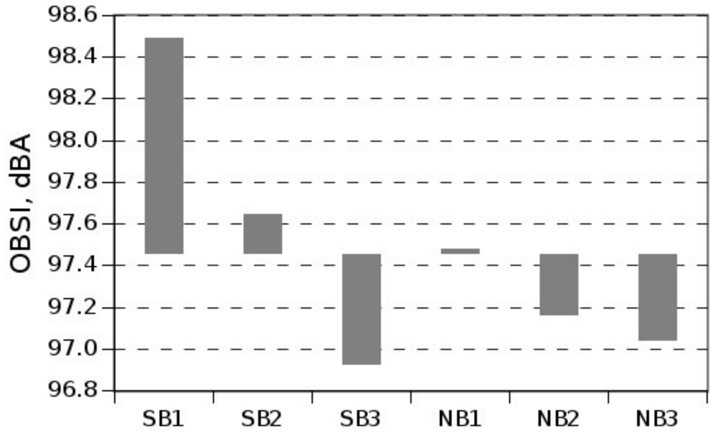


Figure 5.37: OBSI overall levels from TOM on RM12

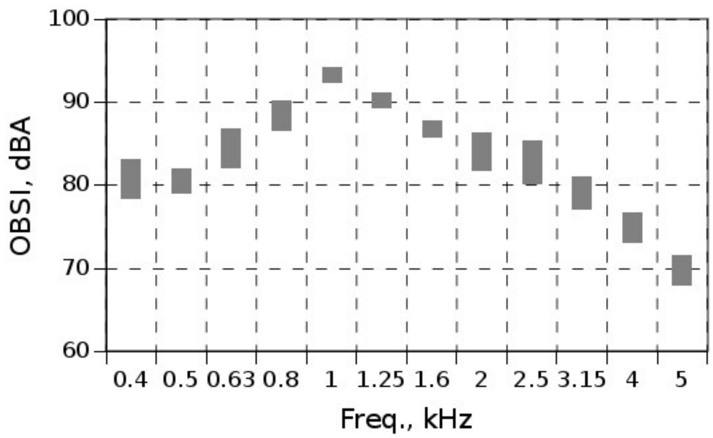


Figure 5.38: OBSI spectra from TOM on RM12

Figure 5.39: TOM surface on northbound IH 35

Figure 5.40: TOM surface on southbound IH 35

Three sections were tested in both the northbound and southbound lanes. Figure 5.41 summarizes the OBSI noise levels measured on the TOM sections and Figure 5.42 shows the spectra of OBSI noise levels with frequency.

The mean OBSI noise level on this TOM section is very low at 97.5 dBA. It is significantly quieter than the DGA reference section.

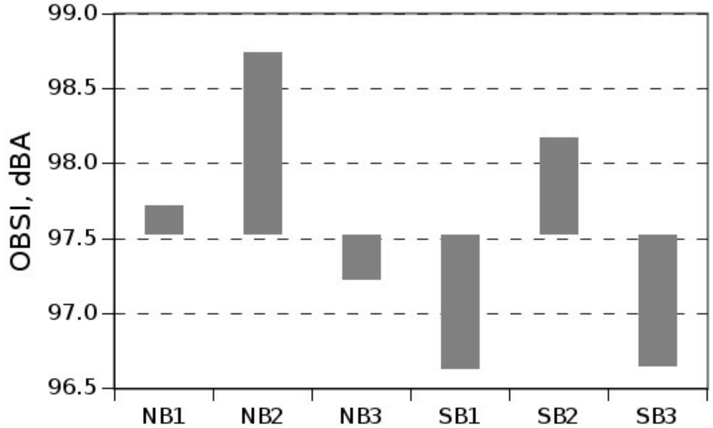


Figure 5.41: OBSI overall levels from TOM on IH 35

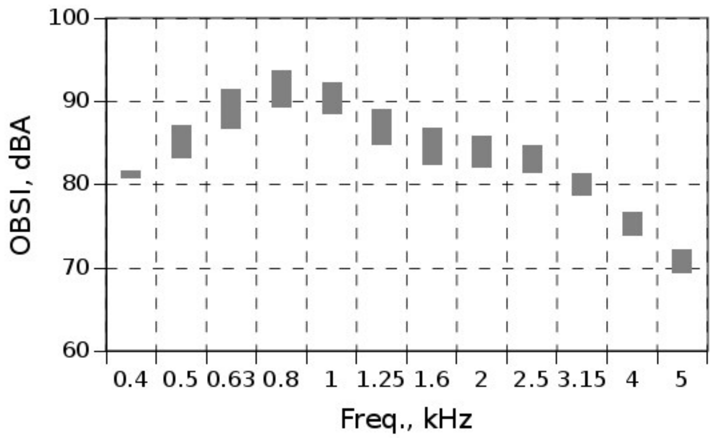


Figure 5.42: OBSI spectra from TOM on IH 35

TOM on US183A (Austin district)

A new TOM section on the southbound frontage road that runs alongside the US183A toll road was tested using the OBSI but the research team were unable to arrange traffic control on this section for field testing.

Figure 5.43 shows a photograph of the road surface. Three subsections were tested on this TOM (A, B, and C) on the southbound outside lanes. Figure 5.44 summarizes the OBSI noise levels measured on the PFC sections and Figure 5.45 shows the spectra of OBSI noise levels with frequency.

Figure 5.43: TOM surface on US183A

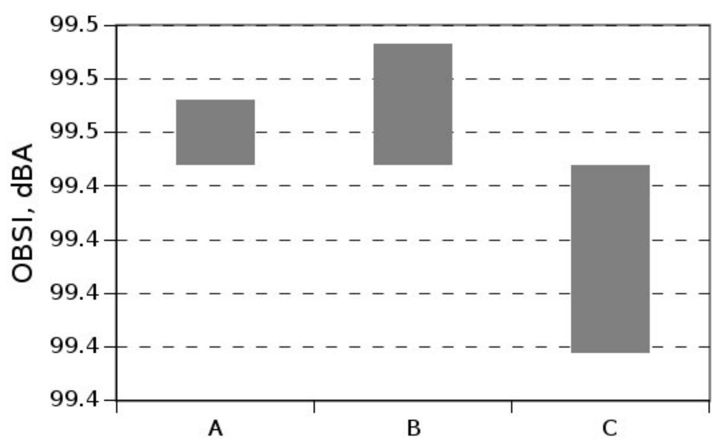


Figure 5.44: OBSI overall levels from TOM on US183A

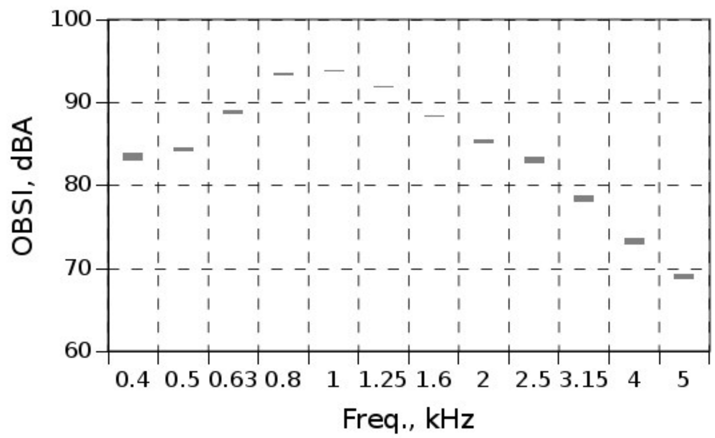


Figure 5.45: OBSI spectra from TOM on US183A

The thin overlay mixture on this section is a coarser TOM-C mix and the average noise level measured is 99.4 dBA, which is lower than the noise levels measured on the DGA reference section.

5.2.4 Concrete pavements

Concrete pavement surfaces are in general noisier than asphalt surfaces and efforts to reduce the noise on these focus primarily on the surface finish or tining that is applied to the surface to improve friction and skid resistance. TxDOT typically uses transverse tining on CRCP even though longitudinal tining is reportedly quieter. This study evaluated noise on both transversely and longitudinally tined sections at the TTI test track as well as on a diamond-ground CRCP.

Diamond-ground CRCP on IH 35W

The diamond-ground section of CRCP on IH 35W near Fort Worth was previously evaluated by the research team as part of a TxDOT implementation study 5-9046 (Buddhavarapu et al., 2014). Follow-up measurements, effectively 2 years following the diamond-grinding, were done as part of the current study to evaluate the noise and texture levels on these sections.

The diamond-ground CRCP comprises three sections, where the construction on the northbound and southbound lanes are the same. Sections 1 and 2 had carpet and burlap drag finishes respectively whereas section 3 was transversely tined. Noise measurements using the OBSI method were collected on the outside lane and texture measurements on the inside and outside lanes on the both the northbound and southbound sections.

Figure 5.46 shows a photograph of the diamond-ground carpet drag road surface on section 1. Figure 5.47 shows a photograph of the diamond-ground transversely tined road surface on section 3.

Figure 5.48 through Figure 5.53 summarize the OBSI noise levels measured on the CRCP sections and the spectra of OBSI noise levels with frequency.

Table 5.7 shows the macrotexture measurements in terms of MPD in millimeters for the diamond-ground CRCP on IH 35W. Measurements on the three sections, on the inside and outside lanes of the northbound and southbound lanes are shown. These MPD values are the means and standard deviations of three measurements each in the right wheel path and in the center of the lane.

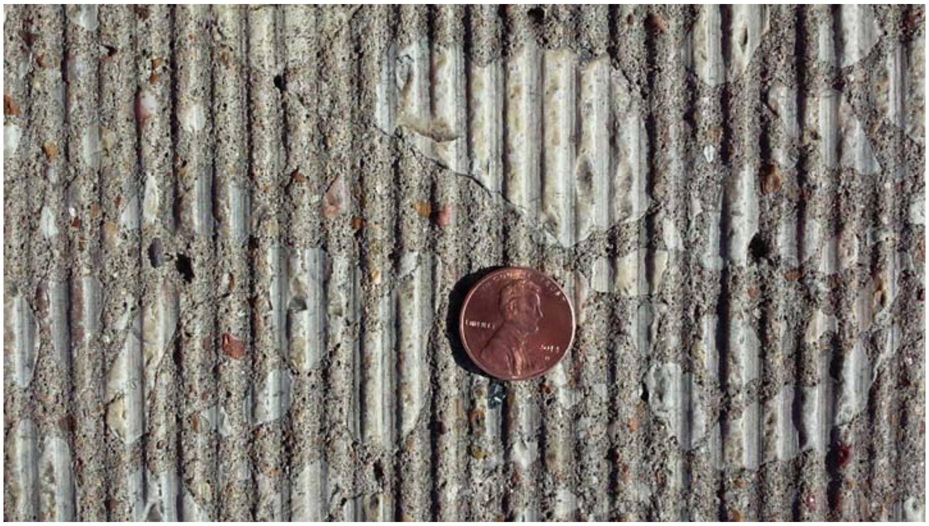


Figure 5.46: Diamond-ground surface on IH 35W (Section 1)

Figure 5.47: Diamond-ground surface on IH 35W (Section 3)

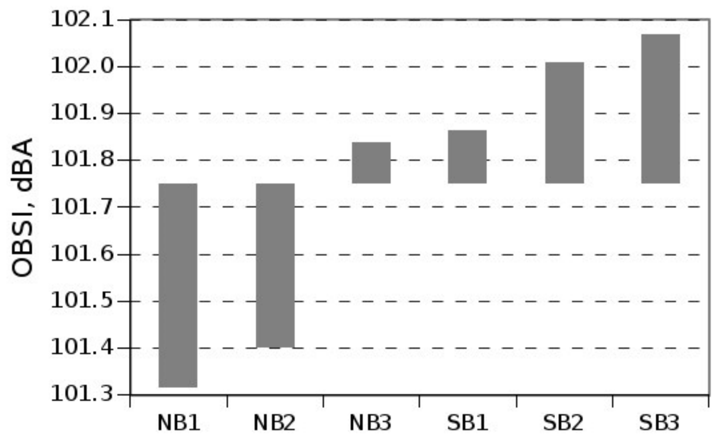


Figure 5.48: OBSI overall levels from CRCP on IH 35W (Section 1)

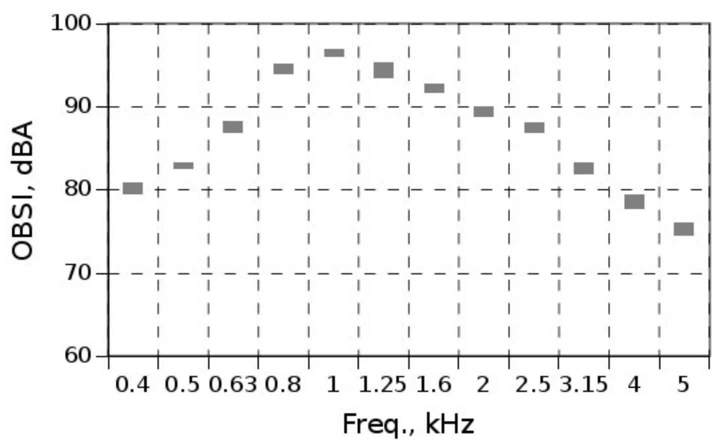


Figure 5.49: OBSI spectra from CRCP on IH 35W (Section 1)

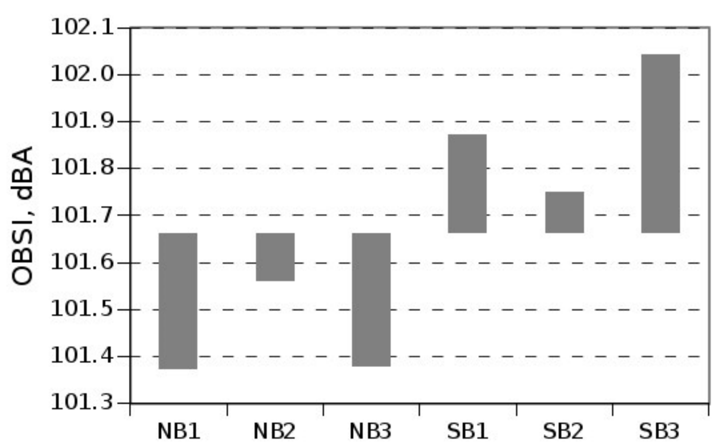


Figure 5.50: OBSI overall levels from CRCP on IH 35W (Section 2)

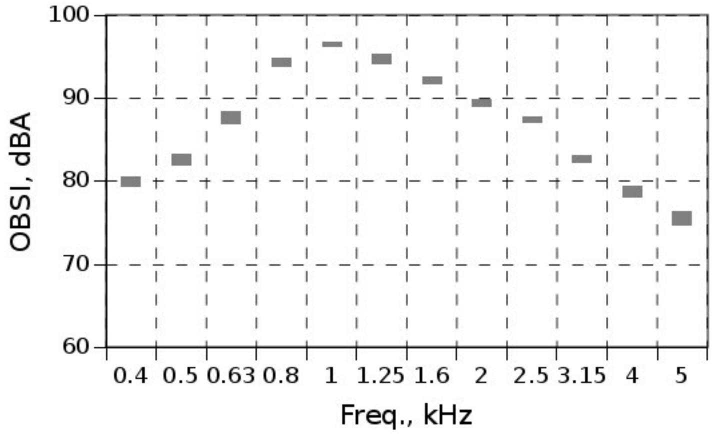


Figure 5.51: OBSI spectra from CRCP on IH 35W (Section 2)

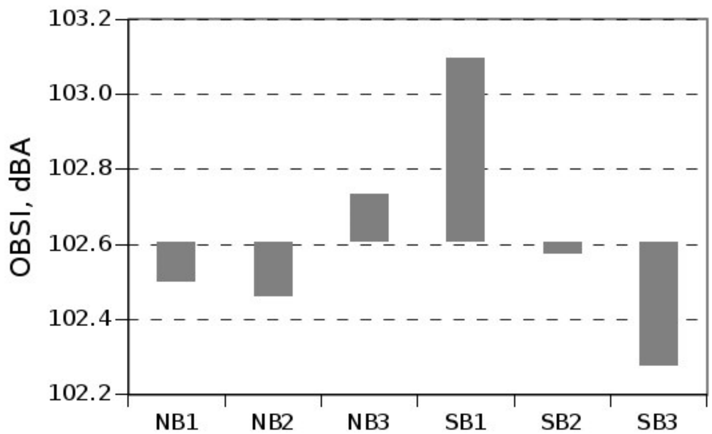


Figure 5.52: OBSI overall levels from CRCP on IH 35W (Section 3)

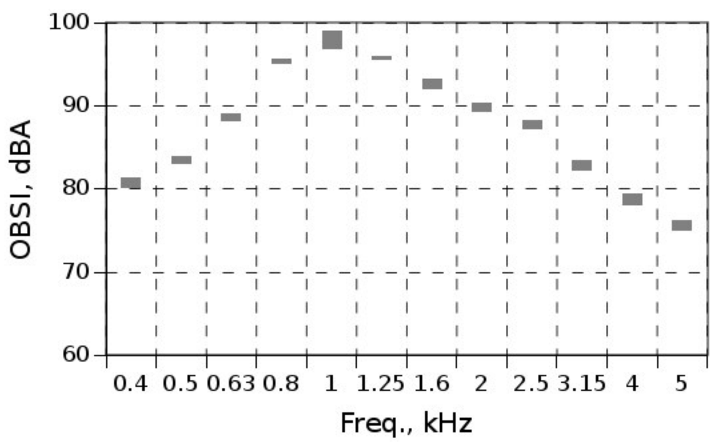


Figure 5.53: OBSI spectra from CRCP on IH 35W (Section 3)

Table 5.7: Macrotexture from CRCP on IH 35W

Direction	Location	Mean MPD	Stdev MPD
NB1 Inside lane	Right	0.81	0.10
NB1 Inside lane	Center	0.97	0.10
NB2 Inside lane	Right	0.84	0.11
NB2 Inside lane	Center	0.94	0.12
NB3 Inside lane	Right	0.85	0.13
NB3 Inside lane	Center	0.96	0.12
NB1 Outside lane	Right	0.58	0.14
NB1 Outside lane	Center	0.96	0.12
NB2 Outside lane	Right	0.66	0.16
NB2 Outside lane	Center	0.89	0.12
NB3 Outside lane	Right	0.60	0.12
NB3 Outside lane	Center	0.89	0.21
SB1 Inside lane	Right	0.99	0.12
SB1 Inside lane	Center	1.06	0.20
SB2 Inside lane	Right	1.03	0.18
SB2 Inside lane	Center	1.03	0.09
SB3 Inside lane	Right	1.00	0.21
SB3 Inside lane	Center	1.00	0.11
SB1 Outside lane	Right	0.74	0.08
SB1 Outside lane	Center	0.98	0.08
SB2 Outside lane	Right	0.67	0.08
SB2 Outside lane	Center	0.99	0.07
SB3 Outside lane	Right	0.69	0.07
SB3 Outside lane	Center	1.00	0.11

NB = northbound; SB = southbound; Stdev = standard deviation

The noise levels on the diamond-ground sections range from 101 to 103 dBA, with the noise on the transversely tined sections about 1 dBA higher than the carpet and burlap drag sections. Diamond grinding was effective in reducing the noise levels on this section, as the pre-grinding levels were on average in the order of 105 dBA. A linear reduction in macrotexture as a result of traffic-related surface wear is evident from the latest macrotexture measurements. Post-grinding macrotexture MPD levels were in the order of 1.2 mm. The most pronounced wear appears to be in the outside lane in the right wheelpath of the northbound carriageway that carries a higher volume of heavier traffic.

Diamond-ground CRCP at TTI test track

OBSI and macrotexture testing of diamond-ground sections was conducted at the TTI test track near College Station. The CRCP test pad includes three pavement sections with different tining:

1. 1-in. transverse tined section (from station 1245 to 2095 going north) of 750 ft (see Figure 5.54)
2. 1/2-in. transverse tined section (from station 693 to 1243 going north) of 550 ft (see Figure 5.55)
3. 1-in. longitudinal tined section (from station 0 to 690 going north) of 690 ft (see Figure 5.56)

Diamond grinding of the entire stretch of CRCP was done over the tined sections. Figure 5.57 summarizes the OBSI noise levels measured on the CRCP sections and Figure 5.58 through Figure 5.60 show the spectra of OBSI noise levels with frequency on the differently tined sections.

Figure 5.54: 1-in. transverse tined surface at TTI test track

Figure 5.55: 1/2-in. transverse tined surface at TTI test track

Figure 5.56: 1-in. longitudinal tined surface at TTI test track

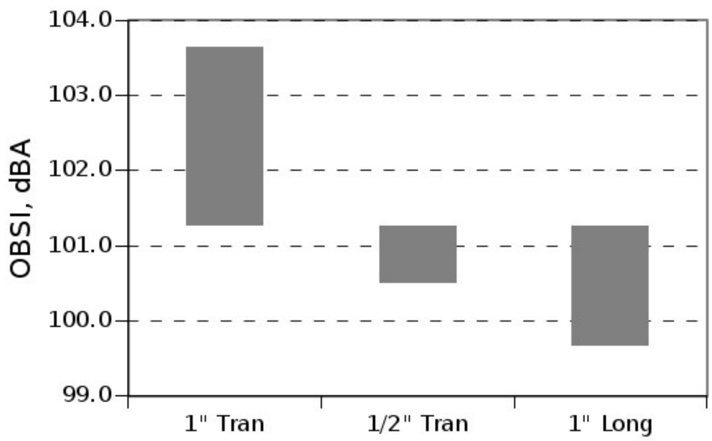


Figure 5.57: OBSI overall levels from CRCP at TTI test track

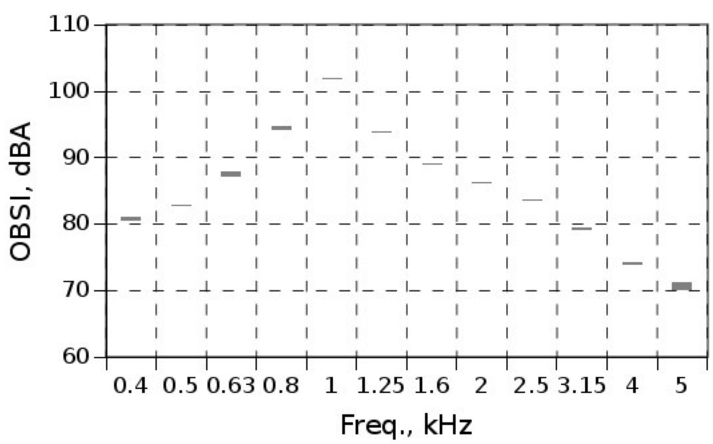


Figure 5.58: OBSI spectra from 1-in. transverse tined CRCP at TTI test track

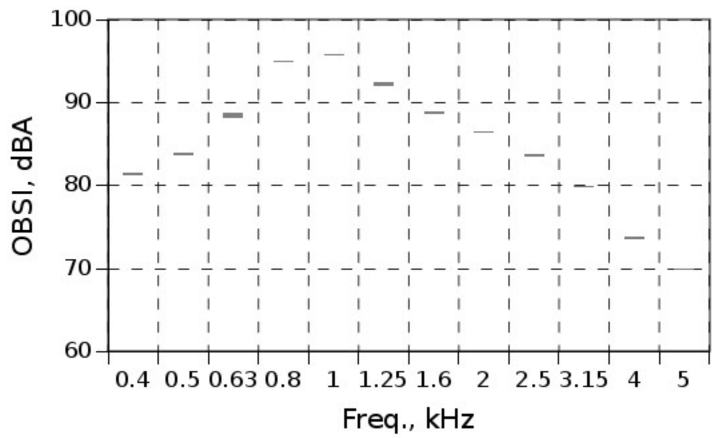


Figure 5.59: OBSI spectra from 1/2-in. transverse tined CRCP at TTI test track

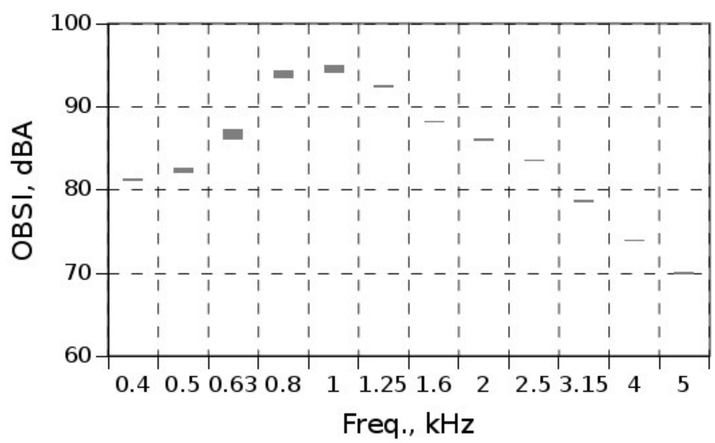


Figure 5.60: OBSI spectra from 1-in. longitudinal tined CRCP at TTI test track

Table 5.8 shows the macrotexture measurements in terms of MPD in millimeters for the CRCP sections at the TTI test track. Measurements on the different tined sections are shown. These MPD values are the means and standard deviations of six measurements each in the right wheel path and in the center of the lane.

Table 5.8: Macrotexture from CRCP at the TTI test track

Tining	Location	Mean MPD	Stdev MPD
1-in. transverse	Right	1.34	0.40
1-in. transverse	Center	1.32	0.14
1/2-in. transverse	Right	1.62	0.17
1/2-in. transverse	Center	1.80	0.55
1-in. longitudinal	Right	1.45	0.42
1-in. longitudinal	Center	1.54	0.32

Stdev = standard deviation

Figure 5.57 shows that the average OBSI noise level on the 1-in. longitudinal tined section at the TTI test track is slightly below 100 dBA and is quieter than the 1/2-in. transverse tined section, which in turn is significantly quieter than the 1-in. transverse tined section. The spectra plot for the different tined sections also show that the 1-in. transverse tined section has a distinctive peak at the 1kHz frequency, which would register as annoying tonal noise from these pavements.

5.3 Summary

The findings from the field testing support evidence from the laboratory tests in that asphalt mixtures with low surface macrotexture with corresponding low variability are quieter surfaces. The lower the surface macrotexture, the lower the tire-pavement noise as measured using the OBSI method. The TOMs tested presented the lowest surface macrotexture and outperformed the other mixtures tested in terms of OBSI noise. These mixtures are impermeable hence no contribution of the low-noise properties can be attributed to surface voids or porosity. In contrast, an evaluation of the PFC mixtures tested in the study indicates that these mixtures are not necessarily low-noise, even newly paved PFC with high porosity and permeability. The possible noise benefits gained through high porosity appear to be offset by the higher surface macrotexture and variability in macrotexture of these mixtures. Diamond grinding of CRCP significantly reduces noise levels of aged concrete surfaces regardless of the pre-grinding condition of the CRCP.

Chapter 6. Case study

6.1 Introduction

The case study for this project consists of an investigation of the various research endeavors undertaken by the Dallas District at different stages to mitigate the noise on Interstate Highway 30 near downtown Dallas. This highway section is of particular interest because it has been studied for several years, and the efforts to reduce traffic noise have included pavement overlays, and a reflective noise barrier, which is also the first transparent barrier in Texas.

6.2 Case study selection

The section in question was selected as the project to be analyzed as a case study because it has been the subject of several studies (both past and present) in order to reduce the noise for receivers in the adjacent neighborhood. These include two different stretches of road that were resurfaced with PFC overlays, and the installation of a lightweight transparent noise wall.

6.3 Background

The highway segment subject of this case study, an elevated structure next to a creek near downtown Dallas, has presented noise problems for the adjacent neighborhood ever since its expansion in the early 2000s. The highway carries substantial commuter traffic as well as heavy trucks. The facility has an average daily traffic of 167,500 vehicles, of which 7.7 percent are trucks. The Kessler Park residential area is hilly and sits at a higher elevation relative to the highway, except for a few residences on the street adjacent to the creek. Many of the Kessler Park neighborhood homes were constructed over 50 years ago, prior to the establishment of the National Environmental Policy Act and traffic noise analysis requirements in 1970. The 2005 IH30 reconstruction/environmental assessment included the first and only traffic noise analysis since the original 1950's construction of the IH30 Dallas/Fort Worth Turnpike. However, the Kessler Park neighborhood did not receive a noise barrier because it did not meet the FHWA abatement cost criteria. The original pavement on this segment of IH30 consisted of CRCP with transverse tining.

The section was first studied by CTR in 2006, as a result of complaints from the Kessler Park neighborhood about the highway noise generated by the original pavement, as part of TxDOT's 0-5836 Project, "Noise Level Adjustments for Highway Pavements in TxDOT." CTR conducted its first set of OBSI measurements in May of 2006 on the original CRCP. Also, neighborhood residential measurements were taken at various locations. Shortly thereafter, a new PFC overlay was placed, in the summer of 2006. The project continued to be monitored by CTR under various studies, as PFCs became more widespread throughout Texas, and elsewhere as a "quieter pavement" type. In 2010, a new PFC, adjacent to the 2006 section was constructed to the west, overlaying a stretch of CRCP reaching Fort Worth Avenue as its westernmost boundary. Also, by the end of 2010 a new TxDOT study was launched by CTR investigating the noise reflections from the north side retaining wall near

Edgefield Avenue back to the Kessler Park neighborhood. As a result of the study, the aforementioned retaining wall was covered with sound absorptive material, and a new test for reflections was developed.

At the beginning of 2013, TxDOT commissioned CTR with a new pilot study to investigate the feasibility of a lightweight traffic noise wall for the elevated structure adjacent to the Kessler Park Neighborhood. As a result of this project, CTR recommended and designed the first transparent noise barrier in Texas installed on IH30 between September and October 2013.

6.4 Project location

The highway segment in question is just west of downtown Dallas, on IH30 as shown in Figure 6.1. A more detailed map of the area is shown in Figure 6.2. The segments that have been studied at various stages are located between Beckley Avenue on the east, and Fort Worth Avenue on the west.

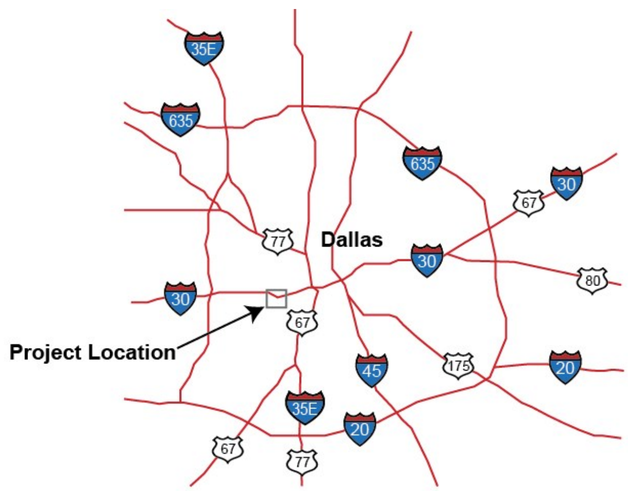


Figure 6.1: Case study project location, on IH30, west of downtown Dallas

Figure 6.2: Detail of project location and Kessler Park neighborhood

6.5 Permeable friction course overlays

The original pavement on this segment of IH30 consisted of CRCP with transverse tining. TxDOT addressed the public noise complaints with a PFC constructed in the summer of 2006. In the summer of 2010 an adjacent section was overlaid with a second PFC. Figure 6.3 shows the locations of the PFC overlays.

Figure 6.4 and Figure 6.5 show the view of the highway section before the overlays, in a photograph from May 2006, and a photograph from 2010 showing the PFC overlays, respectively.

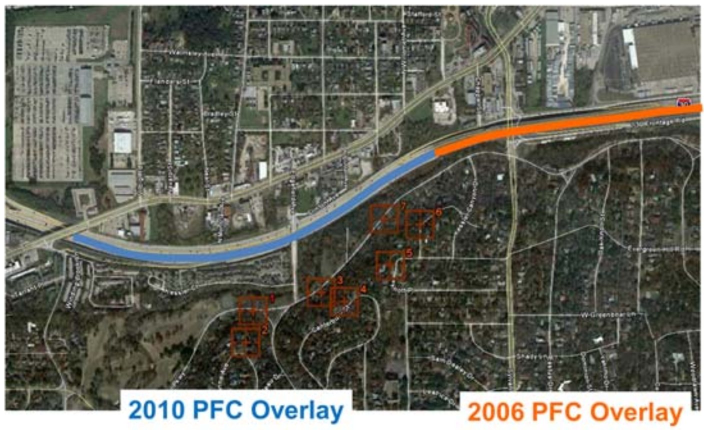


Figure 6.3: Location of the 2006 and 2010 PFC overlays

Figure 6.4: Aspect of the IH30 section showing transversely tined CRCP (2006)

Figure 6.5: Aspect of the IH30 section showing PFC overlays (2010)

6.6 On-board sound intensity tests

OBSI tests have been done on this section at various stages starting in 2006, when the pavement was first studied by CTR at TxDOT's request. OBSI measurements were taken before and after the overlays were constructed. Figure 6.6 shows that the PFC overlays provided significant noise reductions, especially shortly after their construction.

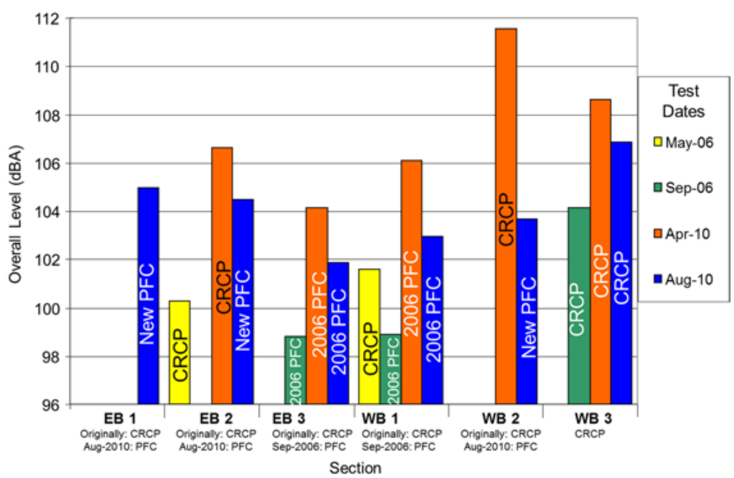


Figure 6.6: OBSI comparison before and after overlay noise levels

The effect of the placement of the PFC is illustrated in Figure 6.7, which shows how the noise generated at the tire-pavement interface on two subsections of the project that were originally paved with CRCP was reduced when they were overlaid with PFC. The tests took place in April (before overlay) and August of 2010 (after overlay).

The spectral change produced by the placement of the overlays is shown in Figure 6.8, in which the frequency distributions of the overlays are compared to that of the original CRCP corresponding to an adjacent section lying just further west of the newer PFC. This chart shows that the characteristic peak at 1 kHz of the CRCP (which represents a whining noise considered annoying by many) was eliminated with the construction of the overlays.

That frequency peak is produced by the vehicle tires hitting the transverse tines of the CRCP at 60 mph, the speed of the OBSI tests. The transverse tining is applied for texturing and drainage purposes to the concrete pavement and it consists of the placement of fine grooves in the pavement surface at approximately 1-in. spacings while the concrete is still plastic.

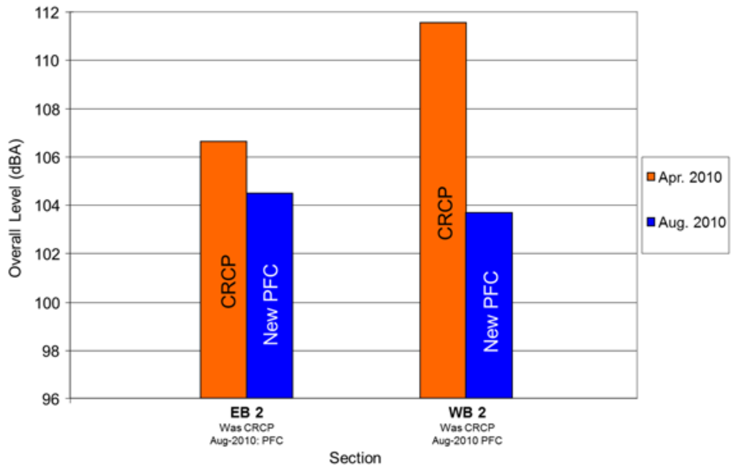


Figure 6.7: Change in noise levels from CRCP to PFC, before (April 2010) and after (August 2010)

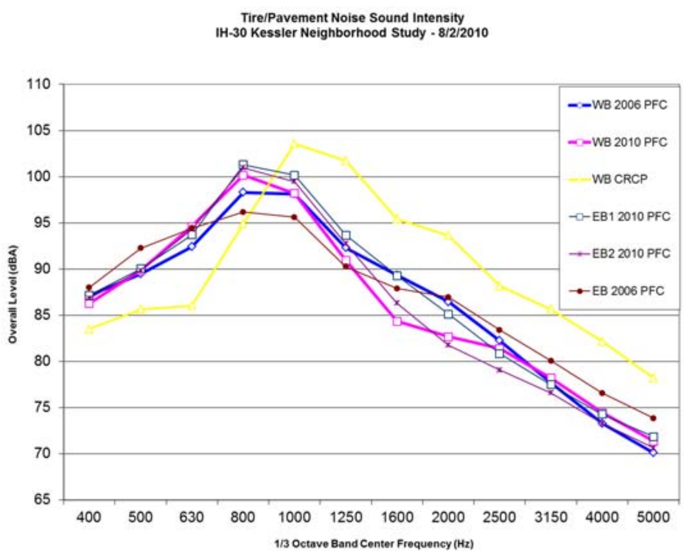


Figure 6.8: Frequency spectra from both PFC overlays and an adjacent CRCP section obtained in 2010

More recent tests, conducted as part of the current study in September 2014 indicate that the first overlay has gotten slightly louder as shown in Figure 6.9. Most of the changes in the pavement's acoustic characteristics occurred between 2006 and 2010, whereas the second overlay has maintained a fairly consistent noise level.

From the OBSI test results it is very noticeable that both overlays were acoustically different from the time of their placement, and those differences have remained as the surfaces have gotten slightly louder over the years. The voids that are a critical part of how these surfaces absorb noise get clogged with debris from the road and also get compacted under the heavy traffic loads over time. Therefore, these surfaces normally experience some decline in their acoustic absorption capabilities with time and traffic. A visual comparison of the aspect of the overlays and the changes over time can be seen in Figure 6.10 and Figure 6.11 for the older PFC constructed in 2006, and in Figure 6.12 and Figure 6.13 for the newer PFC constructed in 2010.

Summarizing the quieter pavements experience obtained through several years of research in this case study, it can be said that the resurfacing of the original CRCP surface with a PFC resulted in a significant reduction in noise levels. The two adjacent overlays, however, have performed differently since the time of their placement. In their present condition, the newer overlay has remained the quieter of the two.

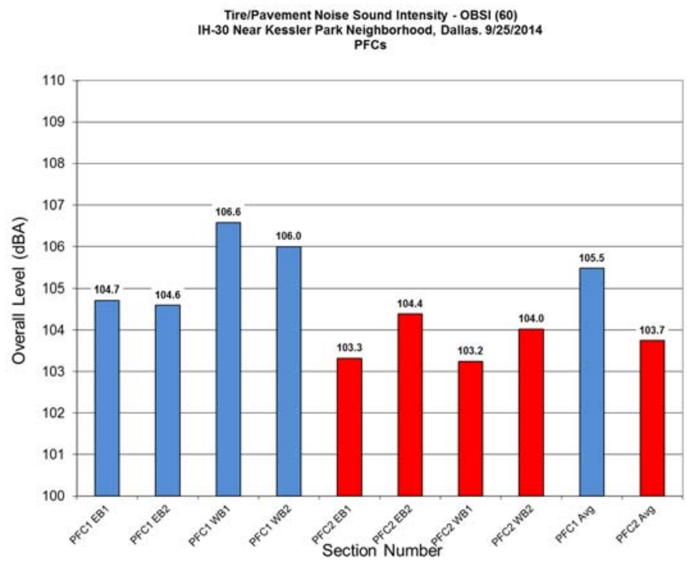


Figure 6.9: Recent OBSI tests on both PFC overlays on IH30 in Dallas (September 2014)

Figure 6.10: IH30 PFC placed in 2006, shortly after construction (September 2006)

Figure 6.11: IH30 PFC placed in 2006 in its current condition (September 2014)

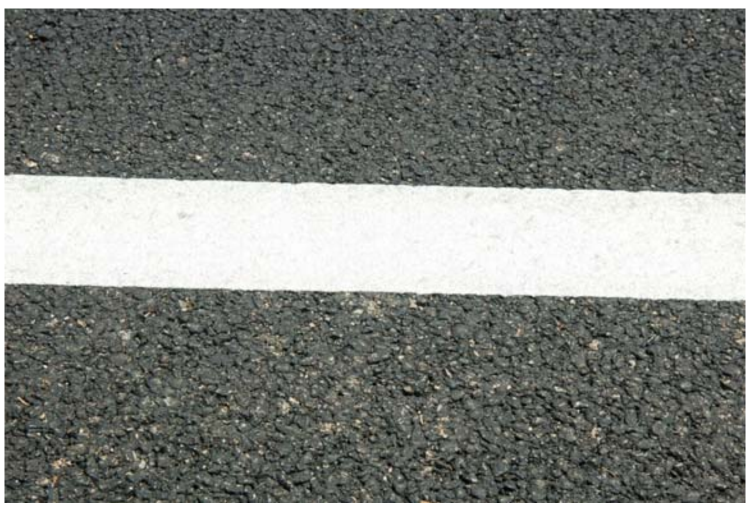


Figure 6.12: IH30 PFC placed in 2010, just after construction (August 2010)

Figure 6.13: IH30 PFC placed in 2010 in its current condition (September 2014)

6.7 Noise barrier

In spite of the significant noise reductions that resulted from the placement of the quieter pavement overlays (compared to the tire-pavement noise levels generated by the original CRCP surface), the noise concerns remained among the residents of the adjacent Kessler Park neighborhood, given the mid-2000s highway expansion. The neighborhood complaints arise from other factors in addition to tire-pavement noise, such as the continuous growth of the traffic volume that circulates over IH30 during most of the day and night and, the high volume of trucks that produce high levels of noise not only at the tire-pavement interface, but also from other sources such as the engine, the exhaust system and most notably the brakes. Therefore, the Dallas District decided to conduct a pilot project to investigate the feasibility of a noise wall for this segment of IH30.

That project started in 2013; its purpose was to investigate the possible use of lightweight noise barriers on the south side of IH30 to mitigate the noise generated at the highway that affects residences in the Kessler Park neighborhood. A noise barrier was planned for installation on top of the existing concrete walls, which are approximately 8-ft. tall for the segment between Edgefield Avenue and Sylvan Avenue; a second phase of this project involves the installation of a similar noise barrier on top of the existing 4.5ft. tall concrete wall for the section between Sylvan Avenue and Beckley Avenue. Both segments are long, elevated structures above Coombs Creek as shown in Figure 6.14 and Figure 6.15, so it was desired that the materials be lightweight and possibly transparent. The lightweight requirement allows for the existing structure to withstand the additional loading from the noise wall without having to structurally reinforce the bridges. Additionally, the lightweight material enables the installation of a taller wall that can cover the line of sight to the highway for as many of the residences in the adjacent hilly neighborhood as possible. From the aesthetics standpoint, it was desired that the walls be transparent. Transparent materials have the advantage over opaque materials in that they block sound without obstructing views, allowing sunlight to pass through. The visual impact on the surrounding area of a tall transparent barrier on top of the existing concrete wall is less than that of a tall opaque barrier. Homes in the Kessler Park neighborhood have scenic views of downtown Dallas and the surrounding area, and the intent was to prevent some of such views from being blocked by an opaque barrier. Figure 6.16 illustrates an example of the scenic views from one of the residences in the neighborhood.

Figure 6.14: Elevated highway structure on the right, above Coombs Creek

Figure 6.15: Easternmost end of Phase I of the project, Sylvan Ave. and IH 30, seen from Kessler Parkway

Figure 6.16: Example of a scenic view from a residence in Kessler Park, next to IH30

A noise wall material investigation was conducted as part of the pilot project yielding a subsequent acoustic design of the proposed wall according to the noise reduction predicted to occur with different heights of barriers. The outcome of this pilot project resulted in the first transparent noise barrier installed in the state of Texas, and it has been regarded as a very successful project, both from the TxDOT and the resident's standpoints.

6.7.1 Noise barriers and material selection

Barriers do not eliminate traffic noise; they only reduce the noise levels perceived for certain benefited receivers, normally those in proximity to the road. Barriers are especially effective for those receivers situated directly behind it; they can experience a decrease in noise level of typically 5 to 10 dBA.

Noise barriers are not effective for homes on a hillside overlooking a road, or for buildings that rise above the barrier; the barrier must be high enough and long enough to block the view of the road. Common materials for barrier construction are concrete and masonry; other materials are metal and acrylic. Such barriers are mostly reflective.

The FHWA noise barriers guidelines (FHWA-HEP-10-025) recommend that to effectively reduce sound transmission through the barrier, the material chosen must be rigid and sufficiently dense, i.e., at least 20 kg/m2 (FHWA, 2011). All noise barrier material types are equally acoustically effective if they have this density.

Noise barriers reduce the sound that enters a community from a busy highway by absorbing the sound, transmitting it, reflecting it back across the highway, or forcing it to take a longer path over and around the barrier (FHWA, 2000). Therefore, noise barriers work by reflecting some of the acoustic energy, while part of the energy is transmitted through the barrier, part of it is diffracted, and some of it reaches the receiver directly, for those receivers with a line of sight of the source as shown in Figure 6.17. Therefore, the density of the barrier material is of foremost importance.

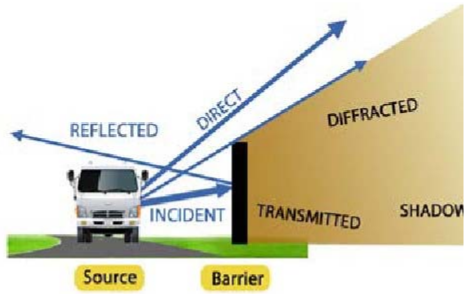


Figure 6.17: Acoustic energy and noise barrier (Bowlby and Knauer, 2012)

There are no federal requirements specifying the materials to be used in the construction of highway traffic noise barriers. Individual state DOTs can select the materials when building these barriers (FHWA-HEP-10-025). The selection is based on structural considerations, safety, aesthetics, durability, materials availability, maintenance, cost, and the desires of the public.

A single-number rating used to compare the sound insulation properties of barriers is the Sound Transmission Class (STC). The STC rating is the transmission loss value for the reference contour at 500 Hz. Thus, the STC rating is not designed for lower frequencies of traffic noise, so it is typically 5 to 10 dB greater than the transmission loss provided (FHWA-EP-00-005). Approximate transmission loss values for common noise barrier materials are as follows: concrete barriers provide 34 to 40 dB; metal barriers, 18 to 27 dB; and transparent barriers, 22 dB (FHWA-EP-00-005).

Lightweight noise barrier projects are not the most common among the existing noise walls installed throughout the country. Relative to barriers made with other materials, transparent barrier cost more, which is one major reason for the low number of installations (McAvoy and Theberge, 2014). In spite of their estimated higher cost relative to other materials, the research team determined that transparent barriers provided a feasible alternative for this project.

Various materials and manufacturers were reviewed for the possible installation of the noise barriers on IH 30. Despite its higher cost, the use of transparent material was considered a viable option, as it is lightweight and offers important acoustic and aesthetic benefits.

6.7.2 Barrier design

A TNM analysis was performed for the IH30 Kessler Park Neighborhood in Dallas. The noise impacts were evaluated for existing and future traffic conditions. Various wall heights were analyzed to supplement the attenuation provided by the existing 8-ft wall situated on the south side of IH 30, between Edgefield Avenue and Sylvan Avenue. The analysis indicates the benefits, quantified as noise level reductions, that the various wall heights proposed are able to provide at several locations.

Twenty-six receivers were included in the model. The locations of the receivers included in the TNM analysis are shown in Figure 6.18. A plan view of the model, from Hampton Road on the west to close to Beckley Avenue on the east, is shown in Figure 6.19.

According to FHWA policies (FHWA-HEP-10-025), a traffic noise impact occurs when the existing or future noise levels approach or exceed the noise abatement criteria (NAC); TxDOT defines the level of approach as 1 dBA. An extract of the NAC is presented in Table 6.1 (TxDOT, 2011). An impact can also occur when predicted future traffic noise levels substantially exceed the existing noise level, even though the predicted levels may not exceed the NAC.

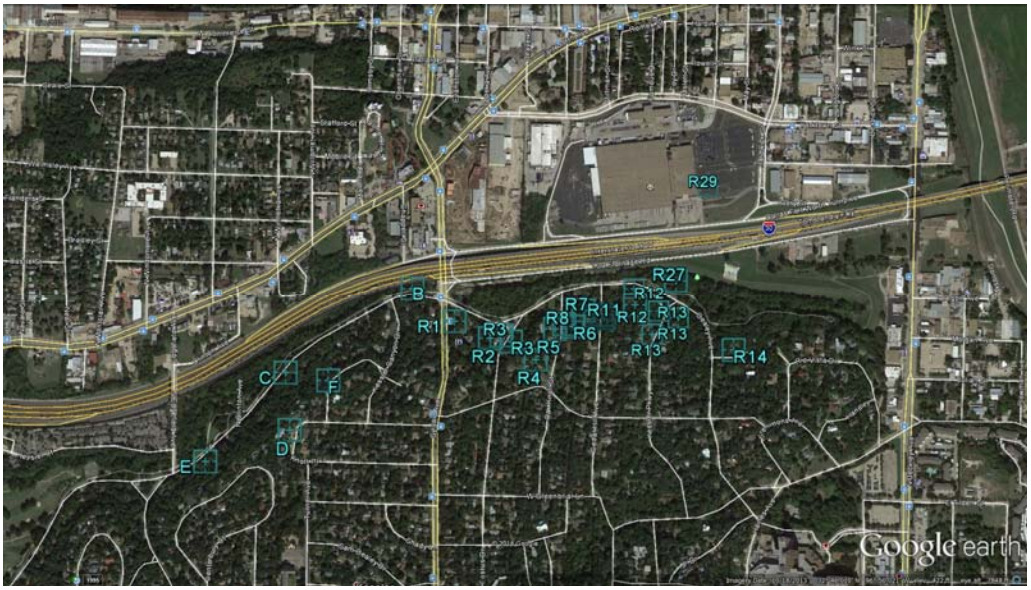


Figure 6.18: Receivers for TNM analysis

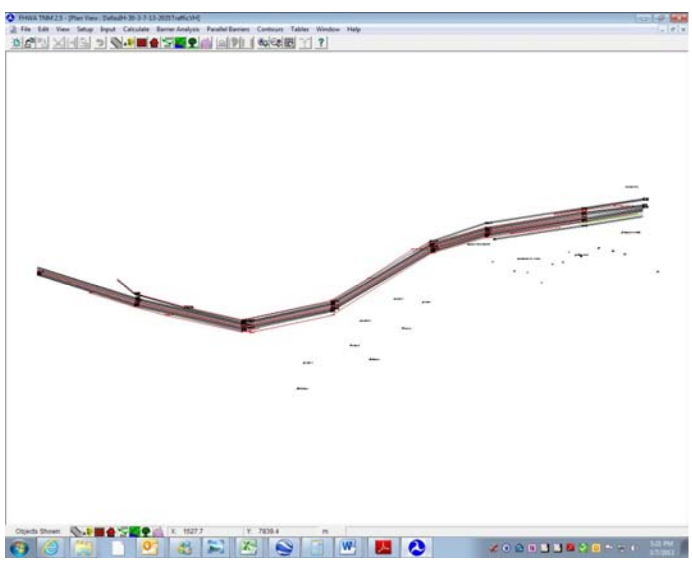


Figure 6.19: Plan view of IH30 TNM model

Table 6.1: Noise abatement criteria

Noise Abatement Criteria		
Activity Category	**FHWA (dB(A) Leq)**	**Description of Land Use Activity Areas**
A	57 (exterior)	Lands on which serenity and quiet are of extra-ordinary 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)	Residential
C	67 (exterior)	Active sport areas, amphitheaters, auditoriums, campgrounds, cemeteries, day care centers, hospitals, libraries, medical facilities, parks, picnic areas, places of worship, playgrounds, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, recreation areas, Section 4(f) sites, schools , television studios, trails, and trail crossings
D	52 (interior)	Auditoriums, day care centers, hospitals, libraries, medical facilities, places of worship, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, schools, and television studios
E	72 (exterior)	Hotels, motels, offices, restaurants/bars, and other developed lands, properties, or activities not included in A-D or F.
F	--	Agricultural, airports, bus yards, emergency services, industrial, logging, maintenance facilities, manufacturing, mining, rail yards, retail facilities, shipyards, utilities (water resources, water treatment, electrical), and warehousing.
G	--	Undeveloped lands that are not permitted.

Thus, TxDOT policy for noise impact indicates that an outdoor residential area, such as the subject of these tests (Type B Land Use Category in Table 6.1, is considered to have an impact if the level is 66 dBA or above (TxDOT, 2011).

TNM analyses were performed for both existing traffic and projected traffic. For both types of runs, an impact was identified for four receivers without additional height added to the barrier (existing wall of 8-ft). Table 6.2 shows the calculated noise levels for the future traffic for the four impacted receivers, considering only the existing 8-ft wall.

Table 6.2: Impacted receivers—existing wall (2035 traffic)

Receiver	Level, dBA
1820 Kessler Parkway (Receiver C)	68.2
R8-1650 Oak Knoll (A)	69.2
Coombs Creek Trail W of Sylvan (B)	80.9
US Post Office (R29)	68.3

According to TNM, the existing wall provides a maximum of 1.4 dBA reduction for Receiver D (not impacted), and an average reduction for all receivers of 0.3 dBA. The maximum reduction provided by the existing wall for an impacted receiver occurs for Receiver C, located along Kessler Parkway, and it is 1.1 dBA. Therefore, there are some small benefits provided by the concrete wall, but these are below a perceptible level.

Barrier increments of 2 ft each on top of the existing wall were calculated, up to 20 ft total, i.e., new barrier heights of 2, 4, 6, 8, 10, and 12 ft on top of the existing wall. The TNM analyses results for impacted receivers are provided in Table 6.3 through Table 6.8.

Table 6.3: Impacted receivers—existing wall + 2-ft (10-ft total) (2035 traffic)

Receiver	Original level (dBA)	With 2-ft addition (dBA)	Noise reduction (dBA)
1820 Kessler Parkway (Receiver C)	68.2	65.8	2.4
R8-1650 Oak Knoll (A)	69.2	69.2	0.0
Coombs Creek Trail W of Sylvan (B)	80.9	80.5	0.4
U.S. Post Office (R29)	68.3	68.3	0.0

Table 6.4: Impacted receivers—existing wall + 4-ft (12-ft total) (2035 traffic)

Receiver	Original level (dBA)	With 2-ft addition (dBA)	Noise reduction (dBA)
1820 Kessler Parkway (Receiver C)	68.2	64.7	3.5
R8-1650 Oak Knoll (A)	69.2	69.2	0.0
Coombs Creek Trail W of Sylvan (B)	80.9	80	0.9
U.S. Post Office (R29)	68.3	68.3	0.0

Table 6.5: Impacted receivers—existing wall + 6-ft (14-ft total) (2035 traffic)

Receiver	Original level (dBA)	With 2-ft addition (dBA)	Noise reduction (dBA)
1820 Kessler Parkway (Receiver C)	68.2	63.7	4.5
R8-1650 Oak Knoll (A)	69.2	69.2	0.0
Coombs Creek Trail W of Sylvan (B)	80.9	78.5	2.4
U.S. Post Office (R29)	68.3	68.3	0.0

Table 6.6: Impacted receivers—existing wall + 8-ft (16-ft total) (2035 traffic)

Receiver	Original level (dBA)	With 2-ft addition (dBA)	Noise reduction (dBA)
1820 Kessler Parkway (Receiver C)	68.2	62.3	5.9
R8-1650 Oak Knoll (A)	69.2	69.2	0.0
Coombs Creek Trail W of Sylvan (B)	80.9	77.0	3.9
U.S. Post Office (R29)	68.3	68.3	0.0

Table 6.7: Impacted receivers—existing wall + 10-ft (18-ft total) (2035 traffic)

Receiver	Original level (dBA)	With 2-ft addition (dBA)	Noise reduction (dBA)
1820 Kessler Parkway (Receiver C)	68.2	61.2	7.0
R8-1650 Oak Knoll (A)	69.2	69.2	0.0
Coombs Creek Trail W of Sylvan (B)	80.9	73.3	7.6
U.S. Post Office (R29)	68.3	68.3	0.0

Table 6.8: Impacted receivers—existing wall + 12-ft (20-ft total) (2035 traffic)

Receiver	Original level (dBA)	With 2-ft addition (dBA)	Noise reduction (dBA)
1820 Kessler Parkway (Receiver C)	68.2	60.3	7.9
R8-1650 Oak Knoll (A)	69.2	69.2	0.0
Coombs Creek Trail W of Sylvan (B)	80.9	70.0	10.9
U.S. Post Office (R29)	68.3	68.3	0.0

In summary, the noise produced by the current and future traffic conditions creates impacts for only a limited number of receivers. Only two residences are impacted, one of which cannot receive benefit from any realistic height of wall in addition to the existing barrier, given its elevation relative to the highway. The other two receivers that are impacted are Receiver B, which is a representative location along a park just below the elevated structures, and the Post Office (R29) on the other side of the highway.

The feasibility criterion indicates that the noise barrier should provide a substantial reduction, defined as a reduction of at least 5 dBA at impacted receivers. In this case, an 8-ft additional height (i.e., on top of the existing 8-ft wall for a total height of 16 ft) or higher is feasible for Receiver C, and only a 10-ft additional height or higher is feasible for Receiver B (the park). The 16-ft wall (in total height) would provide a 3.9-dBA noise reduction for locations along the park, which is a perceptible benefit.

The recommendation to the Dallas District was to install a barrier of at least 8 ft on top of the existing concrete wall, and a barrier of 10 ft if acoustic benefits were desired for the park locations. TxDOT decided to install a barrier consisting of 10-ft tall panels on top of the existing concrete barrier.

6.7.3 Barrier installation

The noise barrier installation began in September 2013, and it concluded by mid-October 2013. The wall consists of transparent acrylic panels, made of a material called Acrylite, manufactured by Evonic, which are 15-mm thick, 7-ft wide by 10-ft tall, placed on top of the existing 8-ft tall concrete barrier on the south side of IH30. The total length of the wall is 2,395 ft. The installation took place at night as shown in Figure 6.20. The finished wall is shown in Figure 6.21 and Figure 6.22 from different locations along IH30.

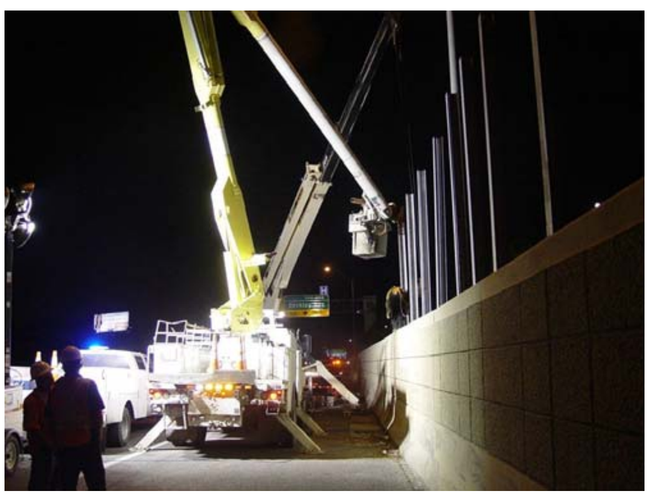


Figure 6.20: Nighttime installation

Figure 6.21: Sound wall as seen from Edgefield Avenue Bridge

Figure 6.22: Sound wall as seen from westbound IH30

6.7.4 Residential measurements

In order to evaluate the wall's effectiveness, a noise testing program was developed. Five sites were selected in the neighborhood for periodic noise evaluation. On every monitoring day, SPL tests were conducted at each site three times during the day, once in the morning, once in the afternoon and once in the evening. Test days were scheduled approximately once a month and were conducted both before and after the wall installation. Besides the sound meter, a portable weather station was used to monitor conditions at the time the sound tests took place. Testing in the vicinity of the wall before and after the installation is illustrated in Figure 6.23 and Figure 6.24 respectively.

Figure 6.25 presents the results, showing the five locations and the average noise levels measured before the wall was installed and the average noise levels measured after the wall was completed. The results of the noise testing program are constantly updated as the measurements are collected.

All the locations show some benefit from the noise wall. The location with the smallest average benefit is location E (0.7 dBA), the westernmost residential location, which is very close to the west end of the noise wall, at Edgefield Avenue. In all likelihood, highway noise coming from west of the end of the barrier still reaches this residence and this could be the reason for the marginal noise reduction after the wall was installed. The location with the highest average noise reduction after the wall was in place is residence C, the closest residence to the highway. This location shows a 3.0 dBA average noise reduction with the noise wall. Besides its proximity to the highway, this location is at a lower elevation relative to the highway, which results in higher benefit from the wall. Another location that is very close to the highway, and at a lower elevation, is the park location, identified as B; its benefit, on average, is 1.5 dBA. It would be expected that this location would obtain a greater noise reduction from the wall, but some of that benefit might be negated by its proximity to the easternmost end of the wall, at Sylvan Avenue. Noise from the highway segment not protected by the wall still reaches this park location, as is the case with location E, at the other end of the project.

Figure 6.23: Noise measurement at Coombs Creek Trail Park (Location B) prior to noise barrier installation

Figure 6.24: Noise measurement at Coombs Creek Trail Park (Location B) after noise barrier installation

Figure 6.25: Preliminary noise test results

Other preliminary findings from this case study indicate that seasonal changes, primarily temperature, have a definitive influence on the noise levels. The sound barrier provided higher noise reduction in the few months following its completion, while the weather was still warm. It is well documented that cold temperatures are correlated to higher tire-pavement noise generation.

Noise levels get high in the colder months, and decrease in the summer, when weather conditions are very hot. Other weather variables appear to have no significant influence on noise levels.

The neighbors are very satisfied with the wall; the public perception is very positive in regards to both acoustic benefits and aesthetics. The psychoacoustical effect of being able to see the traffic flow behind the barrier while not perceiving the same level of noise as before might be an important factor. This project was the recipient of the 2014 TxDOT Environmental Achievement Award.

6.8 Synthesis

This case study has provided valuable experience and important findings in various aspects of highway noise, quieter pavements, and noise mitigation. In regards to pavements, it shows that quieter pavements produced a significant reduction in the noise generated at the tire-pavement interface when compared to the noise levels generated by the original conventional pavement, which in this case was concrete pavement. Even though the quieter pavement overlays may appear to be near the end of their service life, especially the one placed in 2006, they are still providing noise reduction benefits when compared to the original pavement. The characteristic voids of the PFC overlays that enable them to absorb noise as well as drain water from the surface of the road, after years of service, appear to be clogged by debris and compaction from traffic loads. Nevertheless, the noise benefits, although diminished, are still valuable.

In addition to the pavement type and materials, the texture of the pavement surface plays a critical role in the generation of tire-pavement noise. In this case the tining of the CRCP resulted in loud, whiny noise, especially in the 1 kHz frequency band. The PFC overlays were able to eliminate this effect. Therefore, the absorptive capabilities of the PFCs indicate that their benefit is not only in terms of the overall noise level reduction, but also in the elimination of peaks in certain frequencies related to the texturing of the original pavement.

Noise generated at the tire-pavement interface is the foremost component of traffic noise at highway speeds. However, there are other contributors to the overall noise such as engine noise, aerodynamic noise, exhaust noise, as well as noise not necessarily related to the vehicle propulsion, such as braking noise, and reflections. In this case, and certainly in many other cases of noise concerns along a busy highway, there are other sources of noise for which the solution offered by the quieter pavement application may not be enough. For the IH30 case in question, the noise that the nearby residents perceive is the result of numerous components in addition to the highway and its pavement, for which the most viable solution was a noise barrier. In this case it was an innovative approach that led to the first transparent highway noise barrier in Texas. For the conditions of this project, the transparent barrier option was the most suitable solution. Unfortunately, noise barriers do not offer the same benefits to all the receivers due to the topographic conditions and proximity to the highway. The receivers that get more benefits are in close proximity to the highway and at an elevation that is no higher than the height of the wall. Receivers at higher elevations get virtually no benefit from it. The benefits as well as the noise levels vary significantly with the seasons of the year and the weather conditions, most notably, the temperature. Also, the psychological effects of the wall and the noise represent an important contribution to the perception of the benefits of a sound wall. For the case of this project, the widespread public opinion indicates satisfaction with the results and considers the wall a successful endeavor. The project is aesthetically very pleasing, and the fact that residents can still see the traffic through the transparent panels of the wall while perceiving lower noise levels than before is an important factor that contributes to the public's general assessment of overall project success.

Finally, when dealing with noise complaints it is important to consider that not all the noise sources reaching the residential receivers are necessarily related to the highway. Even though traffic noise is in all likelihood the most important aspect to consider, it is certainly not the only one. The placement of a quieter pavement such as the PFCs in this case, was not the ultimate solution that eliminated the problem. The addition of the noise wall itself seems to have been very beneficial as well, but has not eliminated the problem entirely. The combination of both quieter pavement and a noise wall could be regarded as redundant or unnecessary in some instances, but that was not the case for the Dallas IH30 section in question. Even with quieter pavements and a noise wall, the noise problems in this area still exist, although they are not as severe now. The numerous residential noise tests indicated that this busy urban area is affected by many other sources of noise, such as traffic from arterial streets independent from the highway, airplane traffic, construction noise in the neighborhood, and even lawnmowers and dust and leaf blowers used by the residents themselves. All these additional noise sources appear to diminish the perceived effectiveness of the wall and the quieter pavement for anyone who is unaware of the variety of noise sources.

Chapter 7. Conclusions and recommendations

7.1 Study overview

The primary objective of the study outlined in this report was to develop specifications for the design of quieter roadway surfaces. To meet this objective, a number of technical objectives were addressed. An extensive literature review was conducted to develop a fundamental understanding of the mechanisms impacting road noise and the significant influence factors. The purpose of the review was to identify the relevant factors for further evaluation and eliminate those of little or no consequence. It was at this point that the focus of the project shifted to the evaluation of surfaces with low macrotexture and those with high porosity mixtures. Surface stiffness or resilience was eliminated as an impact factor for practical reasons, since it is only relevant for poro-elastic type applications that fall outside the scope of this study. The literature review also introduced a number of interesting concepts used abroad to address road noise, such as surface profile enveloping, the application of which was investigated as part of the study.

A comprehensive noise database was developed specifically for this study and the analysis thereof provided further and conclusive evidence of the noise-reducing benefits of mixtures with low macrotexture and high porosity. It was during this analysis that the research team realized the excellent noise performance of TOM used quite extensively by the Austin District. The laboratory and field components of the study further tested these mixtures in conjunction with others; based on the evidence and findings identified, the researchers highly recommend TOM as the best mixture for low-noise surfaces. The noise benefits of PFC mixtures are highlighted but the research team found that these mixtures do not consistently perform well and are subject to premature aging and clogging that can rapidly reduce the noise-attenuating properties of these mixtures.

A case study is also presented that provides a broader perspective on noise abatement strategies that may be implemented in addition to low-noise surfaces to address noise complaints from residences. The case study examined such an implementation near a residential neighborhood along a noisy and heavily trafficked section of IH 30 near Dallas.

7.2 Study findings

7.2.1 Literature review

The literature review highlighted important aspects to consider for the design of quieter pavement surfaces. Too often efforts to reduce road noise focus exclusively on the surface properties without considering the environment in which the surface is paved, the road geometry, and the roughness profile, which are important for both controlling noise performance and providing sufficient skidding resistance. A balanced ratio between surface megatexture, macrotexture, and microtexture is necessary to achieve effective low-noise surfaces. In this regard the literature review provides a useful summary of the general guidelines that should be followed to achieve a good quality low-noise surface:

- For porous surfaces, the wearing course should be constructed with as high a void content as possible from a durability perspective. An initial void content of more than 20 percent is a minimum to achieve good noise reduction, although 20–30 percent is preferable. The thickness of a porous layer should be at least 40 mm, preferably thicker, in order to also achieve sound absorption at relatively low frequencies.
- For porous surfaces, it is essential to increase the porosity in order to prevent clogging by providing wider channels.
- Megatexture should be minimized, especially around wavelengths of 50 to 100 mm. This can be achieved by, for example, using uniform smaller aggregates that are densely graded.
- Very smooth macrotextures should be avoided. Macrotexture should be maximized at wavelengths around 2 to 6 mm (0.04 to 0.24 in.) for car tires and 4 to 8 mm (0.16 to 0.3 in.) for truck tires.
- The above megatexture and macrotexture requirements are easier to achieve if a small maximum aggregate size is used, ideally in the range 3 to 6 mm (0.1 to 0.2 in.), and if crushed aggregates with sharp edges are used.

7.2.2 Noise database

The analysis of a large number and variety of asphalt mixtures used in Texas indicated a strong correlation between surface macrotexture and the percentage passing the #4 sieve. The relationship between these parameters (shown in Equation 7.1) provides a simple estimation of surface macrotexture in terms of mixture gradation and suggests an increase for coarser mixes and a decrease as the fines in the mix increase.

$$MPD = 1.7 - 0.0164 \cdot P4 \tag{7.1}$$

The study demonstrated how the gradation of asphalt mixtures may be modeled using logistic curves described in terms of slope and size parameters. The slope parameter defines the “openness” of the gradation, whether dense-, gap- or open-graded. The aggregate size parameter was found to be positively correlated to the noise level at frequencies lower than 1,585 Hz. These are critical frequencies that are amplified in the human hearing range. The slope or “openness” parameter was found to be inversely related to pavement noise level at all frequencies; this indicates that open gradations are generally associated with quieter pavements. Therefore, one may adjust an open gradation by modifying its average aggregate size to achieve surfaces that are quieter at either lower or higher frequencies.

Both aggregate size and porosity are critical mixture design parameters for controlling road noise. The statistical analysis of the noise database indicated that surface macrotexture clearly had the greatest influence at the different frequency levels evaluated and appears to dilute the contribution of the gradation parameters, both in terms of aggregate size and mixture porosity. The results of the statistical analysis of the noise data suggest that to reduce pavement-tire noise, the design of quieter pavements should focus more on producing mixtures with reduced macrotexture.

The analysis concluded that adjusting the gradation of a mixture may have a significant effect on noise production, but this effect may not be of practical significance and the effect is minor compared to that of macrotexture. This finding was validated as part of the laboratory study that investigated the influence of varying the gradation of a TOM.

7.2.3 Laboratory testing

A simple yet effective test was developed as part of the study to evaluate the noise properties of laboratory-compacted specimens. Procedures and specifications for application of this test for the design of quieter surfaces is documented in Appendix A of the report as a product of the research study.

Based on preliminary testing done as part of the study, the test as developed shows promise in that it provides repeatable results that appear to accurately reflect noise levels as measured in the field for different surfaces. This allows the laboratory design of quieter pavement surfaces. The test can be run on both laboratory-compacted specimens and field cores and it is proposed that the test be further developed and validated.

7.2.4 Field testing

The study included a comprehensive field testing component that measured OBSI noise, macrotexture, and permeability on a variety of asphalt and concrete pavements in different districts in Texas. Most notable from the field trials was the exceptional noise performance of TOM with low surface macrotexture, where average noise levels on these mixtures were in general about 3 dBA quieter than the PFC surfaces tested. This is a significant reduction in noise compared to PFC, which are traditionally recognized as low-noise surfaces.

In contrast to TOM, an evaluation of the PFC mixtures tested in the study indicates that these mixtures are not necessarily low noise, even newly paved PFC with high porosity and permeability. The possible noise benefits gained through high porosity appear to be offset by the higher surface macrotexture and variability in macrotexture of these mixtures. Most concerning was evidence of clogging and premature degradation or raveling of some of the PFC surfaces tested, which suggests that PFC is not a reliable long-term solution for the need to provide low-noise surfaces.

The application of TOM in Texas is still relatively new and time is needed to judge the long-term noise benefits of these mixtures. Evidence from laboratory testing of these mixtures suggests, however, that their noise properties are relatively insensitive to variations in the volumetric properties of the mix that may occur through densification of the mix with extended trafficking and age.

For the concrete pavements tested, longitudinally tined CRCP was significantly quieter than transversely tined sections. Furthermore, diamond grinding of CRCP is highly recommended as it significantly reduces noise levels of aged concrete surfaces regardless of the pre-grinding condition of the CRCP.

7.2.5 Case study

The case study presented in this report provides guidelines and recommendations for the application of low-noise strategies for noise abatement on noisy and heavily trafficked highways. It addresses the design and construction of noise barriers, which, when used in conjunction with low-noise surfaces, provided an effective means to address noise complaints from residences along IH 30 near Dallas. Based on the strategies applied and lessons learned in this case study, guidelines were developed for District use in selecting candidate projects and designing the appropriate surface to provide long-term noise reductions. These guidelines document the roles and relative importance of roadway surface characteristics, roadway geometry, and other structural features to noise generation. The guidelines are included in Appendix B of the report as the final product of the research study.

7.3 Implementation

The report provides two products in the appendices: Appendix A provides the laboratory test procedures for the design of quieter surfaces (0-6819-P1) and Appendix B relays the District guidelines for selecting appropriate candidate projects for low-noise surfaces and designing surfaces that provide long-term noise reductions (0-6819-P2).

An aspect that needs to be addressed to facilitate low-noise research is traffic control for field testing. The research team experienced numerous problems arranging traffic control for the study. The current process is overly complicated and delays the execution of the research. Consequently, many sections identified for testing in the field component of the study were not tested. While this does not distract for the overall findings of the study, it is recommended that these untested sections be field-tested to establish a future reference.

In addition, the research team recommends noise testing of additional surfaces not extensively addressed in the current study, specifically thin PFC and concrete pavements with longitudinal tining.

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Appendix A: Laboratory Test Procedures

0-6819-P1

LABORATORY TEST PROCEDURES FOR MEASURING NOISE GENERATED BY SURFACE MATERIALS

Research Supervisor:
Jorge Prozzi

TxDOT Project 0-6819: Designing Quieter Pavement Surfaces

DECEMBER 2015; PUBLISHED JUNE 2016

Performing Organization: Center for Transportation Research The University of Texas at Austin 1616 Guadalupe, Suite 4.202 Austin, Texas 78701	**Sponsoring Organization:** Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080
Performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.	

A.1 Introduction

Chapter 4 of the 0-6819-1 report addresses the laboratory design of asphalt mixtures for quieter surfaces. An evaluation of the data collected during the study highlights the noise-reducing benefits of mixtures with low surface macrotexture. A laboratory test procedure was developed as part of the study to evaluate surface macrotexture and noise properties, presented here as a product of the research study.

A.2 Specimen preparation

A simple laboratory test procedure was developed that can be used to test the noise properties of laboratory-compacted specimens. The surface macrotexture of laboratory-compacted specimens was found to be similar in nature to field-compacted mixtures. Thus, specimens for laboratory noise tests can be produced using the Texas or Superpave gyratory compactors. In the present study, 4-inch-diameter specimens were used for the noise testing, although 6-inch-diameter specimens will also work and are preferable, since a larger surface area is available for testing.

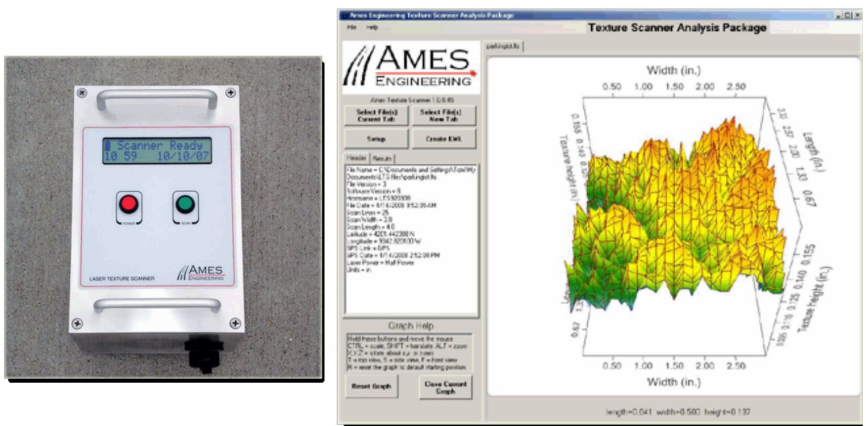

Figure A.1: Ames laser texture scanner

A.3 Macrotexture measurements

The surface macrotexture and the variability in this macrotexture must be measured on the compacted face of the laboratory-compacted specimen as design parameters for low-noise mixtures. In the current study, the surface macrotexture of laboratory-compacted specimens were tested using the Ames laser texture scanner (LTS) shown in Figure A.1 as well as a new 3D laser displacement sensor (LDS) from Keyence. The LTS is a line scanning laser and the LDS provides a very accurate 3D profile of the scanned surface; Figure A.2 shows the 3D surface of a thin overlay mix (TOM) laboratory-compacted specimen. A closer view of the TOM surface as scanned using the LDS is shown in Figure A.3.

Figure A.4 shows a histogram of the distribution of macrotexture measured in terms of mean profile depth (MPD) on a TOM laboratory-compacted specimen. This figure demonstrates that the macrotexture on a specimen can vary considerably depending on where the surface profile is scanned. The variability in surface macrotexture is an important noise parameter that can be controlled as part of the mixture design procedure and should be minimized for low-noise surfaces. It is interesting to note that the variation in surface macrotexture as shown in the figure is log-normally distributed.

Minimizing the surface macrotexture of laboratory-compacted specimens and reducing the variability of this macrotexture provides a simple yet effective procedure to design quieter pavement surfaces. The TOM mixtures tested as part of this study had surface macrotexture in terms of MPD on the order of 0.5 mm with a standard deviation less than 0.2 mm.

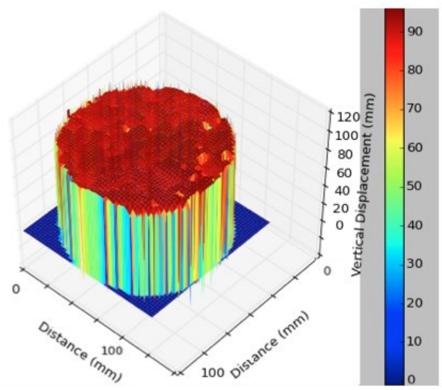

Figure A.2: LDS scanned TOM specimen

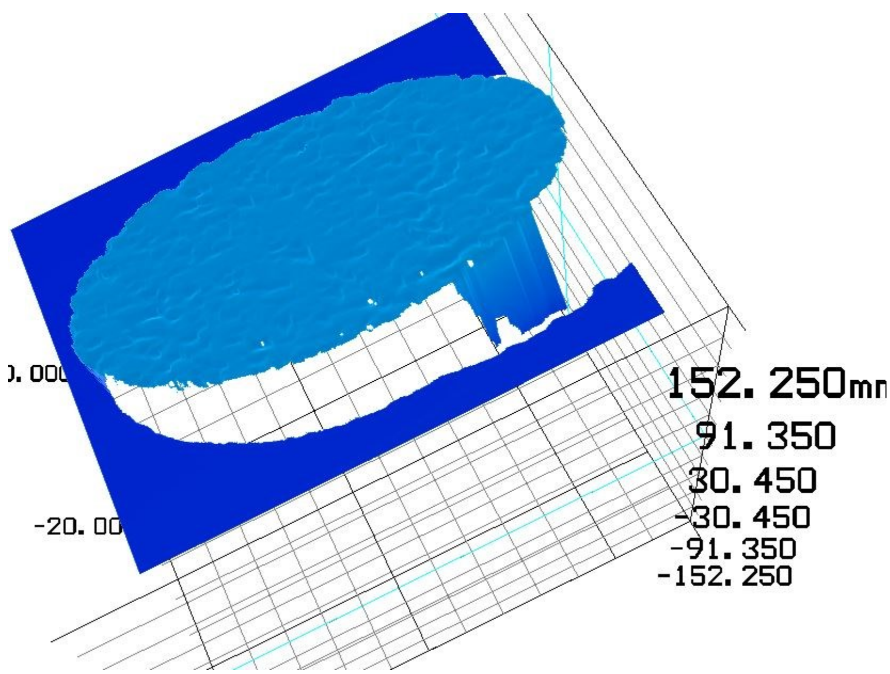

Figure A.3: LDS scanned TOM surface profile

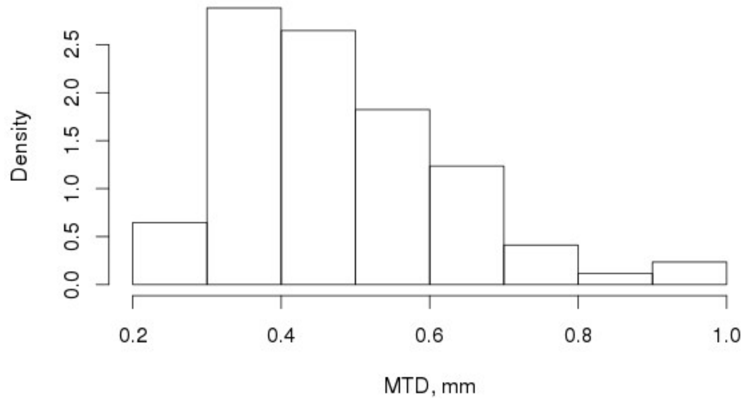

Figure A.4: Surface macrotexture variability

A.4 Noise measurements

The laboratory procedure developed and proposed for laboratory testing for noise is a modification of the standard ASTM E303 procedure: *Measuring Surface Frictional Properties Using the British Pendulum Tester (BPT)*. In this test, laboratory-compacted specimens are tested using the BPT. The noise generated as the rubber slider of the BPT comes into contact with the surface of the specimen is recorded with a sound pressure level meter in a process similar to wayside noise measurements in the field, as shown in Figures A.5 through A.8. Unlike the standard BPT test, the implemented test does not use water on the surface and uses a 4-inch-diameter specimen held in place in the path of the swinging arm of the BPT. The contact path of the slider is manually adjusted to test an area smaller than 4 inches in order to avoid noise due to impact with the side of the sample. A sound pressure level meter is placed 4 inches from the contact of the rubber slider and the surface, and 3 inches above the surface of the specimen as shown in Figure A.8. These distances are the same as those used to align the on-board sound intensity (OBSI) microphones above the road surface for consistency.

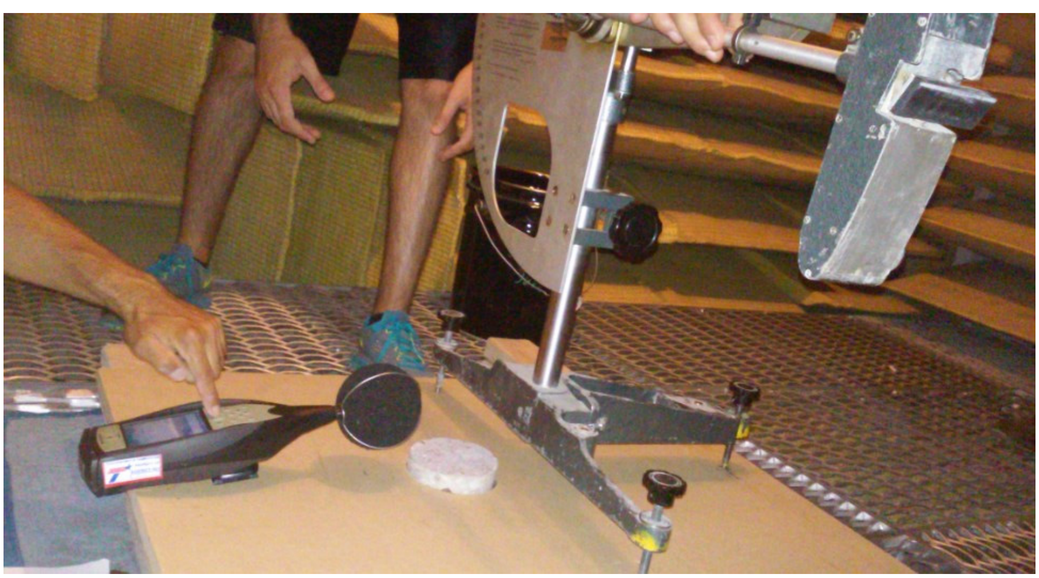

Figure A.5: BPT noise setup

As part of the study, tests using the procedures as outlined were performed to observe the accuracy and sensitivity of the laboratory noise measurements. Three samples of different surfaces, including a portland cement concrete (PCC), permeable friction course, and TOM surface were tested and the macrotextures of these were measured with the LTS. The PCC specimen had transverse tining on one face and was smooth on the other face. Results of the testing are shown in Figure A.9.

This procedure provides a direct measurement of the noise at the surface of the tested specimen and was found to be repeatable and correlated well with relative noise levels of corresponding mixtures tested in the field using the OBSI method.

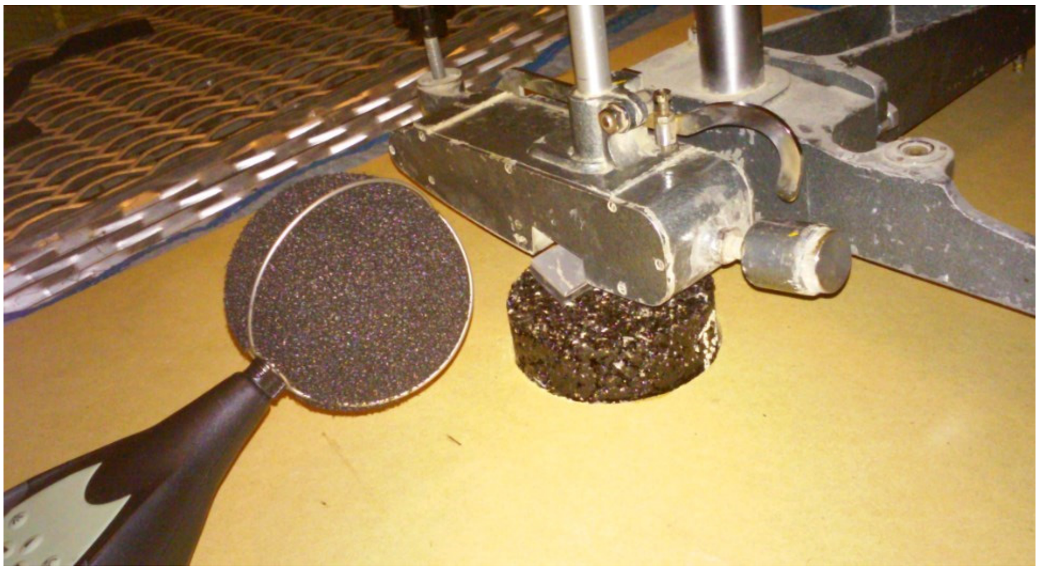

Figure A.6: BPT testing head in contact with specimen

Figure A.7: Side view of test setup

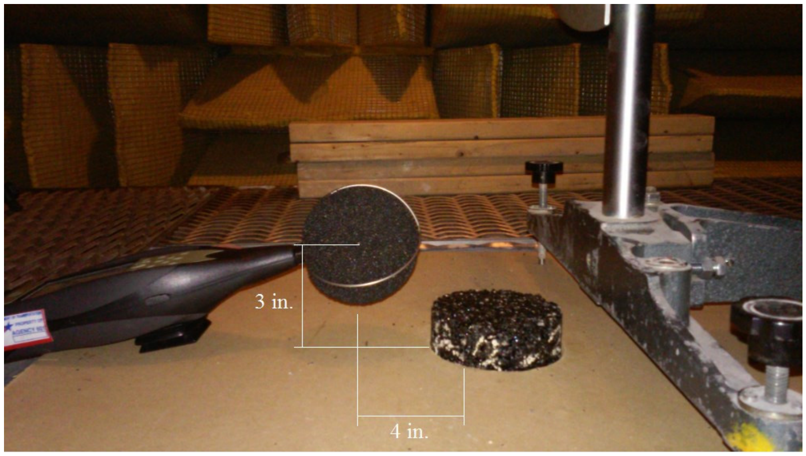

Figure A.8: Sound meter position

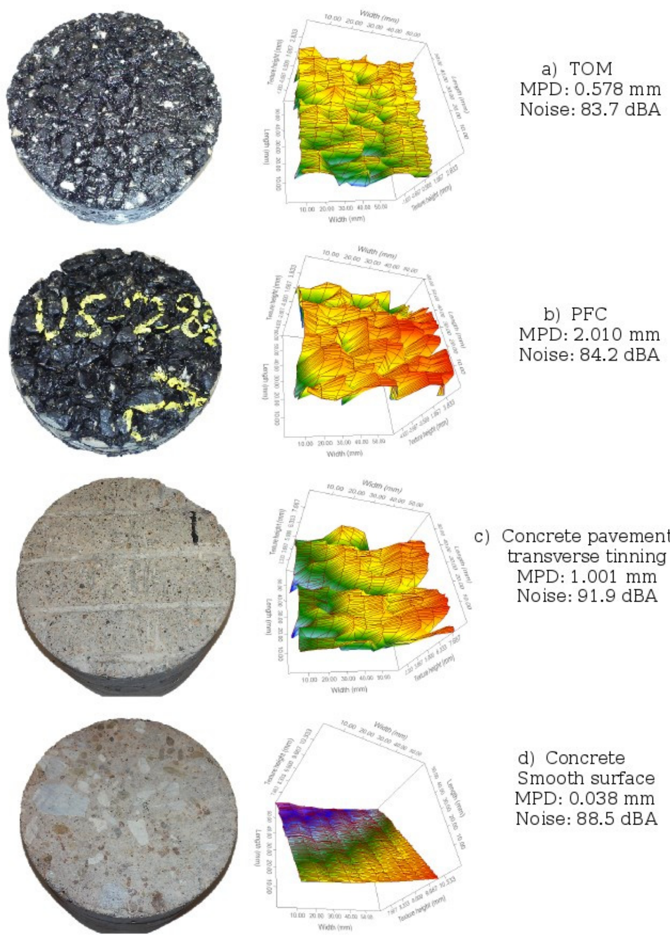

Figure A.9: Preliminary tests results

Appendix B: Guidelines and Recommendations

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

0-6819-P2

GUIDELINES AND RECOMMENDATIONS FOR PROJECT SELECTION AND DESIGNING SURFACES FOR LONG-TERM NOISE REDUCTION

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TxDOT Project 0-6819: Designing Quieter Pavement Surfaces

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

This document presents the guidelines and recommendations that were gathered as the outcome of Project 0-6819, Designing Quieter Pavement Surfaces. These recommendations apply for abatement of highway traffic noise for existing projects, by means of noise barriers and pavements (replacing, modifying, or overlaying them), as well as for new projects that require a new pavement design. For these cases, consideration of a quieter pavement is recommended.

1. Identification of Traffic Noise Impacts

Traffic noise impacts are determined either by sound pressure level (SPL) measurements at the receptors' locations or by modeling the highway by means of the Traffic Noise Model (TNM) program. Current federal law requires that highway agencies determine and analyze expected traffic noise impacts on federally funded projects. If the measured or expected noise levels approach or exceed allowable threshold values, noise abatement procedures must be considered. Currently, the Federal Highway Administration (FHWA) policy (*FHWA-HEP-10-025*) only allows noise barriers to be utilized as a noise abatement measure for federally funded projects. The FHWA has not allowed pavement type to be used as a noise mitigation option because many significant components of highway noise—such as engine noise, aerodynamic noise, and exhaust noise—are independent of pavement type. However, research has indicated that effective noise reductions can be obtained by utilizing quieter pavements, and by managing pavement surface characteristics such as macrotexture and porosity that are independent of pavement type. The use of quieter pavements and appropriate textures, in many cases, can eliminate the need for noise barriers.

Sound Pressure Level Tests

If using SPL tests, the field measurements should be performed along all the existing or proposed roadway segments that may be affected by the project. The locations for such tests should be representative of first-row receivers, wherever frequent outdoor human activity is likely to occur (porch, front yard, back yard, parks, campgrounds, etc.), and inside buildings such as hospitals, schools, or churches.

Measurements shall be made in accordance with the procedures in the FHWA's Measurement of Highway-Related Noise *(FHWA-PD-96-046)* guidelines. Condenser microphones are recommended, such as the microphone utilized by the SPL meter illustrated in Figure 1. The time-averaged value of the SPL during the test interval, i.e., the 'equivalent continuous sound level' [Leq(A)] should be used. Leq(A) is defined as the equivalent steady-state sound level that, in a given time period, contains the same acoustic energy as a time-varying sound level during the same period (Figure 2). Leq(A) is used for all traffic noise analyses for TxDOT highway projects. Measurements should be performed over 15-minute periods in order to be representative of an hourly Leq. Measurements may be discontinued sooner if the Leq has not changed in the last 5 minutes of the measurement when the number is rounded to the nearest whole number. All measurements must have stabilized after 10 minutes to be valid.

Figure 1. Sound pressure level meter

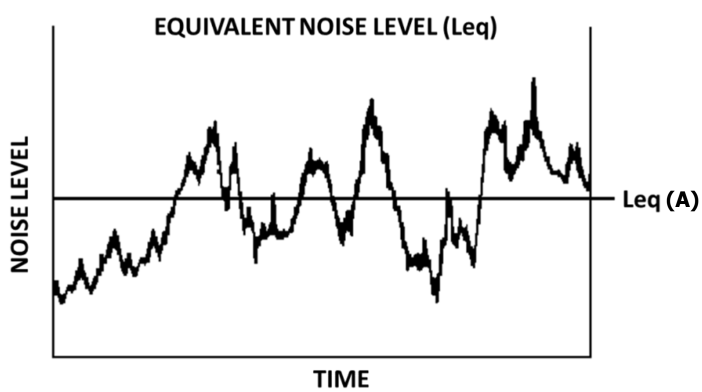

Figure 2. Leq(A): average noise level over a period of time

Measurements must be taken at a time of day that represents the loudest hourly highway traffic noise levels occurring on a regular basis under normal traffic conditions. Therefore, field measurements shall be taken when traffic is moving in free-flow conditions and should not reflect congested traffic conditions near, or during, the AM/PM peak traffic periods or during uncommon traffic events. It is recommended to conduct tests at various times during the day (morning, afternoon, and evening) in order to determine the loudest hourly level.

Traffic Noise Model

A TNM is constructed to represent existing traffic as well as the road's geometry, topography, and receiver locations.

According to FHWA policies (*FHWA-HEP-10-025*), a traffic noise impact occurs when the existing or future noise levels approach or exceed the noise abatement criteria (NAC); TxDOT defines the level of approach as 1 dBA. The NAC are presented in Table 1 (*TxDOT 2011*). An impact can also occur when predicted future traffic noise levels substantially exceed the existing noise level, even though the predicted levels may not exceed the NAC.

Table 1. Noise abatement criteria (TxDOT 2011)

Noise Abatement Criteria		
Activity Category	**FHWA (dB(A) Leq)**	**Description of Land Use Activity Areas**
A	57 (exterior)	Lands on which serenity and quiet are of extra-ordinary 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)	Residential
C	67 (exterior)	Active sport areas, amphitheaters, auditoriums, campgrounds, cemeteries, day care centers, hospitals, libraries, medical facilities, parks, picnic areas, places of worship, playgrounds, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, recreation areas, Section 4(f) sites, schools , television studios, trails, and trail crossings
D	52 (interior)	Auditoriums, day care centers, hospitals, libraries, medical facilities, places of worship, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, schools, and television studios
E	72 (exterior)	Hotels, motels, offices, restaurants/bars, and other developed lands, properties, or activities not included in A-D or F.
F	--	Agricultural, airports, bus yards, emergency services, industrial, logging, maintenance facilities, manufacturing, mining, rail yards, retail facilities, shipyards, utilities (water resources, water treatment, electrical), and warehousing.
G	--	Undeveloped lands that are not permitted.

To assure the noise model is valid and accurate, field measurements of current sound levels shall be compared to the model, with the tests being conducted at the same locations as the receptors in the model. The site review and sound level measurements should also consider major noise sources in the area from non-highway transportation, industry, or other background sources.

For the model to be accurate, it is recommended to get current reliable traffic volumes, as well as predictions for the future that model the traffic growth. It is highly recommended to get traffic counts at the same time the SPL tests are conducted.

The TNM analysis will determine all impacts, as well as identify the number of receivers who could benefit from abatement.

2. Measurement of Roadway Noise

To determine the noise levels generated at the tire/pavement interface, tests should be conducted using the on-board sound intensity (OBSI) method (*AASHTO* TP 76-13). The OBSI test has become the standard for tire/pavement noise evaluation because it isolates the tire/pavement interface, measures the magnitude of the sound as well as its directionality (sound intensity), can be performed without the need for traffic control, and is conducted in a relatively expedited way. The OBSI equipment is shown in Figures 3 and 4. This test will indicate whether the roadway surface needs to be replaced, overlaid, or its texture needs to be modified due to its loudness. However, highway safety must not be compromised in favor of reductions in roadway noise. It is essential that the pavement design process specifically include the selection and design of surface textures that reduce potential for hydroplaning, and provide improved surface friction for both wet and dry conditions.

Figure 3. OBSI equipment and vehicle

Figure 4. OBSI test probe

3. Pavements

Historically, the most common approach to highway noise mitigation has been the placement of sound barriers that block or deflect the sound from nearby receptors. In light of research in recent years, however, reducing the noise at the source has proved to be the most sensible approach. The idea is that by eliminating noise at the source, more potential receivers as well as the driving public are benefitted, as opposed to a noise wall that is only able to benefit certain receivers—those that are in the acoustic shadow of the wall. The foremost component of traffic noise at highway speeds is the noise generated at the tire/pavement interface. Therefore, in regards to highway traffic noise, a quieter pavement is the most viable solution and the first one to consider.

A quieter pavement, as opposed to a conventional pavement, can substantially reduce noise levels for drivers and receptors along the roadway.

Pavement type, materials, and surface characteristics are key elements in the generation of tire/pavement noise. Among the pavement surface characteristics, the texture plays a significant role in the noise generation (as well as in other important safety aspects such as wet-weather friction, splash and spray, rolling resistance and tire wear). In general, stiffer, coarser (i.e., with larger aggregate, in most cases), rougher, more distressed, or jointed pavements generate more noise than their flexible, smoother and in-better-condition counterparts. For certain types of pavements (e.g., permeable friction courses or PFCs) the void content is also an important factor for their noise absorption capabilities.

If the noise analysis with SPL tests and/or a TNM indicates that noise impacts are affecting receptors in the vicinity of the road, changing the pavement type or texture could reduce the noise levels and eliminate the impacts. If the existing pavement is a conventional pavement that has been in service for several years and presents superficial distresses, but is still structurally sound and has years of remaining life, placement of a quieter pavement overlay is recommended. It is important to emphasize that the decision of whether to overlay or to choose another approach depends on the condition of the existing pavement, its age, its expected service life, and its performance in other critical aspects, such as safety, required maintenance, riding quality, friction, etc.

If the existing pavement generates high noise levels and is near the end of its service life, it is recommended to replace it with a new quieter pavement.

Concrete Pavements

The most common concrete pavement type in Texas is continuously reinforced concrete pavement, and the most widespread texturing technique applied to it is transverse tining. Transverse tining can provide good surface friction characteristics for the duration of the pavement's service life. However, this type of texturing is frequently associated with high noise levels, and especially with objectionable tonal qualities of the sound in the perception of roadside receivers and drivers. The objectionable tone could be described as a "whining" noise that the transverse tining produces, which is related to peaks in the noise spectra, particularly at the 1 kHz frequency band. The key to reducing the objectionable tone is to eliminate the peaks in the noise spectra. Random transverse tine spacing patterns can reduce this "whine," but this type of texturing is rarely used. Another option is the use of longitudinal tining, which also eliminates the whining noise.

For the case of a concrete pavement, changing the existing texture is a viable solution instead of an overlay, especially for the case of a pavement that is structurally sound and still has remaining life. The best texturing option for concrete pavement is to apply diamond grinding. Diamond grinding will lessen the objectionable tonal qualities and the noise generation effect of the tining, and will eliminate superficial distresses, thus further reducing noise levels. Besides that, diamond grinding is a highly effective texturing technique that improves pavement profile and ride quality, and restores surface friction under both wet and dry conditions. Therefore, it can be considered an excellent rehabilitation technique for a loud concrete pavement.

Asphalt Pavements

Conventional asphalt pavements have a wide variability in their acoustic performance, which is also dependent on their texture and condition. Specifically, macrotexture has a significant effect on noise generation. These dense-graded asphalt pavements are not placed for their particular noise performance, but for other advantageous characteristics. Dense-graded asphalt pavements can be overlaid with a quieter overlay to reduce noise levels and to improve other surface characteristics, such as riding quality, drainage, friction, night-time visibility, and splash and spray reduction.

Chip seals are not recommended from the acoustic standpoint, as they have been found to be the loudest pavement type.

4. Quieter Pavements

Two quieter pavement types have been successfully applied in Texas: PFCs and thin overlay mixes. PFCs are by far the most widespread, but in recent years, TOMs have shown that they can provide significant noise level reductions as well, and even better performance than PFCs.

Thin Overlay Mixes (TOM)

In terms of quieter pavements, including overlays, the option that produces the lowest noise levels is the TOM with low surface macrotexture. This pavement type has consistently shown that it is quieter than others, including the PFC, which for many years had been the alternative of choice for quieter pavements. TOM overlays can be placed on top of a conventional pavement for noise-reducing purposes. Overlays can be placed as thin as ½ in. and still provide outstanding acoustic performance. As a result of this research, TOMs with low surface macrotexture are recommended as the first choice for quieter pavements.

PFCs

PFCs have demonstrated significant noise reductions over the years. However, these surfaces seem to lose some of their acoustic durability over time. In some instances, worn-out, old PFCs seem to be clogged, with their appearance resembling that of dense-graded asphalt, but they are still capable of reducing noise. Even though PFCs may experience some reduction in their noise-absorption capabilities with time, they still provide significant benefits over conventional pavements. Two types of PG binders have generally been used in PFCs in Texas: PG 76-22 and PG 76-22TR. Excellent performance has been observed with both of these types of binders. Once a PFC surface has reached the end of its life, it must be removed from the pavement surface. It should never be overlaid or seal coated. PFCs are the second choice for a quiet pavement behind TOMs.

5. Noise Barriers

If a pavement solution is not enough to reduce noise levels from the highway, it could be because there are other noise sources in addition to the tire/pavement noise that significantly contribute to the overall noise levels. In such cases, the placement of a noise barrier could be beneficial.

The most frequently used noise abatement measure has been the construction of noise barriers on the side of the road. Such barriers are normally built along highways that carry heavy traffic in urban areas, where noise pollution is likely to be higher and affects more people. Because of their elevated cost, traffic noise barriers are not typically placed in rural areas, where not many people are affected by noise, or on low volume roads, where the noise levels are not consistently high. The barriers, however, are only effective for receivers in the acoustic shadow of the wall. Noise barriers are normally solid wall structures built between the highway and the impacted activity area to reduce noise levels. Barriers do not eliminate the noise; they only reduce the noise levels perceived for certain benefitted receivers, normally those in proximity to the roadway. Barriers are especially effective for those receivers situated directly behind it; they can experience a decrease in noise level of typically 5 to 10 dBA. Noise barriers are not effective for receivers on a hillside overlooking a road, or for buildings that rise above the barrier; the barrier must be high enough and long enough to block the view of the road. Common materials for barrier construction are concrete and masonry; other materials are metal and acrylic. Such barriers are mostly reflective. Absorptive materials can also be used and these include panels with mineral wool or other fibers inside them. Absorptive barriers are more expensive and have shorter service life than reflective barriers constructed with solid materials such as concrete or metal. Therefore, absorptive barriers are not very common.

The height, length, and material used are key components to the effectiveness of the barrier. Openings in the barriers, such as those designed to allow access to side roads or driveways, decrease their effectiveness. Many barriers reduce visibility and lighting; in such cases transparent materials can provide a solution. Barriers could present a problem for businesses along the road by restricting views and access by customers. It is relevant to invite public involvement in the decisions about barrier design and construction.

The FHWA, in its noise barriers guidelines (*FHWA-HEP-10-025*), recommends that, to effectively reduce sound transmission through the barrier, the material chosen must be rigid and sufficiently dense (at least 20 kg/m^2). All noise barrier material types are equally effective, acoustically, if they have this density. Noise barriers reduce the sound that enters a community from a busy highway by absorbing the sound, transmitting it, reflecting it back across the highway, or forcing it to take a longer path over and around the barrier (*FHWA Noise Barrier Design*). Therefore, noise barriers work by reflecting some of the acoustic energy, while part of the energy is transmitted through the barrier, part of it is diffracted, and some of it reaches the receiver directly, for those receivers with a line of sight of the source (Figure 5). Therefore, the density of the barrier material is of foremost importance.

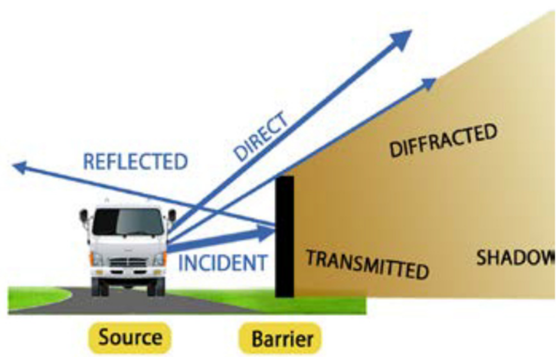

Figure 5. Acoustic energy and noise barrier (Bowlby 2012)

There are no federal requirements specifying the materials to be used in the construction of highway traffic noise barriers. Individual state DOTs can select the materials when building these barriers (*FHWA-HEP-10-025*). The selection is based upon structural considerations, safety, aesthetics, durability, materials availability, maintenance, cost, and the desires of the public.

A single-number rating used to compare the sound insulation properties of barriers is the Sound Transmission Class (STC). The STC rating is the transmission loss value for the reference contour at 500 Hz. Thus, the STC rating is not designed for lower frequencies of traffic noise, so it is typically 5 to 10 dB greater than the transmission loss provided. Approximate transmission loss values for common noise barrier materials are as follows: concrete barriers provide 34 to 40 dB; metal barriers, 18 to 27 dB; and transparent barriers, 22 dB (*FHWA-EP-00-005*).

The acoustic design of the barrier should be performed with the TNM program. The program will indicate the dimensions of the barrier that can provide the desired benefits in terms of noise level reductions for the impacted receivers.

Finally, when dealing with noise complaints it is important to consider all the sources of noise that reach the residential receivers that are not necessarily related to the pavement and those that are not even related to the highway. The combination of both quieter pavement and a noise wall could be a viable solution.

6. References

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