Quieter Pavement

Acoustic Measurement and Performance

February 2018

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13. Supplementary Notes
Most quiet pavement work was performed under several Caltrans contracts. Lower-cost measurement and bench calibration equipment was developed by Transportation Pooled Fund 5(135). AASHTO TP-76 has been renumbered to AASHTO T 360-16.

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David Buehler, PE

15. Abstract
In response to noise complaints, Caltrans's Division of Environmental Analysis began developing a quick, portable, low-cost, and precise pavement acoustic measurement process originally based on General Motors' work measuring tire noise levels. The Caltrans' measurement process has now become AASHTO Designation: T 360-16, Standard Method of Test for the Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OSBI) Method. [T 360-16 was formerly TP-76.]

Roadside noise levels can be significantly influenced by pavement selection and design. At non-stop-and-go, cruising speeds, the primary vehicle noise generator is tire/pavement interaction. Transportation agencies have no control over tire design, but they have direct control over pavement design. This report gives a general summary of the work done in quantifying and comparing pavement acoustics and indexing the relative noise levels of different pavements and roadway surfaces. Quantifying pavement acoustics can become an important tool for addressing roadside noise levels and improving traffic noise modeling accuracy. This document is not meant to be a pavement design guide.

16. Key Words

Highway traffic noise, tire/pavement acoustics, quieter pavement, On-Board-Sound-Intensity, OBSI, AASHTO TP-76, AASHTO T 360-16, TPF-5(135), coherence, pressure intensity index, acoustical longevity

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QUIETER PAVEMENTS:
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List of Tables and Figures

List of Abbreviated Terms

AADT	average annual daily traffic
AASHTO	American Association of State Highway Transportation Officials
AC	asphalt concrete
ACPA	American Concrete Pavement Association
ADOT	Arizona Department of Transportation
AR	asphalt rubber
ARFC	Asphalt Rubber Friction Course
BWC	bonded wearing course
Caltrans	California Department of Transportation
CEQA	California Environmental Quality Act
CPX	close proximity
CTIM	Continuous-Flow Traffic Time-Integrated
dB	decibel
dBA	A-weighted sound level
DGAC	dense-graded asphalt concrete
DLPA	double layer porous asphalt
FHWA	Federal Highway Administration
GM	General Motors
HMA	hot mix asphalt
HOV	High Occupancy Vehicle
Hz	Hertz
I-	Interstate
I&R	Illingworth & Rodkin
IL	intensity level
km/h	kilometers per hour
kPa	kilo-Pascal
LCCA	Life-Cycle Cost Analysis
L_{eq}	equivalent sound level
L_{max}	maximum sound level
m/sec	meters per second
mph	miles per hour
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NITE	Noise Intensity Testing in Europe
NPV	net present value

OBSI	on-board sound intensity
OGAC	open-graded asphalt concrete
PI index	pressure-intensity index
pW	picowatt
QP3	Arizona Quiet Pavement Pilot Program
QPR	Quiet Pavement Research
RAC	rubberized asphalt concrete
REMEL	Reference Energy Mean Emission Levels
SI	sound intensity
SIP	Statistical Isolated Pass-By
SMA	stone mastic asphalt
SPB	Statistical Passby
SP	sound pressure
SPL	sound pressure level
SR	State Route
SRTT	Standard Reference Test Tire
TeNS	Technical Noise Supplement
TNM	Traffic Noise Model
TPF	Transportation Pooled Fund
W/m^2	watts per square meter

Chapter 1 Introduction

Traffic noise pollution has become a growing and widespread problem, particularly in urban areas where the population density near major thoroughfares is high and there is a large volume of commuter and commercial traffic. Federal Highway Administration (FHWA) policies identify five approved highway traffic noise abatement options (Federal Highway Administration 2011), with barriers currently being the primary method of abating traffic noise (National Academy of Engineering 2010). In 2013 alone, the California Department of Transportation (Caltrans) spent more than $44 million dollars on the construction of barriers throughout the state (Federal Highway Administration 2016). However, while noise barriers are effective in many instances, they may not always be the best solution for reducing traffic noise pollution. First, a barrier must break the line-of-sight to be effective. Barrier effectiveness is also reduced in areas with varying terrain and along arterial streets, where gaps are required to allow for driveway or side street access.

Although quieter pavement is not currently listed as an approved abatement option by FHWA, FHWA, state and local transportation agencies, and the general public have shown considerable interest in quieter pavement technology for at least 15 years. This interest has been advanced through research and pilot projects, which have demonstrated traffic noise reductions with application of quieter pavement overlays and surface texture modifications. The understanding of quieter pavements in the United States has increased dramatically with the advent of the on-board sound intensity (OBSI) method of quantifying tire noise performance of pavements at the source (American Association of State and Highway Transportation Officials 2013).

The application of quieter pavement reduces traffic noise levels at the tire-pavement interface, which has been shown to be the primary source of traffic noise when vehicles travel faster than about 30 mph (Donavan et al. 2008). The result of quieter pavement application is lower noise levels for drivers and for those living and working near a roadway. Quieter pavement does not have the same physical site limitations as barriers and typically has a lower upfront cost. However, the noise performance of quieter pavement can degrade over time, resulting in increased maintenance and rehabilitation needs for purposes of noise reduction.

The purpose of this document is to provide comprehensive guidance on quieter pavement to be used by both noise practitioners and pavement engineers. This guidance manual contains a basic overview of pavement acoustics and how they relate to highway traffic noise, a synthesis of quieter pavement research conducted by or initiated by Caltrans over the past 15 years, a summary of current applicable policy and measurement methodology, and recommended best practices in design.

Pavement design and selection is done by a pavement or material engineer based on a number of engineering considerations, such as axle loads, environmental considerations, and cost. Rigid pavements are composed of cement concrete or reinforced slabs. Flexible pavements are a mixture of asphalt bituminous material and various sizes of aggregates. Pavement naming conventions vary by state and by region and many pavement acronyms and naming conventions have changed or evolved over time. This report discusses acoustic measurements collected by acoustic engineers. If a specific pavement was known or identified by a material engineer at the time of a measurement, it was documented based on the acronym or naming convention in place at that time. Current acronyms or naming conventions may be different. The contents of this document are for informational purposes; unless they are referenced in the Caltrans Traffic Noise Analysis Protocol, the contents of this document are not official policy, standard, or regulation.

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American Association of State and Highway Transportation Officials. 2013. *Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method*. AASHTO TP 76-13.

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Chapter 2 Highway Noise Fundamentals

The following is a brief discussion of highway traffic noise and noise reduction concepts (Harris 1998). Please refer to Caltrans Technical Noise Supplement (2013) and the Caltrans on-demand training (2015) for more details.

2.1 Noise

Noise may be defined as unwanted sound. Noise is usually objectionable because it is disturbing or annoying. The objectionable nature of sound could be caused by its *pitch* or its *loudness*. *Pitch* is the height or depth of a tone or sound, depending on the relative rapidity (*frequency*) of the vibrations by which it is produced. Higher pitched signals sound louder to humans than sounds with a lower pitch. *Loudness* is intensity of sound waves combined with the reception characteristics of the ear. Intensity may be compared with the height of an ocean wave in that it is a measure of the amplitude of the sound wave.

2.2 Decibel

In addition to the concepts of pitch and loudness, there are several noise measurement scales that are used to describe noise in a particular location. A decibel (dB) is a unit of measurement that indicates the relative amplitude of a sound. The zero on the dB scale is based on the lowest sound level that the healthy, unimpaired human ear can detect. Sound levels in decibels are calculated on a logarithmic basis. An increase of 10 dB represents a ten-fold increase in acoustic energy, while 20 dB is 100 times more intense, 30 dB is 1,000 times more intense, and so on. There is a relationship between the subjective noisiness or loudness of a sound and its intensity. Each 10-dB increase in sound level is perceived as approximately a doubling of loudness over a fairly wide range of intensities.

2.3 A-Weighted Sound Level

There are several methods of characterizing sound. The most common in California is the A-weighted sound level (dBA). This scale gives greater weight to the frequencies of sound to which the human ear is most sensitive. The A-weighting filter de-emphasizes the very low and very high frequency components of the sound in a manner similar to the frequency response of the human ear and correlates well with subjective reactions to noise. Representative outdoor and indoor noise levels in units of dBA are shown in Table 2-1.

Table 2-1. Typical A-Weighted Sound Pressure Noise Levels

Common Outdoor Activities	Noise Level (dBA)	Common Indoor Activities
	— 110 —	Rock band
Jet fly-over at 1000 feet		
	— 100 —	
Gas lawn mower at 3 feet		
	— 90 —	
Diesel truck at 50 feet at 50 mph		Food blender at 3 feet
	— 80 —	Garbage disposal at 3 feet
Noisy urban area, daytime		
Gas lawn mower, 100 feet	— 70 —	Vacuum cleaner at 10 feet
Commercial area		Normal speech at 3 feet
Heavy traffic at 300 feet	— 60 —	
		Large business office
Quiet urban daytime	— 50 —	Dishwasher next room
Quiet urban nighttime	— 40 —	Theater, large conference room (background)
Quiet suburban nighttime		
	— 30 —	Library
Quiet rural nighttime		Bedroom at night, concert hall (background)
	— 20 —	
		Broadcast/recording studio
	— 10 —	
Lowest threshold of human hearing	— 0 —	Lowest threshold of human hearing

Source: California Department of Transportation 2013.
dBA = A-weighted sound level

2.4 Sound Level Meter

The scientific instrument used to measure noise is the sound level meter. Sound level meters can accurately measure environmental noise levels to within about plus or minus 1 dBA.

2.5 Noise Models

Various computer models are used to predict environmental noise levels from sources such as roadways and airports. The accuracy of the predicted models depends upon the distance from the receptor to the noise source. Close to the noise source, the models are accurate to within about plus or minus 1 to 2 dBA, depending on the model.

2.6 Sound Pressure Level

Sound pressure is the force of sound per unit area, usually expressed in micro Pascals (or 20 micro Newtons per square meter), where 1 Pascal is the pressure resulting from a force of 1

Newton exerted over an area of 1 square meter. The sound pressure level is expressed in decibels as 20 times the logarithm to the base 10 of the ratio between the pressures exerted by the sound to a reference sound pressure (e. g., 20 micro Pascals). Sound pressure level is the quantity that is directly measured by a sound level meter.

2.7 Sound Intensity

Sound intensity is a measure of a directional rate of energy flowing through a unit of area. The units of sound intensity are watts per square meter (W/m^2) and can be expressed in decibels: 1 picowatt (pW) per m^2 (1 pW = 10^{-12} W). This implies that if the entire measurement area around a source is known, its sound power can be calculated if the mean sound intensity for the measurement area is known. The measurement area (usually hemispherical) around a source increases with distance, and, because sound intensity decreases with increasing area, sound power remains constant at any distance. To reduce the influence of background noise, sound intensity measurements are taken close to the source. Caltrans commonly uses OBSI measurements to characterize sound generated by tires on various types of pavement. The process for conducting OBSI measurement is now defined in the American Association of State Highway Transportation Officials (AASHTO) TP 76 procedure[1]. OBSI measurements are discussed in more detail in Chapter 4.

2.8 Coherence

Coherence is a measure of the linear dependency of two signals with a value of 0 being no dependency, and a value of 1 being prefect linear dependence. Mathematically, it is the magnitude of the cross-spectrum between two signals squared divided by the product of the auto spectrum of both signals. In AASHTO TP 76, limits are also set on the coherence between the two microphone channels that compose an OBSI probe. The limits are based on the allowable amount that the coherence can drop below the ideal coherence of 1.

2.9 Pressure-Intensity index (PI index)

The arithmetic average of the sound pressure levels (SPL) of both microphones on the probe minus the sound intensity level (IL), is given by the following equation:

$$PI = SPL_{avg} - IL$$

The PI index for each ⅓ octave band is calculated using the sound pressure levels and intensity level corresponding to that ⅓ octave band. Because the PI index represents a difference in level, the units for the PI index are reported in dB rather than dBA. In the AASHTO TP 76 procedure, limits are set on PI index as an indicator of valid data.

[1] AASHTO TP 76-13, Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method, 2013.

2.10 Noise Descriptors

Environmental sound levels can vary markedly over a short period of time. Various noise descriptors have been developed to describe either the average character of the sound or the statistical behavior of the variations of time-varying noise levels. The following are the noise descriptors most commonly used in traffic noise analysis.

- **Equivalent Sound Level (L_{eq}):** The average of the sound energy occurring over a specified period of time. The most common averaging period and the basis for the Noise Abatement Criteria (NAC) used by Caltrans and FHWA is hourly, but L_{eq} can describe any series of noise events of arbitrary duration.
- **Percentile-Exceeded Sound Level (L_{01}, L_{10}, L_{50}, L_{90})**: The A-weighted noise levels that are exceeded 1%, 10%, 50%, and 90% of the time during the measurement period.
- **Maximum Sound Level (L_{max}):** The highest instantaneous sound level measured during a specified period.
- **Ambient Noise Level:** The composite of noise from all sources near and far. The normal or existing level of environmental noise at a given location.
- **Intrusive:** That noise which intrudes over and above the existing ambient noise at a given location. The relative intrusiveness of a sound depends upon its amplitude, duration, frequency, time of occurrence, and tonal or informational content, as well as the prevailing ambient noise level.

2.11 Human Response to Changes in Noise Levels

Under controlled conditions in an acoustical laboratory, the trained, healthy human ear is able to discern 1 dB changes in sound levels, when exposed to steady, single-frequency ("pure-tone") signals in the mid-frequency (1,000 Hertz [Hz] to 8,000 Hz) range. In typical noisy environments, changes in noise level of 1 to 2 dB are generally not perceptible for the same sound. It is widely accepted that people are able to begin to detect sound level increases of 3 dB of the same sound in typical noisy environments. A 5 dB increase is generally perceived as a distinctly noticeable increase, and a 10 dB increase is generally perceived as a doubling of loudness. Therefore, a doubling of sound energy (e.g., doubling the volume of traffic on a highway) that would result in a 3 dB increase in sound, would generally be perceived as barely detectable.

2.12 Sound Propagation

When sound propagates over a distance, it changes in level and frequency content. The manner in which noise reduces with distance depends on the following factors.

2.12.1 Geometric Spreading

Sound from a localized source (i.e., a point source) propagates uniformly outward in a spherical pattern. The sound level attenuates (or decreases) at a rate of 6 dB for each doubling of distance from a point source. Highways consist of several localized noise sources on a defined path, and, hence, can be treated as a line source, which approximates the effect of several point sources. Noise from a line source propagates outward in a cylindrical pattern, often referred to as cylindrical spreading. Sound levels attenuate at a rate of 3 dB for each doubling of distance from a line source.

2.12.2 Ground Absorption

The propagation path of noise from a highway to a receptor is usually very close to the ground. Noise attenuation from ground absorption adds to the attenuation associated with geometric spreading. Traditionally, the excess attenuation has also been expressed in terms of attenuation per doubling of distance. This approximation is usually sufficiently accurate for distances of less than 200 feet. For acoustically hard sites (i.e., sites with a reflective surface between the source and the receptor, such as a parking lot or body of water), no excess ground attenuation is assumed. For acoustically absorptive or soft sites (i.e., those sites with an absorptive ground surface between the source and the receptor, such as soft dirt, grass, or scattered bushes and trees), an excess ground-attenuation value of 1.5 dB per doubling of distance is normally assumed. When added to the cylindrical spreading, the excess ground attenuation results in an overall drop-off rate of 4.5 dB per doubling of distance.

2.12.3 Atmospheric Effects

Receptors located downwind from a source can be exposed to increased noise levels relative to calm conditions, whereas locations upwind can have lowered noise levels. Sound levels can be increased at long distances (e.g., more than 500 feet) from the highway due to atmospheric temperature inversion (i.e., increasing temperature with elevation). Other factors such as air temperature, humidity, and turbulence can also have significant effects.

2.12.4 Shielding by Natural or Human-Made Features

A large object or barrier in the path between a noise source and a receptor can substantially attenuate noise levels received by the receptor. The amount of attenuation provided by shielding depends on the size of the object and the frequency content of the noise source. Natural terrain features (e.g., hills and dense woods) and human-made features (e.g., buildings and walls) can substantially reduce noise levels. Walls are often constructed between a source and a receptor specifically to reduce noise. A barrier that breaks the line of sight between a source and a receptor will typically result in at least 5 dB of noise reduction. Taller barriers provide increased noise reduction. Vegetation between the highway and receptor is rarely effective in reducing noise because it does not create a solid barrier.

2.13 Traffic Noise Reduction Strategies

Strategies involving quieting the source, disrupting the path, or insulating the receiver may conceptually be used to achieve noise abatement. Using a common analogy of a loud stereo set in a room, there are three options for lowering the sound heard by a listener in an adjacent room. The first is lowering the volume at the stereo, quieting the source. The second option is to close the door between the two rooms, disrupting the path. As a third option, the listener can wear earplugs, insulating the receiver.

Although quieting the source would conceptually be the simplest and most effective method of noise abatement, Caltrans has so far dealt with noise abatement primarily by constructing noise barriers to disrupt the path between the highway traffic noise source and resident receivers. This approach is used because Caltrans has limited options for quieting the highway traffic noise source. For instance, Caltrans has no control over sound that vehicles generate. Vehicle noise has been the responsibility of the U.S. Environmental Protection Agency, which, over the years, through regulatory and legislative action, has mandated stricter new vehicle noise standards, especially for trucks.

However, Caltrans does have control over several aspects of highway design in addition to the construction of barriers that could result in traffic noise reduction through either disrupting the path or quieting the source. For new highways, alignments could be located away from sensitive receivers or depressed below grade of adjacent sensitive areas. Another detail of highway design that affects noise at the source is the type and texture of pavement used. By applying quieter pavement strategies to existing or new highways, traffic noise can be reduced at the source, resulting in lower noise levels for both drivers and for people living and working alongside the highway.

References

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Chapter 3 Tire-Pavement Noise Fundamentals

This chapter describes the fundamentals of traffic noise and tire-pavement noise and provides some background on highway noise source heights for trucks and the development of the OBSI measurement method.

3.1 Traffic Noise Generation

Traffic noise consists of three primary noise sources: propulsion, tire-pavement, and aerodynamic. Propulsion noise includes sounds generated by the engine, exhaust, intake, and other powertrain components. Tire-pavement noise is that which is generated as the tire rolls along the pavement. Aerodynamic noise is caused by turbulence around a vehicle as it passes through the air. Propulsion dominates the total noise at very low speeds. Propulsion noise is a function of vehicle type and operating condition. As car engines become quieter, the relative contribution of tire-pavement noise becomes greater, and quieter pavements become more practical. Only at very high speeds do aerodynamic sources begin to dominate.

Figure 3-1 shows typical passby noise levels generated by different vehicle types under cruise (non-accelerating) and interrupted flow/up-grade (accelerating) conditions at a distance of 50 feet (15.25 meters). As shown in the figure, both accelerating and non-accelerating vehicles conform within 1 dB at a speed of about 50 mph (80.5 km/h) for all vehicle types, indicating that tire-pavement noise is the dominating source under both operating conditions at highway speeds.

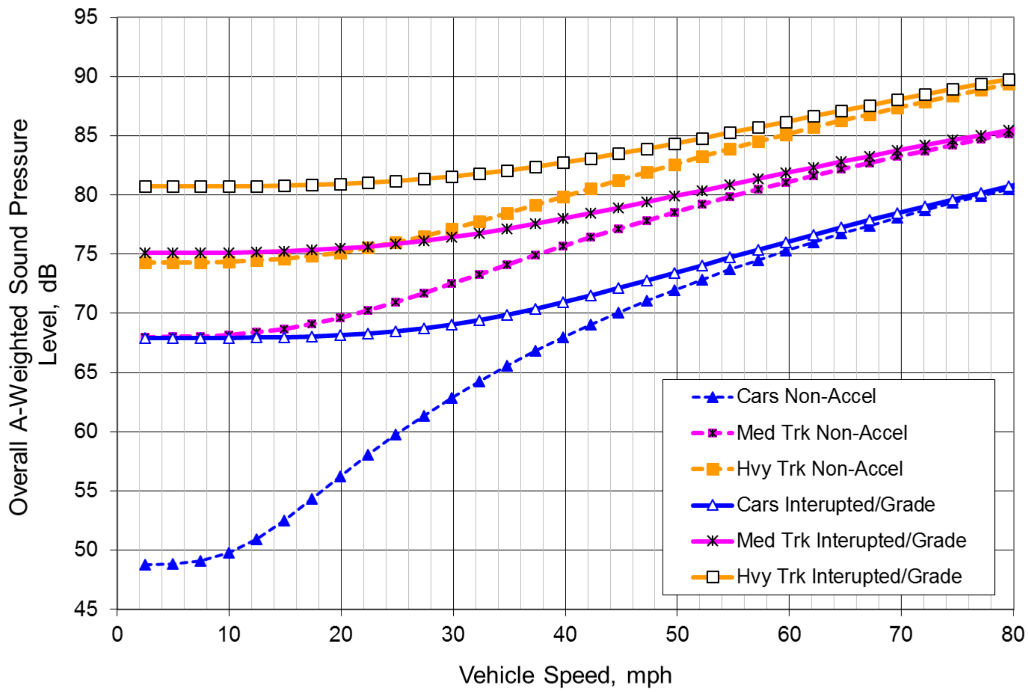


Figure 3-1: Typical 50-foot (15.2-meter) passby noise levels for accelerating and non-accelerating vehicles (Fleming et al. 1995)

Figure 3-2 shows the typical highway noise source breakdown for light vehicles under non-accelerating conditions, indicating that tire-pavement interaction contributes 78% of the overall traffic noise from light vehicles at highway speeds.

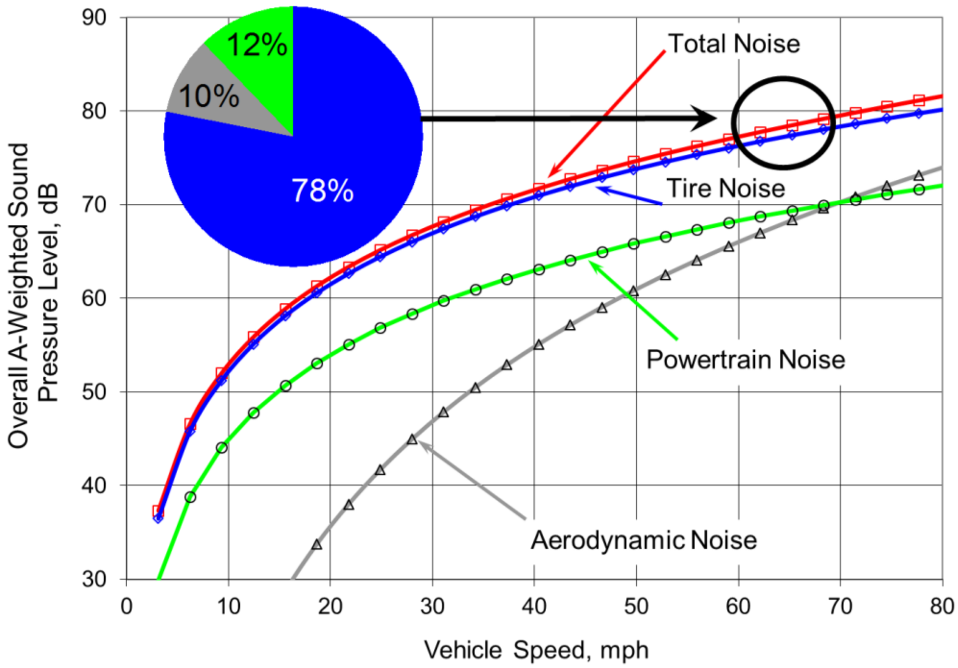


Figure 3-2: Typical highway noise source breakdown for light vehicles (Donavan and Schumacher 2007)

Figure 3-3 shows that the noise source height for a typical truck is at a location very close to the ground plane, indicating that tire-pavement noise is also the largest contributing noise source for heavy vehicles under non-accelerating conditions.

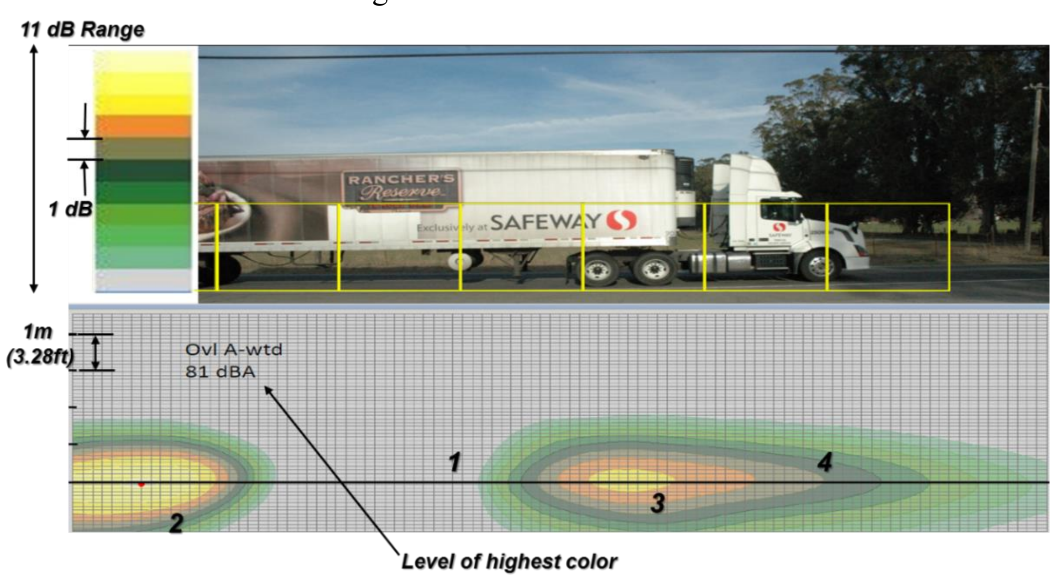


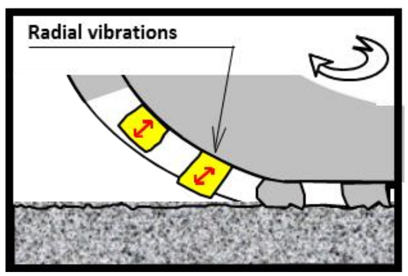
Figure 3-3: Noise source height distribution of typical truck under non-accelerating conditions (Janello 2016)

There are several factors that affect traffic noise levels, including the volume of traffic, vehicle speed, vehicle type and mix, and vehicle operating characteristics. Assuming that the other variables (i.e., vehicle speed and traffic mix) remain consistent, a doubling of the traffic volume will result in a 3 dB increase in traffic noise level. At typical highway speeds, an increase in speed of 10 mph (16 km/h) will result in an increase in sound level of about 2 to 3 dB. Because of their numerous tires and larger propulsion systems, heavy trucks typically generate noise levels that are about 10 dB louder than a typical passenger vehicle. This means that one truck generates the same sound energy as about ten cars. Vehicle operating characteristics including braking (especially engine braking), accelerating, climbing, and cornering also increase noise to varying degrees.

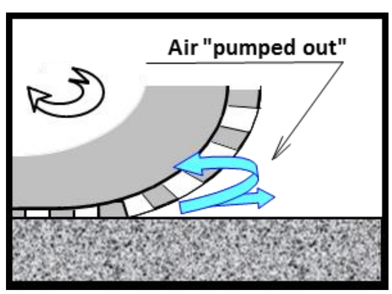
3.2 Tire-Pavement Noise Generation

Tire-pavement noise is complex and is made up of various noise generation mechanisms. The following prominent mechanisms are typically cited (Rasmussen et al. 2007).

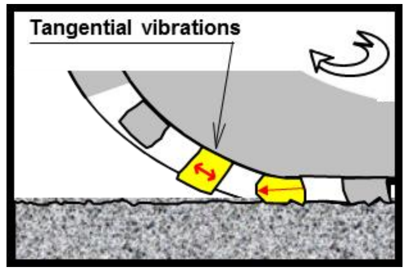
- **Tread Impact:** As the tire rolls along the pavement, each impact of the tire tread with the texture of the pavement comes together as an individual impact, resulting in hundreds or even thousands of impacts each second, with each impact generating sound.



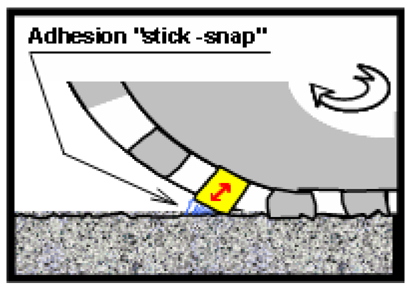
- **Air Pumping:** Air gaps are located between the tire tread and pavement texture. As the tire and the pavement roll together, some of the air is squeezed out and some is trapped and compressed. As the tire loses contact with the pavement, the trapped air is quickly released. All of this happens hundreds or thousands of times a second. This process is similar to clapping your hands, where much of the sound that is heard is air being pushed away quickly.



- **Stick-Slip/Scrubbing:** A sound similar to the distinctive sound of sneakers squeaking on the basketball court can be heard as a tire rolls along the pavement. As the rubber is continually deformed and distorted underneath the tire, it will mostly stick, but also periodically slip once a critical limit is reached. These “corrections” under each tread block happen thousands of times a second, thus generating high frequency sound. Further, when a tread comes into contact with pavement, the rubber is forced to scrub on surface until sufficient friction is developed to lock the tread into place. When it rotates out of contact, the reverse happens as the friction is reduced. This scrubbing sound is broadband and higher in frequency.

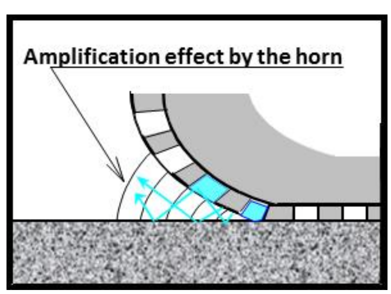


- **Stick-Snap:** A suction cup can stick to a smooth surface because of both adhesion and a vacuum that is created when the air in the cup is pushed out. As tread blocks interact with some pavements, a similar effect could occur, generating sound.

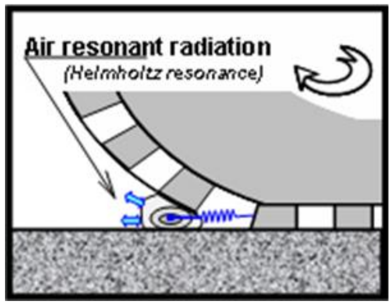


Once the tire-pavement noise is generated, it is amplified through a number of amplification mechanisms, as described below.

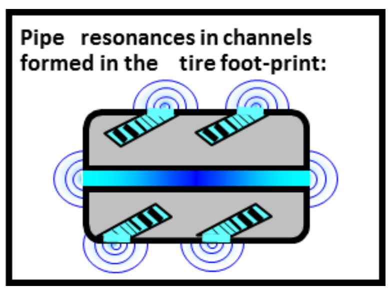
- **Acoustical Horn:** The geometry of a tire and a pavement in contact includes a wedge-shaped segment of open air. Within this wedge, sound generated near the “throat” at the tire-pavement interface can be amplified due to the improved impedance matching between sound in the throat and that radiated at the exit of the horn. In the case of tire-pavement though, the horn is poor because it is open on two sides. The result is a significant amplification in the forward and aft directions, along with a distortion of some frequencies.



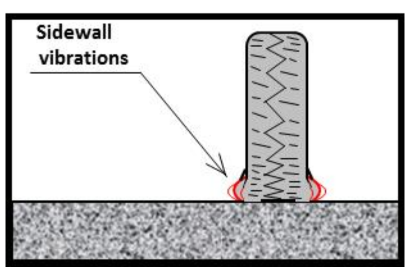
- **Helmholtz Resonance:** When you blow across the top of a bottle, a distinct tone can be heard as result of a phenomenon called Helmholtz resonance. This tone results from the air in the neck of the bottle (acting as a mass) vibrating up and down on the pillow of air inside the bottle (acting as a spring). By itself, blowing creates very little sound. However, blowing across the bottle significantly amplifies the frequency that is distinct to that bottle. A similar geometry can be conceived close into the wedge where the tire and pavement meet. In this case, the spring is the volume of air trapped in tread voids just prior to full contact and closure by the pavement, and the mass is the air in the neck formed between the tread and the pavement. The result is an amplification of some frequencies unique to the geometry of the tire and the pavement.



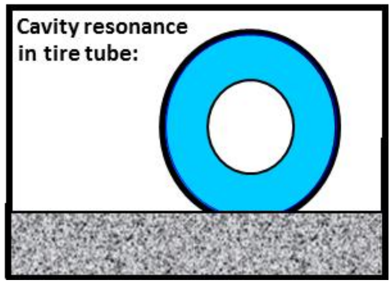
- **Pipe Resonance:** When air is blown across an organ pipe, the amplified sound is unique to the length of the pipe and the number of openings in the pipe. On a tire, similar "pipe" geometries can be found as the various grooves and sipes on a tire are pinched off and opened up at various places underneath the contact patch. For circumferentially ribbed tires, organ pipes with openings at the leading and trailing edges of the contact patch are continuously formed. Sound that is generated elsewhere can be amplified within these pipes.



- **Sidewall Vibrations:** An electric shaver or vibrating cell phone do not make much sound by themselves. However, if one is placed on top of an upside down pie plate, the small vibrations are amplified significantly. Many of the small vibrations described as generating mechanisms could be similarly amplified as vibrations of the tire sidewall.



- **Cavity Resonance:** When a tire is kicked, a distinctive ringing sound can be heard. This sound can actually be better heard inside the vehicle. In fact, this mechanism is less important for noise heard outside the vehicle than it is for noise inside the vehicle, because the vehicle itself tends to further amplify this structure-borne sound that is not efficiently radiated by the tire at the low frequencies where this phenomenon occurs.



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Chapter 4 Development of On-Board Sound Intensity Methodology

From the growing recognition during the early 2000s that pavement selection can be used as an effective traffic noise abatement tool, followed an increased need for developing methods to characterize tire-road noise generation for existing and experimental highway surfaces. To address this need, measurement methodology was developed for application in the State of California that focused on quantifying noise source levels without site-specific, sound propagation effects (Donavan and Rymer 2003).

Several candidate methods for quantifying tire-pavement noise source levels were examined. After review and evaluation of these candidate methods, a near field sound intensity (SI) method was selected based on several factors. First, because of its directivity, the SI method rejects noises that are not on its sensitive axis. As a result, extraneous noise sources, such as wind flow, the vehicle, and surrounding traffic, are attenuated. Signal processing done in the SI calculation rejects flow noise on the microphones relative to a normal sound pressure (SP) by 10 to 15 dB (Oswald and Donavan 1980). Second, unlike SP, SI can be used in the acoustical nearfield to determine the acoustic energy propagating away from the source. SI measurements can also provide metrics used to examine the validity of the data, such as the ratio of SI to SP, propagation direction, and coherence between microphones. In contrast, SP measurement provides none of this information when used in airflows and will measure the reactive sound field (non-propagating energy) in the nearfield of a source. Further, because of SI directivity and short distance to the tire source region, the effects of any reflections from the vehicle body are minimized relative to an SP measurement.

4.1 Fixture Optimization

With the selection of the SI measurement method, this technique was then developed for application in the State of California for in-situ, highway pavement evaluation (Donavan and Rymer 2003). The method originally followed that developed at General Motors (GM) for research purposes in the early 1980s (Donavan and Oswald 1980) and was adapted and further applied for vehicle development purposes at the GM Proving Grounds (Donavan 1993). The original SI method used two closely spaced ½-inch microphones mounted in a side-by-side configuration with the microphones fitted with nose cones pointed in the forward direction of vehicle travel (Figure 4-1). Later, a windscreen was added to help reduce wind-induced noise on the microphones, and fixtures were improved to allow testing on different vehicles with little adaptation (Donavan et al. 1998) (Figure 4-2). The version of the SI probe fixture in use for the Caltrans tire-pavement noise studies in the early 2000s is shown in Figure 4-3 (Donavan and Rymer 2003). In 2010, this method began to be commonly referred to as “on-board sound intensity” (OBSI). The OBSI methodology utilizes SI measurements at specified locations adjacent to the tire-pavement contact patch to provide an objective measure of the tire-pavement noise component. OBSI levels are calculated from the average of measurements made at the leading and trailing edge of the tire-pavement contact patch on the passenger side of the vehicle. Through collaboration between Illingworth & Rodkin (I&R) and the Arizona Department of

Transportation (ADOT), a vertical dual probe orientation was developed, resulting in the fixture shown in Figure 4-4. With the dual probe system, leading and trailing edge contact patch measurements could be made simultaneously, cutting test time by a factor of two (Donavan 2005a). This technique was especially desirable in projects such as Arizona's Quiet Pavement Program, which required on-going pavement noise performance monitoring over a 10-year period at each milepost and in each direction in the 115-mile (185 kilometer) project area.

Figure 4-1: First application of OBSI to tire-pavement noise measurement, as used for truck noise source identification at GM

Figure 4-2: OBSI application to tire-pavement noise measurement on passenger cars at GM

Figure 4-3: OBSI application to tire-pavement noise measurement for purposes of quantifying highway pavement performance (California Department of Transportation 2002)

Figure 4-4: First application of dual probe OBSI method for measuring tire-pavement noise on a CPX trailer (Arizona Department of Transportation 2003)

Validation tests using the dual probe prototype began in July 2003 (Donavan 2005a). The initial application of the two probe fixture was conducted using the ADOT close proximity (CPX) trailer, so as to remove any concerns of flow-induced noise effects due to microphone self-noise or noise generated by flow over the fixture. Laboratory tests using a small loudspeaker noise source to represent the tire-pavement noise indicated that CPX levels with and without the fixture were nearly identical, with the levels with the fixture installed being on average 0.3 dB higher. Initial on-road comparison tests of 193 different sections of freeway in the greater Phoenix area, measured using both the dual probe OBSI fixture and CPX fixture simultaneously, found a one-to-one relationship (Figure 4-5) in which the OBSI levels are 3.4 dB higher than the CPX levels with a standard deviation of 0.6 dB. These results are the same as those for the single probe SI method. The difference in one-third octave band spectra follows a band of about 1 to 2 dB wide from 315 to 5000 Hz (Figure 4-6).

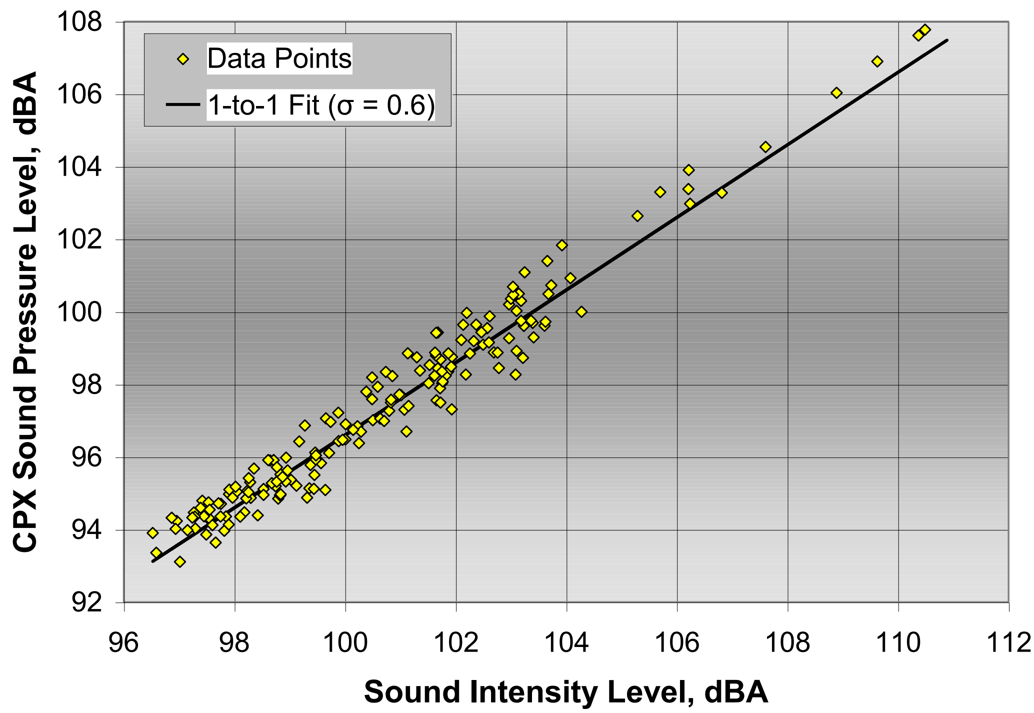

Figure 4-5: OBSI vs. CPX tire-pavement noise levels measured simultaneously on the ADOT CPX trailer using a two probe SI fixture

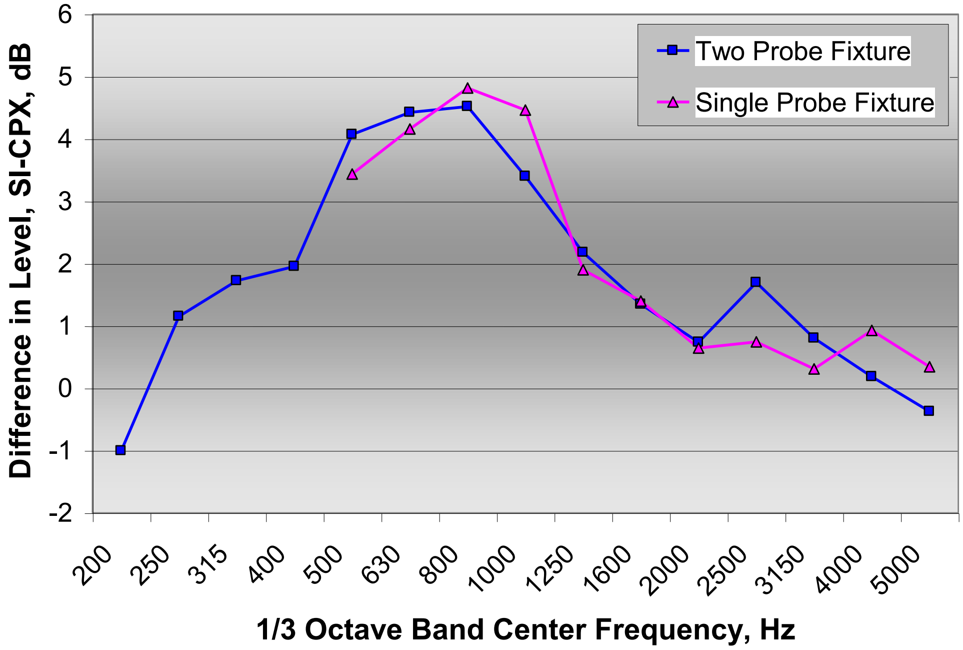

Figure 4-6: Comparison of averages of differences in one-third octave band levels between OBSI and CPX measurements made with the ADOT CPX trailer using single and dual probe fixtures

Following the laboratory test, on-road testing co-sponsored by the American Concrete Pavement Association (ACPA) and Caltrans was conducted in 2005 to compare OBSI measurements made with the single probe fixture and the two probe fixture (Donavan 2005a). For the on-road testing, the OBSI measurements were made directly on the vehicle in exposed air flow. Overall A-weighted OBSI levels for the three sets of measurements are shown in Figure 4-7. The levels from all testing are within about 0.5 dB or less of each other and there is no consistent trend apparent in the OBSI level comparison. The one-third octave band spectra levels were typically within about 1 dB of each other in each frequency band, with the exception of the second dual probe test on the Asphalt Rubber Friction Course (ARFC) Pavement. The reason for this variation is not known; however, it may be attributable to variations within the pavement itself as the ARFC was measured to produce more audible variation than the rigid pavement surfaces. To examine any presence of wind-induced noise contamination in this data, the recorded digital signals were analyzed, including the OBSI data, the difference between OBSI and SPL levels, and the coherence between microphone pairs comprising an intensity probe. From this analysis, flow-induced wind noise contamination in the OBSI data was apparent in frequencies of 400 Hz and lower.

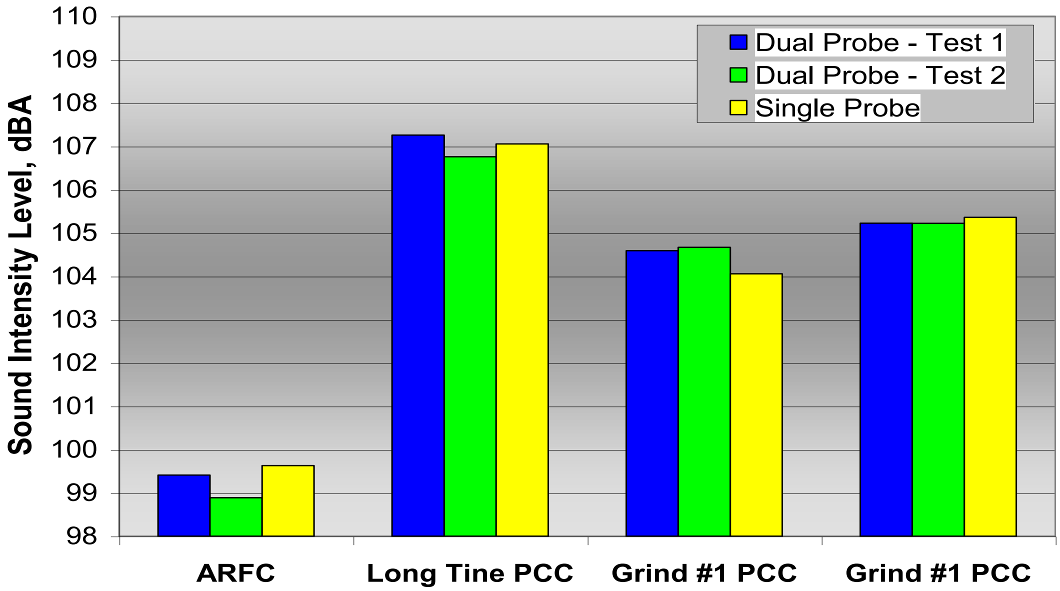

Figure 4-7: Comparison of overall A-weighted OBSI levels measured with single and dual probe fixtures on four pavements

In 2008, measurements were conducted in the GM Aeroacoustic wind tunnel as part of the Caltrans Quiet Pavement Research (QPR) program (Donavan and Lodico 2008). Three different probe fixtures were mounted on a test vehicle exposed to wind of varying speed and yaw angle (simulated cross-wind). The fixture configurations were a single probe mounted horizontally as historically used by GM and I&R, a dual probe mounted horizontally as developed by GM, and a dual probe mounted vertically as developed by I&R for Caltrans applications (see Figure 4-8). In addition, measurements using a microphone holder (specified as the "ideal" fixture), designed to minimize fixture noise generation, were conducted adjacent to the test vehicle at the OBSI trailing edge location, at the front and rear ISO Draft Standard Close Proximity positions (International Organization of Standardization 2000), and in an empty test section after the vehicle was removed. The purpose of this testing was to evaluate different mounting arrangements and to establish limits on allowable wind conditions for on-road OBSI measurements based on the magnitude of the wind-induced SP levels for the microphones.

Figure 4-8: Wind tunnel SI probe configurations
Upper left: Horizontal Single Probe with Windscreen
Upper right: Vertical Dual Probe with Windscreen (On Road)
Lower left: Horizontal Dual Probe with Commercial Windscreen
Lower right: Probe holder ('ideal fixture') in the trailing edge position

The results of the testing indicated that all three OBSI fixtures could be used to accurately measure tire-pavement noise OBSI levels for crosswinds of 0 to –10 degrees of yaw. At +10 degrees yaw and an effective vehicle speed of 60 miles per hour (mph) (97 kilometers [km]/h), it was determined that wind-induced background noise could adversely affect OBSI measurements depending on the strength of the tire noise.

The background noise was found to come from two sources: noise generated by flow around and underneath the test vehicle and noise generated by flow past the OBSI fixture. Using the low noise ideal fixture, the background noise generated by the vehicle was found to be louder at the CPX position, located 4 inches (101.6 millimeters) farther outboard from the tire than the OBSI position. For the CPX position, it was found that wind-induced contamination would be likely, especially at +10 degrees yaw when measuring SP only. Use of the OBSI method reduced the wind-induced contamination to a point where accurate source measurements could be conducted in lower levels of crosswind and its presence could be detected from the coherence between the OBSI microphones.

A portion of the National Cooperative Highway Research Program (NCHRP) 1-44(1) Project (Donavan and Lodico 2011: Appendix E), conducted in 2009, further evaluated the vertical dual probe fixture for wind-induced noise with the intention of identifying potential improvements of the fixture design. The potential for further fixture design improvement can be seen in Figure 4-9, where the dual probe fixture results in wind-induced noise levels of as much as 4 dBA above the ideal fixture in some of the one-third octave bands.

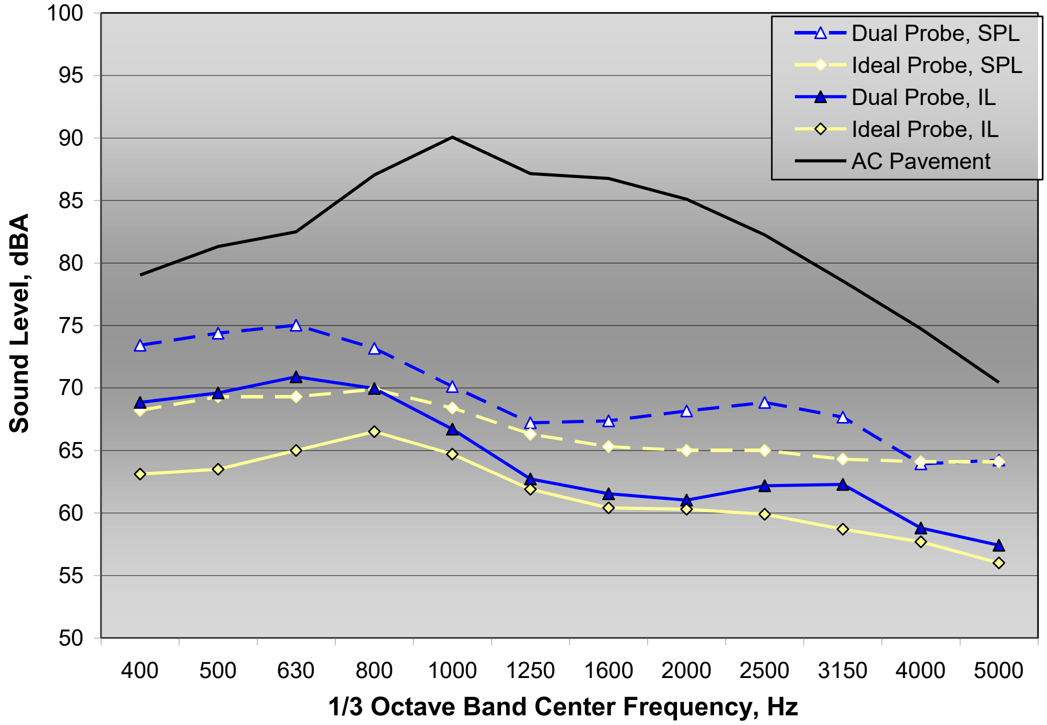

Figure 4-9: Sound intensity and pressure levels with dual and ideal probes for Pontiac G6 vehicle

To evaluate the amount of wind noise generated by various fixture components, measurements were made at the leading and trailing edge positions in the dual probe fixture without the placement of the second probe. Measurements made at the leading edge position were not notably affected by the structure of the trailing edge probe, but, at the trailing edge location, small reductions in wind noise occurred with the removal of the leading edge probe component. Measurements were also made using the ideal fixture during iterations of disassembly of the fixture attached to the vehicle (Figure 4-10). Four iterations of fixture disassembly were made: the full fixture, the fixture with the removal of the leading and trailing edge probe components, the fixture with the removal of the probe and crossbar, and the plate and shaft only.

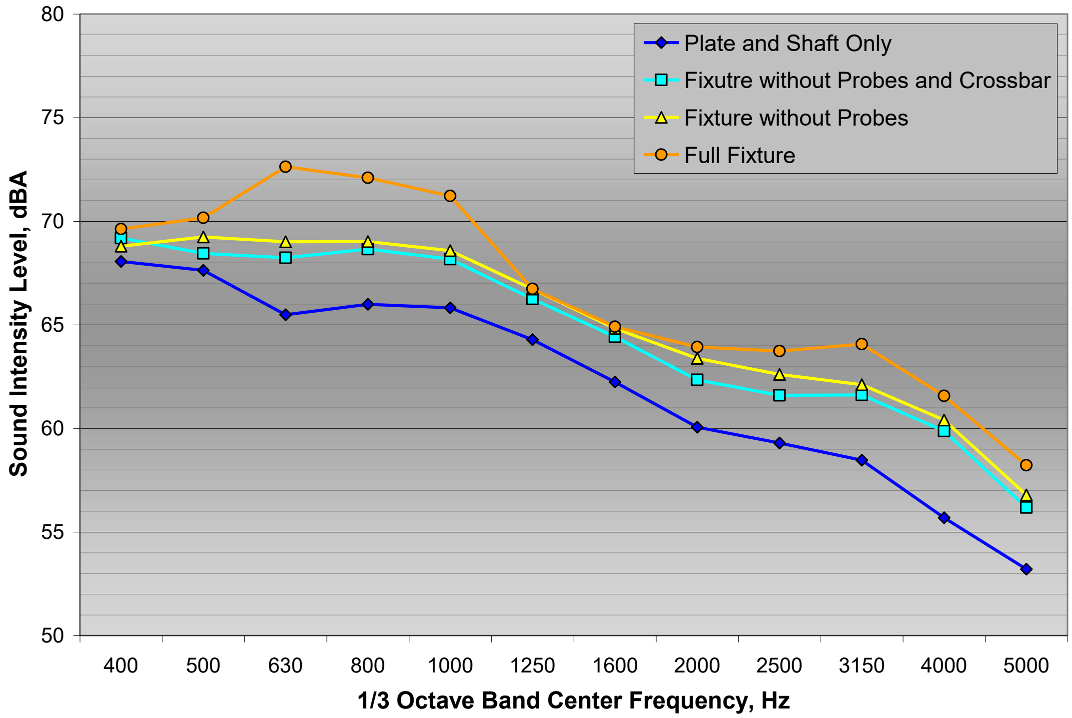

Figure 4-10: Sound intensity levels with different parts removed from the dual probe fixture as measured by the ideal probe 24 inches (609.6 millimeters) to the side

As shown in Figure 4-10, the largest wind noise-generating components are the probes themselves. The greatest differences (up to 3.6 dB) are seen in the frequencies from 630 to 1000 Hz and at 3150 Hz. These are the same frequencies that were found to have the potential for reduction in the comparison between the dual and ideal fixtures in Figure 4-10. Levels with and without the crossbar were within 1.1 dB for all frequencies. As expected, wind noise IL decreased with the removal of the entire fixture (leaving only the shaft and plate). These results indicate that future fixture design should focus on optimizing the probe structures to minimize extraneous noise and turbulence.

4.2 Microphone Windscreen and Nose Cone Performance

With the development of the OBSI measurement system, which introduces microphones to exposed wind flow as the vehicle travels along the roadway, it was important to establish that the flow field around the moving vehicle does not contaminate the data. A typical criterion for the acceptable difference between signal and background sound pressure levels (SPL) is 10 dB, which assures an error of less than 0.5 dB. For SI measurements made in flows of varying levels of turbulence, it has been found that the SI of a source can be measured accurately even if the SPL of flow-induced noise measured by the microphones ***exceeds*** the source level to be measured by as much as 5 dB (Oswald and Donavan 1980). Stated differently, it was demonstrated that the flow-induced background noise in an SI measurement is 15 dB lower than the flow-induced background noise in an SPL measurement exposed to the same flow conditions. The lowest tire-pavement noise level reported at 60 mph is 91.5 dBA for CPX (Hanson 2005) and 94.6 dBA for OBSI (Donavan 2005b). As a result, a wind flow noise level of less than 81.5

dBA should be sufficient to produce accurate results, and a wind flow noise level of less than 99.6 dBA should be sufficient to produce accurate SI results.

The evaluation of the effect of wind and inflow turbulence on OBSI measurements was conducted primarily through wind tunnel testing. Only two studies conducted prior to 2005 were found documenting the performance of wind noise reduction devices, such as nose cones and windscreens. The performances of 10 commercial and experimental windscreens were evaluated in laboratory conditions in 1979 for airflow speeds from 2 to 14 meters per second (m/sec) (31 mph) in 2 m/sec increments (Hosier and Donavan 1979). At 60 mph (97 km/h), the overall level was projected to be about 82 dBA in the absence of in-flow turbulence for all of the tested windscreens. The noise level relationship was found to be virtually identical for grazing and normal flow orientation.

In the mid-1970s, the self-noise and turbulence factors of different sizes of nose cones and microphones in the presence of flow were investigated for 1-, ½-, and ¼-inch microphones with varying levels of turbulence (Oswald 1976). For a ½-inch nose cone with and a turbulence level of 0.5%, the overall A-weighted SPL of wind induced noise at 60 mph (97 km/h) was 71.4 dBA, in comparison with the 82 dBA cited above for a microphone protected by a windscreen. For SI measurements, the flow-induced level would be a further 15 dB lower than the SPL, indicating that OBSI measurements of tire noise should contain virtually no contamination by flow-induced noise for low levels of turbulence. At a higher level of turbulence, 3%, it was found that flow-induced noise increased considerably (Oswald 1976). For this case, the equivalent A-weighted overall level was found to be 87.7 dBA, a 16.3 dB increase over the 0.5% case. For OBSI measurements at 3% turbulence, the overall flow-induced background level is expected to be about 73 dBA, and the one-third octave band OBSI levels will be 10 dB below the tire noise source levels for frequencies of about 400 Hz and above. For windscreen protected SPL measurements in exposed flow, the effects of turbulence are expected to be similar to those of the nose cone case, and the flow-induced level will be greater than that for the no turbulence case.

As part of the GM wind tunnel measurements conducted in 2008, the performance of wind noise reduction devices currently in use for OBSI testing nose cones was assessed (Donavan and Lodico 2008). For the single OBSI probe, measurements were conducted with microphones fitted with nose cones, microphones fitted with windscreens, and microphones fitted with both nose cones and windscreens. For the horizontal dual OBSI probe, measurements were conducted with microphones fitted with custom windscreens and with the 3½-inch diameter commercial windscreens used for the single and vertical dual probe configurations. Photographs of the three wind noise reduction devices, mounted on the single probe and horizontal dual probe OBSI fixtures, are shown in Figure 4-11.

Figure 4-11: Photographs of wind noise reduction devices employed on different fixture configurations during wind tunnel testing, 2008
Upper left: Nose cones on single probe fixture (on-road)
Upper right: Commercial 3.5 inch windscreen on single probe fixture
Bottom: GM custom windscreen on horizontal dual probe

Results of these tests found that the SPL and SI measured for the windscreen and the windscreen with nose cone were within 0.8 dB for frequencies of 250 Hz and above (see Figure 4-12). For both cases, SI levels were more than 10 dB below the tire source levels at frequencies above 315 Hz. For SPL, both windscreen configurations resulted in signal-to-noise ratios below 10 dB at frequencies below 800 Hz and above 2000 Hz, indicating wind noise contamination concerns in those ranges for SPL measurement.

In contrast, large differences between the unaccompanied nose cone and windscreen SPL occurred at all frequencies, particularly below 1600 Hz. At these lower frequencies, the unaccompanied nose cone SPL were up to 12 dB higher than windscreen levels. OBSI levels for the single probe with nose cones also exceed the tire source levels at low frequencies (250 and 315 Hz) and are similar in level to the asphalt concrete (AC) pavement in the 400 and 500 Hz bands. The SPL for the single probe with nose cones exceeded the measured AC pavement noise levels at frequencies below 800 Hz and were within 4 dB of the AC pavement levels at frequencies above 800 Hz. These results indicate that use of nose cones without a windscreen is not advisable for SI or SPL measurements and that nose cone only configurations for tire noise SPL measurements should be avoided completely.

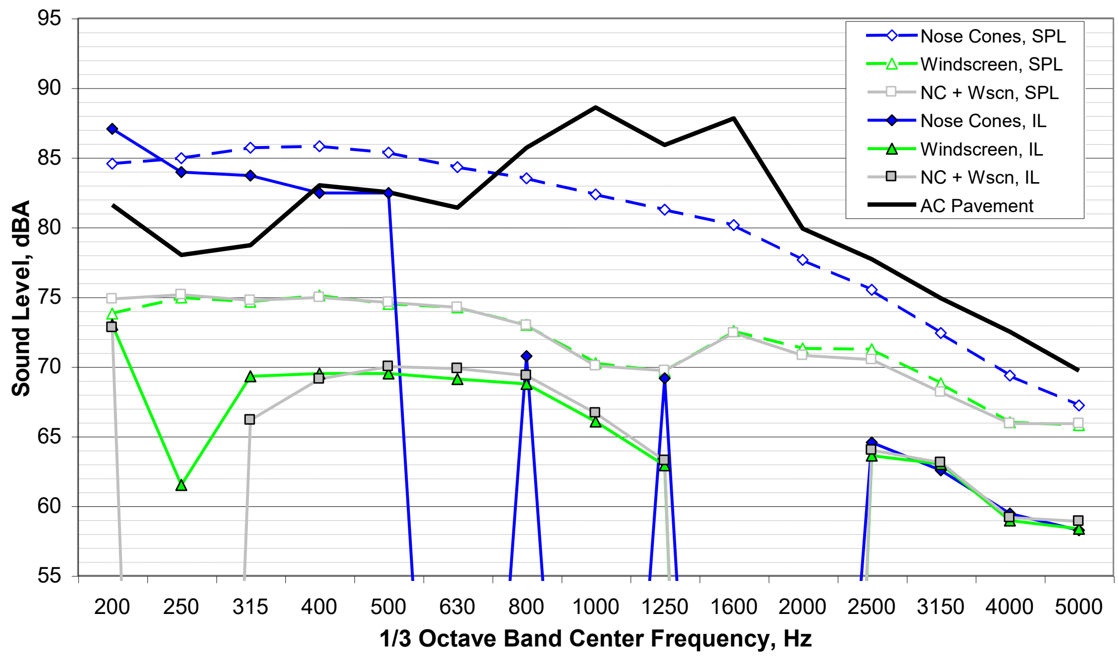

Figure 4-12: SP and SI levels measured with the OBSI single probe fixture with nose cones only, windscreen only, and nose cones plus windscreen at 100 mph (161 km/h), 0° yaw

To confirm that windscreens alone are sufficient for OBSI measurement, on-road measurements were made using the windscreen with and without nose cones installed on the microphones. These tests were conducted on rigid pavement experimental texture sections located on the Mojave Bypass of State Route 58 in California (Donavan 2004). The data indicated the overall levels were virtually identical whether or not the nose cones were used. For one of the quieter pavement sections, the OBSI levels were slightly higher (less than 0.5 dB), throughout the range from 500 to 5000 Hz with windscreens alone. However, for both cases, the levels were well below those that would provide wind noise contamination and there was no clear indication that nose cones provided any clear advantage. Overall, the data suggested that it may be safer to use nose cones in combination with a windscreen; however, with due attention to the OBSI-SPL metric, nose cones are not essential.

With the selection of the commercial windscreen alone as a wind noise reduction device for the OBSI test method, further study of the method of attachment to the OBSI fixture was made as part of the NCHRP 1-44(1) Project (Donavan and Lodico 2011). The attachment method was designed to be free of intervening objects in the path between the tire-pavement contact patch and the microphones. The typical method is to attach the windscreens using a thin piece of tape in the direction of travel of the vehicle, keeping the path between the tire-pavement contact patch and the microphone free from interfering objects. Assessment of three tape thickness configurations indicated that tape thicknesses up to ½ inch-wide located in the direction of the vehicle path of travel would not be expected to affect OBSI measurement.

4.3 Tires

Tires provide the largest source of variation among OBSI levels. The NCHRP 1-44 Project (Donavan and Lodico 2009) recommended that the P215/R16 ASTM International Standard Reference Test Tire (SRTT) (ASTM International n.d.) be used for standardized OBSI measurement. This tire has been adopted for the AASHTO OBSI procedure (American Association of State Highway and Transportation Officials 2008). Initial studies included on-road evaluations and road-wheel simulations. On-road evaluation of six SRTT tires on four asphalt and three concrete pavements produced an average difference in OBSI level of 0.8 dB for tires of varying age and usage (Donavan 2009). Testing conducted on a road-wheel simulator with a smooth asphalt replica surface found that new SRTT tires with minimal break in produced a level 1 dB higher on average than did 1-year-old tires with about 300 miles accumulated (Moore 2007). Although these studies identified variations, the results were not well linked to variables such as tire durometer hardness, tread depth, usage, and age.

The NCHRP 1-44(1) Project conducted a comprehensive SRTT test tire study to link tire parameters to OBSI results (Donavan and Lodico 2011). The study included 17 test tires, with 11 of the tires having the same build date and having been acquired to evaluate the range in OBSI produced by new tires built at similar times. The remaining six tires were in-service tires 1 to 3 years older than the new tires. Four of these tires were older tires used by I&R in previous testing, one was provided by ACPA, and one by the Transtec Group, Inc.

Generally as usage increased, tread depth became less and tires became harder. Although the older tires displayed no trend in OBSI level with build date, they were found to produce OBSI levels that were on average 0.5 dB higher than the new tires. The new tires had lower durometer hardness numbers and age and generally produced lower OBSI levels than did the older tires, but performance varied between pavements. Hardness for all four new in-service tires increased significantly with increased mileage, but the trends varied between right side and left side tires. The tread depth for in-service tires was also reduced more on the front tires than for the rear tires, but, again, no trend could be found relating tread depth directly to OBSI level. The authors concluded that the rubber durometer hardness number may not be an important parameter for newer SRTT tires, but, as a tire ages, hardness may become an important variable.

Given that the effect of aging variables such as hardness, tread depth, time since construction, and mileage may not be consistent from tire to tire, a criterion was established taking into account all of the potential variables. Under this approach, a tire that has more than two of the following attributes would be retired, as recommended in the NCHRP 1-44(1) report and adopted in the AASHTO procedure: (1) being in service for more than 4 years, (2) having more than 11,000 miles, (3) having hardness number of greater 68, or (4) tread depth less than 7.2 millimeters.

4.4 Temperature Effects

Investigations of the effects of temperature on OBSI level have generally found that tire-pavement noise decreases with increasing temperature and that this relationship depends on tire and the pavement (Sandberg 2004; Anfosso-Lédée and Pichaud 2006; Bendtsen et al. 2010;

Buhlmann and Zeigler 2011). In the few initial studies that assessed temperature effects using the OBSI method and the ASTM SRTT (ASTM International n.d.), data were generally obtained for a limited range of temperature or are composite of data not necessarily taken solely to address temperature effects. The NCHRP 1-44 Project (Donavan and Lodico 2009), found a slight downward trend in OBSI level with increasing temperature for the SRTT tire, but concluded that more data were needed to determine normalization values. The NCHRP 1-44 study used four or five temperature data points for each of four pavements over a 37ºF (21ºC) air temperature range. A study by Bendtsen et al. 2010 found an average slope of -0.015 dB/ºF (-0.027 dB/ºC) for AC pavements, with a data set that included five temperature data points for each of five AC pavements over a 35ºF (19ºC) air temperature range. In 2010, Rasmussen reviewed OBSI data taken without isolating temperature from other variables, such as pavement type or age, over a large number of pavements and found average slopes of -0.001 to -0.032 dB/°F (-0.002 to -0.058 dB/°C) for rigid pavement and -0.036 to -0.045 dB/°F (-0.065 to -0.081 dB/°C) for flexible pavement (Rasmussen 2010).

The NCHRP 1-44(1) Project included testing exclusively for the purpose of assessing temperature effects on OBSI results using ASTM Standard Reference Test Tires (Donavan and Lodico 2011; Lodico and Donavan 2012). Tests were conducted over the course of several days on 10 pavement surfaces throughout test periods in February, March, September, and December of 2010. Testing began in the very early morning and continued to the evening during each test day. The data for the primary test tire (TT#5) included 370 data points (37 points for each pavement) over a temperature range from 40 to 101ºF (4 to 38ºC). The results of these measurements are shown in Figure 4-13, with OBSI levels for each pavement plotted versus air temperature. For the secondary test tire (TT#9), the temperatures ranged from 41 to 104°F, although a smaller data set was gathered.

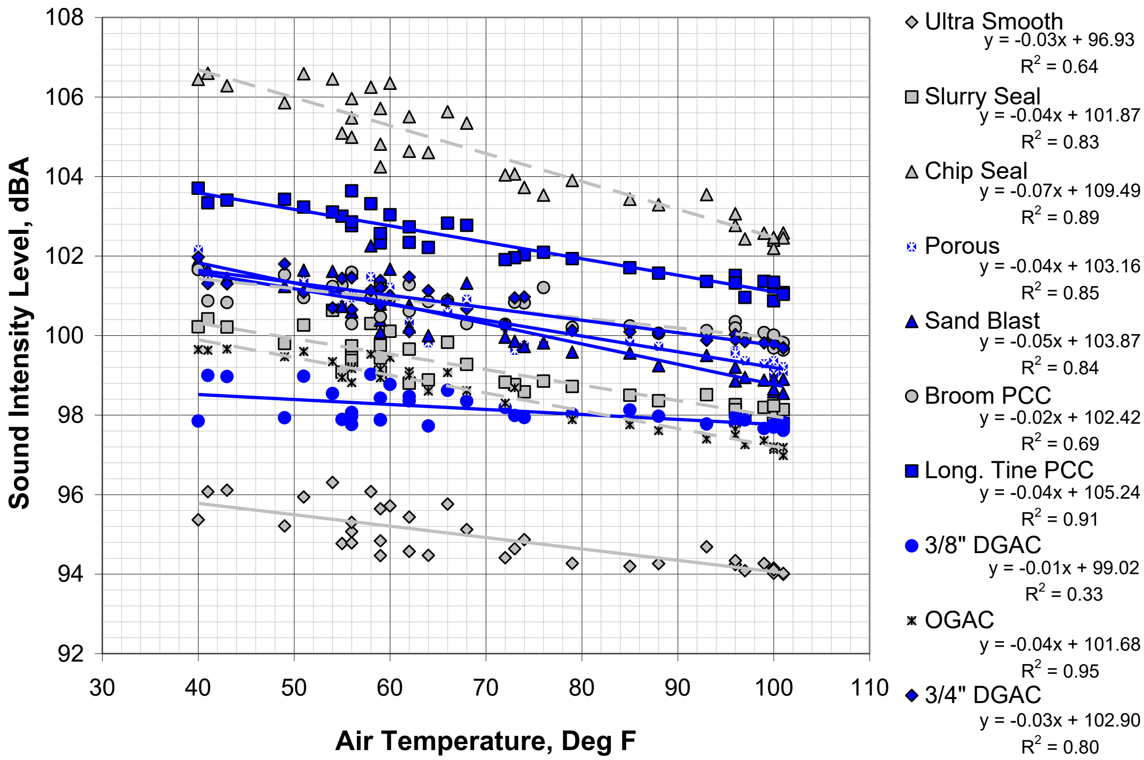

Figure 4-13: Overall OBSI levels for test tire TT#5 versus temperature for all test periods

Consistent with data in the literature, downward trends with increasing temperature were found for both tires for all pavements, with slopes varying by pavement type (Donavan and Lodico 2009; Sandberg 2004; Bendtsen et al. 2010; Buhlmann and Zeigler 2011; Rasmussen 2010). The OBSI levels decreased at an average slope of 0.039 dB/°F (0.070 dB/ºC) for TT#5. Slight changes in the tire and pavements may have introduced some scatter into the data, particularly in the overlapping temperature ranges, although use of the test track environment resulted in limited trafficking on the pavement surfaces. For TT#5, the slopes for each pavement surface were typically in the range of 0.025 to 0.052 dB/°F (0.045 to 0.094 dB/ºC) with the exception of the chip seal and 3/8-inch dense-graded asphalt concrete (DGAC) pavements, which resulted in slopes of 0.068 and 0.015 dB/°F (0.122 and 0.027 dB/ºC), respectively. The rigid pavement rates fell within the flexible pavements range, with one on the higher end and one on the lower end. Similar rates (with low r^2 values) were found for the SRTT at much higher air temperatures in the earlier research (Donavan and Lodico 2009). The NCHRP 1-44(1) Project validated the use of a single temperature normalization value applied to all pavement types by applying the normalization value calculated for TT#5 to the results measured using TT#9. Even though the rates are different for each pavement, applying the general adjustment helped to reduce the variations between measurements almost as much as the pavement-specific adjustment. Following the results of this study, a temperature normalization rate of 0.04 dB/ºF (0.072 dB/ºC) was adopted within AASHTO TP-76 to normalize OBSI levels for air temperature differences (American Association of State Highway and Transportation Officials 2008).

The effects of temperature on traffic noise levels at wayside locations has also been investigated (Lodico 2016). Measurements conducted on Interstate 80 near Davis, California over a period of

14 years (Illingworth & Rodkin 2011a) on an open-graded AC pavement identified a decrease in sound level of about 0.048 dB/ºF (0.087 dB/ºC) at a wayside reference position located 65 feet (20 meters) from the edge of the highway travel lane as air temperature increased. Measurements made behind a barrier over a 3-day period in May 2014 in Oasis Park, Arizona found a similar trend of 0.04 dB/ºF (0.072 dB/ºC) for a reference position located 50 feet (15.2 meters) from the highway (Donavan et al. 2014). The rate of change of traffic noise level as function of temperature was found to generally increase with distance from the highway, with rates of 0.24 to 0.34 dB/ºF (0.44 to 0.66 dB/ºC) occurring at distant measurement locations ranging from 100 to 475 feet (30.5 to 145 meters). Temperature inversion conditions in the Arizona study resulted in sound level increases of 8 or 9 dB above non-inversion conditions, similar to the results found in the ADOT Atmospheric Effects study, which found increases of 5 to 8 dBA at similar distances during nighttime inversion conditions in the Phoenix area (Saurenman et al. 2005).

4.5 Air Density Correction

Unlike SP, OBSI is not a directly measured acoustic quantity. OBSI is determined using a finite difference calculation and is based on the sound pressures at two closely spaced points. As a result, there is no inherent dependence of OBSI on air density or air acoustic impedance because OBSI is only related to the sound power output of a noise source. However, in implementing the finite difference approximation for determining (measuring) OBSI, a term of $1/\rho$ is introduced where ρ is the density of air. To account for air density within the analyzer, which uses the finite difference approximation for determining OBSI, at the time of the measurement, values of ambient temperature and atmospheric pressure can be input directly into the analyzer (or calculation of OBSI) or the OBSI levels output from the analyzer can be corrected during post-measurement processing. The sound power output for mechanisms associated with tire noise also has some dependence on ρ and c, the speed of sound. Taking these into account reduces the effect of ρ in the measurement of tire noise using OBSI. As a result, although theoretically a correction for air density should be made with the use of the finite difference approximation, it is not clear whether applying the correction improves the precision of the OBSI measurement and whether any density corrections are necessary. For derivation, explanations, and validation of the air density correction, see Appendix B in the final report documentation for the NCHRP 1-44(1) Project (Donavan and Lodico 2011).

Because of the uncertainty of the application of an air density correction, OBSI data were collected in the NCHRP 1-44(1) research without adjusting to ambient temperature and pressure at the time of the data acquisition. Density correction factors were later determined, and the uncorrected and temperature normalized OBSI results for two reference test tires were assessed both with and without the addition of the air density adjustment. Unlike the temperature adjustment, the air density correction did not improve the average of ranges or standard deviations of the data. This suggested that more consistent OBSI levels will be achieved if all data were taken using a standardized analyzer reference condition, such as temperature of 68º F (20ºC) and pressure of 101.325 kilo-Pascal (kPa), and then applying the temperature adjustment of 0.04 dB/ºF (0.072 dB/ºC) developed in this research (rounded from 0.039 dB/ºF). This recommendation has been adopted within AASHTO TP-76 (American Association of State Highway and Transportation Officials 2008).

4.6 Correlation of OBSI and Wayside Results

Since the early 2000s, several studies have analyzed the correlation between OBSI and wayside results. Figure 4-14 shows a comparison between OBSI and passby levels for test sites using the Aquatred tire, including pavements on State Route 202, east of Phoenix, Arizona (SR 202) (Donavan and Scofield. 2003), State Route 138 in Los Angeles County (Illingworth & Rodkin 2013b), and the Caltrans test track. Figure 4-15 shows the SR 202 correlation results on a one-third octave band basis. The SR 202 sites include an older uniformly spaced transverse tined rigid pavement, a new random transverse tined rigid pavement, and a 1-inch uniformly spaced longitudinal tined rigid pavement. As seen in these figures, the relationship between OBSI and passby levels is very close to 1-to-1, with OBSI levels being about 23.8 dB higher than the passby levels. The spectral shape is also sustained between the two measurement methods.

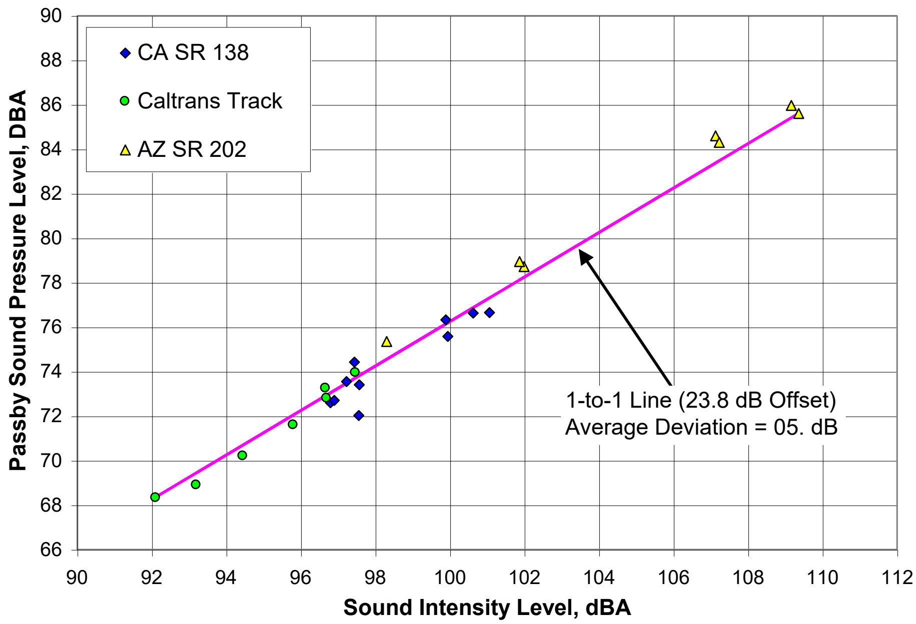

Figure 4-14: 1-to-1 Relationship between overall A-weighted sound intensity and passby level for various test sites including Arizona State Route 202

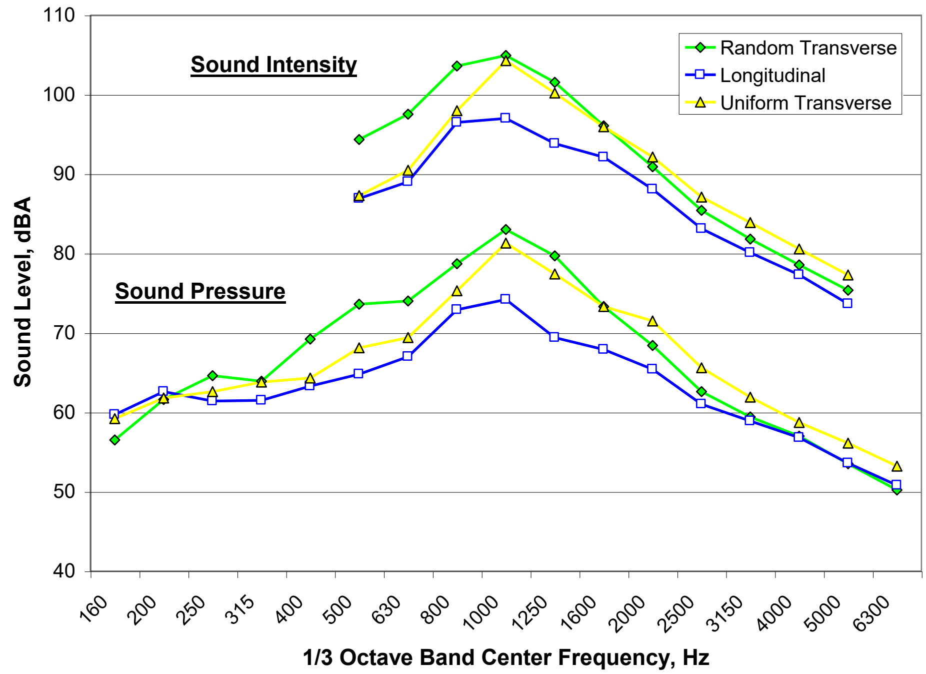

Figure 4-15: Tire-pavement noise for Aquatred test tire at 60 mph (97 km/h) OBSI and passby at 25 feet (7.5 meters)

Correlation testing was conducted to compare OBSI and CPX results against controlled passby results at and around the National Center for Asphalt Technology (NCAT) test track facility in Opelika, Alabama during February of 2006 (Donavan and Lodico 2009; Donavan 2008). Four flexible pavements were selected from the 45 different flexible pavement surfaces available at this facility; a transversely textured surface acoustically similar to transversely tined rigid pavement, a highly porous flexible pavement, a medium textured non-porous flexible pavement, and a fine textured non-porous flexible pavement. In addition, a rigid pavement site was utilized on a public road in the nearby town of Waverly, Alabama. Passby measurements were made at a distance of 25 feet (7.5 meters). The passby measurements were made with sound propagating over the pavement for the four flexible pavement sites. For the Waverly site, however, the roadway was shoulderless and the propagation from the pavement to the passby microphone was over an acoustically softer ground.

At each of these five sites, controlled passby measurements were made under both cruise and coast conditions for two or three vehicle speeds. On-board tire-pavement noise source levels were measured using both CPX and OBSI. Two tire designs were tested for the complete test matrix, specifically, the SRTT and the Dunlap SP Winter Sport M3, chosen to represent a light truck tire because of its more aggressive tread pattern. Figure 4-16 shows a comparison between the passby and the OBSI data for all of the tests, speeds, and the two tire types.

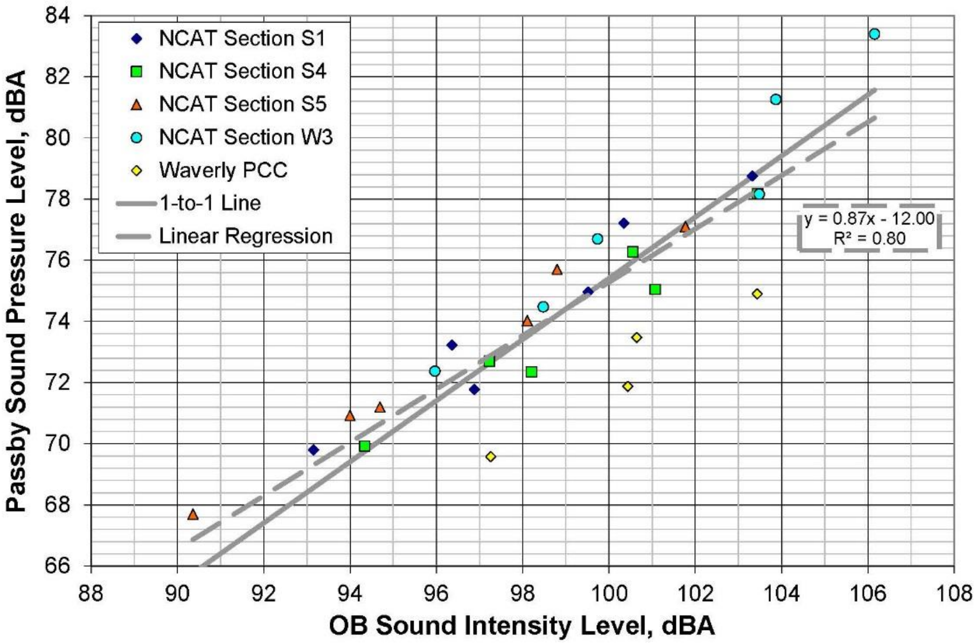

Figure 4-16: Relationship between OBSI and passby noise levels for all sites, SRTT and Dunlop tires, and all speeds

The standard deviation for the best 1-to-1 fit of the data was 1.7 dB, and average deviation, 1.3 dB compared with 0.8 dB and 0.4 dB, respectively, as measured in the study described above. The r^2 values are also smaller, 0.80 compared with 0.98. The points from the Waverly site are noticeably and consistently lower than the others as a result of propagation effects resulting from the soft ground surface.

Plotting only the acoustically hard sites (Figure 4-17) improves the correlation. The standard deviation for the best 1-to-1 fit of the data is reduced to 0.9 dB and average deviation, 0.7 dB, which are similar to those reported in the earlier study. The r^2 values improve to 0.98. Additionally, the offset between OBSI and passby levels at 25 feet is found to be 23.7 dB, virtually identical to that found for the Arizona study. The spectral shapes between OBSI and passby results were also found to track well.

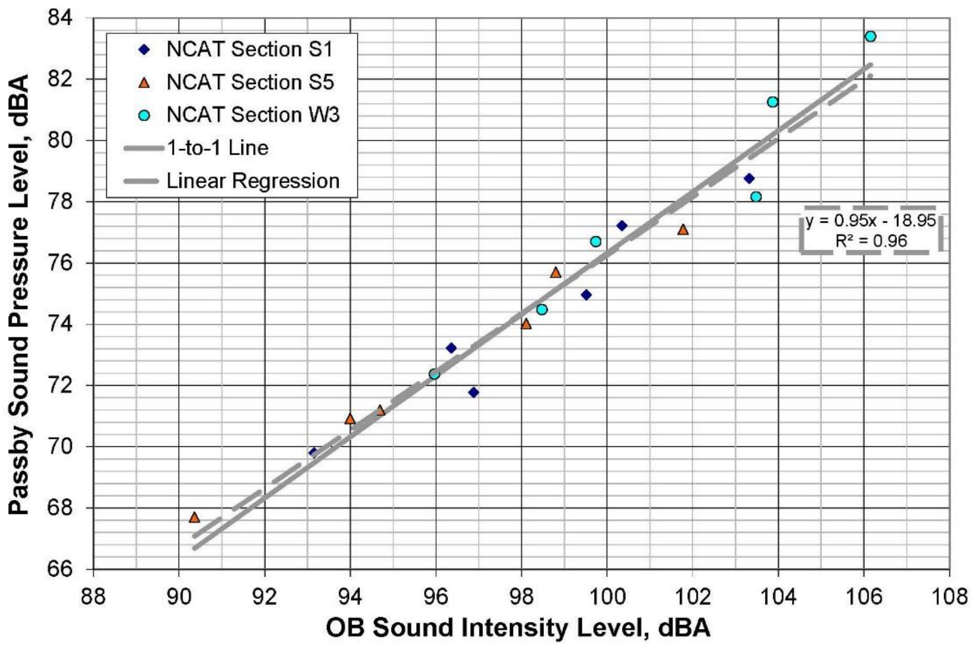

Figure 4-17: Relationship between OBSI and passby noise levels for NCAT Pavement sections S1, S5, and W3 for SRTT and Dunlop tires and all speeds

In summary, OBSI has been found to track well with passby results for acoustically hard sites, with an offset of about 23.7 dB and little spectral distortion. However, because of the increased absorption at acoustically soft sites, additional information on the acoustical properties of the site would be needed to predict passby levels from OBSI data in these locations.

4.7 Rodeos

With the development of the OBSI application and initial standardization as described above, the OBSI method has become widely used by highway agencies for research and application of quieter pavements. The systems used for acquiring the sound intensity data include commercially available analyzers, commercial software-based systems, and independently developed systems. With the variety of OBSI practitioners and methods for acquiring the SI data, a method of validating data was needed. Unfortunately, there was no convenient, standardized way to calibrate these different systems using commercial self-contained sound intensity calibrators in a similar manner to that done for SPL measurements. As a result, those interested in comparing their OBSI system with another's system have had to rely on OBSI "rodeos," in which users gather at one location, perform OBSI measurements on the same pavements under the same environmental conditions, and compare the results. OBSI rodeos are typically used to compare results of specific pavement sites among multiple users with the intention of ensuring that all results fall within an acceptable range of OBSI levels on both an overall and spectral bases. Where measured levels fall outside of this range, quality control checks are made to identify any features of the system that might be impacting the results. Many of the innovations within the OBSI measurement system have come from comparison testing, where users discuss differences between systems and work together to develop improvements.

Some examples of OBSI rodeos are comparison testing among three teams (Lodico 2007) on pavement test sites near Davis, California in 2007 and a comparison among four test teams on nine pavement surfaces in Mesa, AZ in 2006 (Donavan 2006). The Tire/Pavement Noise Research Consortium Pooled Fund TPF-5(135) sponsored four sets of comparative testing (rodeos) among OBSI users in 2010 and 2011. The first set of testing was conducted at the NCAT test track (Donavan 2010a), the second at the GM Desert Proving Ground in Yuma, AZ (Donavan 2010b), the third on in-service roads in the vicinity of Austin, TX (Lodico 2010), and the fourth on in-service roads near the town of Elkin, NC (Donavan 2011). In 2012, three groups conducted comparison testing on 19 pavement sites, which included the swapping of tires among test teams (Donavan 2013). Other comparison testing has been conducted throughout the country with the purpose of training new users on the OBSI system.

4.8 Sound Intensity Calibration

OBSI rodeos allow for the comparison of data acquired for specific sites by OBSI practitioners. However, due to environmental and physical variables inherent in on-road measurements, the rodeo method is not conclusive in identifying measurement system differences. With tire swaps among participants in closely monitored rodeo conditions, undetermined differences of up to 0.8 dB remain even with participants all using the same type of SI analyzers (Donavan 2011).

An OBSI calibrator was developed to address the need for a convenient, standardized method of calibrating different measurement systems using commercial self-contained SI calibrators in a similar manner to that done for SPL measurements. The development of the calibrator was sponsored by the FHWA Pooled Fund Program, TPF-5(135) Tire/Pavement Noise Research Consortium. The intent of the calibrator was to check the relative performance of the various measurement systems in a lab or field environment. The goals for this calibrator were stability over time, insensitivity to environmental conditions, and reproducibility for single and multiple users. It was also desirable that the calibrator consist of off-the-shelf components rather than specially fabricated components.

A system was developed using components from various suppliers to perform relative calibration among users over the range from 400 to 5,000 Hz (see Figure 4-18). The system is made up of a noise generator and coupler. The coupler checks the phase matching of the channels comprising the SI probe by exposing the two microphones and acquisition chain to identical sound pressures, simultaneously producing an essentially zero phase shift between the pressures presented to the individual channels. The two microphones for each OBSI probe are inserted into the coupler, opposite one another, as shown below, to compare OBSI, SPL, and PI index levels and identify any issues with coherence measurement. To assure proper use, the knobs for all controls were removed, and control shafts were hot glued to the reference positions. As a result, the user need only turn the device on and set the remaining control to pink noise.

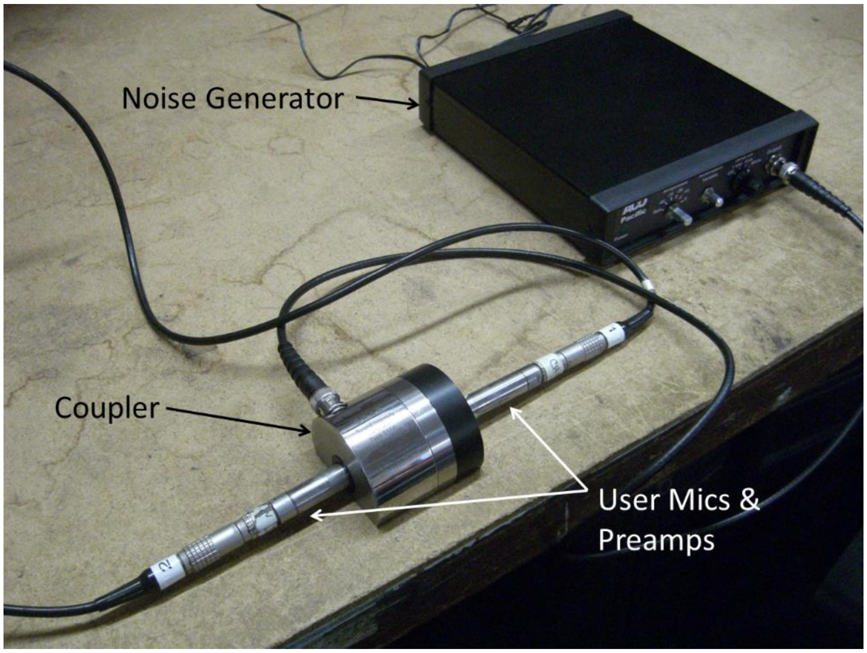

Figure 4-18: OBSI Calibrator Developed under TPF-5(135)

Through benchtop testing, the calibrator has proven to be very stable over both short and long time periods with the results being within 0.1 dB over 3 years using the same system components and operator (see the results in Figure 4-19). The calibrator was also found to be insensitive to environmental conditions within the range of most laboratory or instrumentation room conditions, with the daily range in SI levels varying by ±0.2 dB, and the range over a day typically ±0.1 dB. Benchtop testing of measurement systems resulted in the identification and rectification of several discrepancies between analyzer calculation techniques of the PI Index and coherence measurement of the systems evaluated.

Although this calibrator does not provide an absolute SI calibration, it does allow the comparison of different systems on a relative basis. This has been successfully done with several different users and measurement systems, as shown in Figure 4-19. This device is well-suited for comparing commercially available OBSI based systems, as well as validating systems that are individually developed. This device may not negate the need for OBSI rodeos, but it does provide a means for eliminating one potential source of uncertainty between users. In addition to OBSI, SPL, and PI Index comparisons, the calibrator can be useful in identifying issues with coherence measurement in specific analyzers. A user's manual for the OBSI calibrator is available.

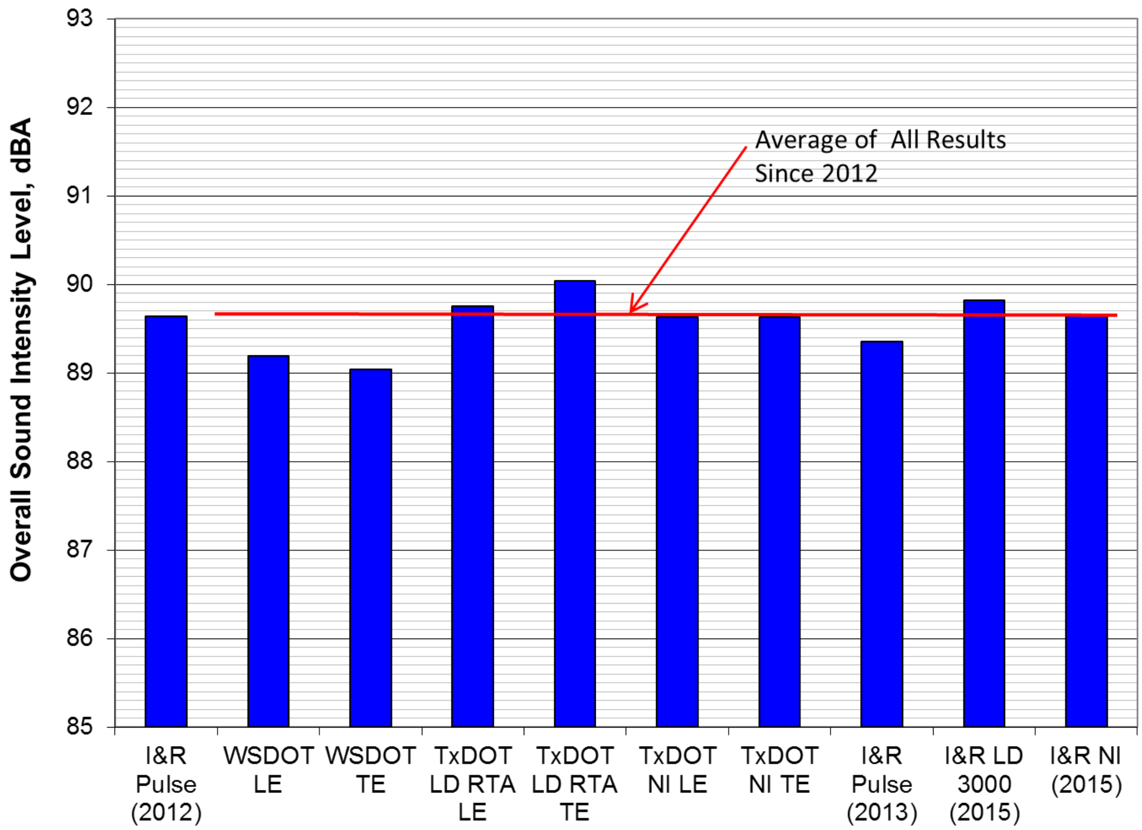

Figure 4-19: Comparison of overall sound intensity levels measured for the OBSI calibrator over time and different users

4.9 OBSI Parameter Limits

The NCHRP 1-44(1) Project, "Measuring Tire-Pavement Noise at the Source: Precision and Bias Statement," evaluated OBSI parameter limits using a series of test track measurements completed in four events spanning a 10-month period, laboratory measurements conducted on a tire noise dynamometer with replica road surfaces and in an aero-acoustic wind tunnel, and four comparative OBSI rodeos (Donavan and Lodico 2011). Parameters evaluated were:

- Environmental variables (temperature, air density, wind, dampness),
- Test tires,
- Vehicle loading,
- Test parameters (start location, background noise, reflecting objects, test speed, vertical and horizontal curves),
- Instrumentation (equipment and calibration),
- Vehicle operator effects
- Repeatability/reproducibility.

The testing was done on both asphalt and cement concrete pavements using two different test tires; the ASTM SRTT and the Dunlap SP Winter Sport M3 tire. The intent of this investigation was to provide guidance on test variables in order for users to determine the control limits needed to implement the OBSI procedure. The resulting recommendations on parameter limits are summarized in Table 4-1. These limits have been adopted within AASHTO TP-76 (American Association of State Highway and Transportation Officials 2008).

Table 4-1: Recommended OBSI Parameter Limits

Parameter		Criteria
Environmental Variables	Air Temperature Range	40 to 100ºF
	Air Temperature Normalization	-0.04 dB/ºF to Standard Conditions
	Air Density	Do NOT Use Correction
	Crosswind Conditions	<8 mph (12.9 km/h)
Test Tires	See Discussion in Section Above	
Instrumentation and Equipment	Probe Location, Vertical	3 ± ¼ inch above pavement
	Probe Location, Fore/Aft	Leading/Trailing edge ± ½ inch
	Probe Distance from Tire Sidewall	4 ± ½ inch
	Tire Loading	850 ± 100 lbs
Test Parameters	Vehicle Test Speed	60 ± 1 mph (97 km/h)
	Tire Inflation Pressure (Cold)	30 ± 2 psi
	Reflecting Surfaces	>15 inches (0.4 meter) away
	Start Location	±10 feet (0.23 seconds at 60 mph [97 km/h])
Quality Control	Run to Run Repeatability, Overall A-Weighted OBSI Level	Within 1 dB
	Run to Run Repeatability, One-Third Octave Band Levels	Within 2 dB
	Coherence	> 0.8 for frequencies below 4000 Hz
	PI Index	< 5 dB for data reported as valid

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Chapter 5 Measurement Methodology

Noise evaluations of pavement surfaces have been conducted using a number of different measurement methodologies. These fall into two broad categories: wayside measurements and at-the-source measurements. Wayside measurements are made at measurement positions set back specified distances from the center of the nearest lane of travel to measure existing traffic, individual roadway vehicles, or control vehicles (Blokland and Meier 1993). At-the-source methods involve the direct measurement of noise generated at the tire-pavement interface using either sound pressure measurements made with a trailer system or SI measurements from instruments mounted directly on a test vehicle. Some studies have employed separate measurements using each approach (Chapnik 2001; Berge 2001).

This chapter describes and compares the procedures of the primary measurement methods used in California for the noise evaluation of pavements. For background information on the development of the OBSI test method, see Chapter 4.

5.1 Wayside Measurement Methods

Wayside methodologies include the Continuous-Flow Traffic Time-Integrated (CTIM) method (AASHTO TP 99-13) (American Association of State Highway and Transportation Officials 2015a), the Statistical Isolated Pass-By (SIP) method (AASHTO TP 98-13) (American Association of State Highway and Transportation Officials 2015b), the Statistical Passby (SPB) method (ISO 11819-1) (International Organization of Standardization 2000a), and the FHWA procedure for vehicle noise emission levels (Lee and Fleming 1996). The CTIM and FHWA methods utilize time-averaged data for larger volumes of traffic. The SIP and SPB methods utilize statistical processing of individual vehicle passby events. For noise evaluations of pavement surfaces in the United States, the SIP and CTIM methods are typically preferred over the SPB and FHWA procedures due to the standardization of the procedures for purposes of pavement evaluation.

5.1.1 FHWA Procedure for Measurement of Highway-Related Noise

The objective of FHWA's "Measurement of Highway-Related Noise" document is to provide a uniform, state-of-the-art reference for highway noise practitioners and researchers that addresses measurement and analysis instrumentation, site selection, measurement procedures, and data reduction and analysis techniques (Lee and Fleming 1996). The document identifies procedures for performing existing noise measurements in the vicinity of highways. The procedures can be used for 1) establishing an overall sound level for the purpose of assessing noise impact of a nearby highway, and 2) quantifying the change in sound level along a highway segment prior to and upon completion of a project.

For pavement evaluation purposes, the method specifies the measurement of continuous time-integrated A-weighted sound levels at specified positions from the roadway. Although not specified, the method is meant to be applied on highways with continuously flowing, relatively dense traffic. Use of a reference microphone 5 feet (1.5 meters) above the ground and within 100 feet (30.5 meters) of the center of the near travel lane is strongly recommended. Traffic and meteorological data are collected simultaneously with the noise data collection. Sampling periods are recommended based on the temporal nature of the traffic noise source. This method does not allow for site-to-site comparisons.

5.1.2 Continuous-Flow Traffic Time-Integrated Method

The CTIM method (AASHTO TP 99-13) is essentially a standardized version of the FHWA procedure, discussed in Section 5.1.1, for the specific purpose of measuring the acoustical performance of pavement at one site. CTIM measurements capture the sound from existing traffic for all vehicles on all roadway lanes. The CTIM method is meant to be applied on roadways where measuring single vehicle pass-by events would be difficult due to continuously flowing, relatively dense traffic. With these types of higher trafficked roadways, sound levels from single vehicles cannot be properly captured because of contamination from other vehicles' sound.

The procedure includes specifications for both measurement and analysis techniques. The method utilizes continuously measured A-weighted time-integrated sound pressure levels, traffic volumes, speeds, and vehicle categories, and meteorological data to determine either: (1) the difference in sound levels before and after the application of a new surface on the highway; or (2) the difference in sound levels as the pavement on a highway ages. A preferred reference position is specified at a distance of 50 feet (15.25 meters) from the center of the near travel lane and at least 5 feet (1.5 meters) above the elevation of the ground surface. Additional positions are described and recommended. Measurements are conducted over a period of time that captures enough data to properly represent the site and are then repeated at the same site at a later time to allow for comparisons. Noise modeling is used to normalize for differences due to variations in traffic. However, to compare data sets, traffic and site conditions should be similar to minimize variation; for example, measurements should be taken at the same time of day, on weekdays but not the weekend (or vice-versa), and at the same time of year. Figure 5-1 shows a typical CTIM setup.

The CTIM method is based on measurement methods developed for the FHWA procedures, as well as those used for the Interstate 80 Davis Pavement Noise Study (Illingworth & Rodkin 2011) and the Arizona Quiet Pavement Program (Donavan 2005). Measurements were conducted to evaluate propagation effects over the roadway pavement and adjacent terrain to the nearby measurement location. As a result, this method does not allow for site-to-site comparisons.

Figure 5-1: CTIM measurement setup

5.1.3 Statistical Passby Method

With the SPB method (ISO 11819-1), sound pressure levels from isolated vehicles in existing traffic are measured for the purpose of evaluating different road surface types. This method is intended to be used for two main purposes: 1) to classify surfaces in typical and good condition according to their influence on traffic noise (surface classification), and 2) to evaluate the influence on traffic noise of different surfaces at particular sites irrespective of the condition and age of the pavement. Sound levels representing either light or heavy vehicles at selected speeds are assigned to a certain road surface. The method is applicable to traffic travelling at constant speed under free-flowing conditions of 35 mph (50 km/h) and upwards. Individual passby events are measured and analyzed statistically.

5.1.4 Statistical Isolated Passby Method

SIP method (AASHTO TP 98-13) measurements capture the SPL from isolated vehicles in existing traffic and are meant to be applied on roadways where measuring sound levels from single vehicle passby events is possible without contamination from other vehicles' sound. This test method provides an objective measure of the influence of road surfaces on traffic noise at locations adjacent to a roadway. Traffic noise on roadways of varying surfaces can be evaluated by comparing measured sound levels with those representing the tire-pavement noise for the Reference Energy Mean Emission Levels (REMELs) pavement average, thus allowing comparison of results across studies.

In the SIP method, the maximum A-weighted sound pressure levels and vehicle speeds of a statistically significant number of individual vehicle passbys for each desired vehicle classification are measured at a specified roadside location, as shown in Figure 5-2. The evaluation of automobile and heavy truck categories is considered essential to determine the influence of a roadway surface, with other vehicle categories considered optional. There are two primary microphone positions: (1) a position located at a horizontal distance of 25 feet (7.6 meters) from and a height of 5 feet (1.5 meters) above the center of the lane of travel for the vehicles to be measured, and (2) a position located at a horizontal distance of 50 feet (15.25 meters) from and a height of 12 feet (3.7 meters) above the center of the lane of travel for the vehicles to be measured.

Figure 5-2: SIP measurement setup

A linear regression of the maximum A-weighted SPL versus the logarithm of the speed is calculated for each vehicle category on each roadway surface or pavement type. From this regression line, a measured vehicle sound level, L_{veh}, and regression uncertainty are calculated at a designated speed. The L_{veh} value for each vehicle category on each roadway surface or pavement type is compared with a reference $L_{veh, ref}$. The difference between the two values is calculated and reported as the Statistical Isolated Passby Index.

Although this method was originally based on the SPB method, some significant changes to the measurement positions and analysis procedures were made to be more representative of U.S. roadway facilities and needs. As a result, this method is generally preferred over the SPB method in the United States.

5.2 At-the-Source Measurement Methods

At-the-source methodologies include the OBSI method (AASHTO TP 76-16) (American Association of State Highway and Transportation Officials 2013), which is primarily used throughout the United States, and the ISO CPX method (ISO 11819-2) (International Organization of Standardization 2000b), which is used throughout many areas of Europe. The OBSI method has the advantage of being mounted directly to the vehicle, eliminating the need for costly trailer systems. As a result, OBSI is generally the preferred at-the-source measurement method in the United States.

5.2.1 On-Board Sound Intensity Method

The OBSI method (AASHTO TP-16) provides an objective measure of the acoustic power per unit area at points near the tire-pavement interface. The measurement procedure evaluates the tire-pavement noise component resulting from the interaction of an ASTM F 2493 SRTT (ASTM International n.d.) on a pavement surface. Measurements are taken at defined locations near the tire-pavement interface. The OBSI method measures tire-pavement noise in isolation of other noise sources, allowing the noise performance of pavements to be compared.

Using this method, SI levels are calculated from the average of measurements made at the leading and trailing edge of the SRTT contact patch on the passenger side of the vehicle. Open air measurements are made directly on the vehicle, as shown in Figure 5-3 for the dual probe system. For each OBSI probe, two 0.5-inch microphones are situated at fixed positions, with four microphones being required for the dual probe system, as shown in Figure 5-4 (shown without the required windscreen).

Figure 5-3: Dual probe vertical OBSI setup

Figure 5-4: Close up of dual probe vertical OBSI setup (shown without required windscreens)

A standardized test speed of 60 mph (97 km/h) is recommended, with alternate speeds of 25, 35, or 45 mph in case the roadway does not allow for a vehicle speed of 60 mph. Measurements are time-averaged over a 440-foot (134-meter)-long test section, corresponding to a 5-second averaging time at a speed of 60 mph. At least two test runs must be made over each section, with the results being within 1 dB on an overall A-Weighted basis and within 2 dB for each one-third octave band with a center frequency between 400 and 5,000 Hz. The average overall A-weighted SI level and average one-third octave bands with center frequencies from 400 to 5,000 Hz are reported within 0.1 dB.

Chapter 4 provides a full description of the history and development of the OBSI procedure.

5.2.2 ISO Close-Proximity Method (ISO 11819-2) (International Organization of Standardization 2000b)

Under the ISO CPX method, SPL is measured by two microphones placed at specified points adjacent to the tire. The microphones are protected from airflow noise contamination by a trailer surrounding the test tire. The CPX method was found to correlate reasonably well with controlled passby data and has been used extensively throughout Europe. However, comparison testing between the OBSI and CPX systems conducted under the NCHRP 1-44 (Donavan and Lodico 2009) resulted in the selection of OBSI as the preferred test method due to 1) slightly better correlation between OBSI and passby data, 2) lack of spectral distortion seen in comparing OBSI and passby data, 3) expense of an enclosed trailer for CPX measurements, and 4) the practical issues of acquiring, validating, operating, maintaining, and storing a CPX trailer.

5.3 Measurement Method Selection

The selection of the appropriate pavement evaluation techniques depends largely on the intent of the investigation. When the intent is to assess the effect of pavement on traffic noise under “real world” conditions such as a community would perceive, then time-averaged measurements of existing traffic are often appropriate (CTIM method or FHWA procedures). These approaches offer the advantage of averaging vehicle types and tire types, providing a directly measured exposure. However, the results of time-averaged wayside measurements are site- and traffic-specific and generally cannot be applied to other sites without some form of modeling. Statistical processing of individual passby measurements of existing traffic (SIP or SPB) can be used to evaluate different pavements (Phillips and Abbott 2001; Lee et al. 1996). These methods require sites where individual vehicles can be isolated from each other and many samples of each vehicle category can be acquired and averaged to account for vehicle-to-vehicle variation. As with time-averaged measurements, statistical passby testing of individual vehicles in existing traffic is again site-dependent and cannot be readily applied in all situations of interest, such as bridge decks and elevated or depressed freeways. All wayside traffic measurement methods also have the advantage, or disadvantage, of not isolating tire-pavement noise from other sources on passing vehicles.

To more precisely isolate the effect of the pavement on tire-pavement noise generation, at-the-source methods are preferred (OBSI). As it is known that traffic noise generation primarily originates at the tire-pavement interface, this can be a direct measure of the effect of a change in pavement on traffic noise levels (see Chapter 6). For these measurements, the same vehicle(s)/tire(s) are measured on different pavement surfaces and vehicle operating conditions can be controlled to standardize the measurement results and minimize noise sources other than tire-pavement noise. The variables associated with wayside methods are eliminated (e.g., site dependence, tire type, vehicle type, operating condition, and vehicle speed). Additionally, these measurements are more efficient and less costly than wayside measurement methods, because measurements that could take several days using the CTIM or SIP methods could be acquired in only a few hours using OBSI. However, the data is removed even further from real world exposure cases because it must be assumed that the vehicles and standardized tires used in the measurements represent the range or average of actual vehicles and tires in use. Using the at-the-source data to make real world predictions requires the added complication of correlating or modeling the passby levels based on the close-in measurements.

To utilize the advantages of both wayside and at-the-source measurement methods, concurrent use of two or more methods is recommended. OBSI measurements can supplement wayside methods to indicate the portion of the noise at the receptor position that is attributable to tire-pavement noise or to identify acoustical “hot spots” in the pavement. Both the CTIM and SIP methods recommend the use of supplementary OBSI measurements. A comparison of the three primary measurement methods used in the United States is given in Table 5-1.

Table 5-1: Comparison of Common Pavement Noise Measurement Methods

Method	Use	Pros	Cons
CTIM (AASHTO TP-99)	Continuous measurement of existing traffic for all vehicles on all roadway lanes on roadways with continuously flowing, relatively dense traffic	Measures real-world conditions, not as time-consuming as SIP	More time consuming than OBSI, site and traffic dependent, requires traffic noise modeling, does not allow for site-to-site comparisons, includes all ambient noise sources
SIP (AASHTO TP-98)	Captures the sound pressure level from isolated vehicles in existing traffic on roadways where measuring sound levels from single vehicle pass-by events is possible without contamination from sound from other vehicles.	Representative of real vehicles in traffic, site-to-site comparisons can be made	Most time-consuming, severe restrictions on acoustical environment and traffic conditions, site dependent
OBSI (AASHTO TP-76)	Measures tire-pavement noise generation directly	Less time-consuming, flexible, not site dependent, isolates tire-pavement noise generation, allows for pavement comparisons	Does not capture real-world variation due vehicle or tire differences and only partially represents porous pavements

5.4 Sound Intensity Calibration

A standardized OBSI calibrator was developed under the FHWA Transportation Pooled Fund (TPF) Program, TPF-5(135) Tire/Pavement Noise Research Consortium (Donavan 2016). This is discussed further in Chapter 4. The calibrator is meant to facilitate the exchange of OBSI results between users enabling the use of noise performance as one basis for pavement selection. There is one system currently owned by the TPF-5(135) Program that can be made available to state transportation departments or other interested parties by request.

The system was developed using components from various suppliers to perform relative calibration between users over the range from 400 to 5,000 Hz (see Figure 5-5). A noise generator and coupler are used for generating a progressive sound field for intensity calibration. The two microphones to be used to make up each OBSI probe are inserted into the coupler, opposite one another, as shown in Figure 5-5, to compare OBSI, SPL, and PI index levels and identify any issues with coherence measurement. The device is suited for comparison among commercially available OBSI based systems and for validation of individually developed systems.

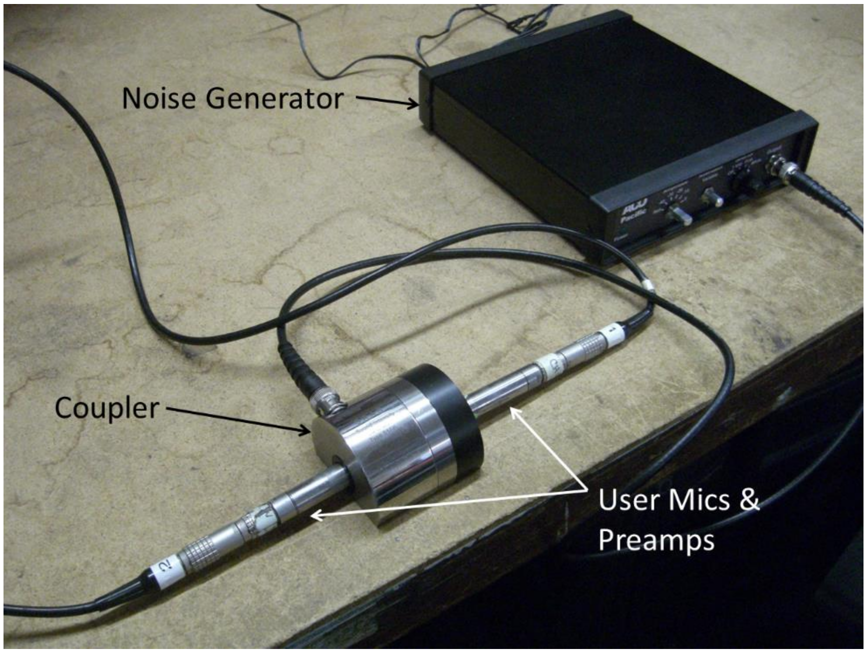

Figure 5-5: OBSI calibrator developed under TPF-5(135)

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Chapter 6 Tire-Pavement Noise Studies and Discussion

6.1 Tire-Pavement Noise Levels

Tire-pavement noise measurements have been made on numerous pavements. This section summarizes the results of OBSI measurements conducted from about 2002 to 2016. Specific topics are described in Sections 6.2 through 6.6.

6.1.1 Tire-Pavement Noise Levels at Highway Speeds

Since 2002, the OBSI method has been used extensively throughout California to quantify the acoustical performance of different pavements. Studies have analyzed most types of pavement typically used on California highways, as well as experimental surfaces that are being assessed for their acoustical properties. Pavement surfaces have also been measured in Arizona in cooperation with ADOT (Donavan and Scofield 2003, 2004), as well as in other states. These data provide good insight regarding current noise levels and quieter alternatives already in use.

The range in overall A-weighted noise level using the Aquatred test tire at a test speed of 60 mph (97 km/h) was found to be about 13 dB, excluding bridge decks (Figure 6-1). Tire-pavement noise levels measured at 60 mph with the SRTT resulted in a similar range for almost 600 pavement surfaces, as shown in Figure 6-2. Figure 6-3 indicates the range and average OBSI level by pavement category using the SRTT. A database summarizing the 60 mph SRTT test data is available in Appendix A.

The OBSI database provides information relating to the noise level, location, and measurement specifics associated with each measured pavement. The database has been used for several purposes. Overall, it defines the range of performance that can be expected for different pavement types. Quieter pavements can be identified throughout the full range or within each pavement category to help in the early decision-making process for alternatives for noise abatement. The database has also been used to examine pavement parameter differences and relate them to noise performance. With basic knowledge of the type and condition of existing pavement on a highway, engineers may use the data to roughly estimate what improvement might be expected by modifying an existing surface. Once a project is better defined, OBSI measurements can be made of the existing roadway surface to more accurately determine the expected improvement.

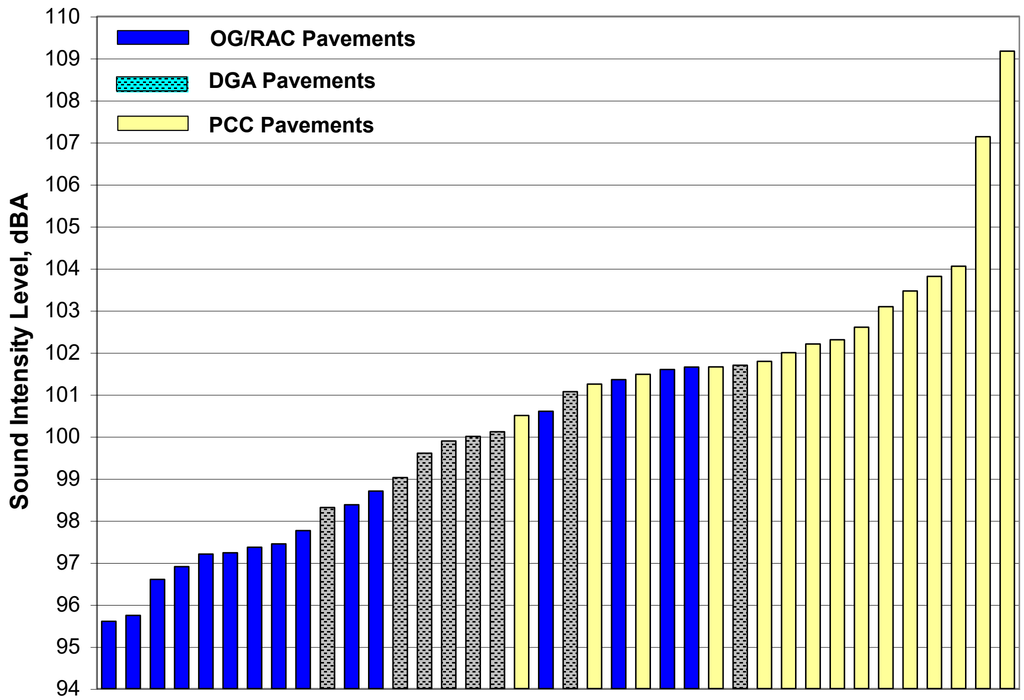

Figure 6-1: Tire-pavement noise for representative, at-grade highway surfaces from the California/Arizona Sound Intensity Database – Goodyear Aquatred 3 at 60 mph (97 km/h)

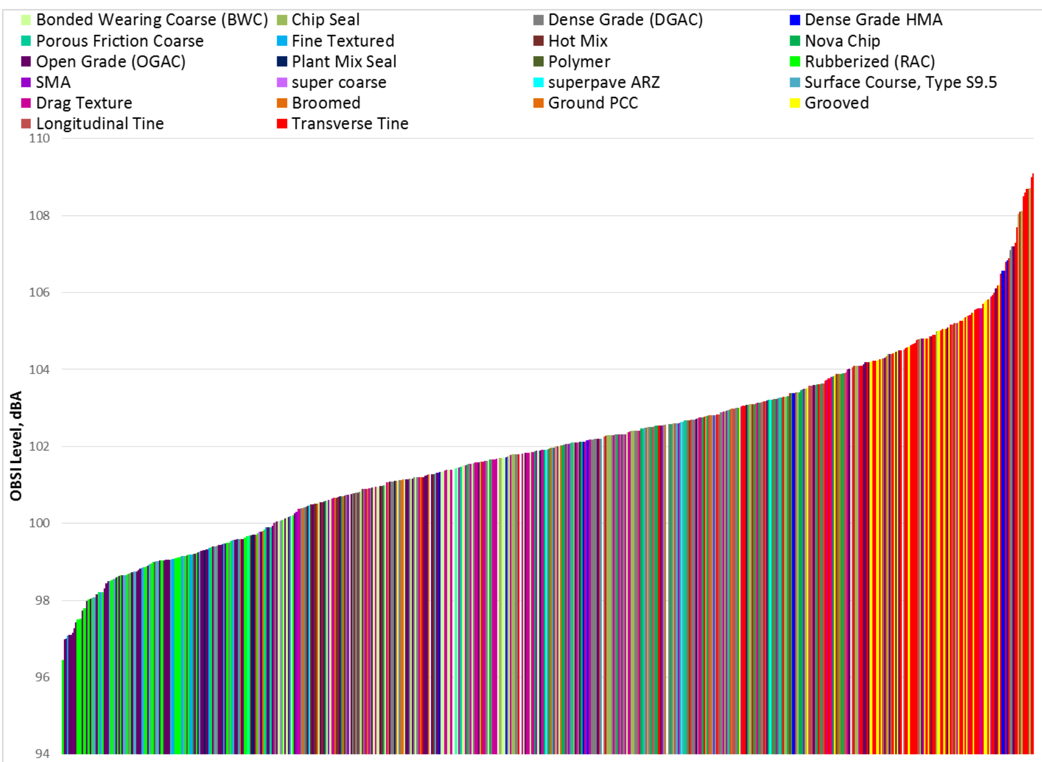

Figure 6-2: Tire-pavement noise for representative, at-grade highway surfaces–SRTT at 60 mph

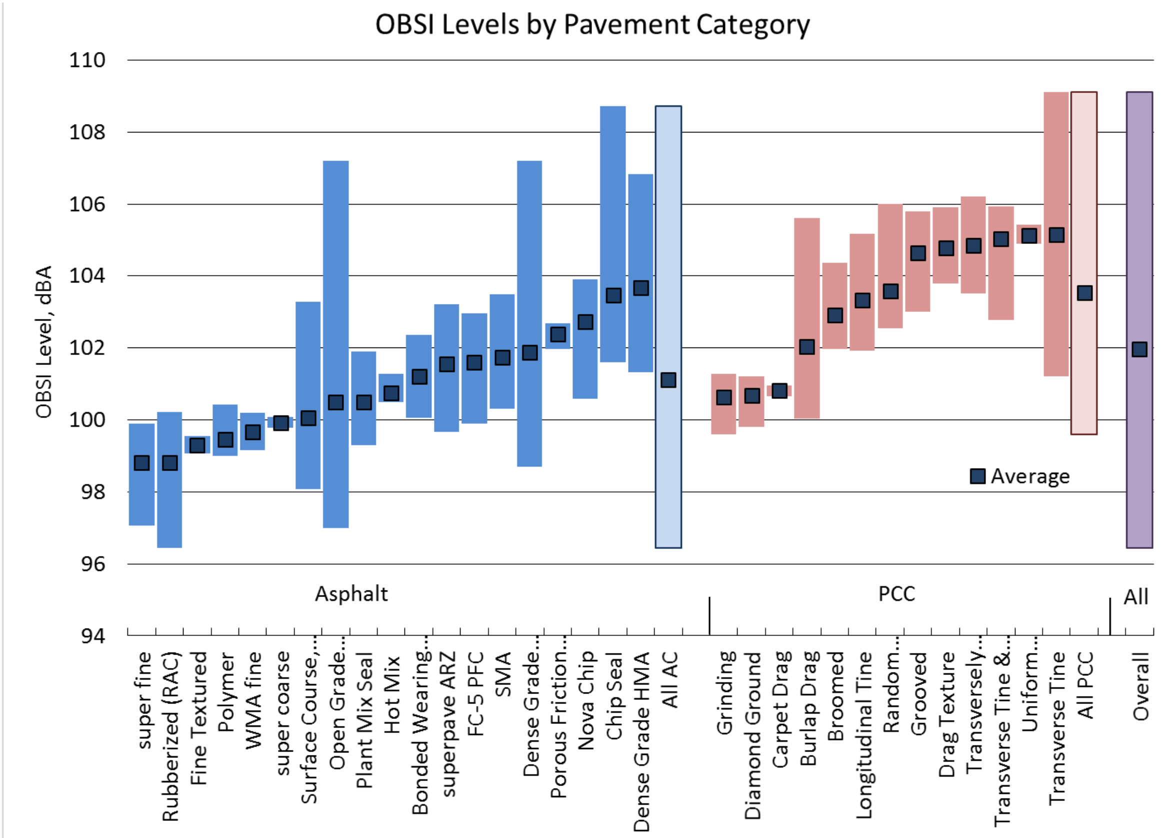

Figure 6-3: Range of OBSI levels by pavement category for pavements measured at 60 mph (97 km/h) with SRTT tire

As shown in Figures 6-2 and 6-3, there is a range in tire-pavement noise levels of about 13 dB at 60 mph (97 km/h) with the SRTT, with OBSI levels ranging from about 96 to 109 dBA. An even quieter pavement, an "Ultra Smooth" flexible pavement with an OBSI Level of 92.6 dBA, was measured in 2008 at the Hyundai Kia Motors California Proving Grounds (HATCHI), near Mojave, California (Lodico 2008). With the Aquatred test tire, which typically results in noise levels of about 0.5 dB higher than those measured with the SRTT, tire-pavement levels have reached 112 dBA for aggressive transversely tines textures on elevated structures (Donavan 2003a). With the inclusion of these two outliers, the range in level would extend to almost 20 dB. Table 6-1 shows the attainability of desired sound attenuation using a sound barrier, as given in FHWA guidance (FHWA 2011). For reference, a typical sound wall in California is designed to provide 5 to 7 dB reduction; so, a 13 dB spread means there may be potential for a readily noticeable reduction in noise levels by examining pavement acoustics. A noise reduction of 20 dB would be "nearly impossible" to achieve using a noise barrier.

Table 6-1: Barrier Attenuation[1]

Reduction in Sound Level	Reduction in Acoustic Energy	Difficulty to Obtain Reduction
5 dB(A)	70%	Simple
10 dB(A)	90%	Attainable
15 dB(A)	97%	Very Difficult
20 dB(A)	99%	Nearly Impossible
[1] Highway Traffic Noise: Analysis and Abatement Guidance, U.S. Department of Transportation, Federal Highway Administration, FHWA-HEP-10-025, December 2011.		

Although there is considerable variation among noise levels of pavements within any given broad category, some trends are apparent. The overall quietest pavements are generally flexible pavements with fine aggregate or rubberized surfaces. As seen in Figure 6-3, both flexible and rigid pavement types reach the highest noise levels. For rigid pavements, the loudest surfaces are typically transversely tined surface textures. Louder flexible pavement types include chip seal and hot mix asphalt (HMA), although some louder open-graded asphalt concrete (OGAC) and DGAC pavements have also been measured. These pavements are discussed in more detail in Sections 6.2 and 6.3.

6.1.2 Comparison of US and European Pavements (Donavan 2006a)

In the fall of 2005, pavements in four European countries were measured for their tire noise performance using the OBSI testing method in a manner identical to that done in California and Arizona. The Noise Intensity Testing in Europe (NITE) study was conceived as a logical follow-up to complement the AASHTO/FHWA Quiet Pavement Scanning Tour (Federal Highway Administration 2005). The study allowed the comparison of pavements that provided a range of noise performance from quiet to noisy and the examination of pavement design approaches that differ between Europe and the southwestern states. A total of 68 pavements were measured in Europe for comparison with more than 200 pavements measured in California and Arizona.

Portions of overall results of the NITE testing are provided in Figure 6-4 in a format analogous to the California and Arizona results of Figure 6-1. Figure 6-4 spans from a transversely tined rigid pavement in the Netherlands with an overall A-weighted level of 107.6 dBA to a double layer porous asphalt (DLPA), also in the Netherlands, with a level of 94.6 dBA. This range was almost identical to that in the California and Arizona database at that time (95.6 to 109.2 dBA), although the absolute levels are shifted slightly downward.

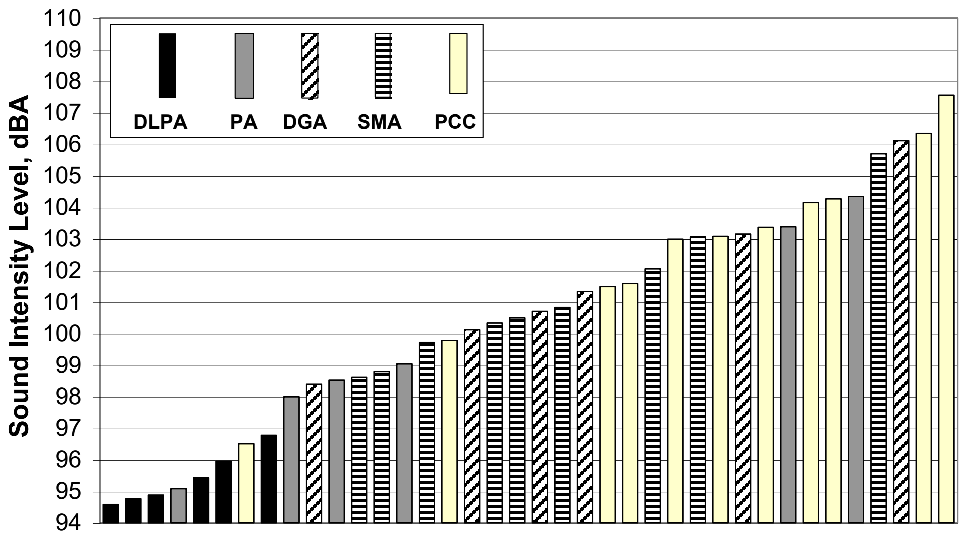

Figure 6-4: Tire-pavement noise for representative, at-grade highway surfaces from the European NITE Sound Intensity Database – Goodyear Aquatred 3 at 60 mph (97 km/h)

The NITE results supported most of the observations from previous California and Arizona testing. The range of potential tire-pavement noise reduction is common, ranging up to 8 to 10 dB depending the existing and final pavements. The total range of tire-pavement noise for the pavement measured was found to be about 13 dB, as it is in California and Arizona for on-grade pavements. With the exception of the European DLPA and porous rigid pavements, generic groupings of pavements displayed significant and overlapping ranges of the performance. Also, surface roughness/texture was found to be one of the major controlling factors in tire-pavement noise generation in the frequencies below about 1000 Hertz. Based on very limited data, the European results also indicated that grinding of rigid pavement surfaces could produce lower tire-pavement noise levels.

One of the most remarkable findings of the NITE testing was that porous rigid pavement could perform almost as well as the quieter porous flexible pavements. Another significant finding was that, although the very quietest DLPA surfaces were remarkably quiet, they were only slightly (1 to 2 dB) quieter than the quieter rubberized asphalt concrete (RAC) and OGAC pavements in California and Arizona. Although not systematically investigated, it was found that exposed aggregate rigid pavement has the potential to achieve performance within the range of California and Arizona ground and longitudinally tined rigid concrete. It was also found that stone mastic asphalt (SMA) surfaces provided a similar range of the performance as DGAC surfaces and that surface texture appears to be a dominant factor in both. Finally, variation in tire-pavement noise performance for pavement constructed to the same specification could be as much as 2 dB. Photos of some of the quieter European surfaces are shown in Figures 6-5 and 6-6.

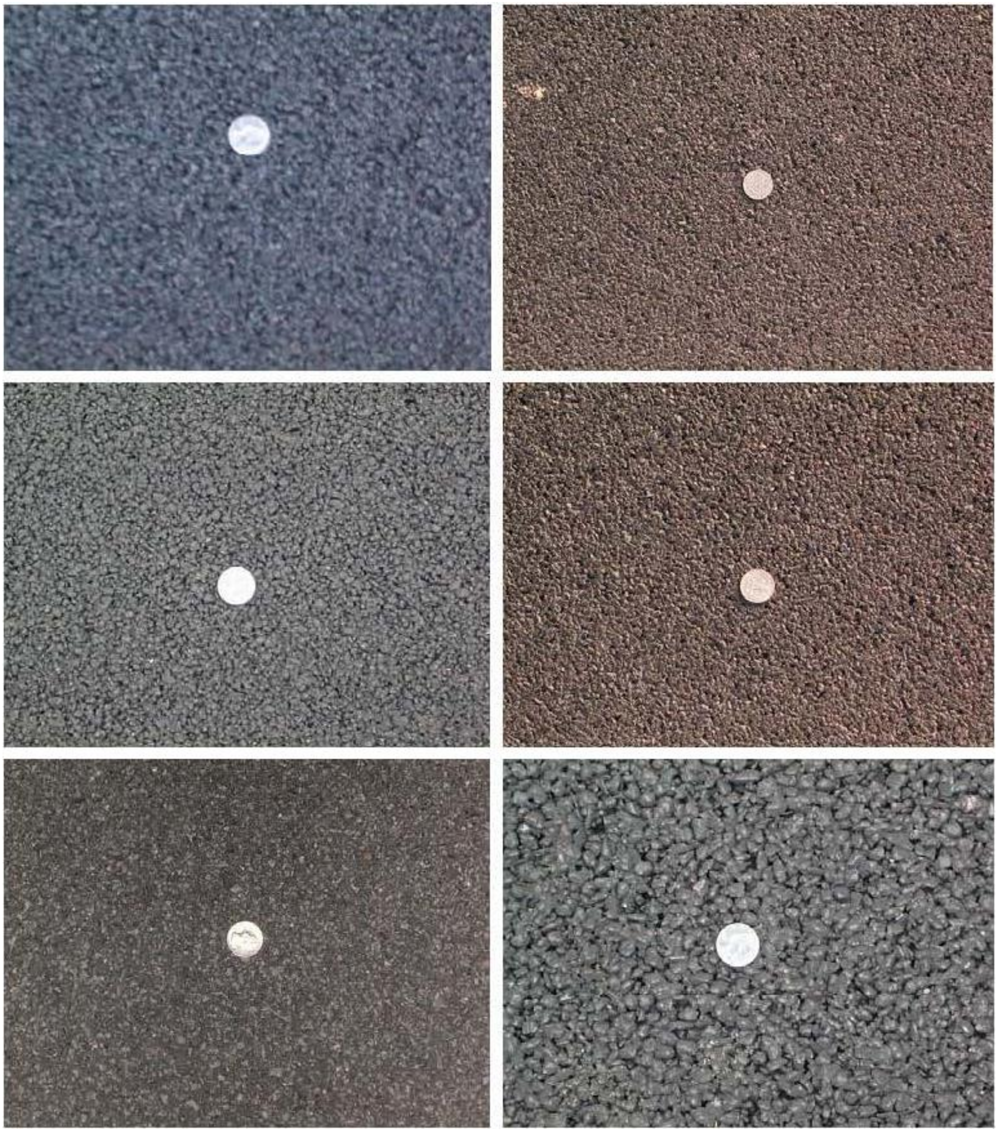

Figure 6-5a: Photographs of quieter double layer porous asphalt sections in the Netherlands
Upper left: Double layer porous asphalt 2/6 mm (DPLA). OBSI = 94.9 dBA, 60 mph (97 km/h) Aquatred
Upper right: Double layer porous asphalt 2/6 mm (DPLA). OBSI = 94.8 dBA, 60 mph (97 km/h) Aquatred
Middle left: Double layer porous asphalt 2/6 mm (DPLA). OBSI = 95.08 dBA, 60 mph (97 km/h) Aquatred
Middle right: Double layer porous asphalt 2/6 mm (DPLA). OBSI = 95.4 dBA, 60 mph (97 km/h) Aquatred
Lower left: Double layer porous asphalt 2/6 mm (DPLA). OBSI = 94.7 dBA, 60 mph (97 km/h) Aquatred
Lower right: Double layer porous asphalt 2/6 mm (DPLA). OBSI = 96.2 dBA, 60 mph (97 km/h) Aquatred

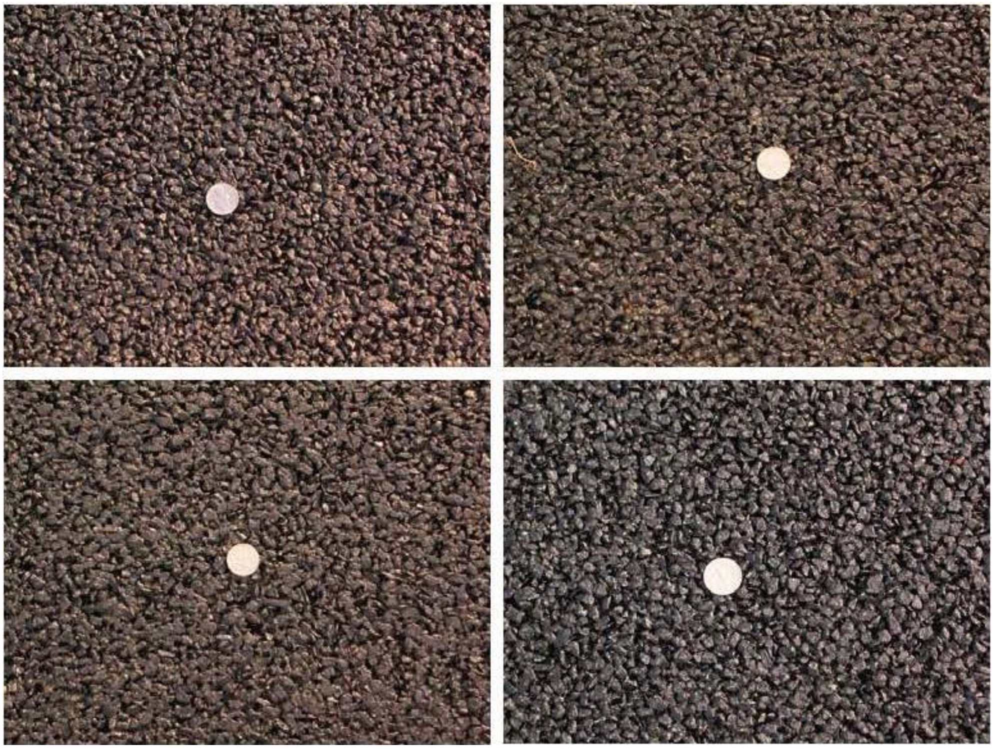

Figure 6-5b: Photographs of quieter double layer porous asphalt sections in the Netherlands
Upper left: Double layer porous asphalt 4/8 mm (DPLA). OBSI = 94.6dBA, 60 mph (97 km/h) Aquatred
Upper right: Double layer porous asphalt 4/8 mm (DPLA). OBSI = 95.5 dBA, 60 mph (97 km/h) Aquatred
Lower left: Double layer porous asphalt 4/8 mm (DPLA). OBSI = 95.7 dBA, 60 mph (97 km/h) Aquatred
Lower right: Double layer porous asphalt 4/8 mm (DPLA). OBSI = 95.8 dBA, 60 mph (97 km/h) Aquatred

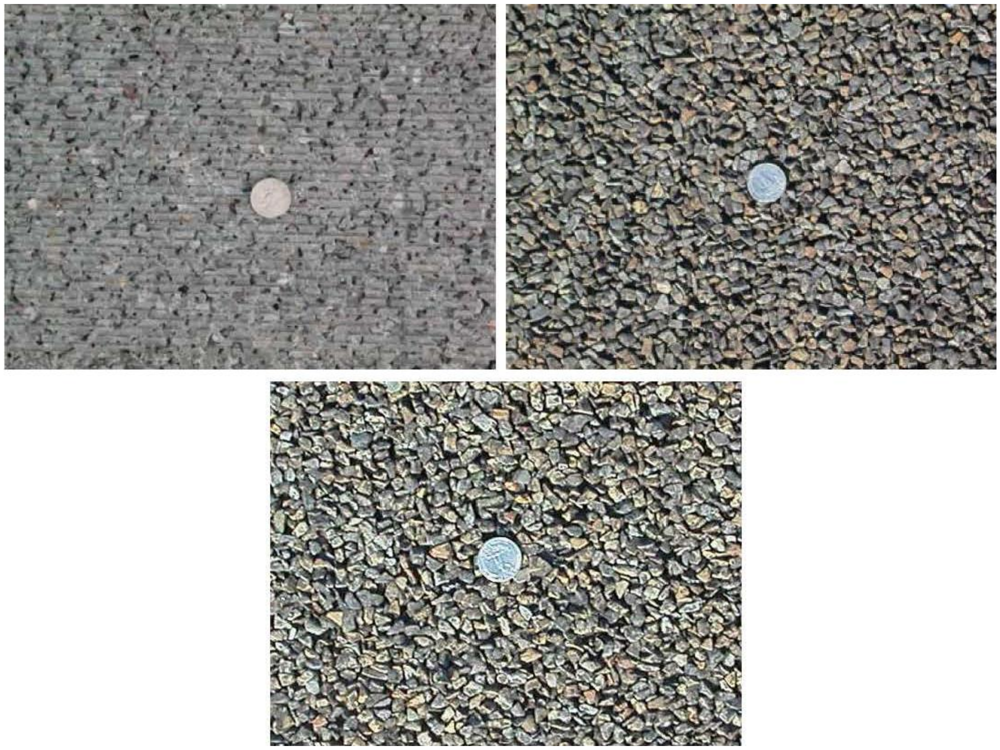

Figure 6-6: Photographs of quieter porous asphalt and concrete sections in Germany
Upper left: Ground porous cement concrete 4.8 mm. OBSI = 9.5dBA, 60 mph (97 km/h) Aquatred
Upper right: Porous asphalt 4/8 mm, PA. OBSI = 95.1 dBA, 60 mph (97 km/h) Aquatred
Lower: Double layer porous asphalt 4/8 mm. OBSI = 94.9 dBA, 60 mph (97 km/h) Aquatred

The data from the U.S. and Europe indicated that the range of tire-pavement noise levels was similar in both regions, with the quietest European pavements performing slightly better than the best in California or Arizona. Several constructions not generally in use in the United States were evaluated in Europe and found to perform well within their respective pavement category. These included DLPA of fine aggregate size, porous rigid pavement, and exposed fine-aggregate rigid pavement. Pavements common to both Europe and to California and Arizona produced similar noise levels when pavement textures and aggregate sizes were considered. California and Arizona rubberized asphalt pavements, which were not encountered in Europe, displayed performance approaching that of the quieter DLPA constructions.

6.1.3 Low-Speed Roads (Donavan 2005a)

Tire-pavement noise has been found to account for as much as 41% of light vehicle exterior noise emissions under the full throttle passby test procedures such as the ISO 362 or SAE J986 (Donavan et al. 1998). Under moderate acceleration, more consistent with how light vehicles operate in the community, this percentage is more typically 70% or greater. For cruise conditions of 30 mph (50 km/h) or more, almost all of the light vehicle noise emission is due to the tire-pavement interaction for vehicles meeting the current passby noise requirements. At a test speed of 35 mph (56 km/h), it has been found that pavement type can create a 10 dB or more variation in tire-pavement noise (Donavan and Rymer 2004a). This has significant implications for both community noise and vehicle noise emission testing. The effectiveness of using quieter pavements in lower speed traffic situations has been demonstrated to produce significant traffic noise reductions both at the source and in neighboring backyards (Donavan 2004).

Although quiet pavement research has focused on highway speeds, a database has also been developed for lower speed roads to better represent urban roadways for purposes of documenting tire-pavement noise. The range in tire-pavement noise sound intensity levels of the 33 European NITE pavements that were measured at 35 mph (56 km/h) is shown in Figure 6-7 for the Aquatred test tire. Figure 6-8 shows OBSI levels measured on California roadways at 35 mph with the Aquatred tire. The SRTT database is available in Appendix A. Figures 6-7 and 6-8 indicate a range in tire-pavement noise levels of about 10 dB at 35 mph. This range is only slightly smaller than that measured at 60 mph (97 km/h) (13 dB).

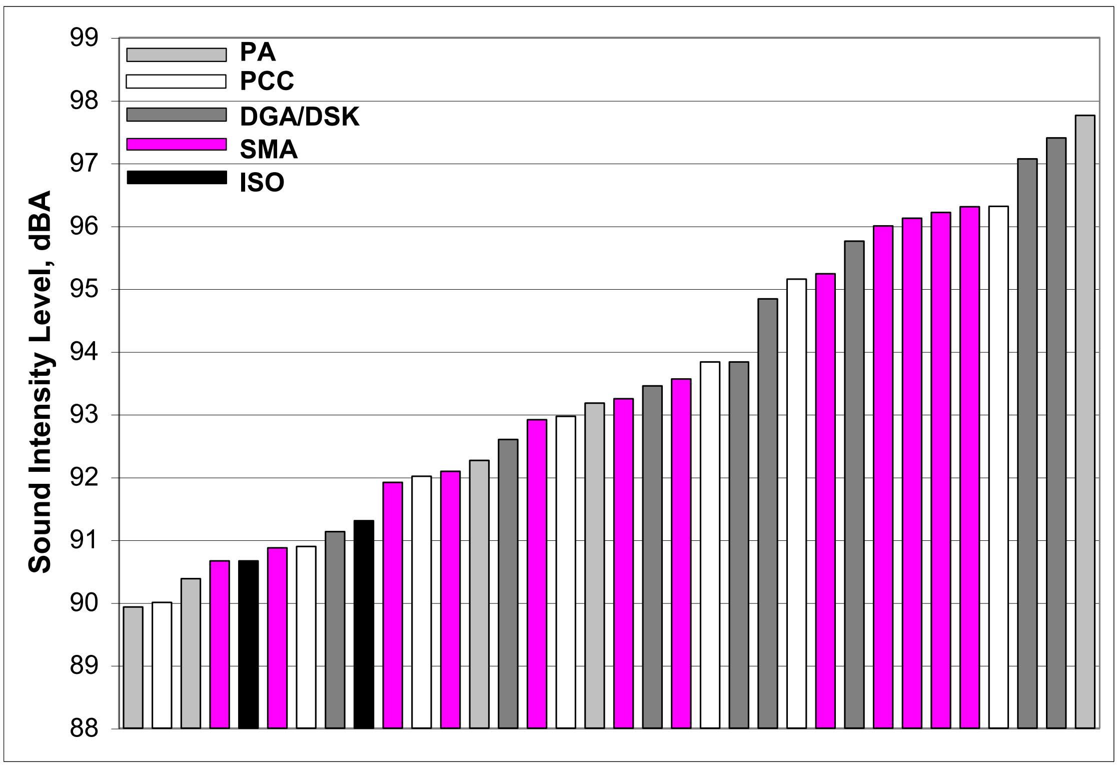

Figure 6-7: OBSI for Pavements in Europe under the NITE Project Measured at 35 mph (56 km/h)

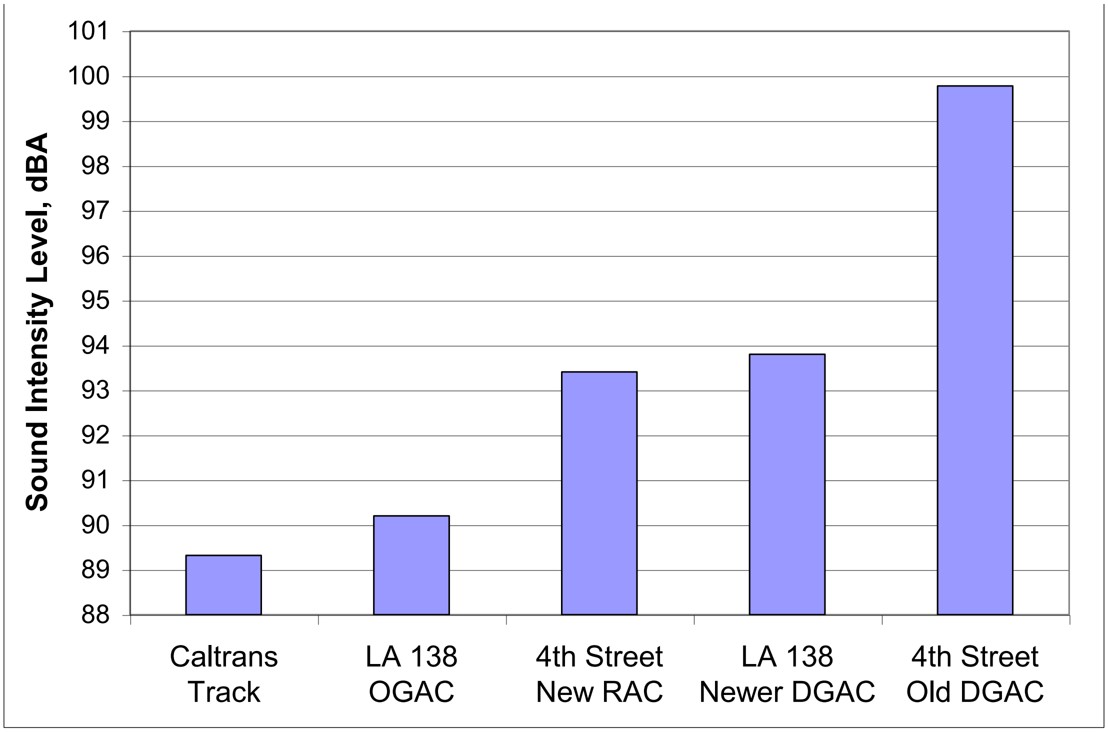

Figure 6-8: OBSI Levels for Pavements in California Measured at 35 mph (56 km/h)

The significance of pavement for low-speed traffic was demonstrated in measurements made in 2003 to document the change in noise level resulting from a pavement rehabilitation project in the City of San Rafael, California (Donavan 2004, 2003b). In this project, a 3,625-foot (0.8 km) section of six-lane urban arterial roadway was re-paved with RAC replacing an older DGAC surface (See Figure 6-9). The roadway has a posted speed of 35 mph (56 km/h) and traffic flow that consists primarily of light vehicles. The change in noise level was documented both by tire-pavement noise OBSI measurements and SPL measurements made in the backyards of residences backing toward the roadway. The pre- and post-project measurements indicated an improvement in noise level of slightly more than 6 dB in the OBSI data, and more than 5 dB in the backyard SPL data (Figure 6-10).

Figure 6-9: Photographs of Miracle Mile Pavement Surfaces, Santa Rafael, California
Left: Older DGA surface. OBSI = 99.8 dBA, 35 mph (56 km/h) Aquatred
Right: New RAC surface. OBSI = 93.4 dBA, 35 mph (56 km/h) Aquatred

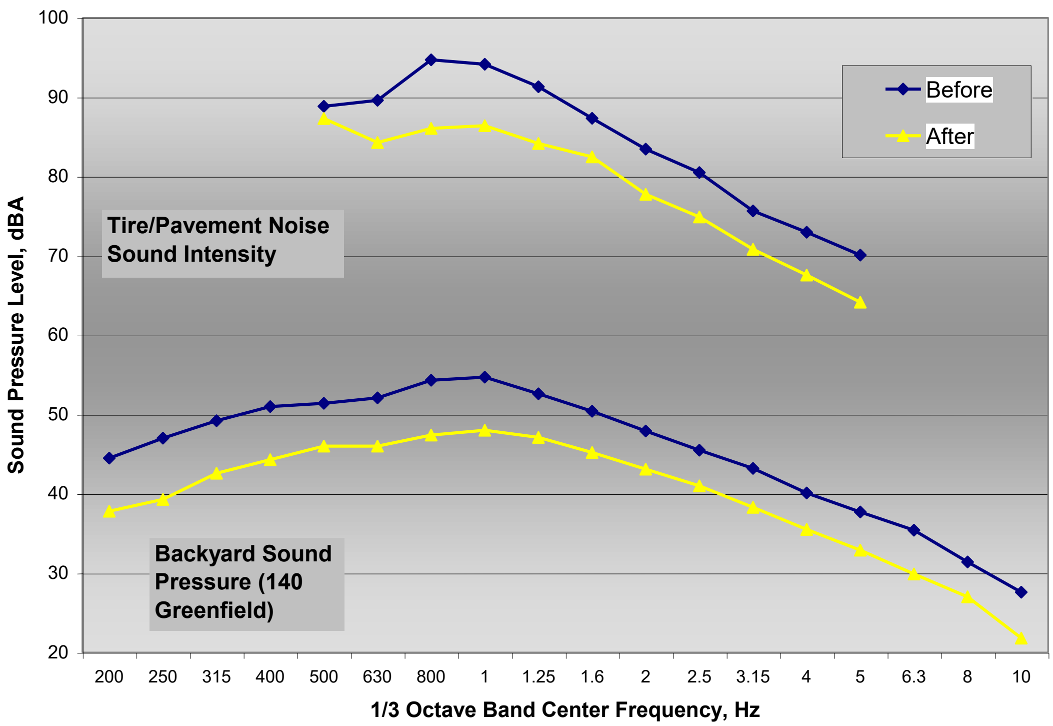

Figure 6-10: Comparison of tire-pavement and backyard traffic noise levels before and after pavement rehabilitation

A 1-inch overlay of OGAC in late 2013 along Point San Pedro Road in Marin County, California produced a tire-pavement noise level reduction of about 3.5 dB, with the overall reduction in traffic noise levels at the wayside ranging from 9.2 dB for passenger cars to 3.1 dB for accelerating heavy trucks (Donavan 2014). This additional noise reduction at the wayside was found to be due to sound absorption provided by the porous OGAC, which further attenuates the noise as it propagates over the pavement surface to the receiver location. Similar effects were noted when US Highway 101 north of North San Pedro Road was rehabilitated with OGAC in 2011 (Illingworth & Rodkin 2013a). For heavy trucks accelerating away from the entrance of the adjacent San Rafael Rock Quarry, the reduction is smaller as engine and exhaust noises become more dominate sources compared to tire-pavement noise. Figure 6-11 shows the pre- and post-rehabilitation surfaces. Figure 6-12 shows the pre- and post- project passby and OBSI measurement results.

Figure 6-11: Photographs of San Pedro Road Pavement Surfaces
Left: Older DGA surface. OBSI = 100.1 dBA, 40 mph (64 km/h) SRTT
Right: New OGAC surface. OBSI = 96.6 dBA, 40 mph (64 km/h) SRTT

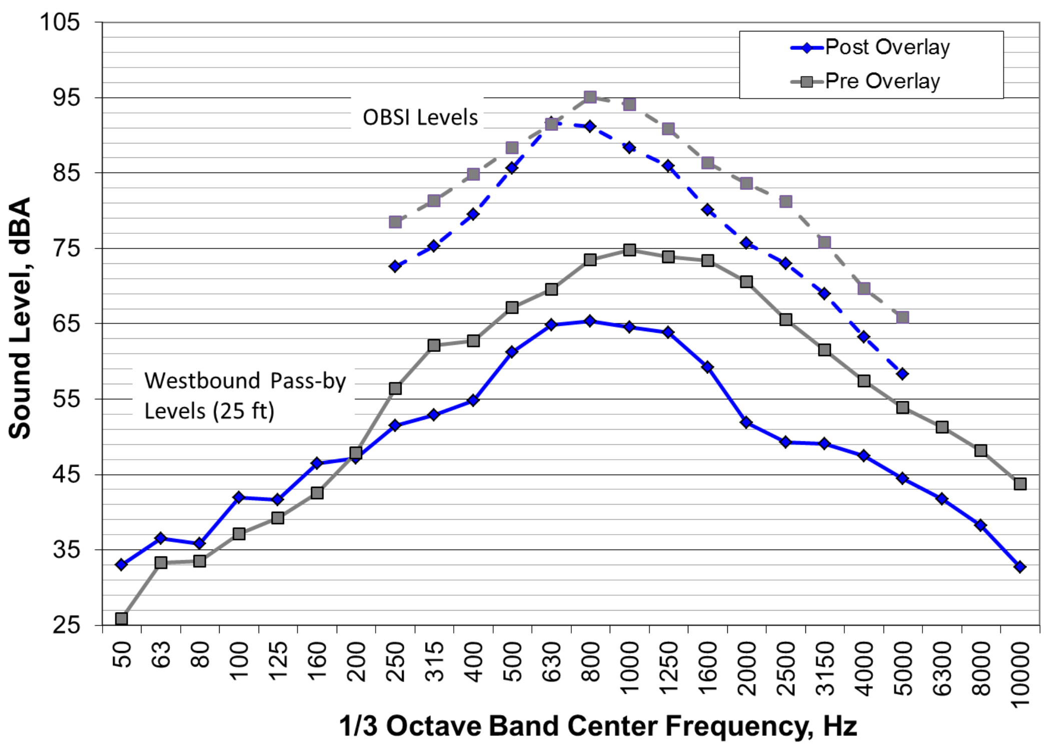

Figure 6-12: San Pedro Road light vehicle passby and OBSI spectra at 40 mph (64 km/h)

6.1.4 Relationship between Interior and Exterior Perceptions of Tire-Pavement Noise

Public perception of quieter pavements often extends well beyond those who live adjacent to the highways, as was the case with the application of the Asphalt Rubber Friction Course (ARFC) applied over transversely tined rigid pavement in the greater Phoenix area for the Arizona Quiet Pavement Pilot Program (Donavan and Janello 2015). Drivers travelling on quieter pavement in the Phoenix area were found to appreciate the reduced interior noise associated with the ARFC. This implies that public perception of quieter pavement may be driven by interior noise as much as by exterior noise, with interior noise potentially effecting a much greater population than exterior noise.

Concentrating on reducing highway noise for the wayside public, it is possible to overlook the importance of the interior of the vehicle in the public perception of noisier and quieter pavements. To examine the relationship between vehicle exterior and interior noise improvement (or degradation) with pavement noise performance, exterior and interior noise was measured on 26 pavements consisting of rigid pavement and flexible pavement construction and texturing as part of Caltrans' QPR program. This data set displayed good correlation between exterior on-board sound intensity levels and overall interior A-weighted noise levels with the range in level for both types of data being about 11 dB, as shown in Figure 6-13.

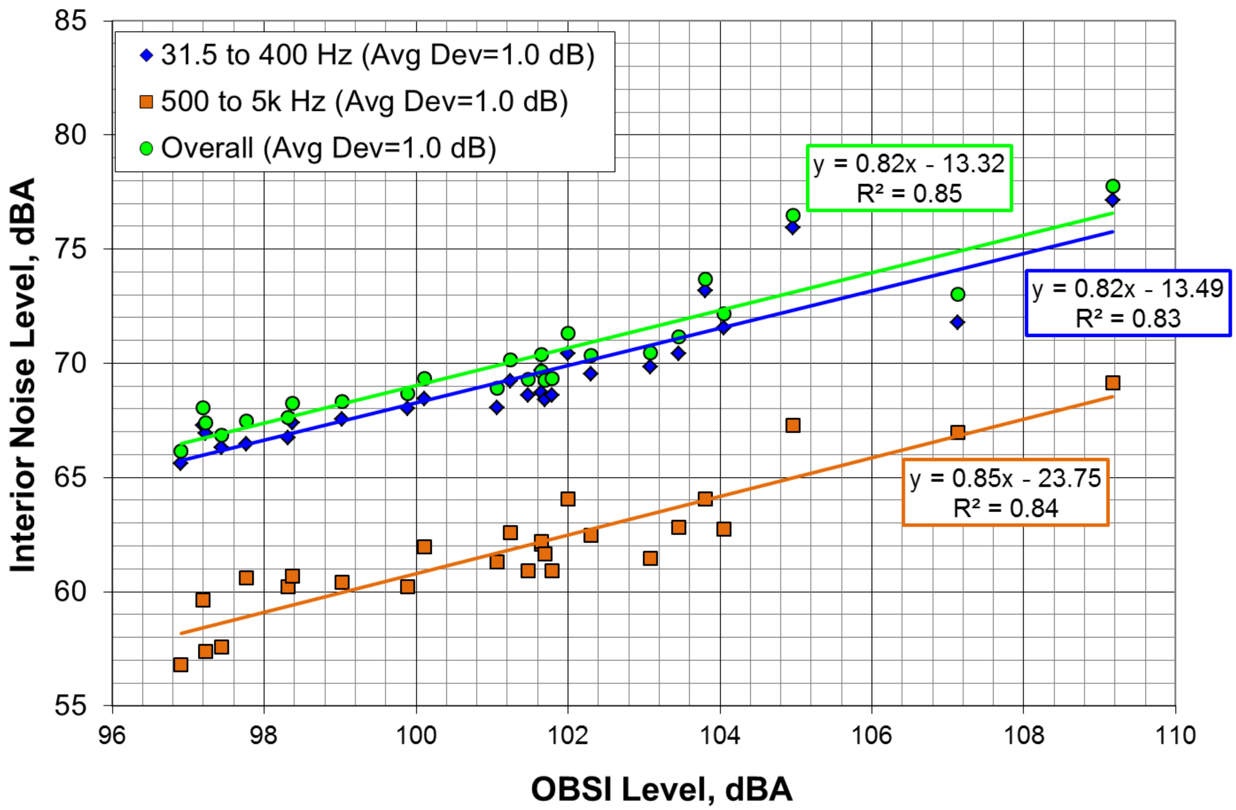

Figure 6-13: Overall and band-passed interior noise levels vs. OBSI

The interior noise levels were also processed into Loudness in Sones, Speech Interference Level, and Articulation Index to better understand the effects of higher tire-pavement noise on interior occupants. It was found that pavement performance is critical for speech communication, with higher tire-pavement levels resulting in higher voice effort and the limiting of speech perception, including both person to person conversation and entertainment systems (see Figure 6-14). Higher interior tire-pavement noise levels could also limit warning information and introduce quality-of-life issues related to comfort and enjoyment during the driving experience.

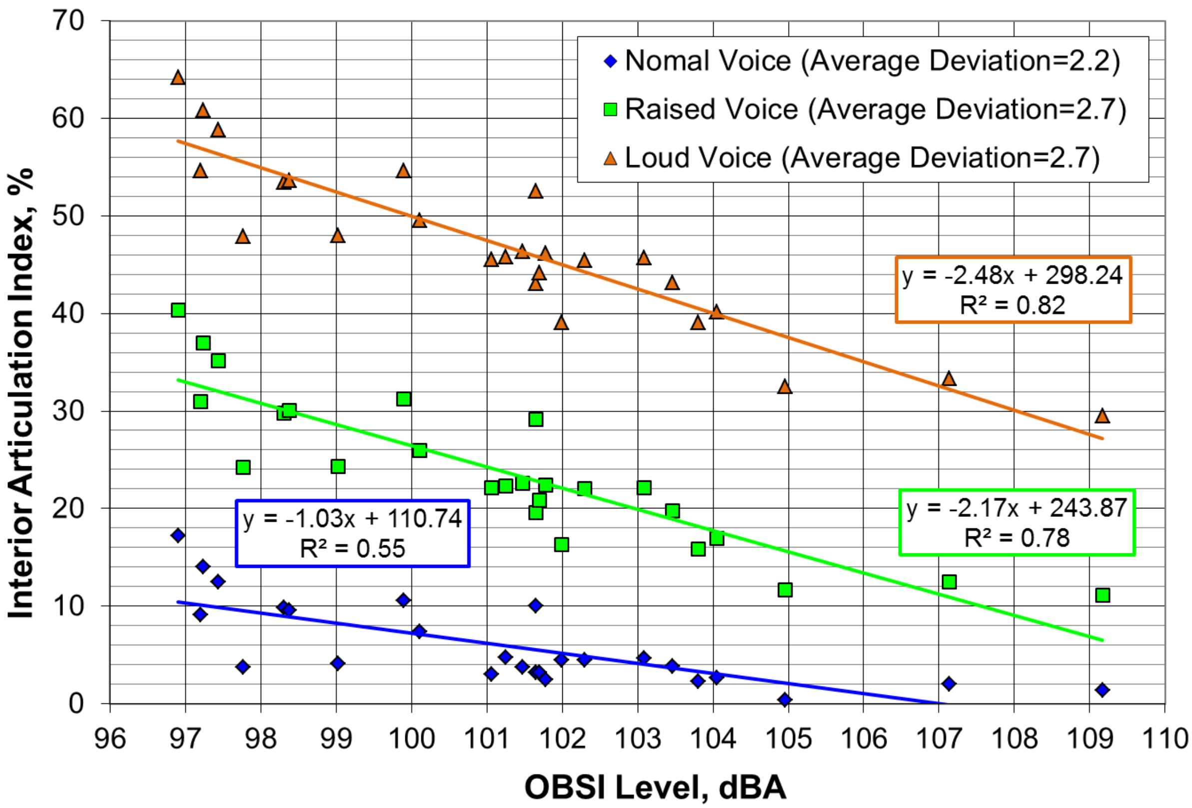

Figure 6-14: Interior percent articulation vs. OBSI level

Where exterior traffic noise is dependent primarily on tires and pavement, interior noise depends on many additional vehicle design and environmental factors. In addition to tire-pavement noise, engine noise and wind noise can also contribute significantly to interior noise levels. Due to the dependence of interior noise levels on vehicle design, standardized measurements would need to be tied to a specific test vehicle, limiting data comparisons. Additionally, the effect of environmental condition has been found to be especially difficult to quantify. To address these concerns, the interior metrics were correlated to exterior OBSI levels in an effort to develop a generic conversion factor between the two parameters. The resulting "filter" for the test vehicle used is shown below in Figure 6-15, which results from the averaging of the difference between the OBSI and interior noise levels for all 26 pavements measured with the test vehicle.

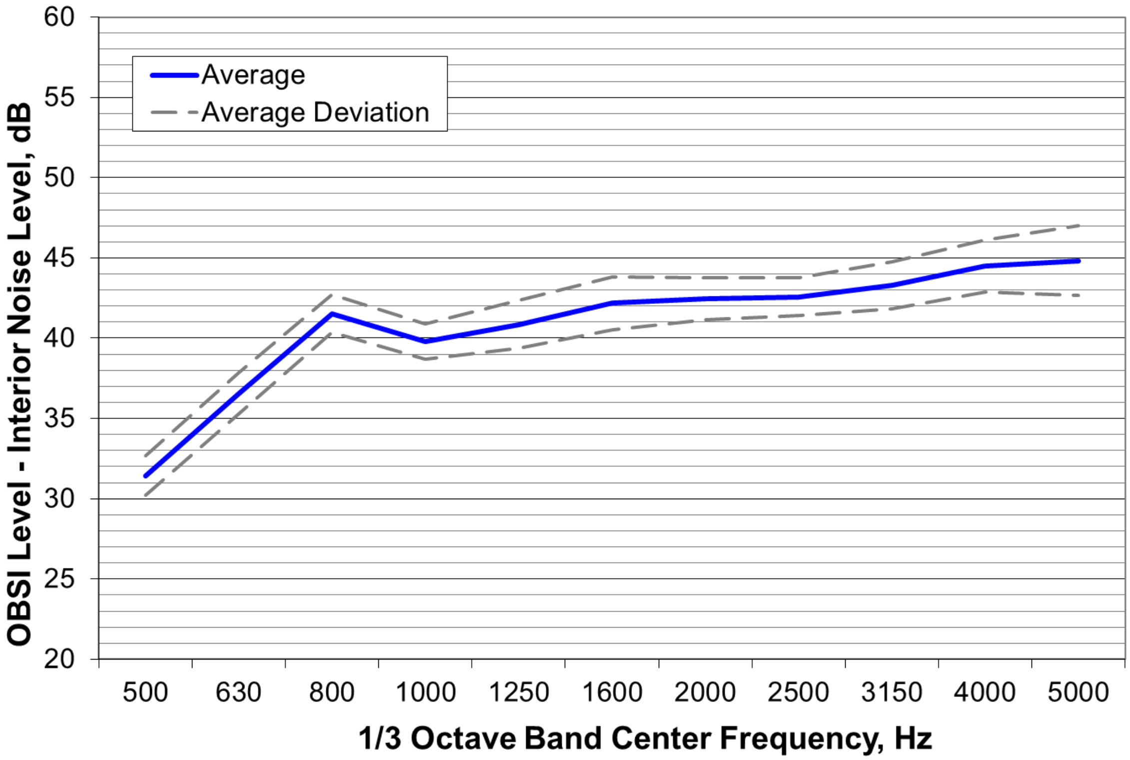

Figure 6-15: Average difference between OBSI and interior noise levels for test vehicle

6.1.5 Determining the Limits of Quiet Pavement Project

With the decision to use a quieter pavement, the end limits for the pavement must be determined. The problem is analogous to deciding where to terminate a sound wall relative to the location of the roadside receivers.

To address this problem, a line source model approach was developed, incorporating the OBSI data of quieter and noisier pavements to estimate the increase in noise level due to the transition from the quieter pavement to the noisier one as a function of distance from the nearest receiver. Examining a number of different geometries, it was found that the traffic noise level change associated with increased distance from the roadway was not very sensitive to the number of lanes or median width of the roadway cross section. The effect of the quieter pavement termination position was, however, very sensitive to the absolute OBSI difference between the quieter and adjoining noisier pavements.

For application in California, a 6 dB difference in noise level between the quieter and noisier pavements was examined as being typical of the changes in noise level experienced in the state between the two pavement categories. Based on the results of the model for this difference and considering a number of different geometries, a distance of three times the offset distance between the end noise receiver and the center of the nearest lane of traffic is recommended, as shown in Figure 6-16. Note that this guidance was adopted for Caltrans based on the expected differences in pavement in the state. For wider application, each jurisdiction should determine the expected difference in OBSI level between its quieter pavement and noisier pavements and repeat the analysis tailored to the specific case.

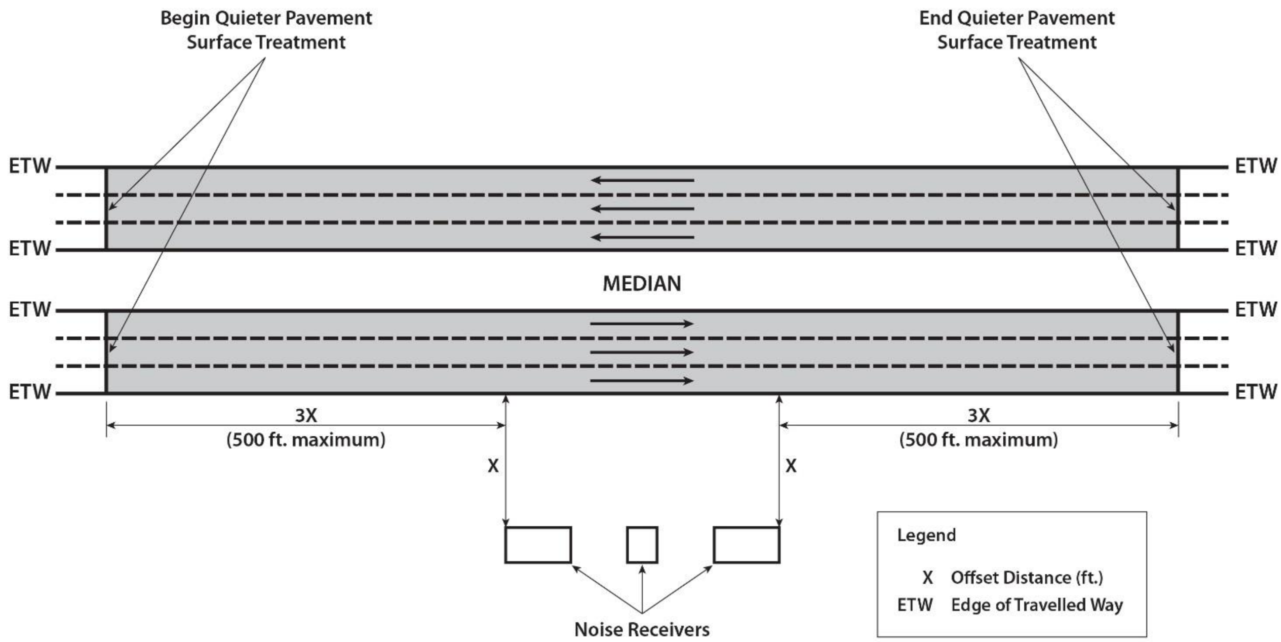

Figure 6-16: Diagram from Caltrans Quiet Pavement Policy Bulletin defining limits of quieter pavement projects

6.2 Asphalt Concrete Pavement Surfaces

Tire-pavement noise levels from 385 AC surfaces measured using the OBSI measurement method with the SRTT test tire at 60 mph (97 km/h) are shown in Figure 6-17 and 6-18.

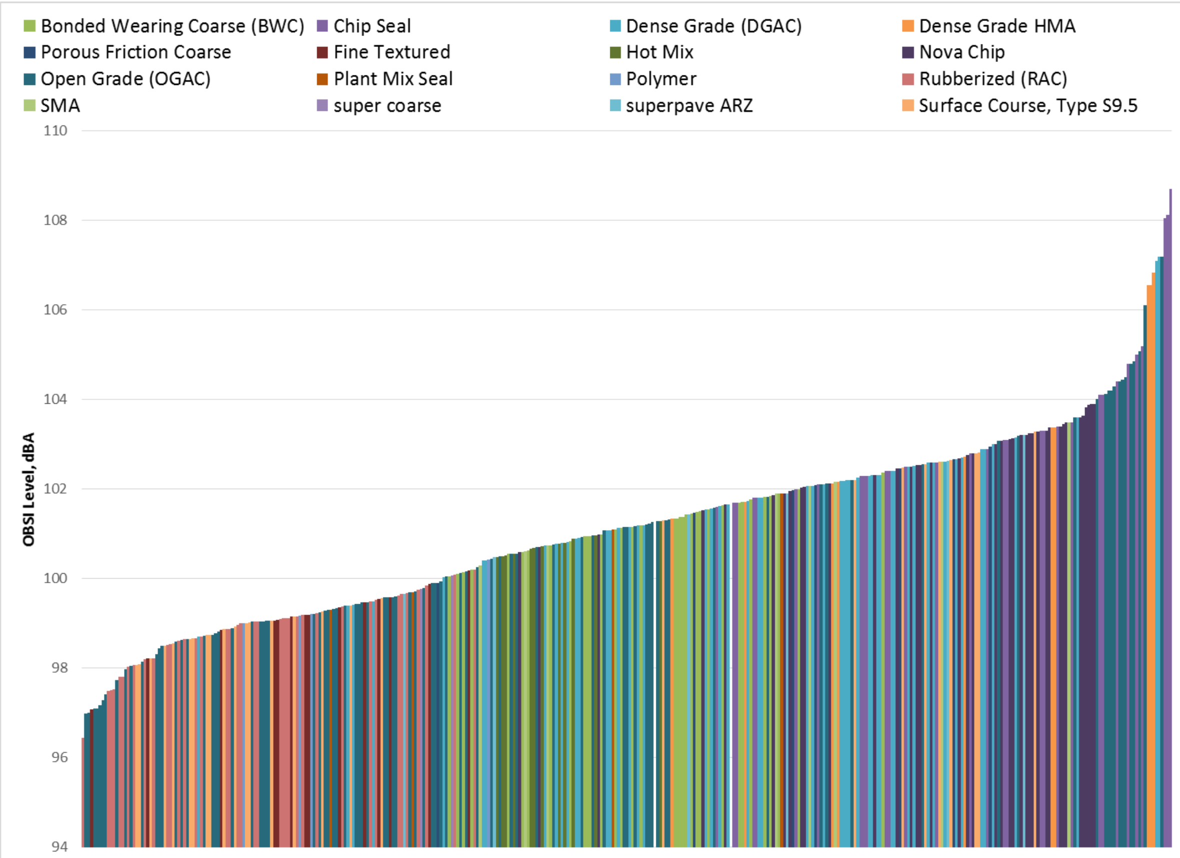

Figure 6-17: Overall A-weighted OBSI levels of AC pavements measured at 60 mph (97 km/h) using the SRTT

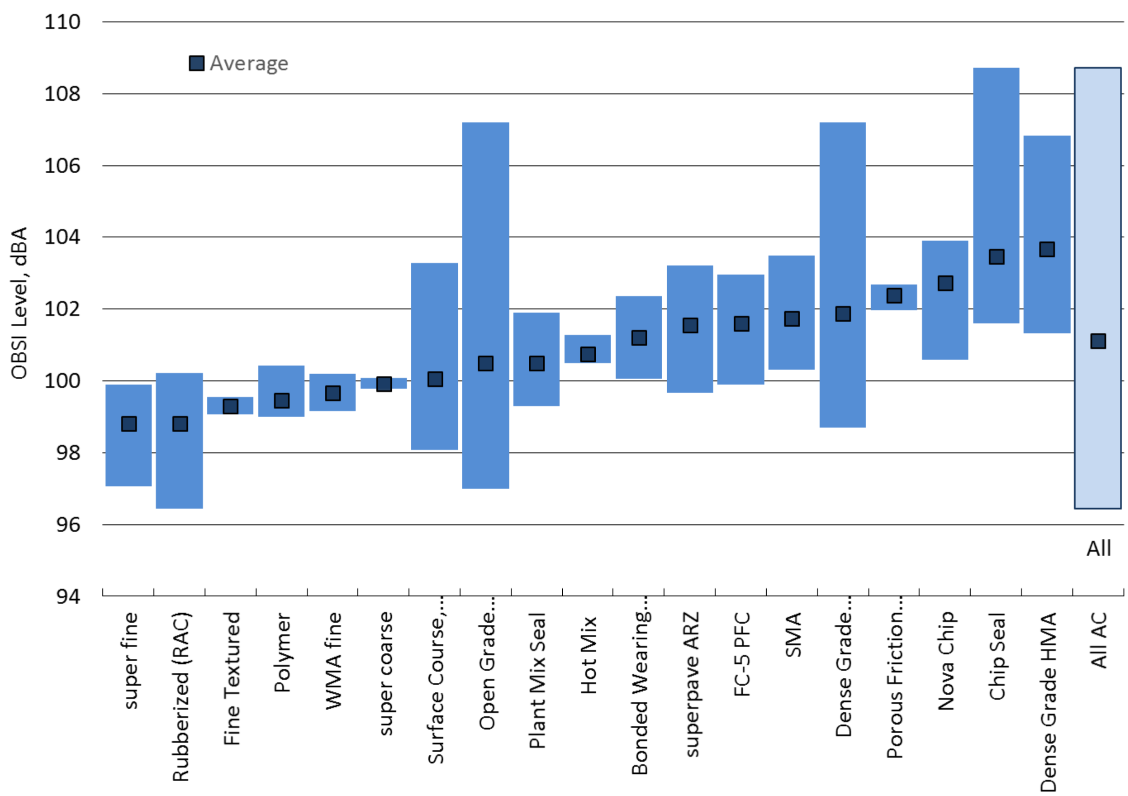

Figure 6-18: Range of OBSI levels by pavement category for AC pavements measured at 60 mph (97 km/h) with SRTT

As shown in Figures 6-17 and 6-18, the range in tire-pavement noise levels of typical flexible pavements is about 13 dB at 60 mph (97 km/h), with OBSI levels ranging from about 96 to 109 dBA. An even quieter pavement, an "Ultra Smooth" flexible pavement with an OBSI level of 92.6 dBA, was measured in 2008 at the HATCHI, located near Mojave, California (Lodico 2008). The quietest flexible pavements are generally pavements with fine aggregate or rubberized surfaces. Louder flexible pavement types include chip seal and hot asphalt mix (HMA), although some louder OGAC and DGAC pavements have also been measured. Some of the quieter flexible pavement surfaces measured to date include 75 millimeter porous OGAC and non-porous rubberized asphaltic concrete open-graded RAC(O) pavements installed on State Route (SR) 138 near Lancaster, California (Illingworth & Rodkin 2013b), the ARFC overlay installed as part of the Arizona Quiet Pavement Pilot Program (QP3) (Donavan and Janello 2015), the HATCHI Ultra Smooth AC pavement (Lodico 2008), and double layer porous and super fine aggregate pavements installed at the NCAT (Donavan 2010a), as shown in Figure 6-19.

Figure 6-19: Photographs of quieter AC pavement surfaces
Upper left: LA 138, 75 mm OGAC. OBSI = 96.9 new, 100 = 100 dBA after 8 years
Upper right: LA138, non-porous RAC(O). OBSI = 97.2 new, 99.6 after 8 years
Middle left: ARFA installed for ADOT QP3. OBSI = 96 dBA new, 101 dBA after 10 years
Middle right: HATCHI ultra smooth pavement. OBSI = 92.6 dBA
Lower left: NCAT double layer porous section N13. OBSI = 98.1 dBA
Lower right: NCAT super fine section N7. OBSI = 98.3 dBA

The primary method of reducing tire-pavement noise of an existing noisy flexible pavement is to overlay the existing pavement with a quieter surface. Caltrans has applied this method successfully in several real-life projects. In 1998, Caltrans initiated a 10-year study to monitor the noise performance of a section of OGAC that was installed on a high volume, multilane portion of Interstate (I-) 80 near Davis, California. This study continued through the 16-year lifespan of the pavement, as described in Section 6.4 (Lodico and Reyff 2009; Illingworth & Rodkin 2014, 2011). Initially, the OGAC overlay resulted in traffic noise levels that were about 6 to 7 dB below those measured for the baseline DGAC pavement. The OGAC continued to maintain its acoustical characteristics and performance after a period of 10 years, with only a slight increase (~ 1.5 dB) in noise levels over time. After 10 years, a more rapid increase in noise level occurred likely due to pavement raveling, and the OGAC pavement resulted in levels that were similar to the original DGAC pavement after 16-years. Figure 6-20 is a photograph of the OGAC pavement. Figure 6-21 shows the CTIM one-third octave band data for the baseline and OGAC overlay pavement, measured over the 16-year period. As seen in Figure 6-21, the primary noise reduction is achieved in frequencies of 1000 Hz and greater, with a dip in levels in the frequencies around 1600 Hz. This noise reduction is attributable to the porosity of the OGAC surface. In the lower frequencies, the OGAC, which has a coarse texture with larger aggregate, results in higher noise levels than the baseline pavement; again typical of porous surfaces.

Figure 6-20: Photograph of OGAC overlay on I-80, Davis, California

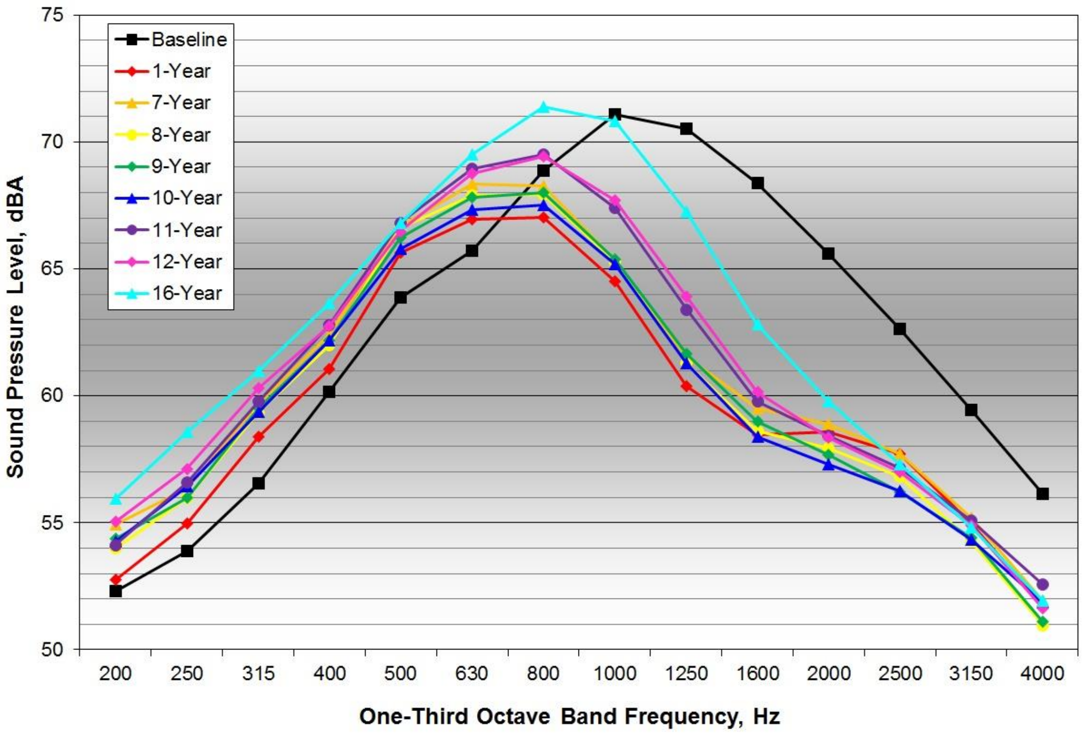

Figure 6-21: One-third octave band spectra for summer measurement periods, as well as October 2010, at the Westbound Reference CTIM microphone location for Davis I-80

A "European Style" pavement overlay on State Route 19 in El Monte, California was evaluated in 2005. Figure 6-22 shows photographs of the pre and post-construction surfaces. This overlay resulted in a 4 dB reduction in tire-pavement noise levels (Anderson 2005), as indicated in Figure 6-23.

Figure 6-22: Site photo of SR 19, indicating pre- and post-construction surfaces

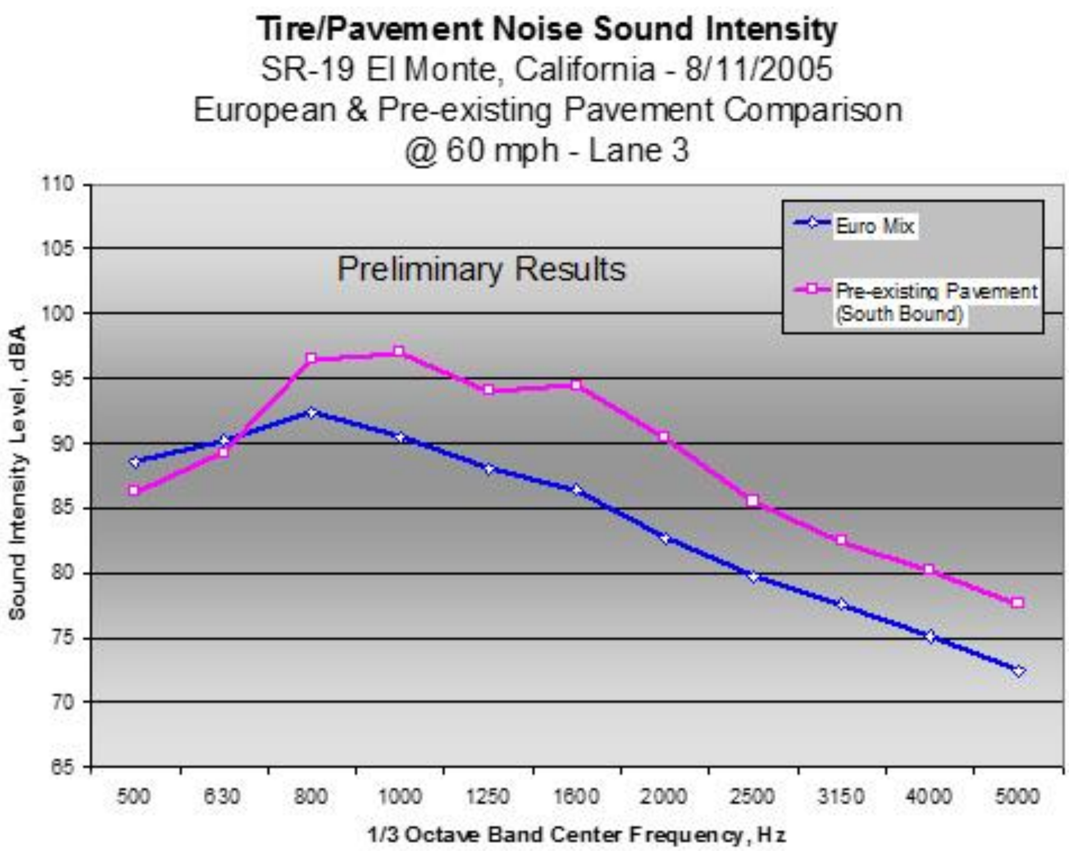

Figure 6-23: Average sound intensity spectra for pre- and post-construction pavements on SR 19

On Shasta 299 near Redding, California, placement of a RAC(O) overlay in 2007 resulted in an average noise reduction of about 3 dB below levels measured on the pre-construction Type A DGAC (Lodico 2007a). Figure 6-24 shows photographs of the pre and post-construction surfaces. Figure 6-25 shows the OBSI spectra for both pavements.

Figure 6-24: Photographs of Shasta 299 pavement surfaces
Left: Type A dense grade asphalt concrete (DGAC). OBSI = 103.0 dBA (SRTT)
Right: Rubberized asphalt concrete (RAC-O). OBSO = 99.7 (SRTT)

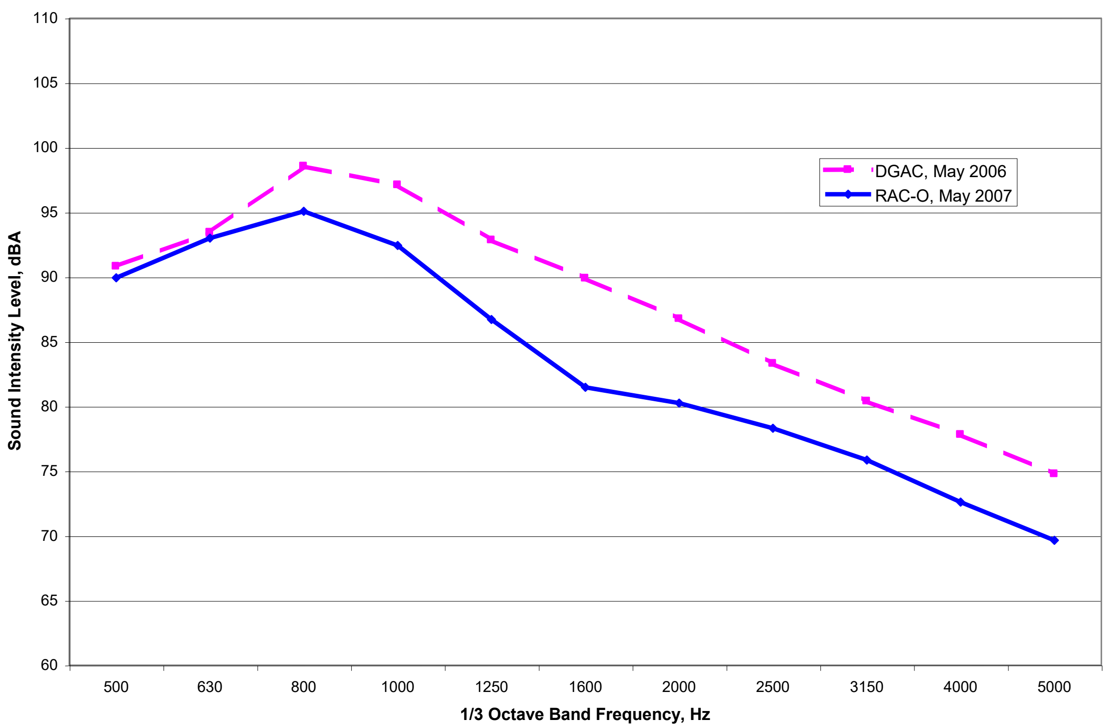

Figure 6-25: Average sound intensity spectra for DGAC and RAC(O) pavements on Shasta 299

6.2.1 Porous Pavement

In single and double layer constructions, some porous pavements have been shown to be the quietest of pavement constructed with conventional materials (Donavan 2008a). The lower highway noise levels on porous pavements have been attributed to reduction of air-pumping from the tire tread voids and additional sound attenuation as noise from a vehicle propagates over the sound absorbing surface (Sandberg and Ejsmont 2002). Porous, sound-absorbing pavement may also reduce the apparent sound power emission of the tire noise source as it propagates out above and below the pavement (Donavan 2011a). Isolating the effect of porous pavements through the comparison of statistical passby tests for light vehicles on a range of pavements has proven to be difficult due site-to-site differences that obscure the relatively small differences for porous and non-porous pavements when the propagation over the porous pavement occurs over shorter distances (7.5 to 15 meters) (Donavan and Lodico 2009).

As shown in Figure 6-26, OBSI measurements of 22 pavements at the National Center for Asphalt Technology (NCAT) facility in Opelika, Alabama produced three groupings based on one-third octave band spectral characteristics (Donavan 2011a). Spectral groupings were most dependent on pavement porosity and age of construction, with porous pavements shown in light blue in Figure 6-26. Significant sound attenuation in frequencies above 1250 Hz was found for all of the porous pavements in comparison with the non-porous pavements. One factor influencing this additional attenuation was the depth of the porous layer. Attenuation was also found to vary with pavement age. For ground level sources such as tire-pavement noise, the amount of additional attenuation increased with the distance over which the sound propagated over the porous pavement.

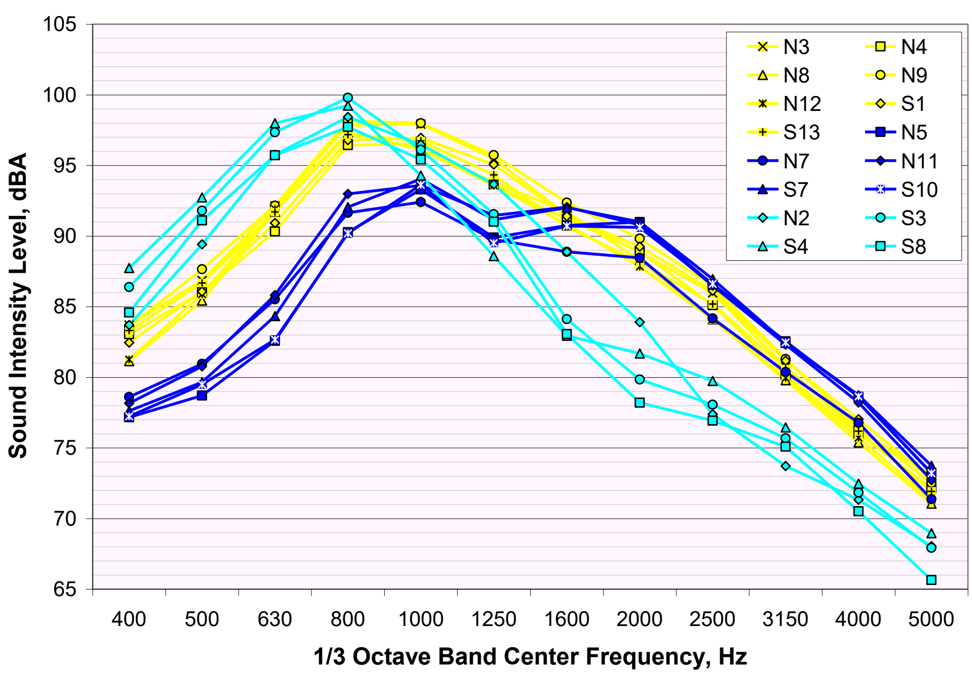

Figure 6-26: One-third octave band OBSI levels for 22 pavements at NCAT (porous sites are indicated in light blue)

To more precisely examine the effect of sound being absorbed as it propagates over a porous pavement surface, controlled passby measurements on the NCAT test track were made in conjunction with both tire-pavement source measurements using the OBSI technique and sound propagation tests (Donavan 2011b). For the testing, four pavements were selected that, based on previous measurements, produced a large range in measured noise level (see Figure 6-27). For all four sections, the track was wide enough to allow for passby measurements to be made with the sound propagating over the pavement surface to a distance of 50 feet (15.25 meters).

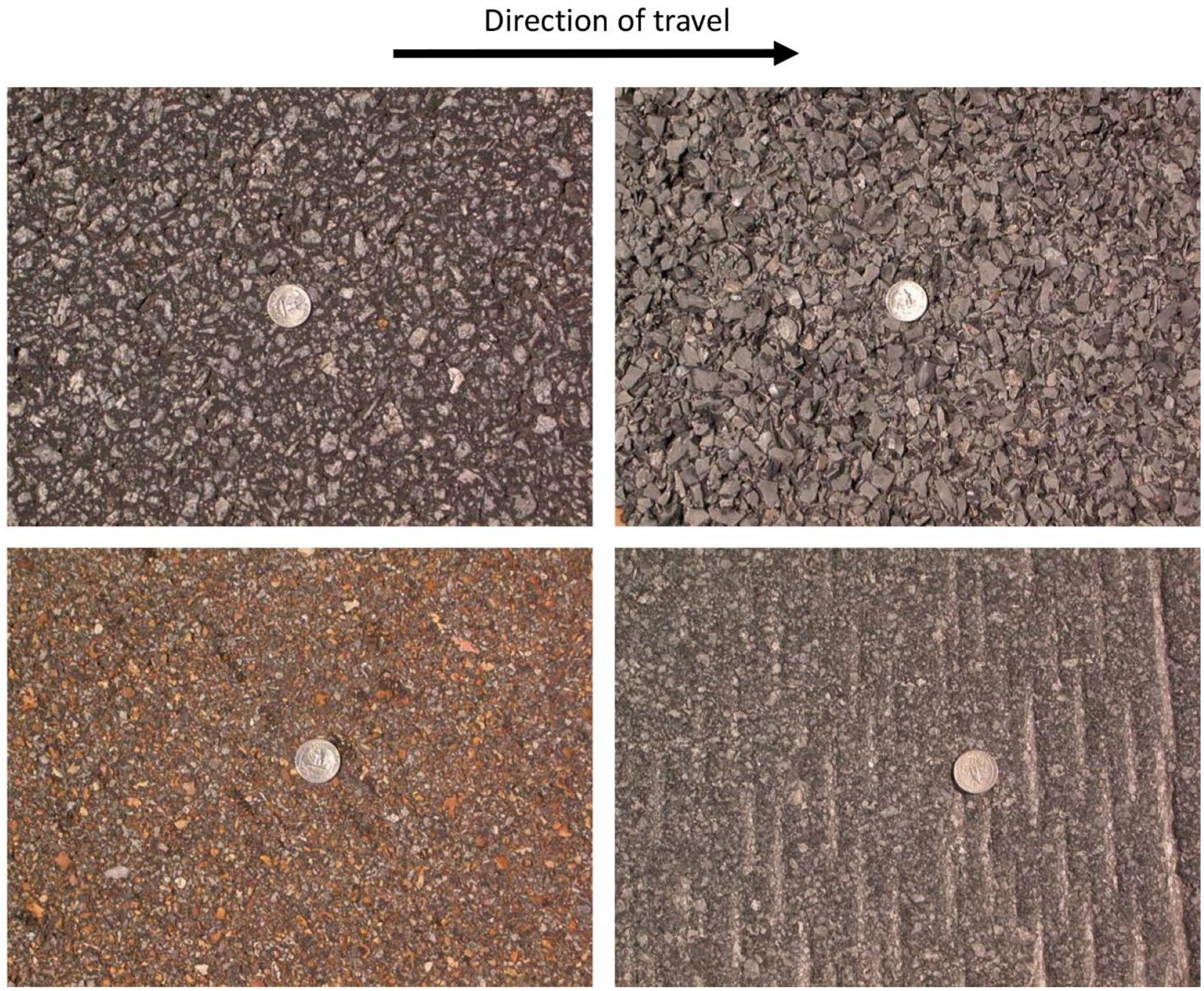

Figure 6-27: NCAT test surfaces
Upper left: S1
Upper right: S4
Lower left: S5
Lower right: W3

The OBSI and passby data are compared on a one-third octave band basis in Figures 6-28 and 6-29. In Figure 6-28, the passby spectra for the SRTT on the four pavements are plotted for speeds of 60 mph (97 km/hr) and 55 mph (88 km/hr) on W3. The corresponding OBSI data are shown in Figure 6-29. Comparing these, the relative spectral shapes of the two data sets are similar. The porous pavement displays a characteristic “dip” of about 9 dB starting at 1000 Hz, and continuing to higher frequencies. This dip is similar to that identified in the porous OGAC pavement used in the I-80 Davis Study (Lodico and Reyff 2009). In the frequencies of 630 Hz and below, the coarse texture of the porous pavement results in higher levels than any of the other pavements. This is another typical characteristic of porous pavements, as porous pavement is often composed of larger size aggregate and less fine material.

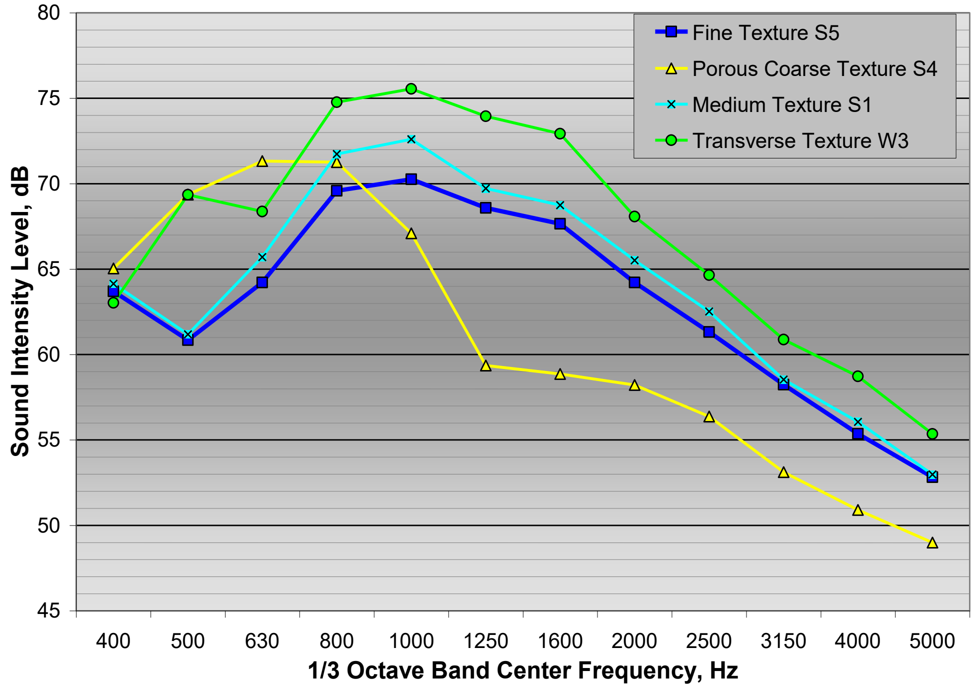

Figure 6-28: One-third octave band passby spectra for SRTT at 60 mph (97 km/hr)

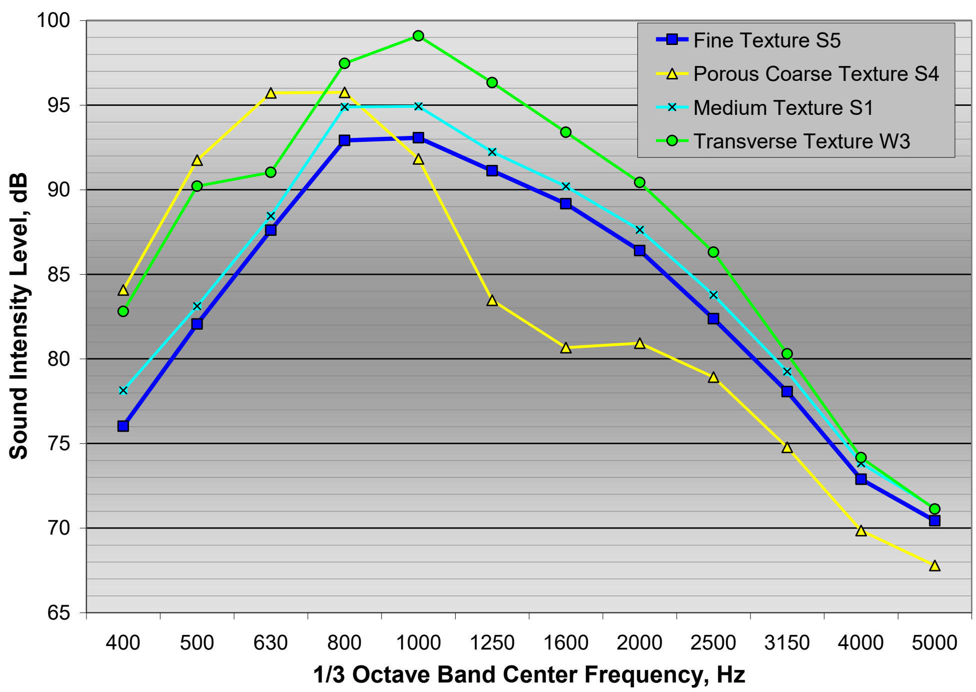

Figure 6-29: One-third octave band OBSI spectra for SRTT at 60 mph (97 km/hr)

Figure 6-30 shows overall A-weighted passby levels plotted against the corresponding OBSI levels. The results display a good deal of correlation, achieving a coefficient of termination (R^2) of 0.93 for a linear regression and with a constant offset of 24.0 dB. Similar results have been found in other research (Donavan 1993, 2011c). The data points for the porous S4 pavement fall consistently below both the regression line and the constant offset. With the porous site removed, the data for the three non-porous surfaces (S1, S5, and W3) result in a constant offset of 23.7 dB, while the S4 pavement has an average difference of 25.1 dB. This indicates that at a distance of 50 feet (15.25 meters), traffic noise levels are reduced or attenuated by an average of 1.4 dB for the porous pavements in comparison with the non-porous pavements for the same source strength as measured by OBSI.

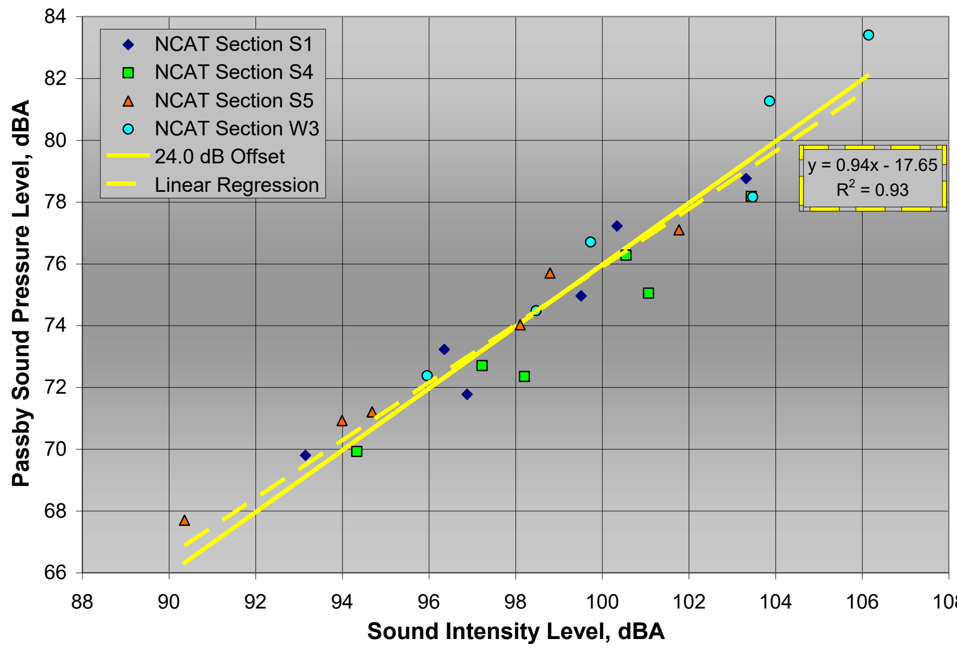

Figure 6-30: Overall OBSI vs. passby levels for multiple speeds and pavements

The effect of sound absorption over porous pavement is further isolated with sound propagation measurements. Figure 6-31 shows the differences between the average SI measured at the face of a loudspeaker and the SPL measured at the passby microphone location for the four pavements. The porous pavement resulted in additional reduction in the 1000 Hz band and above indicating that attenuation occurs on the porous surface as the sound propagates over the absorptive surface.

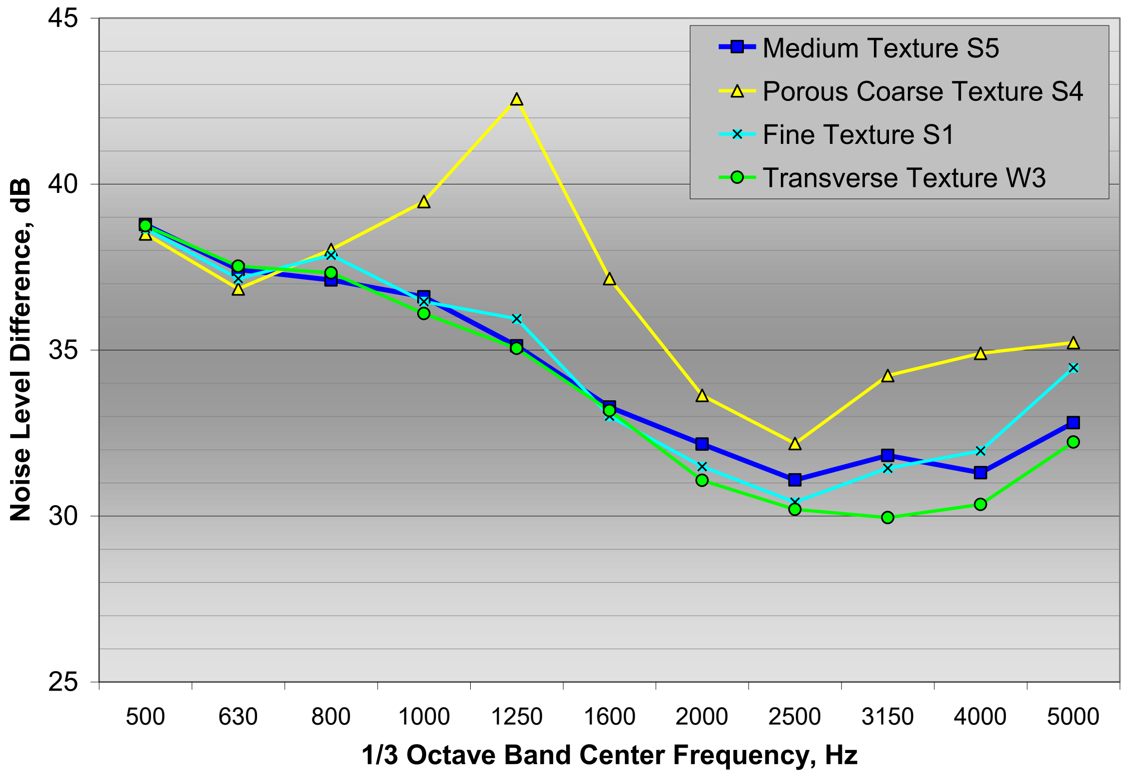

Figure 6-31: One-third octave band difference loudspeaker level minus passby microphone level

By comparing OBSI, controlled passby, and sound propagation results for light vehicles, it was demonstrated that porous pavements reduce passby noise through a combination of reducing the tire-pavement source strength and providing additional attenuation as the sound propagates over the absorptive surface. Source strength appears to be reduced by several means, including relieving air-pumping from the tire tread voids, reducing the horn effect, and reducing the energy of the composite tire-pavement source in the acoustic near field. The sound absorption provided by porous pavements produces additional attenuation relative to non-porous pavements by about 2 dB or more in the critical frequency bands around 1000 Hz even for short distances (about 6 feet [1.8 meters]) of propagation over the porous pavement.

An investigation of the influence of porous pavement on truck tire noise at the NCAT facility found that porous pavements are particularly effective at reducing passby noise from heavy trucks. As a result of several factors, trucks tend to generate more low frequency noise than light vehicles generate (Donavan 2011b). Because of the larger diameter of truck tires relative to light vehicle tires, truck tires have lower rotation rates than light vehicle tires at the same speed. Additionally, a truck tire's tread elements are typically larger, which can result in relatively more void area in its tread patterns than in light vehicle tires, leading to the production of more air-pumping noise (Donavan 2010b). As shown in Figure 6-32, the trucks typically produce passby noise levels 10 to 15 dB greater that light vehicles over the one-third octave bands that contribute to highway noise, except at 500 Hz. In the 500 Hz band, the truck levels on non-porous pavements are typically 20 to 25 dB greater. On porous pavement, indicated in Figure 6-32 as the "Redding" site, the difference between truck and light vehicle levels at 500 Hz remains at only about 10 dB. These lower levels in the 500 Hz band are attributed to the ability of porous pavement to relieve tread air-pumping mechanisms. On non-porous pavements, the noise levels at 500 Hz are typically greater than or equal to the levels in the bands above 500 Hz on an A-weighted basis. As a result, reducing truck noise at 500 Hz will typically make a significant contribution to reducing the overall A-weighted truck passby noise levels.

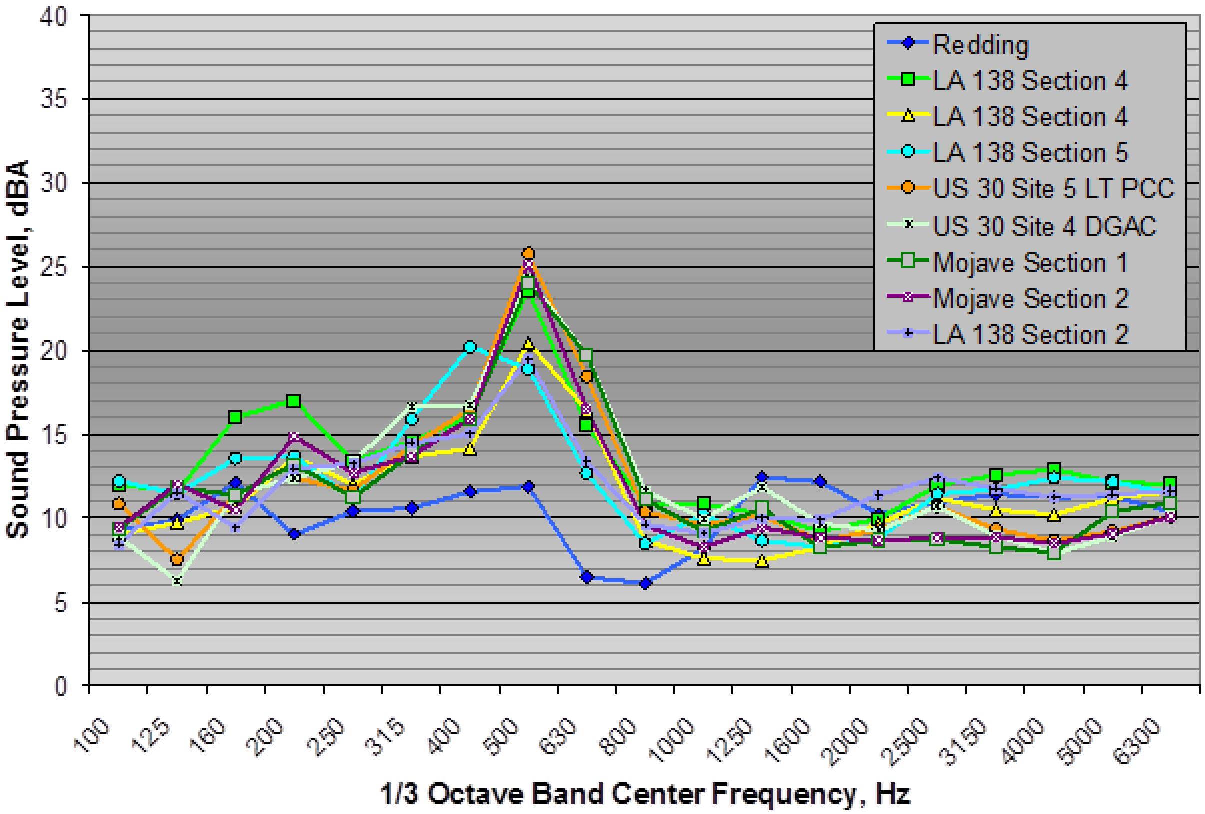

Figure 6-32: One-third octave band difference of statistical heavy trucks passby levels minus light vehicle passby levels (porous pavement shown as "Redding")

A comparison of theoretical and experimental investigations indicates that the sound absorption produced by porous pavements has a noise-reducing effect on both measured and predicted traffic noise levels (Rochat and Donavan 2013). This effect of sound absorbing pavement is not insubstantial. More accurate modeled sound levels can be achieved by properly accounting for the sound absorption of pavement in the noise model. Further, predictions can be made as to the effect of sound absorbing pavement by using modeling or measurement techniques. For assessing the performance of quieter, porous pavements over time, monitoring and accounting for the effects of sound absorbing pavement is of some importance. Although the effect of porous pavements on tire-pavement source levels can be monitored with on-board measurements, the effect of the sound absorption on the propagation of sound to the receiver location needs to be considered as an added noise-reducing feature of the pavement. If absorption is included in the FHWA Traffic Noise Model (TNM) as part of the analysis of noise mitigation for a project, then some means of monitoring the performance of the pavement and its absorptive characteristics over time should be added to monitoring tire-pavement source levels.

6.2.2 Asphalt Rubber Pavement (Donavan and Rymer 2010)

The introduction of rubber content into asphalt mixes began more than 40 years ago. Rubber was initially used for its durable and anti-raveling performance (Scofield and Donavan 2003). Since that time, ADOT has extensively developed and improved the use of asphalt rubber (AR) in the Arizona road system. In the early 1990s, it was determined that AR could also produce noise reduction benefit and provide some added durability over conventional AC pavement designs (Scofield and Donavan 2005). In this same time period, Caltrans started trial applications of AR pavements as a method of disposing of used tires, in additional to the reasons stated by Arizona.

In the 2000s, both agencies built research test sections to compare AR pavement with flexible pavements. AR pavement also began to be used in cases where noise abatement was an issue with local residents. Research test sections have included SR 138 near Lancaster, California (Illingworth & Rodkin 2013b) and I-10 near Casa Grande, Arizona (Donavan 2010c). Some example cases where AR was used as noise abatement include SR 299 near Redding, California (Lodico 2007a), the ARFC overlay applied more than 115 miles (185 kilometers) of freeway in Arizona (Lodico 2008), I-280 in San Mateo County, California (Janello and Donavan 2011a), I-5 in Sacramento County (Illingworth & Rodkin 2008), and I-515 near Las Vegas, Nevada (Lodico and Donavan 2008). The reductions provided by AR pavement can be on the order of at least 10 dB, depending on the condition and type of pavement being overlaid or rehabilitated. As described in Section 6.4, acoustic longevity of quieter AR and non-AR pavements has found to be similar, in the range of about 0.3 to 0.5 dB per year. As with any pavement type, the use of rubber in AC does not assure quieter performance, and mix design and construction parameters, such as aggregate size and placement, can result in noise levels higher than would be expected from the quieter applications of AR pavements.

6.3 Rigid Pavement Surface Textures

Tire-pavement noise measurements have been made on numerous rigid pavement sections. As indicated in Figure 6-33, a 9.5 dB range in pavement noise levels from about 99.5 to 109.0 dBA has been measured using the SRTT at a test speed of 60 mph (97 km/h). Figure 6-33 includes both experimental and typical pavement sections.

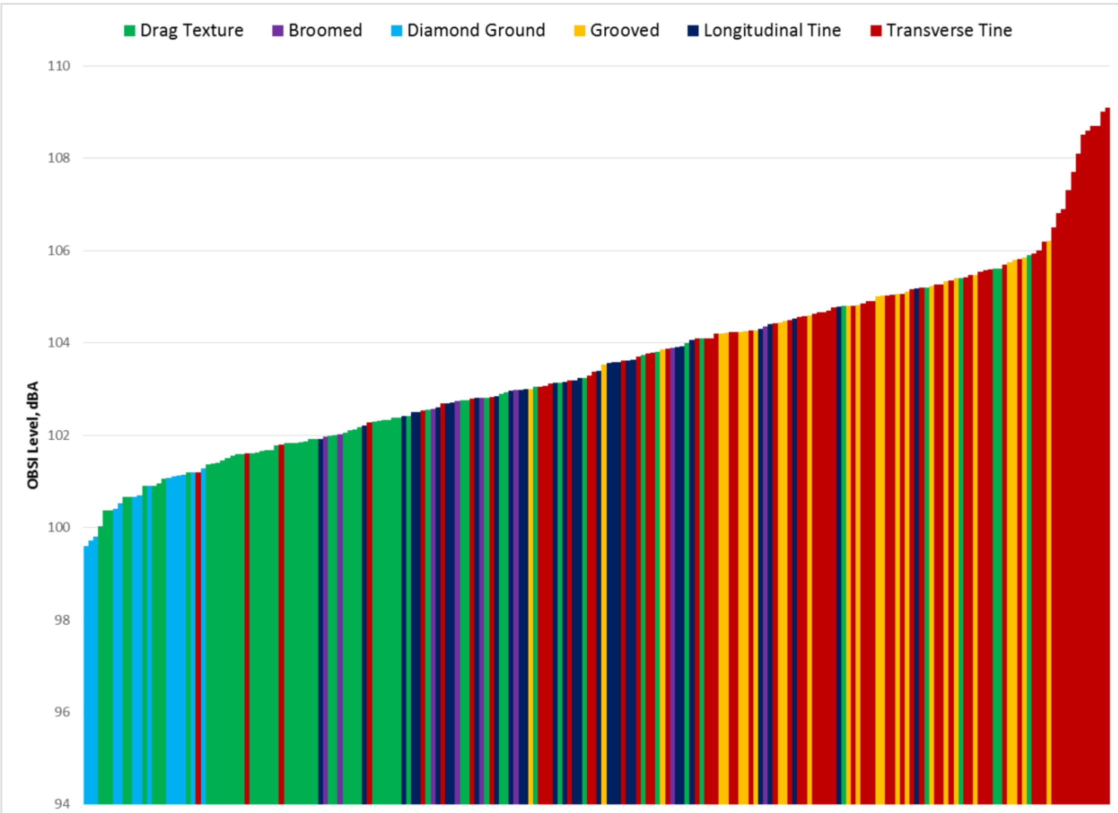

Figure 6-33: Overall A-weighted OBSI levels of rigid pavements measured at 60 mph (97 km/h) using the SRTT

Some categorical differences between pavement types can be observed from Figure 6-33, with the ground and drag textures generally resulting in the quietest levels, broomed and longitudinal tined textures resulting in mid-range levels, grooved textures resulting in mid to high noise levels, and transverse tined textures generating the loudest levels. However, the range of noise levels measured within these general pavement categories is as high as 6 dB (see Figure 6-34) and there are some clear exceptions. For example, a transverse tined rigid pavement on I-275 near Union Township, Ohio resulted in levels between 101 and 102 dBA (Illingworth & Rodkin 2010a) and one of the experimental drag textures on County Road 32A near Davis, California resulted in a noise level close to 106 dBA (Lodico 2007b; Scofield 2007).

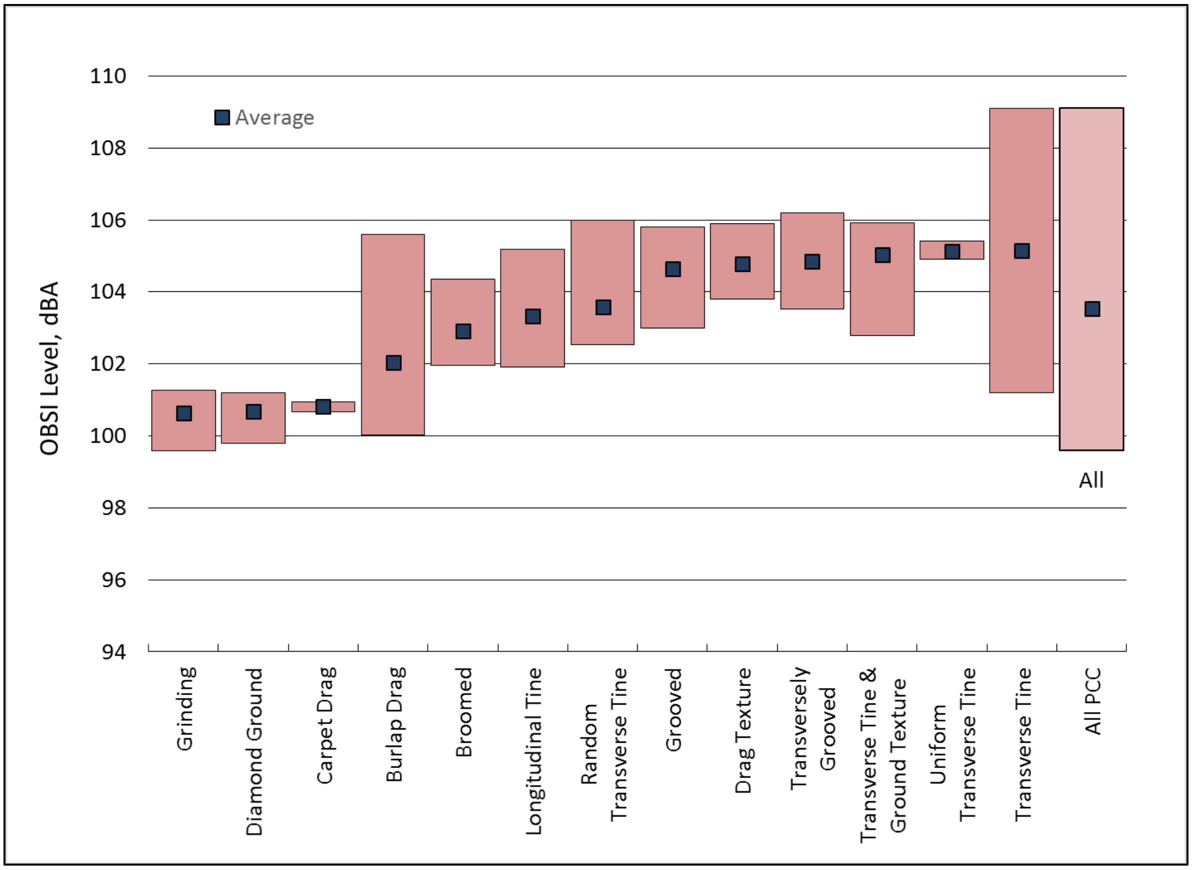

Figure 6-34: Overall A-weighted OBSI levels of PCC pavements measured at 60 mph (97 km/h) using the SRTT

6.3.1 Longitudinal Tining

Longitudinal tining is a standard practice for rigid roadways on grade throughout California. It has also been used as the preferred method of texturing of rigid surfaces in Arizona and many other states because of its generally lower noise levels compared with transverse tining. Again, noise levels vary within this specification, with levels ranging from 102 to 105 dBA. Figure 6-35 shows photographs of four longitudinal tined surfaces. Figure 6-36 shows the one-third octave spectra for these same four longitudinal tined surfaces. Visual inspection of these pavements indicates that the larger scale texture in the I-210 pavement may have induced more friction-related noise in the frequencies above 1,250 Hz (Rymer et al. 2010). The lower sound levels in the low frequencies of the California SR 85 and Arizona SR 202 pavements are attributed to reduced positive texture (Donavan 2013a).

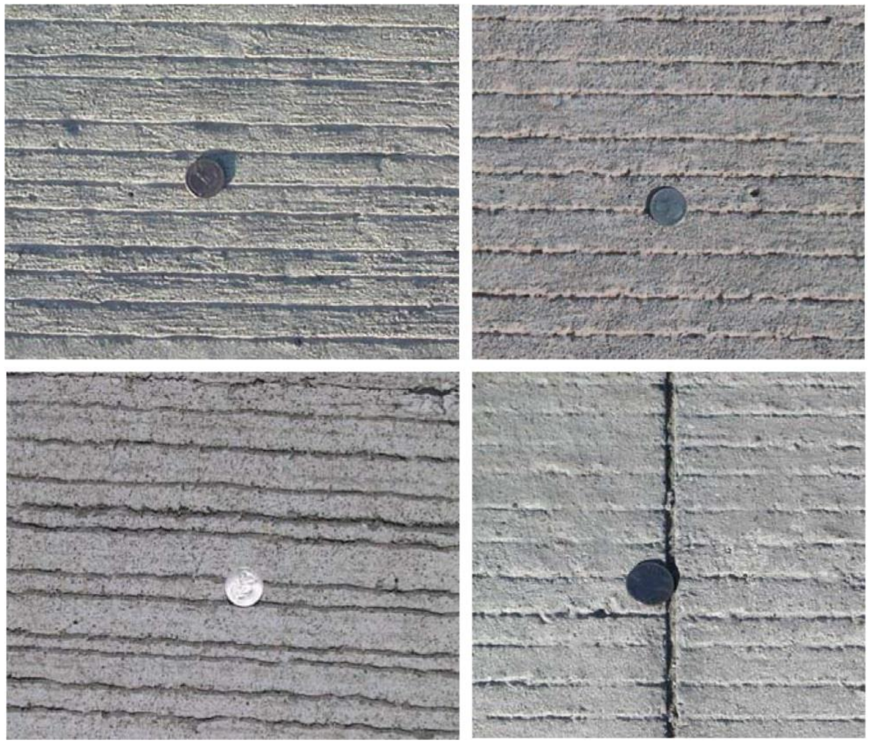

Figure 6-35: Photographs of four longitudinal tined rigid pavement surfaces
Upper left: Santa Clara SR85 LT PCC. OBSI = 101.7 dBA
Upper right: I-210 LT PCC. OBSI = 104.1 dBA
Lower left: Mohave Bypass LT PCC. OBSI = 103.5 dBA
Lower right: Arizona SR 202 LT PCC. OBSI = 102.0 dBA

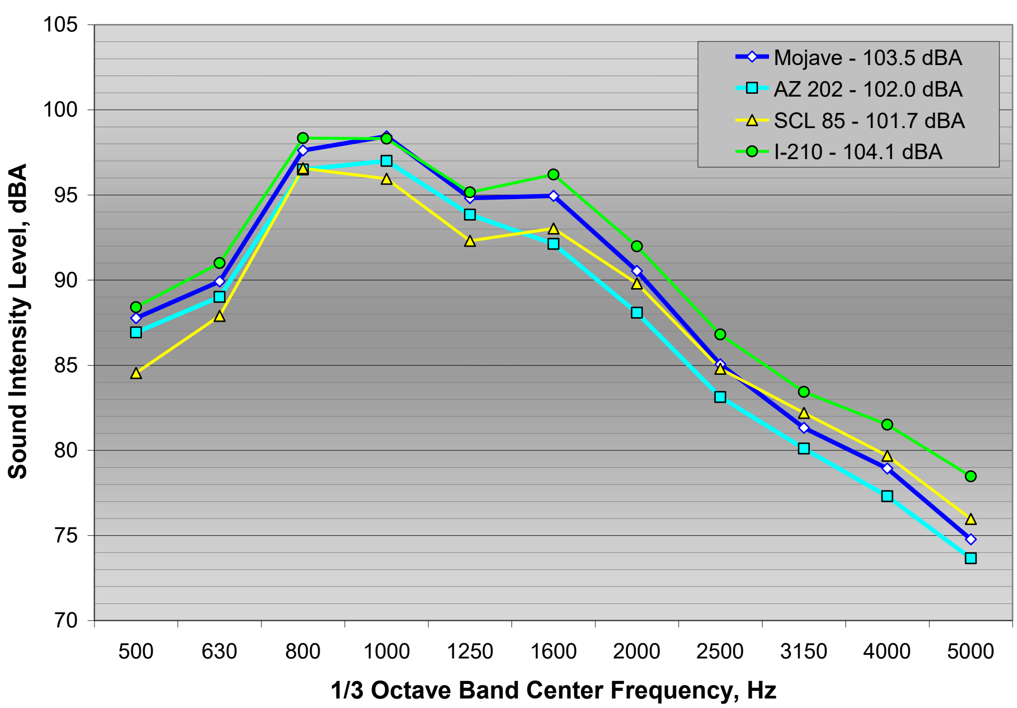

Figure 6-36: One-third octave band spectra for four longitudinal tined rigid pavement surfaces

6.3.2 Broomed and Drag Surface Textures

Figure 6-37 shows the average spectra for five broomed and drag surface textures, averaged over the individual pavements that fell into each category. The drag texture surface resulted in much higher levels below 1,600 Hz, which is attributable to the exposed aggregate of the surface (Lodico 2007b; Scofield 2007). The remaining pavement texture types resulted in similar spectral shapes, with the broomed surfaces generally resulting in higher levels and the carpet drag surfaces resulting in lower levels (Donavan 2008b).

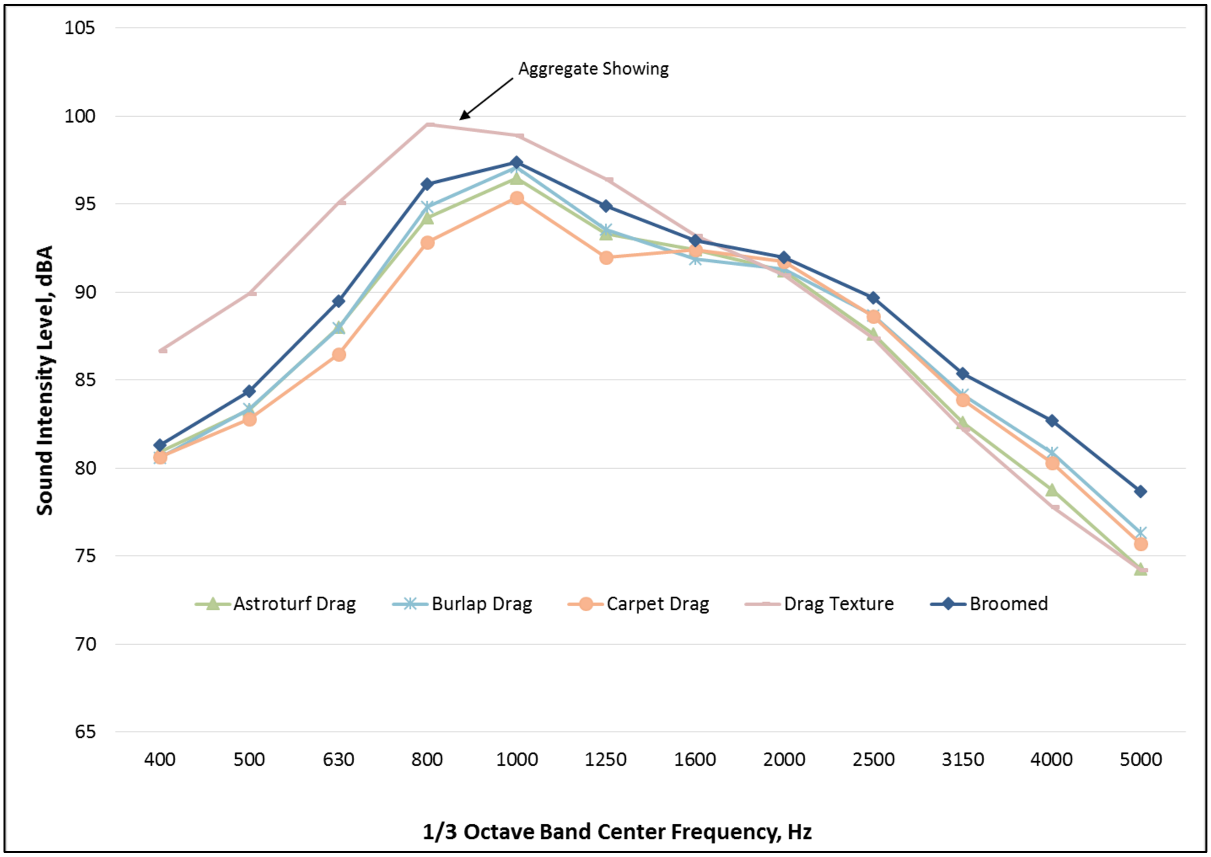

Figure 6-37: Average one-third octave band levels for broomed and drag surface categories

6.3.3 Transverse Tining

Transversely tined rigid pavement has had widespread use throughout California and was uniformly applied to rigid pavement sections on structure, as described in Section 6.3.5. Figures 6-32 and 6-33 include 87 transversely tined and transversely grooved pavements (out of 210 rigid pavements measured in total), including both random and uniform textures. Transverse pavement textures tend to be the loudest of the rigid pavement surfaces, with average OBSI levels of about 105 dBA. OBSI levels using the SRTT at 60 mph (97 km/h) ranged from 102 dBA up to 109 dBA for a transversely tined pavement on I-90 in Montana, near the Idaho border (Illingworth & Rodkin 2010b). A transversely grooved pavement measured at the GM Yuma Proving Grounds in 2010 also resulted in an OBSI level of about 109 dBA (Donavan 2010d).

Pavements with even higher tire-pavement noise levels have been measured on bridge decks, as indicated in Figure 6-42 in Section 6.3.5, which includes an aged transversely tined pavement on Shasta County I-5 Bridge Deck that was measured to produce an OBSI level of 112.4 dBA with the Aquatred tire (Donavan 2003a).

6.3.4 Rigid Pavement Rehabilitation Strategies

Rehabilitation strategies are dependent on many factors. Generally, two options are available for reducing tire-pavement noise on existing rigid pavements. Caltrans has applied each of these in real-life projects. One recommendation is to grind the existing surface. The grinding procedures producing the quietest surfaces include the Mojave Bypass ("texture grind" with a 0.105-inch blade spacing) (Donavan 2003c), the Kansas US Highway 69 texture grind with a 0.120-inch groove spacing using a single saw joint (Donavan 2008b), or one of the "whisper" grinds used in Arizona (Scofield 2003). For the whisper grinds in Arizona, the blade spacing was 0.120 inches or less (Figure 6-38).

Figure 6-38: Examples of Quieter Ground Rigid Surface Textures
Upper left: Mohave Bypass Texture Grind, 0.105 inch spacing
Upper right: Arizona "Whisper Grind
Lower left: Next Generation Concrete Surface (NGCF)
Lower right: Sacramento 50 Groove and Grind

The second recommended method of reducing tire-pavement noise is to overlay the existing rigid pavement with OGAC or RAC(O). This method would not be preferred in areas where heavy axel loads occur, as rigid pavement is designed for heavy axel loading and durability. Some examples of Caltrans applications include I-280 in San Mateo County (Donavan 2005b), and I-5 in Sacramento County (Illingworth & Rodkin 2008). In both cases, favorable public reaction was received. The magnitude of the noise level reduction is dependent on both the noise level of the initial pavement and the noise level of the overlay. Tire-pavement noise reductions for I-280 ranged from about 3.5 to 6.5 dB. In addition to the reduction in overall A-weighted level, the use of the overlay tends to be quite noticeable in the community because of the reduction of mid to high frequency noise. In both the I-5 and I-280 cases, shown in Figure 6-39 against the longitudinal tined rigid pavement measured along I-210, significant reductions were measured at 800 Hz and above. Relative to each other, the I-5 pavement produced more improvement in the higher frequencies, above 1600 Hz, while the I-280 pavement achieved better mid frequency reduction from 800 to 1250 Hz. If a RAC(O) overlay is considered, due to a lowering of overall level and change in the frequency content of the noise, the reduction would be both measurable and perceptible even for a less-than-ideal overlay.

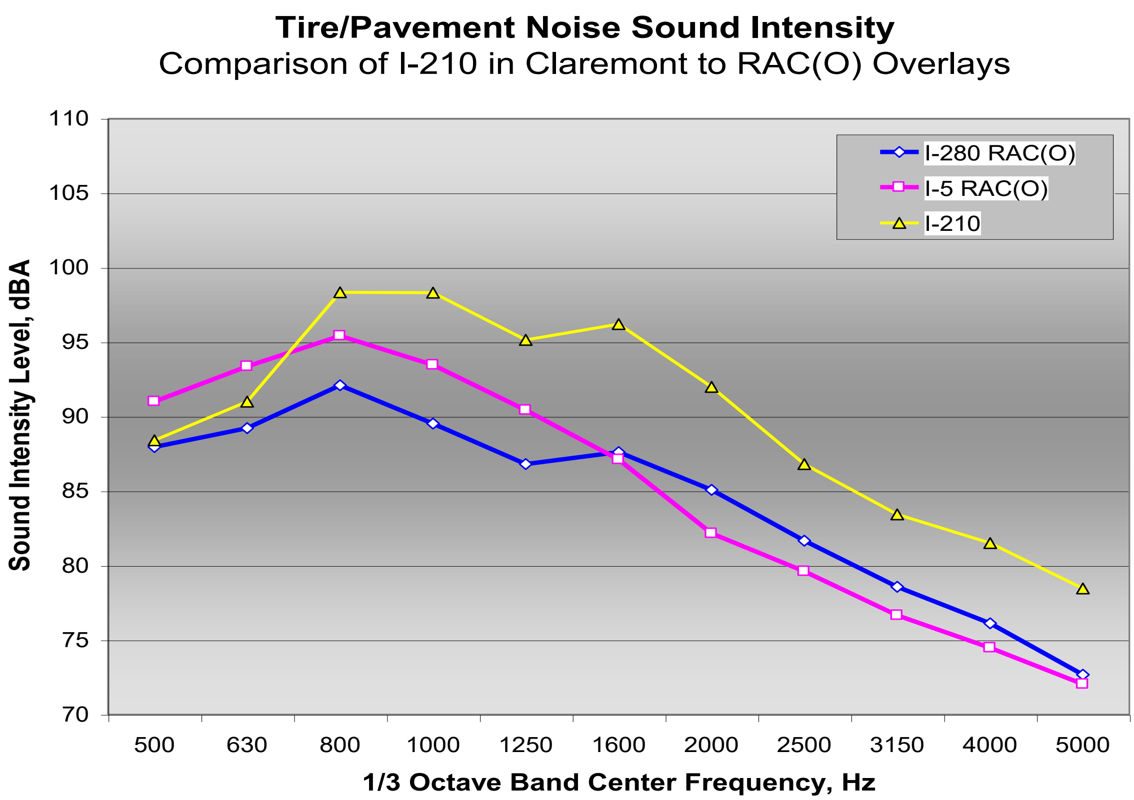

Figure 6-39: One-third octave spectra for RAC(O) overlay

In Arizona, the overlay of existing rigid pavement surfaces with a 1-inch thick ARFC overlay over about 115 miles of freeway in the Phoenix metropolitan area resulted in an initial average noise reduction of about 8 dB, depending on the pre-construction surface. The noise reduction varied because the pre-construction pavement varied over the 115-mile project site, and noise reduction is directly related to the existing pavement noise level. After 10 years, the ARFC pavement continued to result in levels that were about 3 dB lower than those from the initial rigid pavement surfaces (see further discussion in Section 6.4). Figure 6-40 shows the CTIM ⅓ octave band data for the baseline and ARFC overlay pavement, measured over the 10.5-year period at one of the wayside site locations, Site 3D.

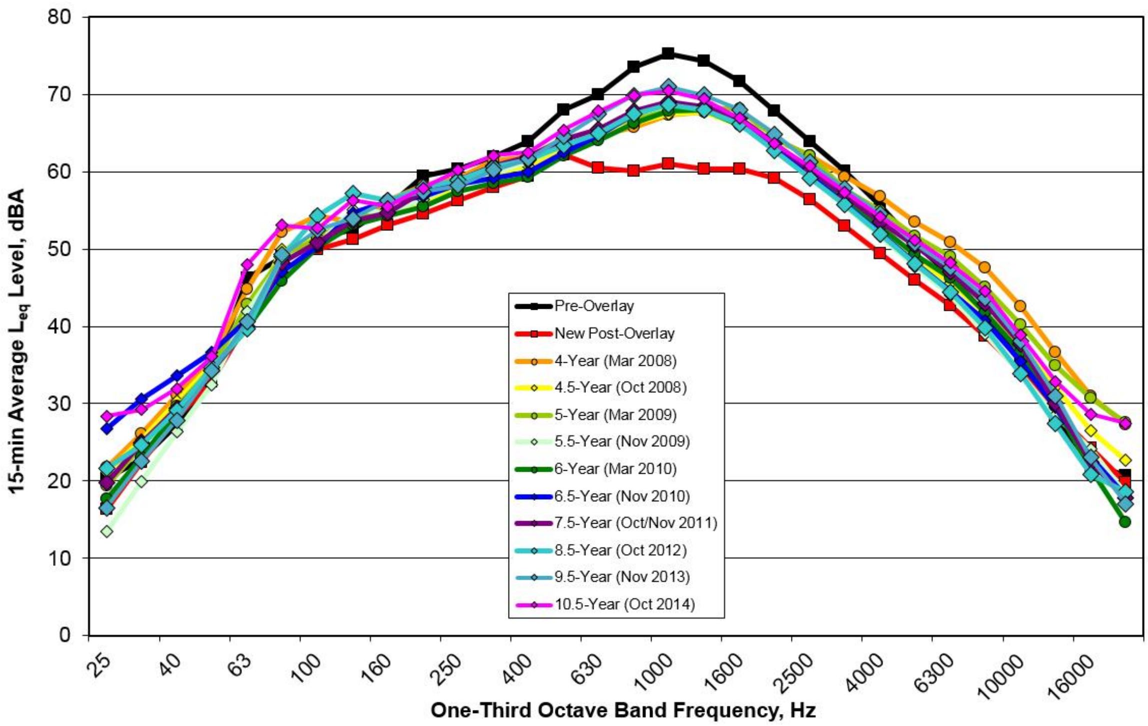

Figure 6-40: One-third octave band spectra for CTIM noise levels at Site 3D with microphone at 50 feet from the roadway and 5 feet above the ground

6.3.5 Quieter Bridge Decks

Caltrans traditionally uses rigid pavement on all bridge decks and structures, causing transitions between asphalt and concrete as the roadway switches between at grade and on structure components. This can increase the noise generated by traffic driving over the bridge since the noisiness of any given structure is perceived to be worse when adjacent to quieter pavement roadways.

Traditionally, transversely tined texture was aggressively applied to rigid pavement sections on structure. In response to public complaints about noise, some bridge decks have now been ground or resurfaced with polyester overlays. In 2006, as part of its QPR plan (California Department of Transportation 2006), Caltrans proposed the study of noise generated by four existing bridge deck surface types (polyester overlay, diamond grinding, transversely tined, and longitudinally tined) for high and low truck traffic highways. Measurements were made along several bridge decks from 2003 to 2011 at Carquinez Bridge/Crocket Viaduct (Donavan and Rymer 2004b), Ruckman Bridge in San Francisco (Janello and Donavan. 2011b), San Francisco-Oakland Bay Bridge (Donavan and Janello 2011a), Shasta County I-5 Bridge Deck (Donavan 2003a), and Thomes Creek Bridge deck on I-5 near Corning (Janello and Donavan 2011c). A summary of the results of these measurements is given in Figure 6-41, along with a photograph of each pavement. The overall A-weighted OBSI levels are given in Figure 6-42 for comparison purposes.

Figure 6-41a: Photographs and Summary of Pavements Measured on Bridge Structures in California

Upper left: Thomes Creek Bridge Deck, May 2011 Aged Transverse Tine. OBSI = 109.2 dBA @ 60 mph (97 km/h), SRTT
Upper right: Thomes Creek Bridge Deck, May 2011 Aged Transverse Tine. OBSI = 106.7 dBA @ 60 mph (97 km/h), SRTT
Lower left: Thomes Creek Bridge Deck, June 2011 Shot-Blasted Aged Transverse Tine. OBSI = 107.0 dBA @ 60 mph (97 km/h), SRTT
Lower right: Thomes Creek Bridge Deck, June 2011 Aged Transverse Tine with Methacrylate Seal Surface Treatment. OBSI = 102.9 dBA @ 60 mph (97 km/h), SRTT

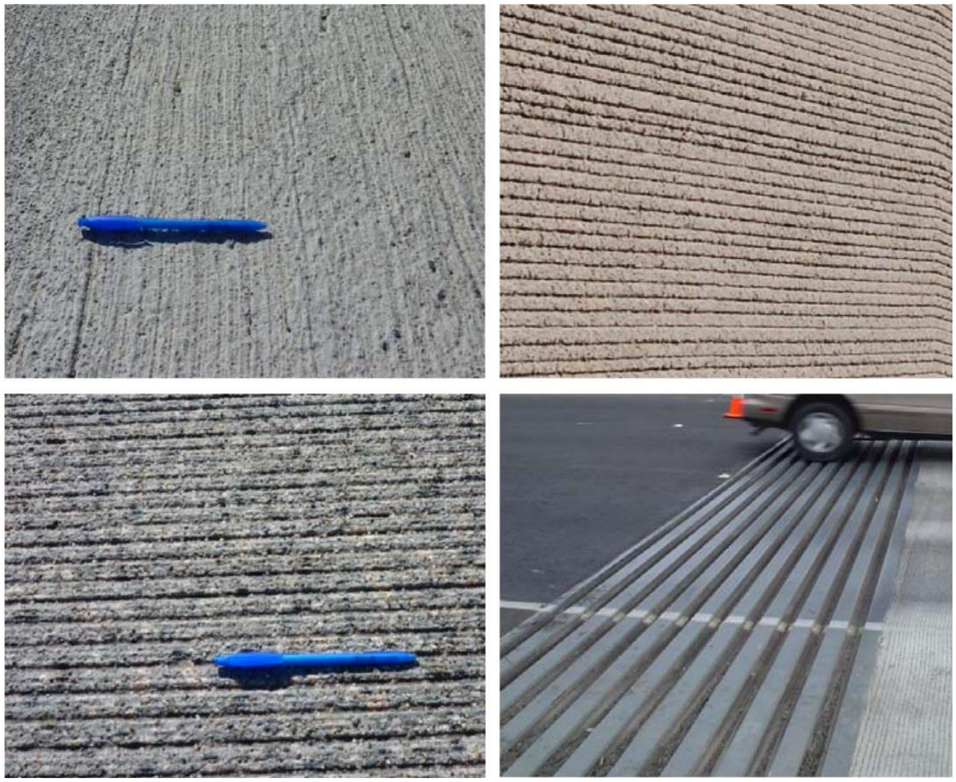

Figure 6-41b: Photographs and summary of pavements measured on bridge structures in California

Upper left: Bay Bridge Touchdown, October 2010 New Transverse Tine. OBSI = 107.3 dBA @ 60 mph (97 km/h), SRTT. OBSI = 103.2 dBA @ 45 mph (72 km/h), SRTT
Upper right: Bay Bridge Skyway, October 2010 New Longitudinal Tine with Polyester Overlay. OBSI = 104.2 dBA @ 60 mph (97 km/h), SRTT
Lower left: Bay Bridge Touchdown, October 2010 Ground Longitudinal Tine. OBSI = 102.8 dBA @ 60 mph (97 km/h), SRTT. OBSI = 98.5 dBA @ 45 mph (72 km/h), SRTT
Lower right: Carquinez Bridge Expansion Joint (Similar to Bay Bridge) Increased OBSI by 2.1-2.6 dB @ 60 mph (97 km/h). Increased frequencies < 1,000 Hz by 4 to 5 dB

Figure 6-41c: Photographs and summary of pavements measured on bridge structures in California

Upper left: Shasta 5 Bridge Deck, May 2004 Newly Ground Aged Transverse Tine. OBSI = 102.3 dBA @ 60 mph (97 km/h), Aquatred
Upper right: Ruckman Bridge Deck, October 2010 Longitudinal Tine with Dry Deck Texture (Temporary during Construction). OBSI = 99.6 dBA @ 45 mph (72 k/h), SRTT
Lower left: Carquinez Bridge Viaduct, March 2004 New Transverse Tine, Pre-Grind. OBSI = 107.5 dBA @ 60 mph (97 km/h), Aquatred
Lower right: Carquinez Bridge Viaduct, October 2005 New Ground Transverse Tine. OBSI = 104.0 dBA @ 60 mph (97 km/h), Aquatred

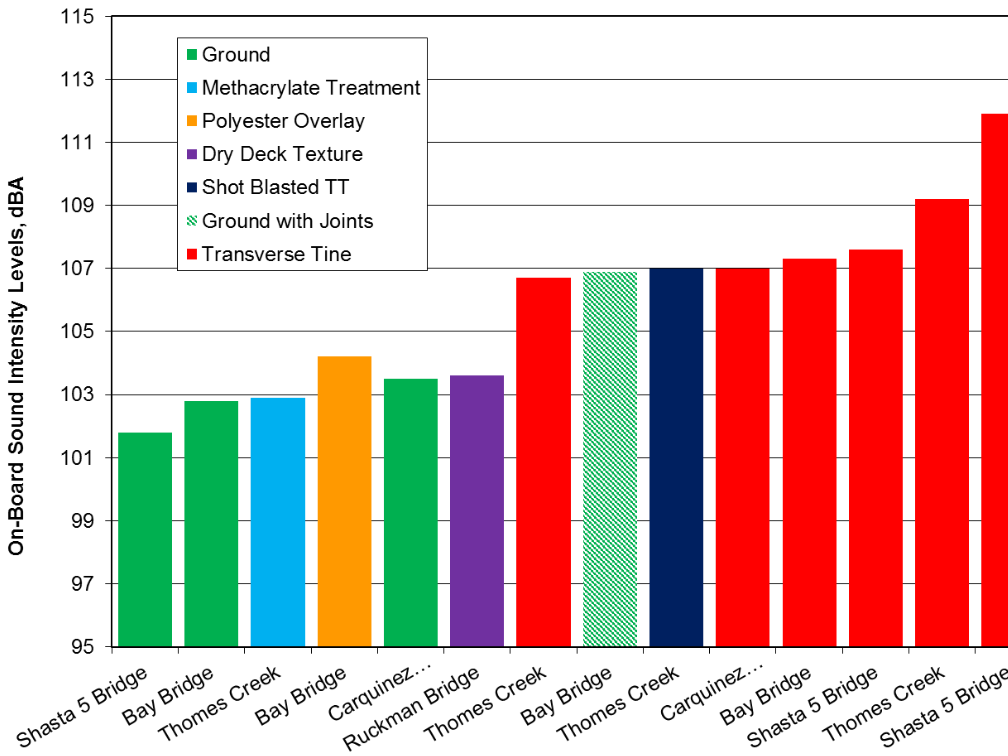

Figure 6-42: Overall A-weighted OBSI levels for rigid pavements on bridge structures, 60 mph (97 km/h) with SRTT

Noise levels for 45 mph (72 km/h) data were adjusted to 60 mph (97 km/h) data by adding 4 dBA (Donavan and Janello. 2011). Noise levels measured with the Aquatred test tire were adjusted to SRTT levels by subtracting 0.5 dBA (Donavan 2013a).

As indicated in Figure 6-42, grinding of a rigid pavement or use of a pavement treatment or overlay can reduce the tire-pavement noise levels generated along a bridge deck by 4 dB or more. Use of other quieter textures, as described under the general rigid pavements discussion, may result in further noise reductions. Expansion joints have also been found to be a primary noise generator. Expansion joints on the Bay Bridge were found to result in an increase in the average OBSI level over a section of pavement by 2 to 3 dB, with increases of 4 to 5 dB in the individual one-third octave bands below 1,000 Hz (Donavan and Janello 2011a). Expansion joints were found to increase the average OBSI level by 1 to 3 dB on the Carquinez Bridge and Crocket Viaduct (Donavan and Rymer 2004b). Additionally, with the grinding of the viaduct for the Carquinez Bridge and Crocket Viaduct, community response indicated that joint noise was more apparent as the overall traffic noise levels were reduced.

6.3.6 Pavement Joints

As described above, expansion joints such as those used for the Bay Bridge and Carquinez Bridge and Crocket Viaduct in California can result in an increase in the average OBSI level over a section of pavement by 1 to 3 dBA (Donavan and Janello. 2011; Donavan and Rymer 2004b). Pavement joints measured along the Mohave Bypass SR 58 (Donavan 2013a) were found to produce an audible "slap" sound perceived both inside the test vehicle as it was driven on the surfaces and outside the vehicle as it passed by (see photographs in Figures 6-42 and 6-

43). Impulsive noise associated with the passage of the tires over the joints between rigid pavement has been studied theoretically, in laboratory research, and in on-road studies.

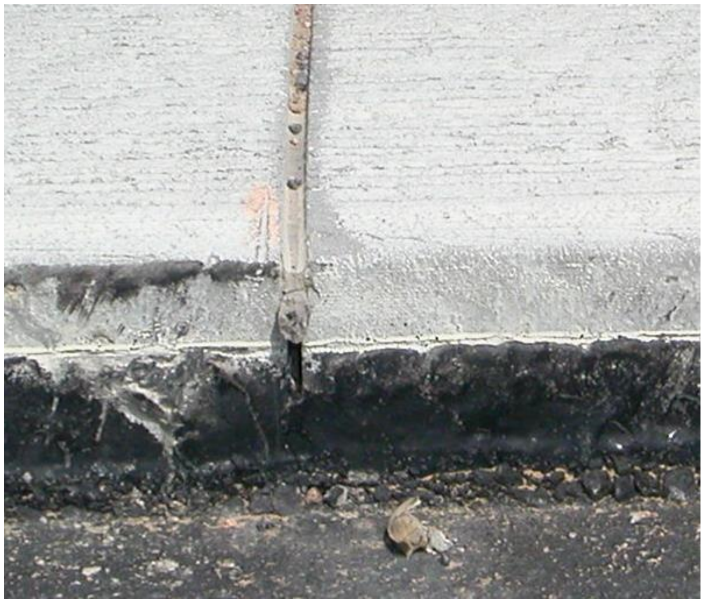

Figure 6-43: Cross-section of typical Mohave Bypass joint section

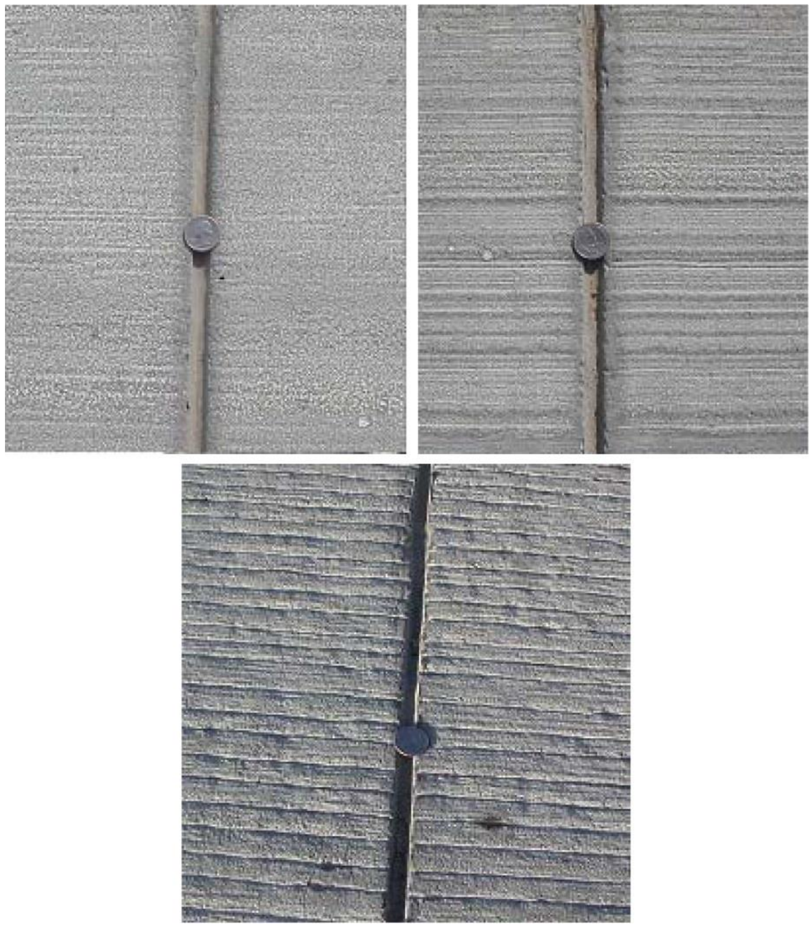

Figure 6-44: Typical pavement joints for Mohave Bypass sections
Upper left: Burlap drag
Upper right: Broomed
Lower: Longitudinally tined

Research Laboratories in the late 1970s and early 1980s considered sound generation and radiation from grooves in tires (Wilken 1976; Donavan 1981). This research found that as the tire rolls over the joint, air is squeezed out of the channel, forming an “organ pipe” that is open at two ends. The sound radiation is produced by the initial pumping of air out of the groove and is maintained by organ pipe resonances that persist until the tire lifts off of the joint. The corresponding mechanisms for grooves in tires operating on uniform pavement have been documented for both longitudinal (circumferential) grooves and lateral grooves in tires. The driving force for the source strength of the both the tire and pavement groove is the change in volume as the air is expelled from the groove.

Examples of the impulses are shown in Figure 6-45 for two different rigid highway surfaces in California, an older longitudinally textured pavement (I-80) and new longitudinally broomed textured pavement (Mojave SR 58) (Donavan 2003d). As shown, the impulses that begin at about 0.004 seconds are clearly higher than the residual sound pressure occurring after 0.010 seconds due the pavement texture only. The impulse persists for about 0.005 seconds and the time history displays “ringing” or oscillatory resonate behavior that decays away with time. This behavior can be seen in Figure 6-46, which expands the impulses shown in Figure 6-45, that the ringing occurs with about the same repetition rate (0.001 seconds) for both cases at least through the first three oscillations. Also, in both cases, the initial pressure rise is slightly less in absolute amplitude than the second peak as well as the negative peak in the impulse. Another indication of a resonance phenomenon is the observation that the period of oscillation is not effected by vehicle speed as shown in Figure 6-47.

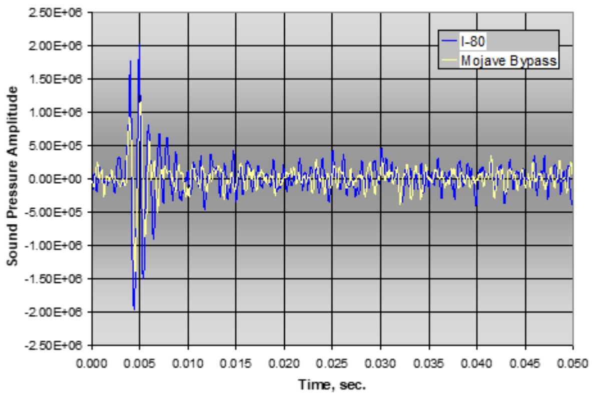

Figure 6-45: Joint slap for 2 different California rigid pavements – sound pressure vs time

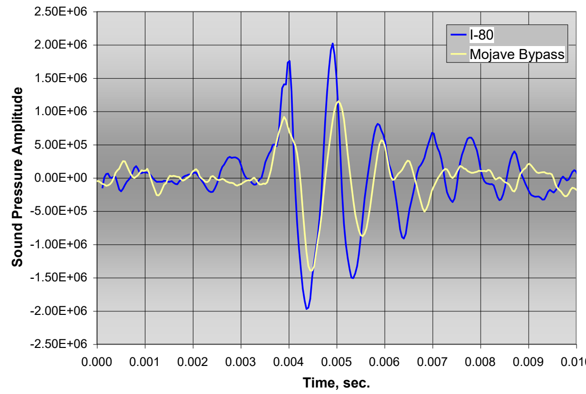

Figure 6-46: Joint slap for 2 different California rigid pavements with expanded time scale

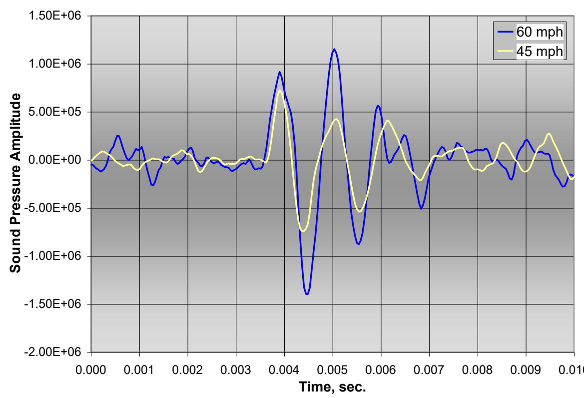

Figure 6-47: Joint slap for Mojave Bypass pavement at 60 and 45 mph (97 and 72 km/h)

Research at Purdue University, sponsored by the ACPA (Dare et al. 2008), measured the effect of different joint parameters in carefully controlled laboratory conditions. The effects of joint width and joint depth were evaluated along with the effect of pavement slab offset. A typical time trace for passage over a joint is provided in Figure 6-48 for a case where no slab offset is present and the groove is 0.375-inch wide and 1-inch deep for a test speed of 30 mph (48 km/h). Oscillatory behavior occurs with a repetition rate of approximately 0.001 second. The signal decays with time, with the initial positive pressure rise is being slightly less than the negative peak or second positive peak. The higher levels associated with the event last about twice as long as they do for 60 mph (97 km/h) cases in Figures 6-44 and 6-45, about 0.01 second at 30 mph versus 0.005 second at 60 mph. Given a tire footprint length of about 5.3 inches (135 millimeters), these times correspond approximately to the time duration that the tire is actually covering the joint.

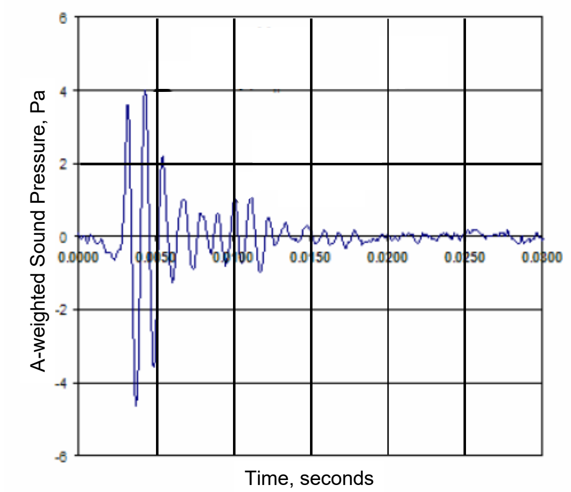

Figure 6-48: Joint slap recorded on the Purdue TPTA at 30 mph (48 km/h)

A conceptual model of the sound generation and radiation due to the passage of tire over a rigid pavement joint groove was adopted from the analysis of analogous grooves in tires through research by I&R sponsored by ACPA (Donavan 2008c). The developed model includes air pumping from the groove as the initial excitation with continuing radiation at the groove organ pipe frequencies until such time as the organ pipe is opened as the tire lifts off of the pavement. This model accounts for the behaviors noted both in the research conducted at Purdue, as well as those noted in data from actual highways. These behaviors include an increase in amplitude as a function of vehicle speed, oscillation in the sound pressure time history while the tire encloses the groove, an insensitivity of prominent frequency content to groove dimensions, and increasing level with either increasing groove width or groove depth.

The model indicated three methods of reducing the air pumping noise from pavement grooves: (1) narrowing the width of the groove to something on the order of 0.125 inch; (2) filling the groove such that the remaining open area is on the order of 0.10 inch; and (3) adding a substance to the groove that increases flow resistance.

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6.4 Acoustical Longevity/Durability and Long-term Studies

One of the main FHWA and Caltrans concerns over using quieter pavement surfaces is the changes in noise mitigation properties over time. Four major long-term studies have been conducted to address this concern: the Caltrans I-80 Davis pavement noise study, the Caltrans asphalt research on State Route 138 in Los Angeles County (LA 138), the Caltrans rigid pavement research on SR 58 Mohave Bypass, and the ADOT QP3 study. In addition, repeat measurements have been made on several other pavement surfaces over time. Because of the large bulk of information that has come out of the four primary studies, they are described in detail below as they apply to the question of acoustical longevity and are referenced in the other sections of this document. The smaller studies are summarized in Table 6-3 in Section 6.4.6.

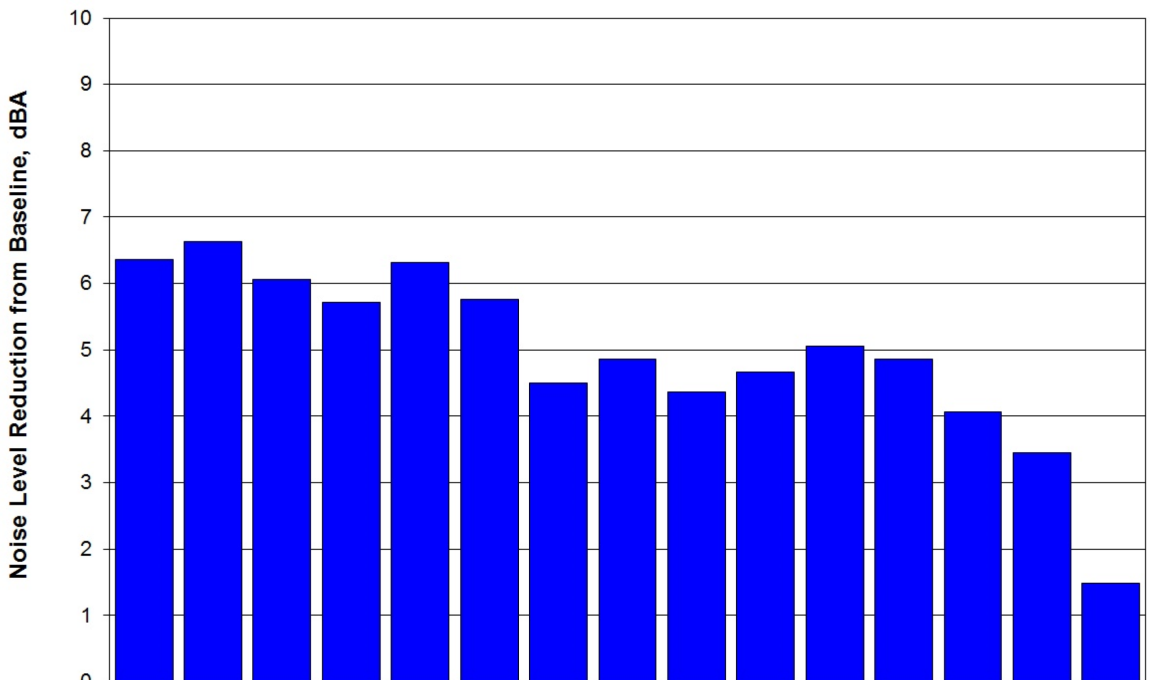
6.4.1 Caltrans QPR Research on I-80 Davis, California

During June and July of 1998, an OGAC pavement overlay was applied to a 5.6-mile (9-kilometer) stretch of DGAC along I-80 east of Davis, California. Beginning in 1998, noise conditions were monitored by I&R as part of an ongoing study conducted by the Caltrans to evaluate the long-term effects of highway pavement types on traffic noise. Caltrans reported a daily traffic volume of 146,000 vehicles for 2006 (California Department of Transportation 2008) along this segment of freeway, with a truck percentage of about 7.6%. The OGAC pavement at the I-80 Davis site has been measured to have an air void content of approximately 23%. With this level of void content, it would be classified as porous pavement. The maximum aggregate size has been measured to be ¾-in. A photograph of the OGAC pavement overlay is shown in Figure 6-49.

Figure 6-49: Photograph of I-80 Davis OGAC overlay

Noise evaluation of the OGAC pavement was made using both OBSI and CTIM measurements. CTIM locations ranged from 65 to 475 feet (20 to 145 meters) from the roadway and at heights ranging from 5 to 15 feet (1.5 to 4.5 meters). Measurements were conducted on 76 days over 16 years, resulting in a total of more than 300 hours of noise measurements and an extensive data set.

Based on the noise measurements, the OGAC pavement initially resulted in noise levels that were about 7 dB below those measured for the baseline DGAC pavement (see Figures 6-50 and 6-51). CTIM levels were found to increase at an average rate of about 0.2 dB/year over the first 10 years. The OBSI levels, which were measured starting in 2004, were found to increase at an average rate of about 0.3 and 0.4 dB/year for the westbound and eastbound directions, respectively. Between 10 and 16 years, pavement degradation became apparent, with the CTIM and OBSI levels increasing at a rate of about 0.6 dB/year. After 16 years, the OGAC overlay was about 1.5 dB quieter than the original DGAC pavement and about 5 dB louder than the new installation.



	New OGAC	1-Month	1-Year	2-Year	3-Year	4-Year	5-Year	6-Year	7-Year	8-Year	9-Year	10-Year	11-Year	12-Year	16-Year
■	6.4	6.6	6.1	5.7	6.3	5.8	4.5	4.9	4.4	4.7	5.1	4.9	4.1	3.5	1.5

Figure 6-50: Calculated noise reductions from the 1998 baseline DGAC noise levels at the westbound reference position

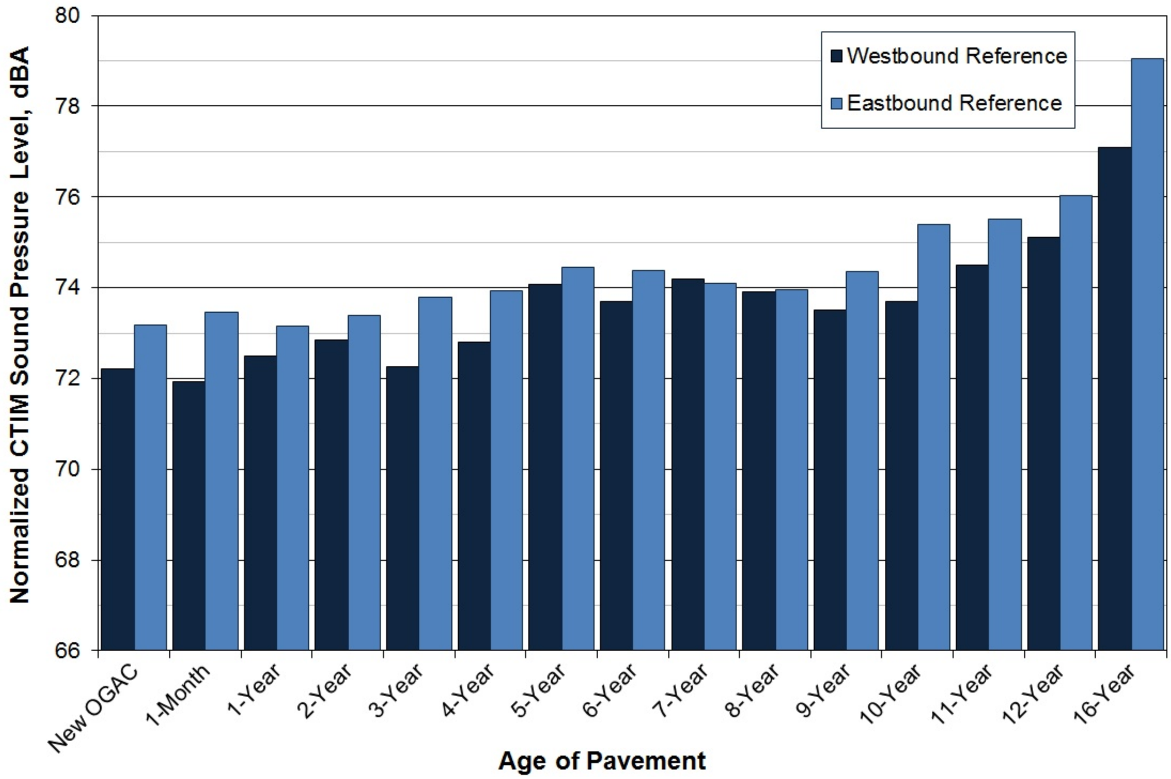


Figure 6-51: Normalized reference CTIM levels during summer monitoring periods

Figure 6-52 presents the one-third octave band spectra for the OGAC overlay for the CTIM location against the aged DGAC pavement, measured during the summer monitoring periods. Although the levels increased somewhat over time, the spectral characteristics for the pavement were maintained for both the CTIM and OBSI measurements through the first 10 years. After 10 years, an increase in the mid-range frequency bands between 800 and 2000 Hz occurred. Note that the CTIM data are not normalized for traffic or meteorological conditions, so increases in the overall levels of the spectra are at least partially attributable to these variables. In addition, lane-to-lane variations found during this study suggest that traffic volume and mix contribute to pavement acoustic longevity differences.

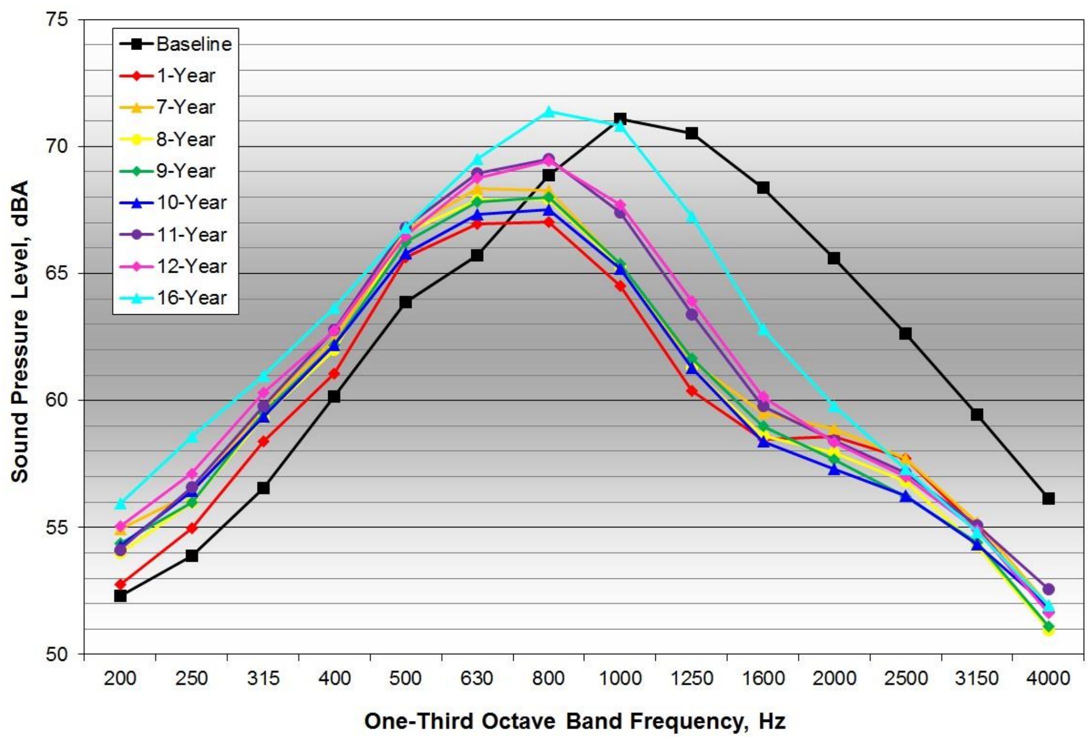


Figure 6-52: One-third octave band spectra for the I-80 Davis summer measurement periods, as well as October 2010, at the westbound reference microphone location

6.4.2 Caltrans QPR Asphalt Research on LA 138

In 2001, Caltrans began designing and planning for the construction of five flexible pavements along LA 138 (see Figure 6-53). Caltrans reported a daily traffic volume of 4,400 vehicles for 2007 along this segment of freeway, with about 14% trucks (California Department of Transportation 2008).

The LA 138 sections were some of the first applications of the OBSI methodology on in-service highways (Donavan and Rymer 2003). The purpose of these sections was to provide acoustic performance data on several quieter pavement constructions. Tested pavements included DGAC, two overlay sections of OGAC (75-millimeter in thickness and 30-millimeter in thickness), a RAC(O) pavement, and a bonded wearing course (BWC). The pre-overlay pavement, which was a DGAC leveling course, was measured in March 2002.

Figure 6-53: Photographs of LA 134 pavement surfaces in 2002
Upper left: Pre-Overlay – Dense Graded Asphalt (DGA)
Upper right: Section 1 – Dense Graded Asphalt (DGAC
Middle left: Section 2 – Open Graded Asphalt Concrete (OGAC-1), 75-mm Thick Overlay
Middle right: Section 3 – Open Graded Asphalt Concrete (OGAC-2), 30-mm Thick Overlay
Lower left: Section 4 – Rubberized Asphalt Concrete (RAC(O))
Lower right: *Section 5* – Bonded Wearing Course (BWC)

Noise measurements were made by I&R and the Volpe Center from 2002 to 2012. The initial test plan called for SPB measurements (International Order of Standardization 2000; Rochat 2001). With the development of the OBSI methodology, OBSI measurements were conducted beginning in October 2002. Noise measurements, durability, permeability, and friction performance were evaluated by Caltrans in partnership with the University of California Pavement Research Center at UC Davis and Berkeley from September 2005 to January 2006 (Ongel and Kohler 2006).

The overall A-weighted OBSI levels for the fall and spring measurements using the Aquatred test tire are shown in Figure 6-54. For all of the test sections except the DGAC reference, there was a clear upward trend in sound levels over time. For the quieter pavements (i.e., both OGAC pavements and RAC(O)), the increase was about 0.4 dB/year for the first 10 years. The increase was less than 0.1 dB/year for the DGAC reference pavement and was about 0.3 dB/year for the BWC pavement. The upward trend was not uniform and shows some scatter. The cause of this scatter is unknown and no consistent trend was identified for seasonal and temperature effects or any other parameter. Because of the smaller increase in level over time for the DGAC pavement, the difference between the DGAC reference pavement and the quieter pavements has declined over time from approximately 4 dB to slightly more than 2 dB for both the OGAC (75 millimeter) and RAC(O) pavements, and less than 2 dB for the OGAC (30 millimeter) pavement after 5 years (2007) (see Figure 6-54). The relative rank ordering of the pavements remained similar through 2010. However, in 2011, the BWC pavement increased in level above the DGAC.

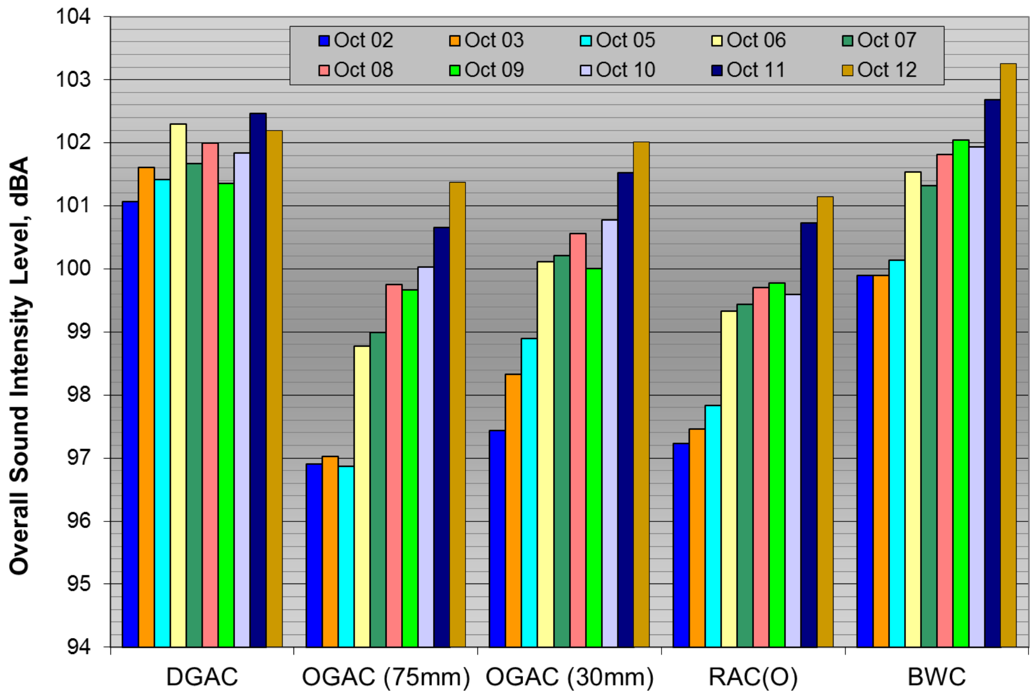


Figure 6-54: Overall A-weighted OBSI levels for each LA 138 test pavement from October 2002 through October 2012 measured with the Aquatred test tire

Longevity trends from 2006 to 2012 with the SRTT are shown in Figure 6-55. Generally, the results for the SRTT from 2006 to 2012 appear similar to those for the Aquatred; however, there are some differences. The SRTT shows higher levels in the 2010 data relative to prior years, but these differences even out after 2010. For the 75-millimeter OGAC, the levels for the SRTT increased almost 3.5 dB over the 6-year span, while for the Aquatred, it was slightly less than 3 dB. For the 30-millimeter OGAC and RAC(O) pavements, the increase from 2006 to 2012 for SRTT was similar to that for the Aquatred.

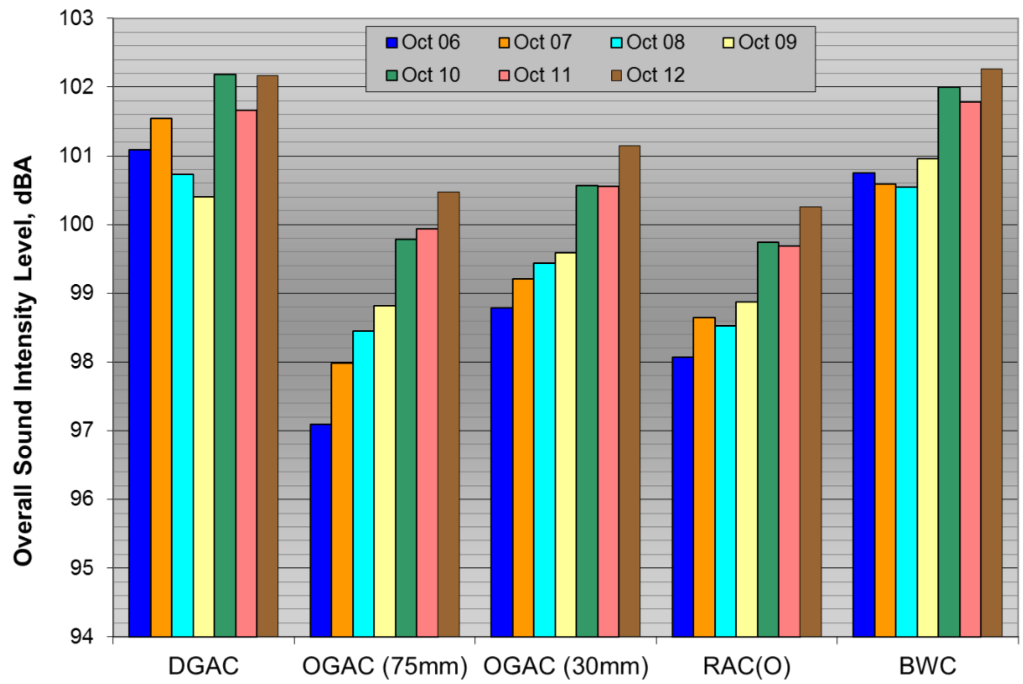


Figure 6-55: Overall A-weighted OBSI levels for each test pavement from October 2002 through October 2012 measured with tire SRTT #1

In terms of the one-third octave band spectra, the DGAC showed very little relative change over time (see Figure 6-56 for the Aquatred tire), with levels increasing uniformly with pavement age in the 2,000 to 3,150 Hz bands. This result is thought to be due to the polishing of the aggregate over time. The BWC spectra changed similarly over time (Figure 6-57 for the Aquatred tire), with both pavements sharing similar visual appearance and spectral characteristics by 2008 (Figures 6-58 and 6-59).

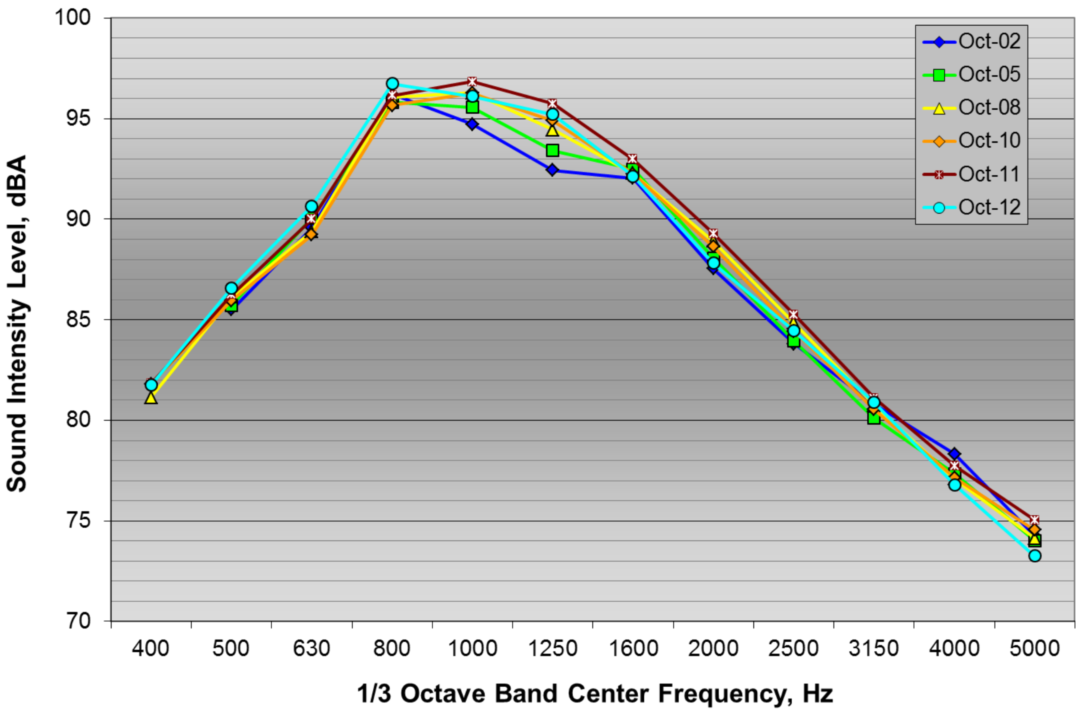


Figure 6-56: One-third octave band levels for DGAC Section 1 pavement from October 2002 through October 2012 for Goodyear Aquatred test tire

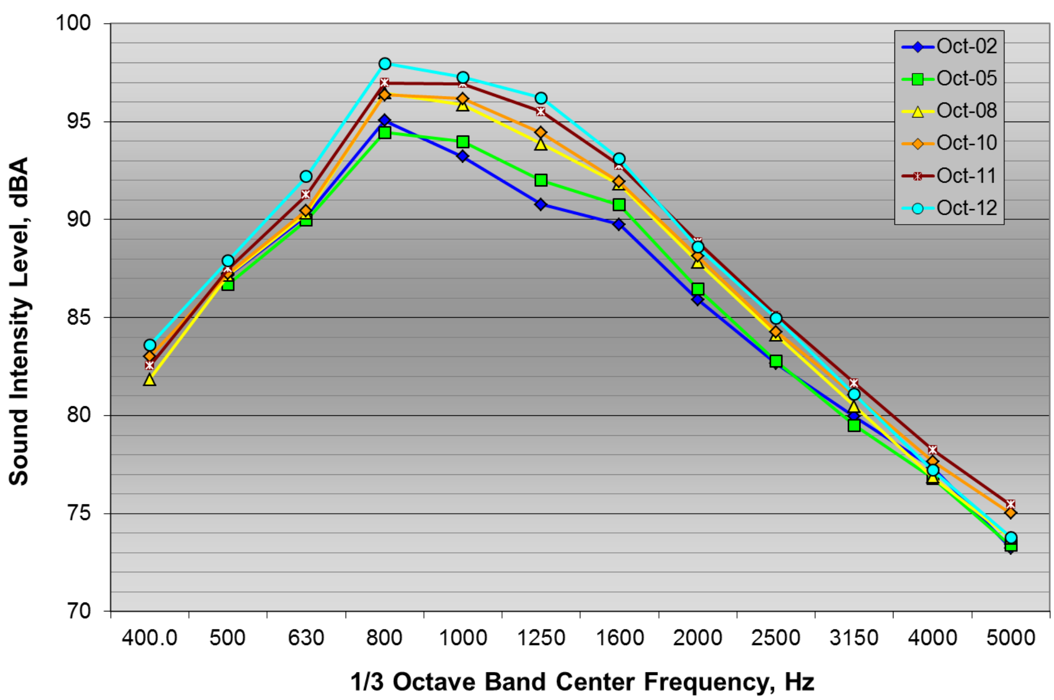


Figure 6-57: One-third octave band levels for BWC Section 5 pavement from October 2002 through October 2012 for Goodyear Aquatred test tire

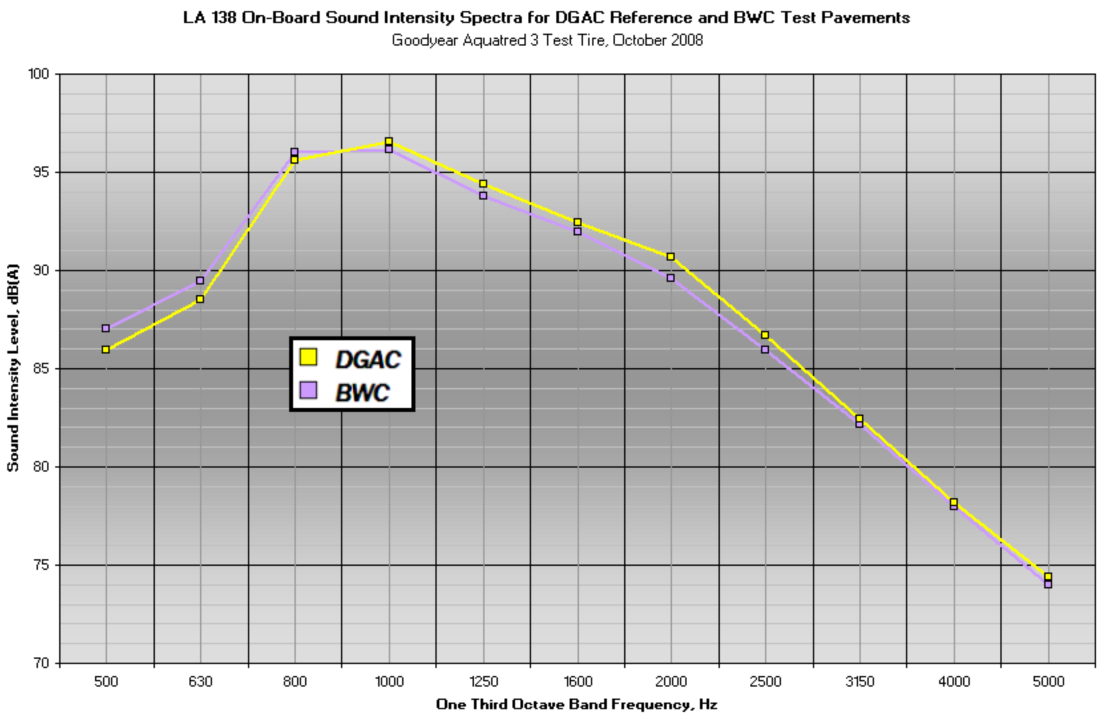


Figure 6-58: One-third octave band levels for DGAC and BWC test pavements, October 2008

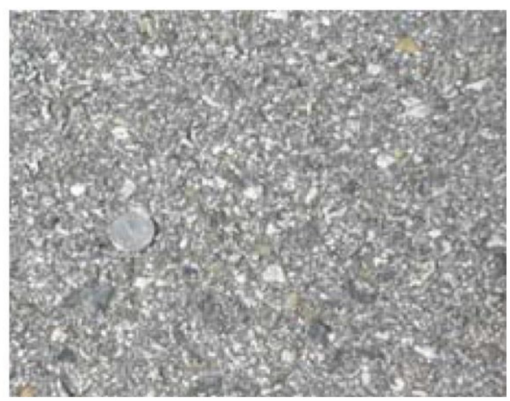
 

Figure 6-59: Photographs of DGAC pavement at Section 1 (left) and BWC Section 5 (right) in 2008

The spectra for the three open graded sections also show similar trends with aging, with the largest differences occurring in the one-third octave bands above 800 Hz (Figures 6-60 through 6-62). For 800 Hz and below, the differences were smaller (2 dB to 3 dB) and the upward trend with pavement age less apparent. Throughout the study period, the 30-millmeter OGAC had consistently been about 1 dB higher than the 75-millimeter OGAC and the RAC(O) pavements; comparing the spectral directly in Figure 6-63 indicates that the higher levels for the 30-millimeter OGAC results from a constant 1 dB upward offset in the spectra above 800 Hz. Photographs of these surfaces from October 2008 provide little understanding of the noise performance in these mid- to higher frequencies. Similar to the DGAC and BWC, these open graded pavements also show increased exposure and polishing of the aggregate relative the photographs from 2002.

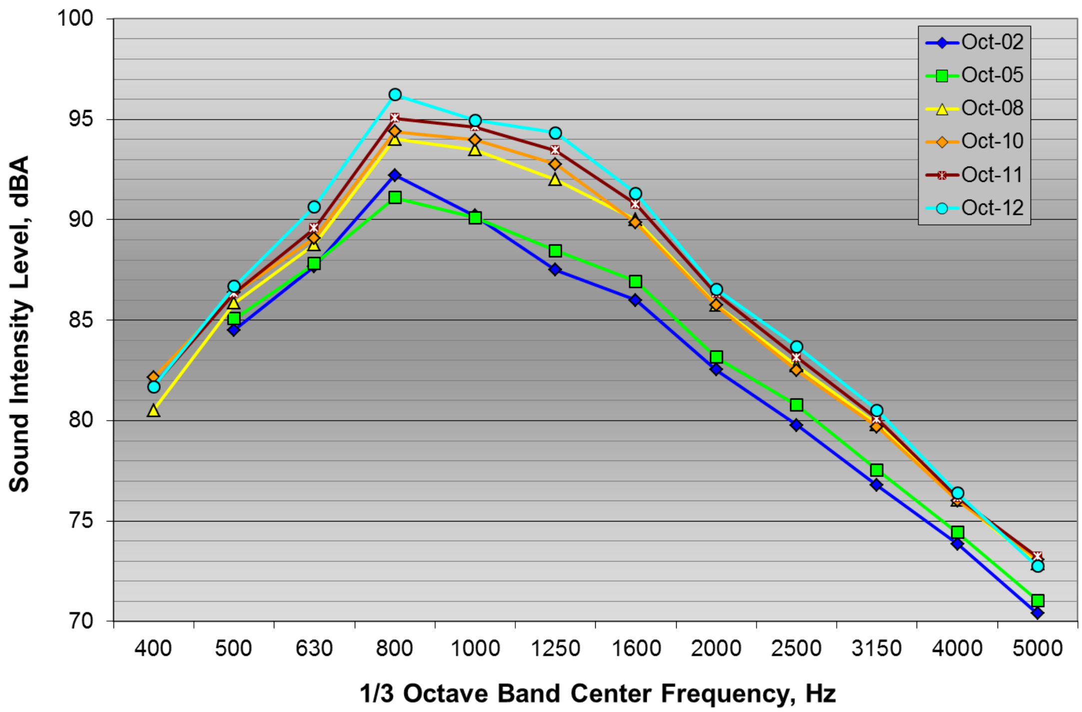


Figure 6-60: One-third octave band levels for 75mm OGAC Section 2 pavement from October 2002 through October 2012 for Goodyear Aquatred test tire

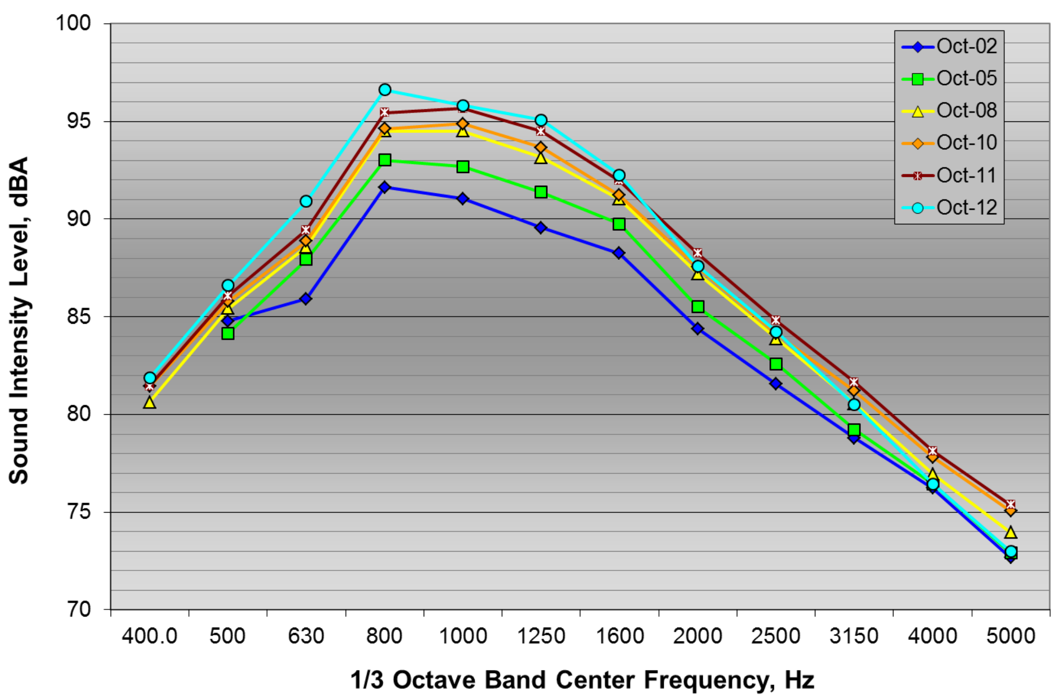


Figure 6-61: One-third octave band Levels for 30mm OGAC Section 3 pavement from October 2002 through October 2012 for Goodyear Aquatred test tire

Figure 6-62 shows the linearized rates of overall A-weighted OBSI level versus time since construction for the five pavements through 10 years (2002 to 2012). Of these, the DGAC resulted in the lowest rate of increase, 0.09 dB/year. This rate is consistent with rigid pavements, which typically were found to increase from 0.08 to 0.13 dB/year at the Mojave Bypass rigid pavement test sections (Donavan and Rymer. 2011). The increases for other flexible pavements fall into a range from 0.33 to 0.46 dB/year, which are typical of AC rates reported in the literature (Donavan 2010c). Of the quieter pavements, the RAC(O) pavement had the best acoustic longevity performance, with an increase of 0.36 dB/year, while the initially quietest pavement, the 75-millimeter-thick OGAC on Section 2, had the worst, with an increase of 0.45 dB/year.

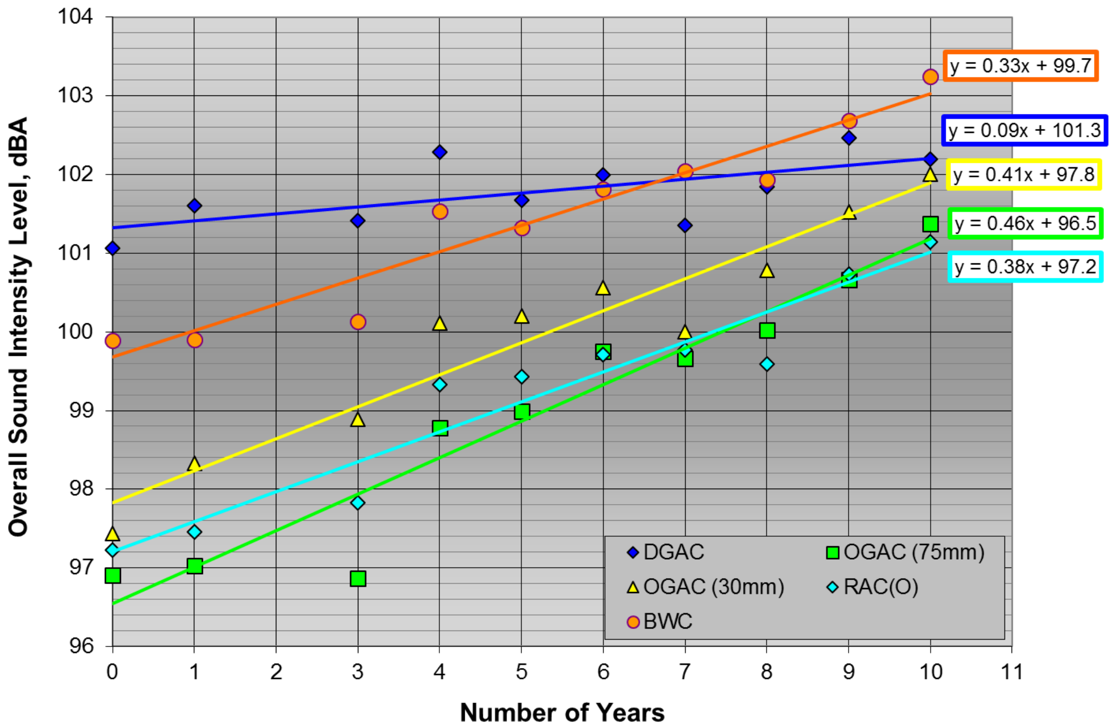


Figure 6-62: Overall A-weighted OBSI levels for each test pavement versus years since construction, October 2002 through October 2012

6.4.3 Caltrans QPR Rigid Pavement Research on State Route KN 58 Mojave Bypass (Donavan 2013a)

Caltrans initiated an investigation into concrete texturing methods in March 2003 with the intent of determining which would provide the lowest tire-pavement noise level. The research included three surface textures applied to a new rigid pavement road surface on a newly constructed portion of a four-lane, divided highway, SR 58, that bypasses the City of Mojave in Kern County. The surfaces consisted of typical California longitudinally tining, burlap drag, and longitudinally broom textures (Figure 6-63). Several months after the time of the initial measurements, eight sections of the original pavements were ground and/or grooved to various surface texture geometries. The original three textures were initially measured in March 2003 and again in June 2003 along with the eight new applied textures. Measurements continued through 2012. Initial noise measurement types consisted of controlled passby noise, OBSI, and interior noise in the test vehicle. Specific information on the eight surface textured sections is provided in Table 6-2 and photographs are in Figure 6-64.

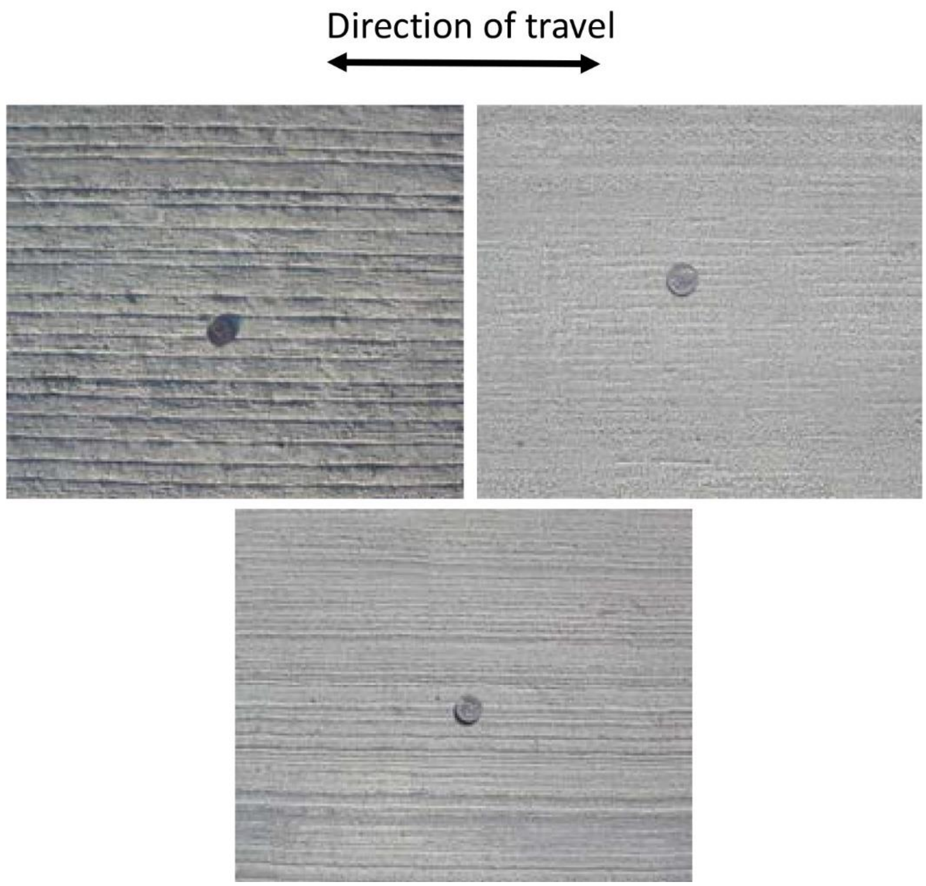


Figure 6-63: SR 58 Bypass rigid pavement baseline test section textures

Table 6-2: Mohave SR 58 Pavement Surface Treatments Applied to Baseline Rigid Pavement

Test Section	Description		Base Texture
	Type	Details	
1	Texture Grind	0.120" Blade Spacing*	Longitudinal Tined
2	Texture Grind	0.120" Blade Spacing	Burlap Drag
3	Grooved	3/4" apart, 1/8" deep	Burlap Drag
4	Grooved	3/4" apart, 1/4" deep	Burlap Drag
5	Texture Grind	0.105" Blade Spacing	Burlap Drag
6	Texture Grind & Grooved	0.120" blade spacing & grooves 3/4" apart, 3/8" deep	Broom
7	Grooved	3/8" apart, 1/4" deep	Broom
8	Texture Grind	0.120" Blade Spacing	Broom

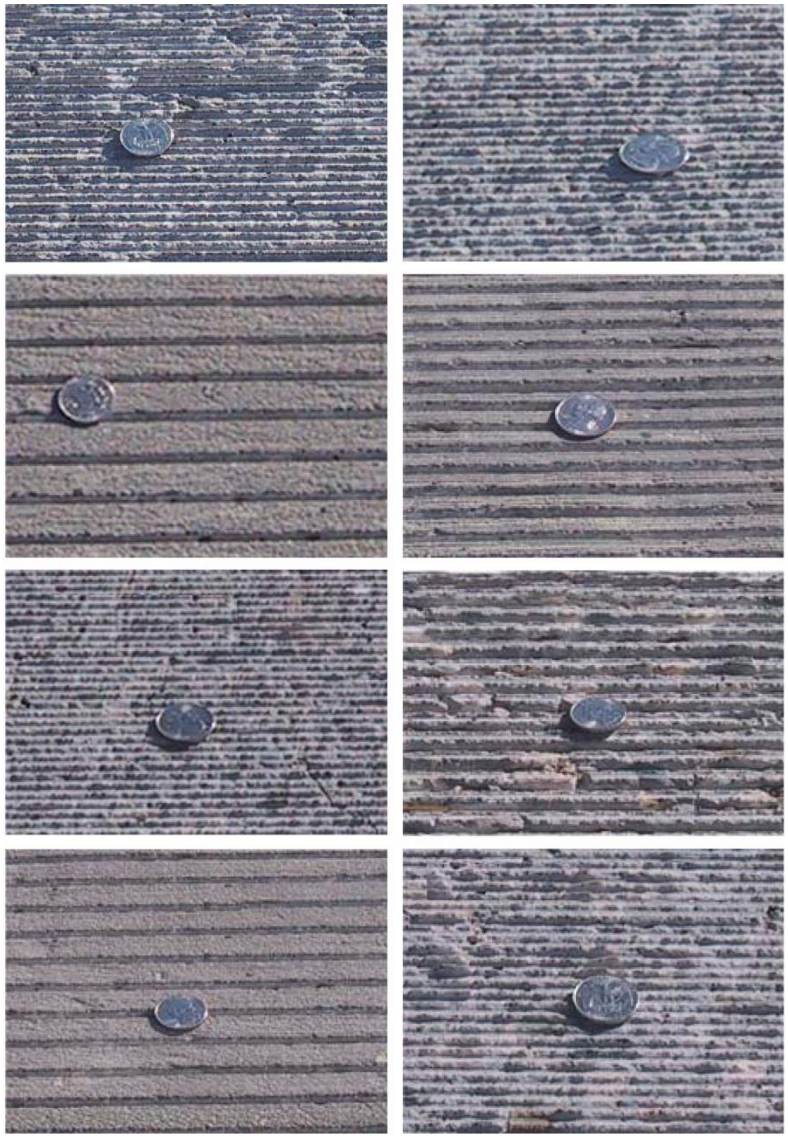


Figure 6-64: Photographs of modified Mohave SR 58 surfaces
Upper left: Ground
Upper right: Ground
Upper Middle left: Grooved
Upper Middle right: Groove
Lower middle: Ground
Lower middle: Groove and ground
Lower left: Groove
Lower right: Ground

The overall A-weighted OBSI levels measured on the Aquatred tire for the longitudinal tined, burlap drag, ground Sections 1 and 5, and grooved Sections 3 and 4 are shown in Figure 6-65 for the initial year of 2003 and the aged years of 2010, 2011, and 2012. The rates of increase in OBSI levels shown in Figure 6-66 range from 0.09 to 0.16 dB/year through 9.6 years. This is a notably lower increase rate from those of the quieter AC pavements described for the LA 138 and Davis I-80 sites in Sections 6.4.2 and 6.4.1. However, note that even with this lower increase rate, the rigid pavement levels remain 2 to 3 dB higher than the quieter flexible pavement surfaces after about 10 years.

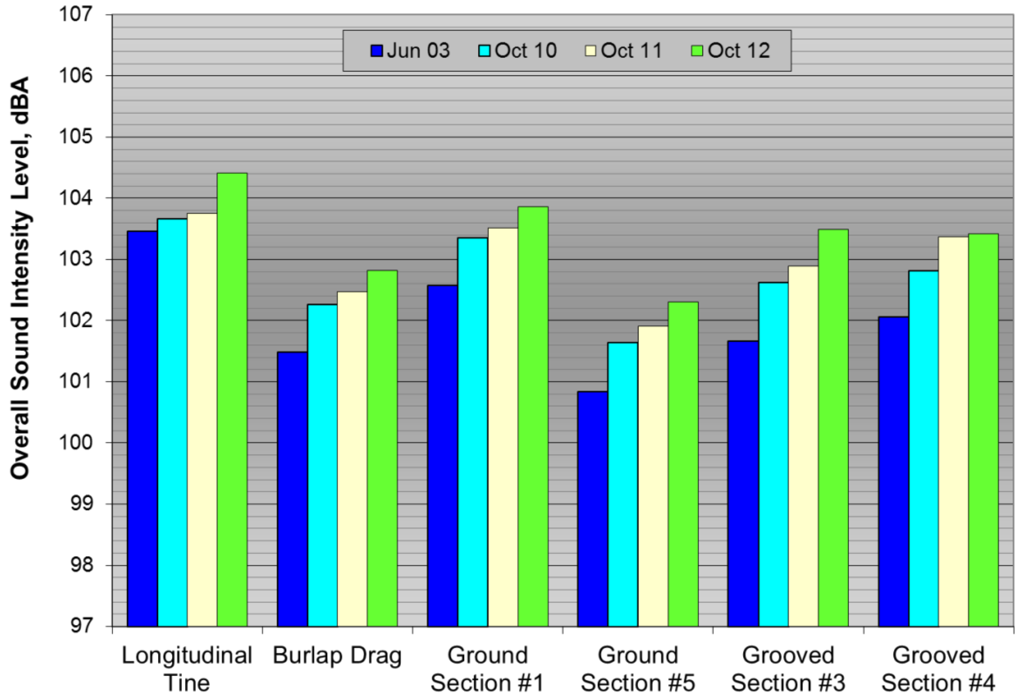


Figure 6-65: Overall A-weighted OBSI levels for each test pavement from initial testing in October 2003 and later testing in 2010, 2011, and 2012 for the Goodyear Aquatred test tire

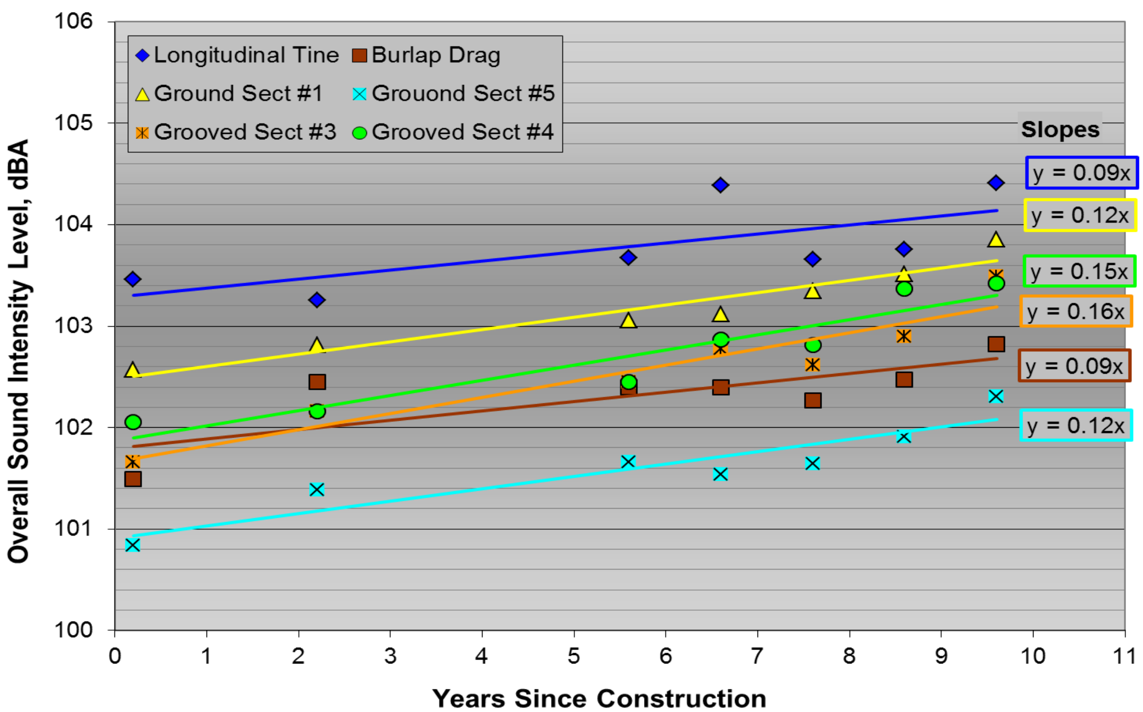


Figure 6-66: Overall A-weighted OBSI levels for each test pavement from 2003 to 2012, with rate of increase per year shown for the Goodyear Aquatred test tire

Typically, most of the increases in the one-third octave band levels occur at 800 and 1,000 Hz (see Figures 6-67 through 6-72). This common behavior may be related to the increased size and apparent depth of the fissures occurring in the surfaces. Air pumping of larger fissures may be contributing to the increased noise level in a manner similar to air pumping from the joints between slabs (Donavan 2010b). Another possibility is that fissures are beginning to create some additional surface roughness, providing more displacement (vibration) input to the test tire. The notion that fissures are creating additional surface roughness is also supported by the increases in level generally seen for the frequency bands below 800 Hz. In the higher frequencies (above 1250 Hz), there was little to no increase in level from 2009 to 2012. The more rapid changes attributed to polishing that occurred from 2003 to 2008 appear to have stabilized after 2008. If pavement polishing has occurred, it has had little additional effect on noise performance in later years. In addition, lane-to-lane variations found during this study suggest that traffic volume and mix contribute to pavement acoustic longevity differences.

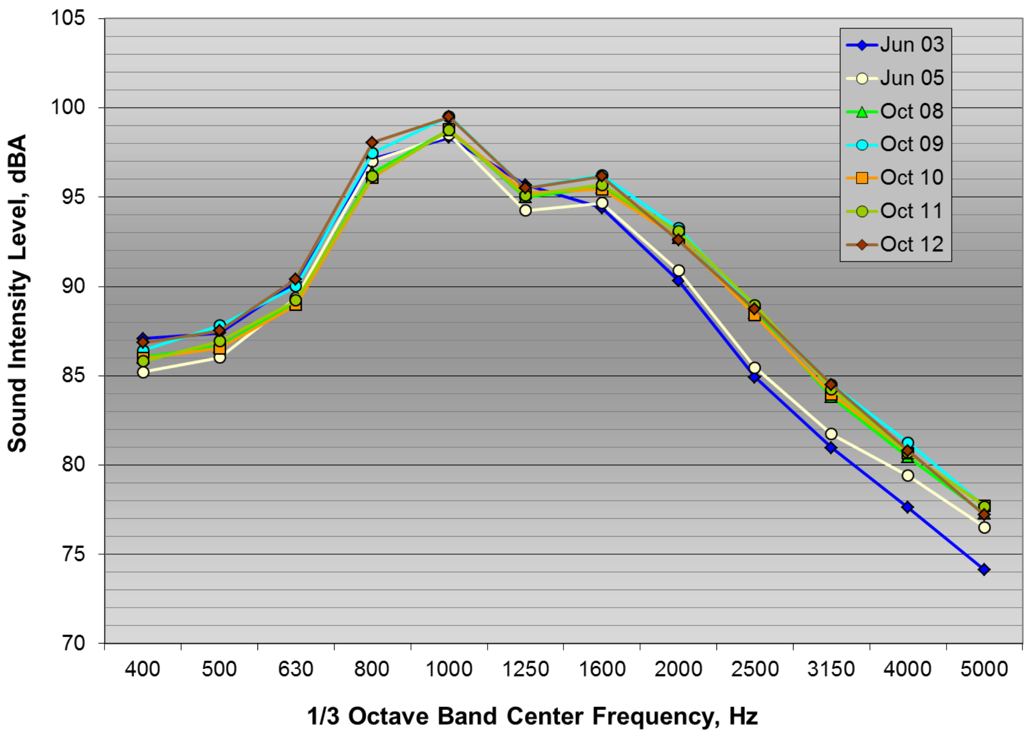


Figure 6-67: One-third octave band levels for the longitudinal tined pavement from June 2003 through October 2012 for Goodyear Aquatred test tire

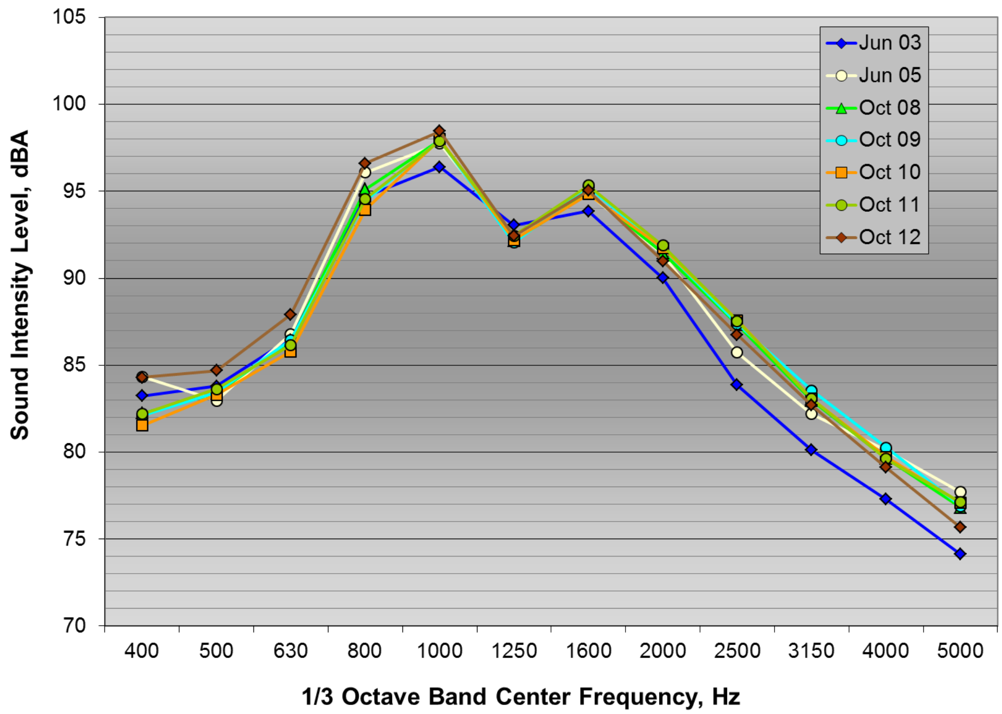


Figure 6-68: One-third octave band levels for the burlap drag pavement from June 2003 through October 2012 for Goodyear Aquatred test tire

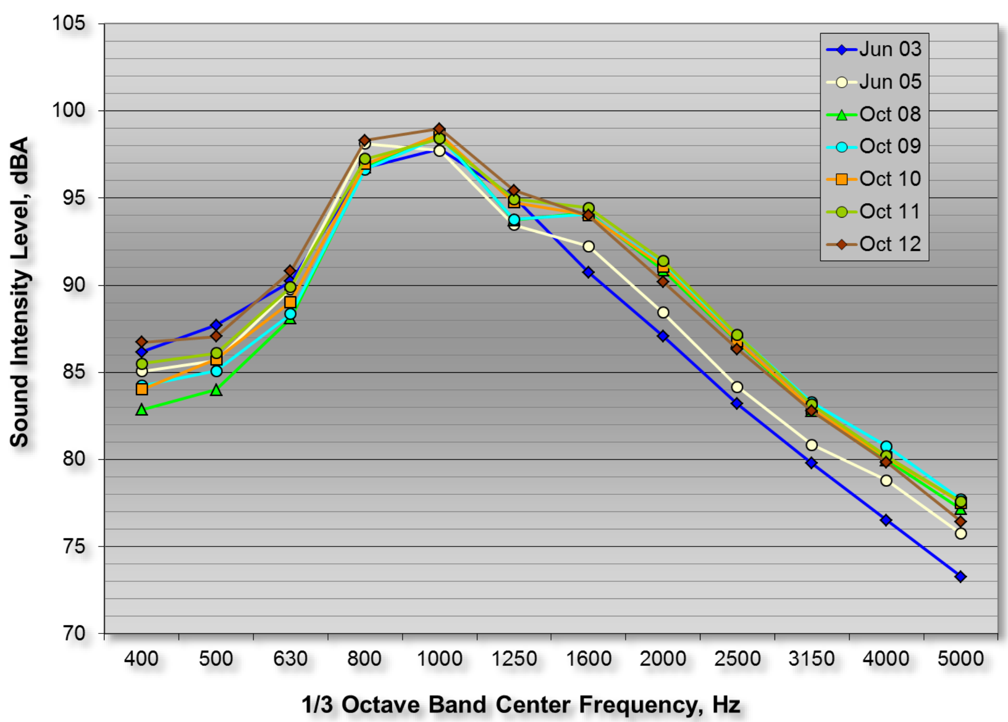


Figure 6-69: One-third octave band levels for ground Section 1 pavement from June 2003 through October 2012 for Goodyear Aquatred test tire

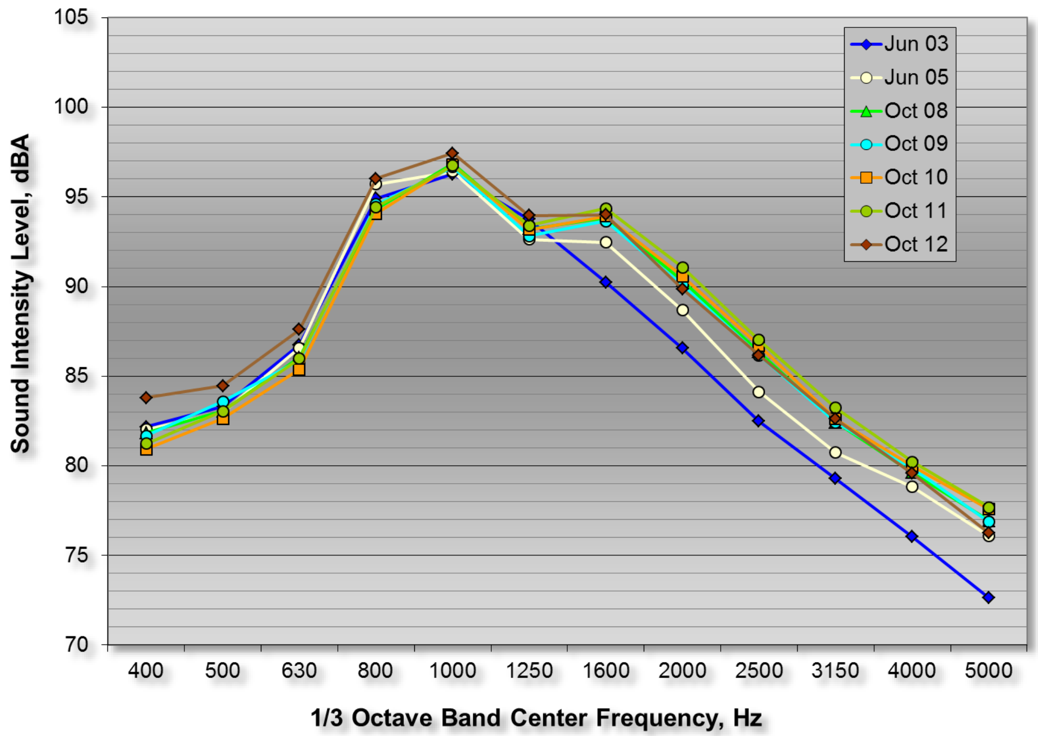


Figure 6-70: One-third octave band levels for ground Section 5 pavement from June 2003 through October 2012 for Goodyear Aquatred test tire

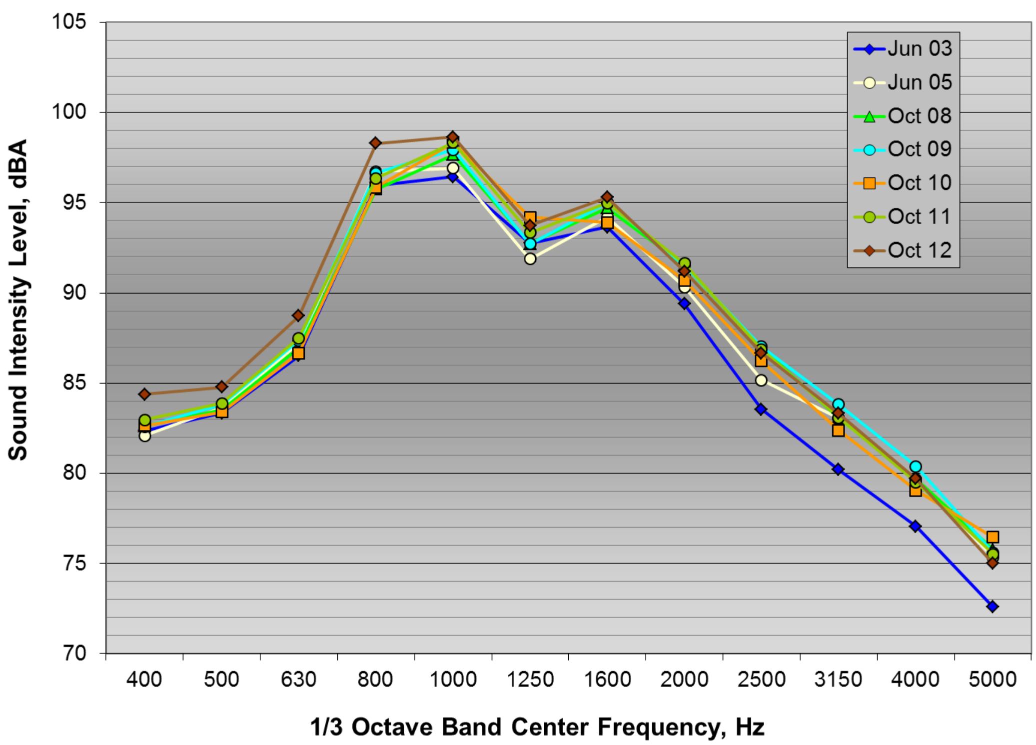


Figure 6-71: One-third octave band levels for ⅛-inch grooved Section 3 pavement from June 2003 through October 2012 for Goodyear Aquatred test tire

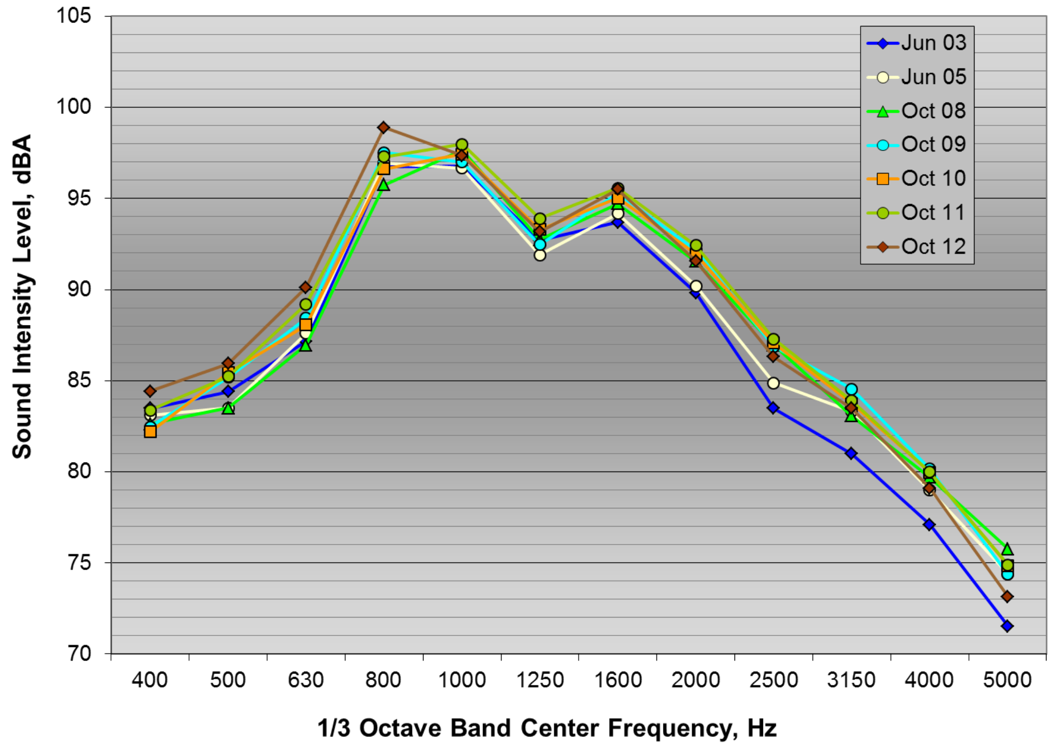


Figure 6-72: One-third octave band levels for ¼-inch grooved Section 4 pavement from June 2003 through October 2012 for Goodyear Aquatred test tire

6.4.4 Arizona Quiet Pavement Pilot Program

In the fall of 2003, ADOT initiated QP3 in cooperation with FHWA. Under this program, many freeway segments in the Phoenix metropolitan area with rigid pavement surfaces received 1-inch thick ARFC overlays to reduce highway-related traffic noise. A photograph of the ARFC pavement is shown in Figure 6-73. The overlays were applied to existing freeways and will be applied to newly built freeways as they are completed. This pilot program represents the first time that pavement surface type has been allowed as a noise mitigation strategy on federally funded projects. As a condition of using pavement type as a noise mitigation strategy, ADOT developed a 10-year research program for FHWA to evaluate the efficacy of using quiet pavement solutions. Noise performance was evaluated by means of OBSI (Site 1 measurements), wayside measurements (Site 3 measurements) following the FHWA measurement procedures (Lee and Fleming 1996), and community measurements (Site 2, not discussed). One of the primary purposes of the QP3 was to evaluate the acoustic longevity of the ARFC overlay.

Figure 6-73: Photograph of asphalt rubber friction coarse (ARFC) pavement

The overlay project was widely accepted by the public in the greater Phoenix area, who found the noise reduction to be quite noticeable. Initially, the application of ARFC in Arizona provided wayside noise reductions of 9 to 12 dB below levels measured on the original, uniformly spaced (¾-inch) transverse tined rigid pavement. This reduction is on the same order as would be expected from a 12- to 14-foot high roadside barrier. As would be anticipated, the noise reduction is dependent on the acoustical qualities of the initial pavement.

The Site 1 average OBSI levels are shown in Figure 6-74, indicating an increase of about 0.5 dB/year for all post-overlay measurements. The results for the three wayside sites, Site 3A, 3D, and 3E, are shown in Figures 6-75 through 6-77, including the Site 1 OBSI data and the wayside SPL measured at the 50-foot/5-foot, 50-foot/12-foot, and 100-foot/5-foot microphone positions. The OBSI levels at these sites increased by 0.48 to 0.71 dB/year, depending on the site, with the higher rate occurring at Site 3D. Noise levels increased by 0.39 to 0.60 dB/year at the 50-foot wayside positions, 0.24 to 0.61 dB/year at the 100-foot wayside positions, and 0.07 dB/year at the Site 3D 250-foot wayside position. Averaging the OBSI levels for all three of the Site 3 locations, the rate of increase is 0.59 dB/year, which is slightly higher than the overall Site 1 average (0.50 dB/year). For the wayside data, the average rate of increase for all the 50-foot positions was 0.48 dB/year and 0.42 dB/year for the 100-foot positions. Variations between sites are at least partially attributable to traffic loading differences.

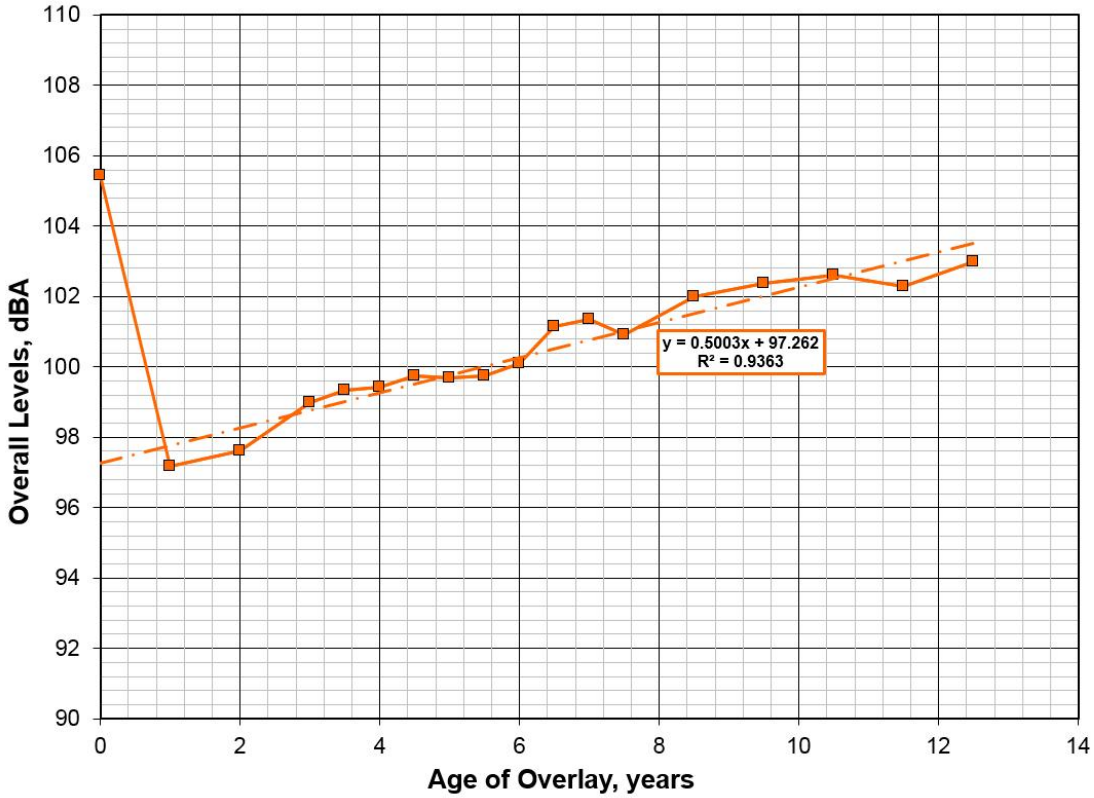


Figure 6-74: Change in OBSI averaged for all Site 1 locations

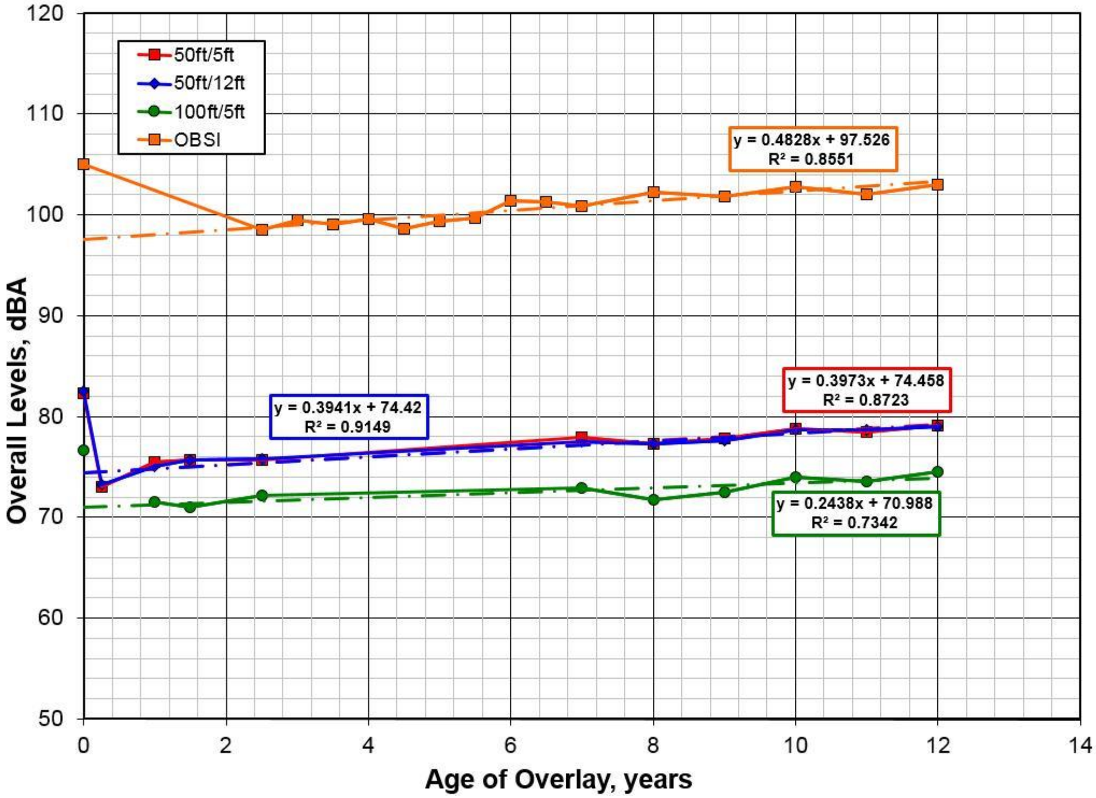


Figure 6-75: Change in OBSI and wayside noise levels with pavement age for site 3A

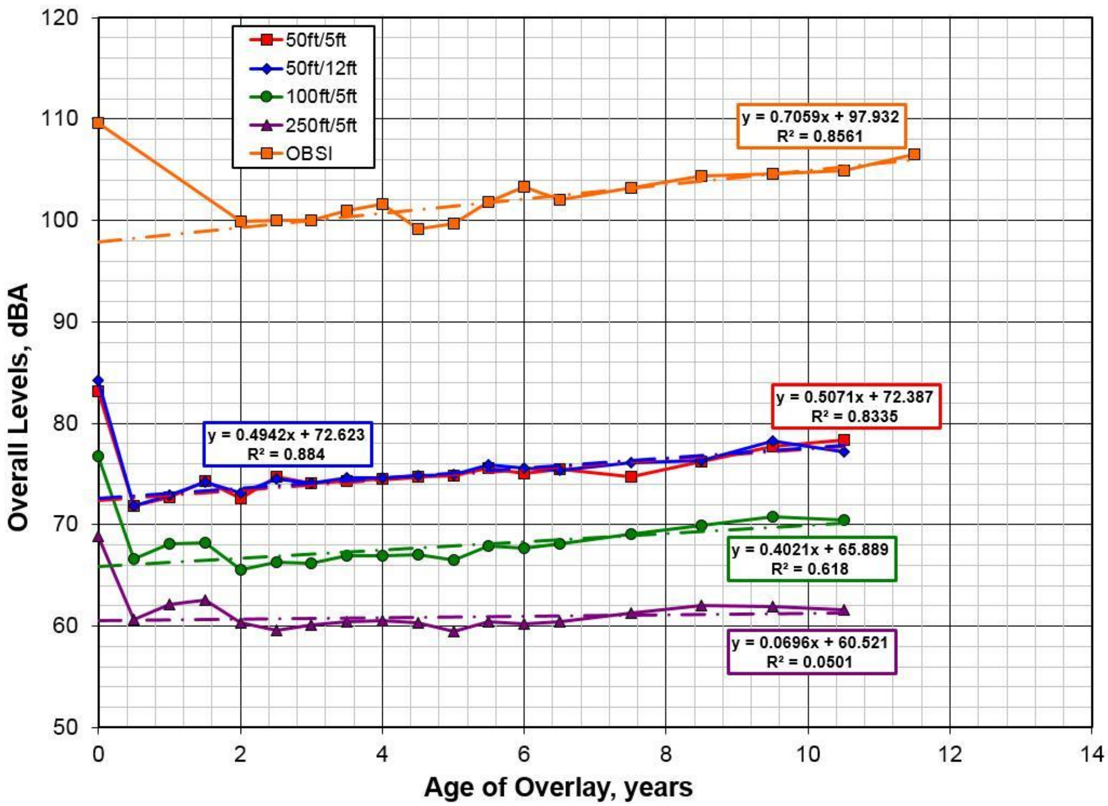


Figure 6-76: Change in OBSI and wayside noise levels with pavement age for Site 3D

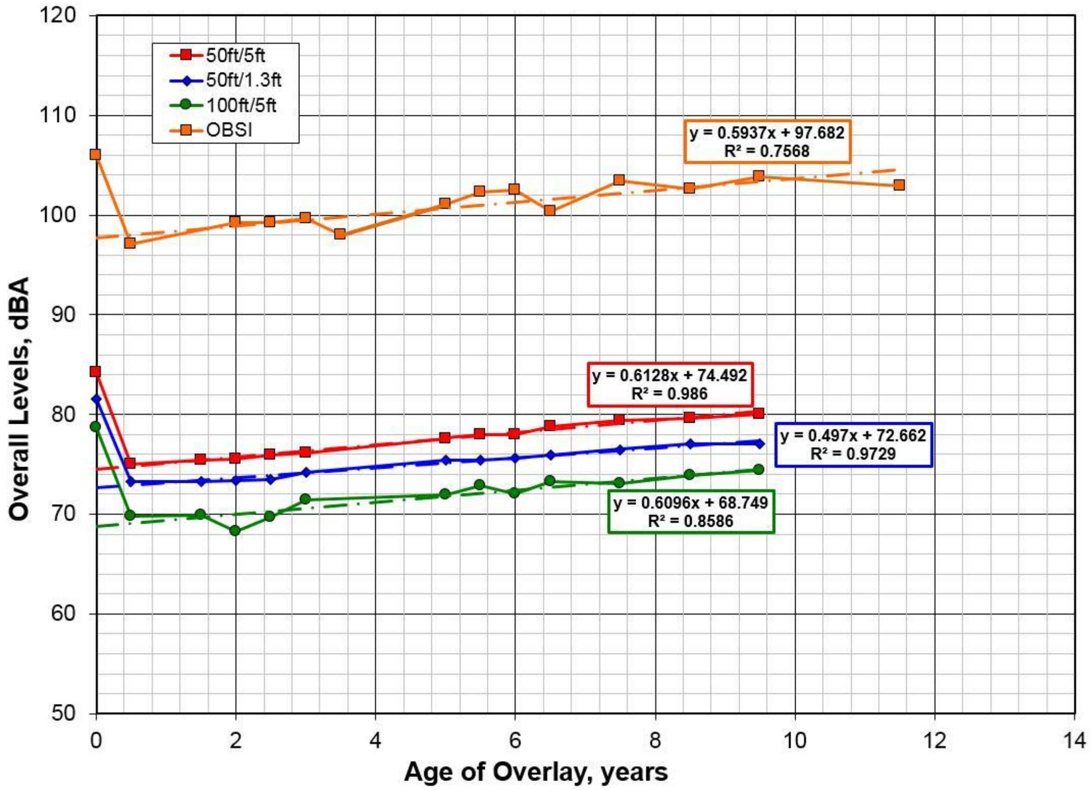


Figure 6-77: Change in OBSI and wayside noise levels with pavement age for Site 3E

Consistent with other quieter pavement research described in Sections 6.4.1 through 6.4.3, noise reduction did deteriorate over time as the pavement aged. Traffic noise levels increased by about 0.5 dB/year, in terms of OBSI and wayside levels measured at 50 feet (15.25 meters); about 0.4 dB/year at 100 feet (30.5 meters); and less at the farther distances. With a 10-year pavement rehabilitation schedule, the ARFC would increase in noise by 4 or 5 dB within 100 feet of the roadway and less at farther distances. After 10 years, the ARFC maintained about a 7 dB noise reduction from the initial pavement. This would meet the Barrier Design Goal criteria of 7 dB used by Arizona and many other state agencies. Additionally, unlike noise barriers, the acoustic noise reduction "footprint" extends farther in the community, and reductions were maintained over the 10-year duration of the QP3 project at distances as far as 250 feet (76 meters). From the Sites 1, 2 (neighborhood noise level), and 3 QP3 correlation study (Donavan 2013b), it was found that the ARFC overlay produced reductions in traffic noise typically on the order of 5 dB, even when other noise reduction features (e.g., barriers, berms, recessed highways) were present for the Site 2 locations. This finding indicates that quiet pavement application can benefit additional receivers, not only those not currently shielded by barriers. Additionally, unlike with barriers, the noise reduction performance of the ARFC is inherently not dependent on meteorological conditions. This is particularly important in areas, such as Phoenix, where temperature inversions often exist.

6.4.5 Summary of the Results of Four Long-Term Quiet Pavement Research Studies

Long-term pavement research was conducted on several potentially quieter pavements in California and Arizona. A summary of the initial and 10-year old pavement OBSI levels, along with the average increase measured over a 10-year period, are shown in Table 6-3 and Figure 6-78.

The overall OBSI levels were found to increase at different rates for the different pavements. Lane-to-lane variations found along I-80 Davis and the Mohave Bypass suggest that traffic volume and mix likely contribute to pavement acoustic longevity differences. Of the asphalt pavements, the DGAC resulted in the lowest rate of noise increase over time, about 0.09 dB/year, which is consistent with the rigid pavements. Noise increases for the other AC pavements, including both porous and non-porous pavement types, all fell into a range from 0.3 to 0.5 dB/year. In terms of the one-third octave band spectra, the DGAC and BWC levels increased uniformly with pavement age in the 2,000 to 3,150 Hz bands, with the other bands remaining fairly consistent. This result is thought to be due to the polishing of the aggregate over time. The spectra for the four open graded sections showed the largest differences in the one-third octave bands between 800 Hz and 2,000 Hz, attributable to the filling of the air voids and eventual reduction of pavement porosity.

Relative to flexible pavements, the rigid textured pavements indicated lower rates of overall noise level increase over time. The overall A-weighted levels are determined primarily by frequencies bands from 800 to 1250 Hz. Aging of rigid pavements had only minimal effects on sound levels in these bands. In the higher frequencies above 1600 Hz, the increase in noise with time is significant, averaging 0.42 dB/year compared with 0.10 dB/year for the overall levels. This effect appears to be due polishing on the surfaces, corresponding reduction of surface friction, and an increase in noise generated by the scrubbing mechanism. Even with the noise level increase over time, most of the quieter pavements continue to generate low to mid-range tire-pavement noise levels after 10 years.

Table 6-3: Summary of OBSI Levels and Increase Rates for 13 Research Test Sites in California and Arizona

Project	Pavement Details	OBSI Level, dBA[1]		Rate of Increase, dB/Year[5]	Mid-Project Year Traffic Loading
		New Pavement	10-yr Pavement		
ADOT QP3	ARFC[3]	97.3	102.3	0.50	Varies
Davis I-80 (6-lanes)	OGAC[2]	100.3[4]	104.1	0.3 to 0.4	146,000 AADT, 7.6% Trucks (2006)
LA 138 (2-lanes)	DGAC	101.1	102.2	0.09	4,400 AADT, 14% Trucks (2007)
	OGAC 75 mm[2]	96.9	101.4	0.47	
	OGAC 30 mm[2]	97.4	102.0	0.41	
	RAC(O)[2,3]	97.2	101.1	0.38	
	BWC	99.9	103.3	0.33	
Mohave Bypass SR 58 (4-lanes)	LT PCC	103.5	104.4	0.09	17,000 AADT, 37% Trucks (2007)
	Ground PCC, S1	102.6	103.9	0.12	
	Ground PCC, S5	100.8	102.3	0.12	
	Burlap Drag PCC	101.5	102.8	0.09	

	Grooved PCC, S3	101.7	103.5	0.16	
	Grooved PCC, S4	102.1	103.4	0.15	

[1] Measured using Aquatred test tire.
[2] Porous Pavement.
[3] Rubberized Pavement.
[4] Calculated based on increase rate from OBSI levels measured for pavement aged from 4 and 10 years.
[5] Rate of increase is based on linear regression analysis over multiple years of data acquisition.

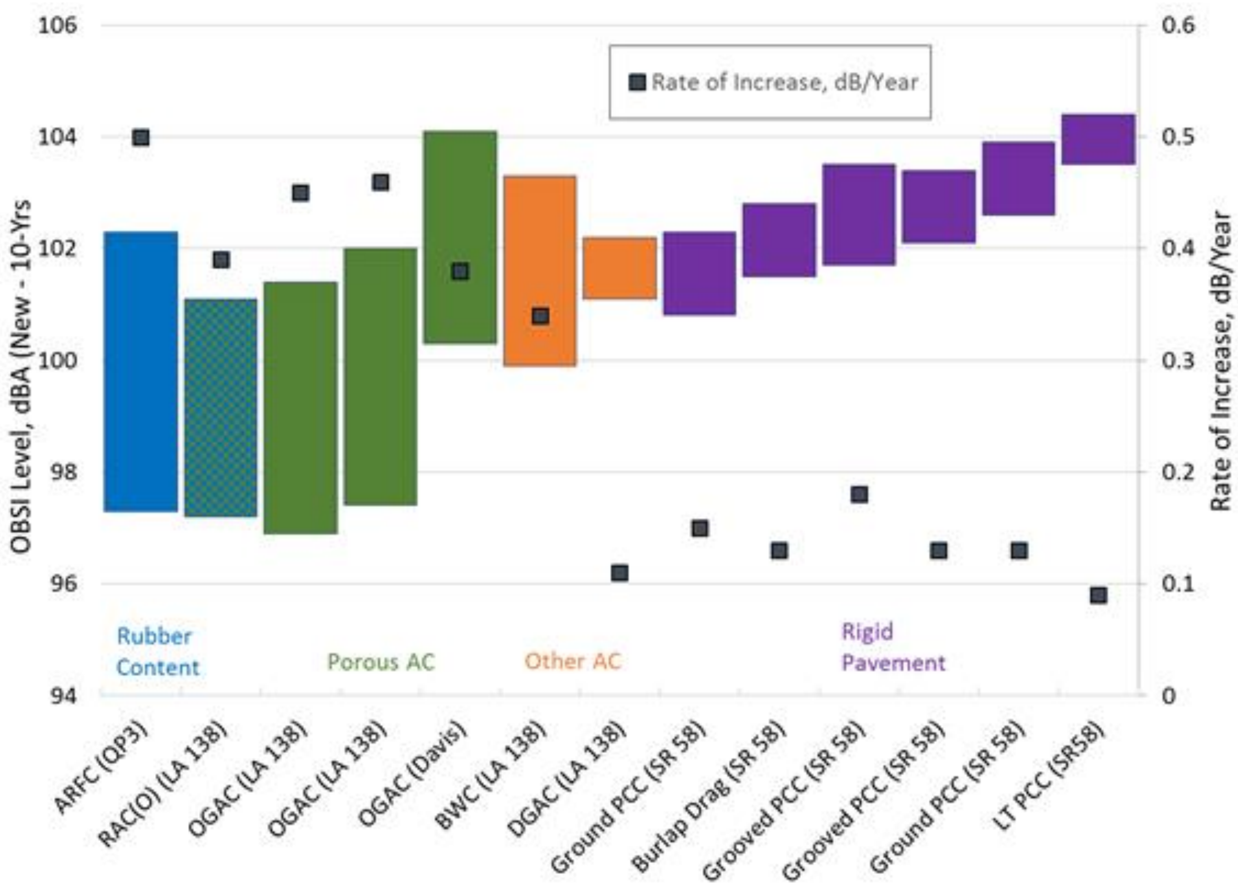


Figure 6-78: New and 10-year old OBSI levels and average rate of increase for long term studies

6.4.6 **Summary of Repeat Measurements**

In addition to the four primary long-term pavement studies described in Sections 6.4.1 through 6.4.5, several smaller studies have included repeat measurements of pavement types over time. A summary of the initial and aged pavement OBSI levels, along with the average increase, are shown in Table 6-4. Note that the data represented in Table 6-4 are from limited data sets, typically with two data points (new and aged) per pavement type, unlike the extensive data sets contained in the four primary long-term studies.

Table 6-4: Summary of OBSI Levels and Increase Rates for Smaller Acoustical Longevity Studies in California and Arizona

Project	Pavement Details	OBSI Level, dBA[1] New Pavement	OBSI Level, dBA[1] Aged Pavement	Rate of Increase, dB/Year[4]	Mid-Project Year Traffic Loading
SR 85, Saratoga, CA (6-lanes)	Ground and Grooved Long. Tined PCC	102.3	104.2 (5-Yr)	0.38	122,000 AADT, 0.57% Trucks (2007)
I-280, San Mateo County (6-lanes)	Diamond Ground PCC	102.8	105.0 (8-Yr)	0.28	105,000 AADT, 2.3% Trucks (2006)
	Texture Ground PCC	102.9	105.7 (8-Yr)	0.35	
	RAC(O)[3]	97.5	102.1 (8-Yr)	0.58	
	OGAC[2]	96.8	103.3 (8-Yr)	0.81	
I-10, Casa Grande, AZ (6-lanes)	AR-ACFC[3]	97.3	99.3 (6-Yr)	0.33	51,000 AADT (2007)
	ACFC	100.2	102.8 (6-Yr)	0.43	
	SMA	100.6	102.4 (6-Yr)	0.30	
	Porous-ACFC[2]	100.9	105.0 (6-Yr)	0.68	
	Porous Euro Mix[2]	101.9	101.7 (6-Yr)	negligible	

[1] Measured using Aquatred test tire.
[2] Porous Pavement.
[3] Rubberized Pavement.
[4] Due to limited data, linear regression analysis was not possible. Rate of increase is based on the difference between data points, divided by the number years between measurement periods.
Sources: Donavan and Janello 2011b; Janello and Donavan 2011a; Donavan 2010c.

Table 6-4 indicates that the highest rates of increase were found for the porous pavements (RAC[O]), OGAC and porous ARFC), with increases ranging from 0.58 to 0.81 dB/year. An exception to this was the porous European mix on I-10, which had a negligible increase over the 6-year period. The non-porous rubberized surface (AR-ACFC) resulted in an increase of about 0.33 dB/year, somewhat lower than the Arizona ARFC described in Section 6.4.4. The non-rubberized friction coarse (ACFC) and SMA surfaces at Casa Grande resulted in increases similar to those found for the LA 138 sites, with higher, although still relatively low, average annual daily traffic (AADT).

The rigid textured pavements in Table 6-4 show increase rates that were similar to the Davis I-80 OGAC and the LA 138 AC pavements, but about 2 to 3 times those measured on the Mohave Bypass rigid pavement sites. This difference from the Mohave rigid pavement sites is likely due to the traffic loading along SR 85 and I-280, which is considerably greater than that on the Mohave Bypass.

6.4.7 Acoustical Longevity and Vehicle Loading

Figure 6-79 shows the new and 10-year-old pavement levels for both the long-term and smaller studies and the average rate of increase for each pavement surface, based on the differences between the new and 10-year-old tire-pavement noise levels. Pavement type (Rubber Content, Porous, Other AC, and Rigid) is indicated by color. Note that the smaller studies include limited data sets, typically with two data points (new and aged) per pavement type, unlike the extensive data sets used in the four primary long-term studies.

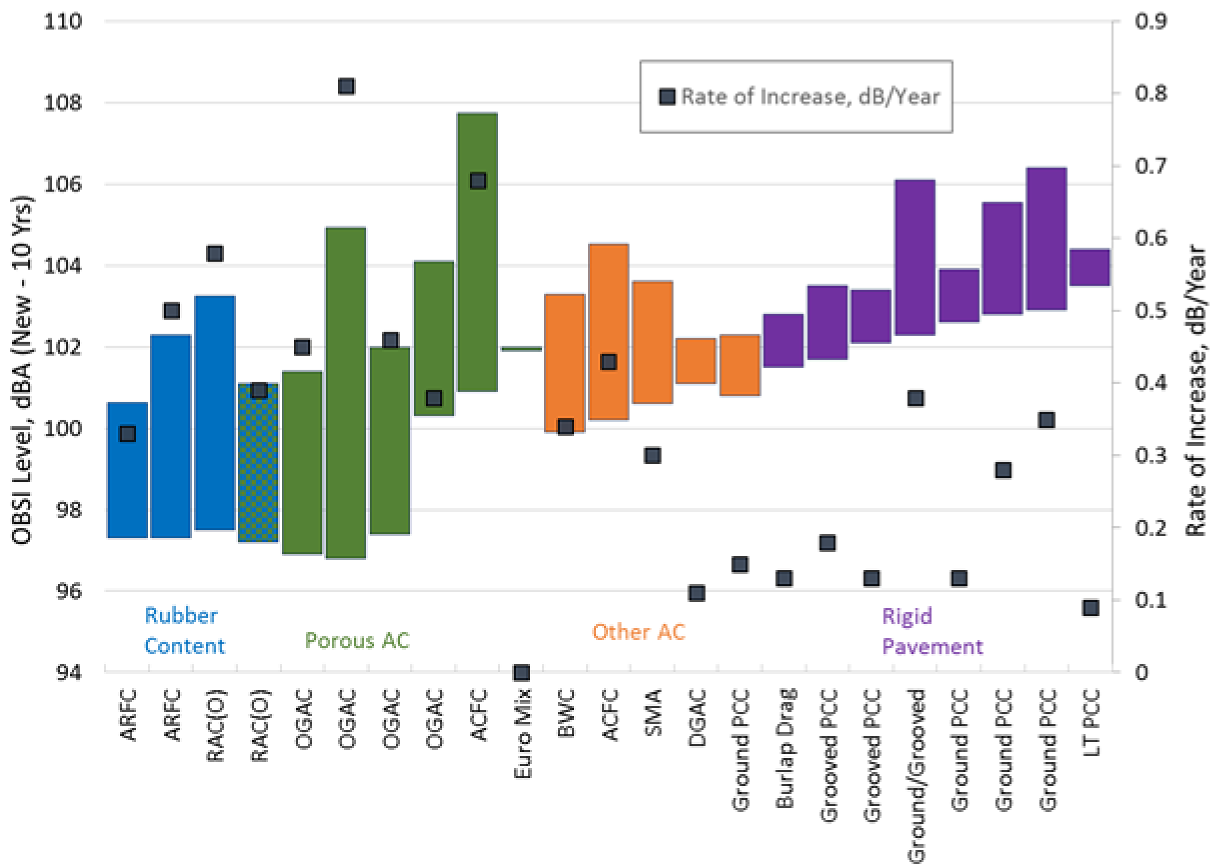


Figure 6-79: New and 10-year-old OBSI levels and average rate of increase for long term and smaller repeat studies

Figure 6-79 indicates that although rigid pavement types generally resulted in lower noise level increase rates, there is considerable scatter in the data, with one porous AC pavement (Euro Mix) resulting in almost no increase at all over the measurement period and some of the ground PCC sites increasing at rates similar to the rubberized and porous AC pavements. Additionally, even with the noise level increase over time, many of the quieter pavements continue to generate low- to mid-range tire-pavement noise levels after 10 years and continue to be quieter than some of the new rigid pavements.

As described in Section 6.4.1 and 6.4.3, lane-to-lane variations found along I-80 Davis and the Mohave Bypass suggest that traffic volume and mix likely account for at least some of the pavement acoustic longevity differences. This hypothesis is reinforced through review of Figure 6-80, which shows the rate of increase and vehicle loading by lane (based on the mid-project traffic volumes) for each of the long term and smaller repeat measurement studies. The rate of noise level increase trends well with vehicle loading for both flexible (AC) and rigid (PCC) pavements. Further study is needed to confirm this hypothesis.

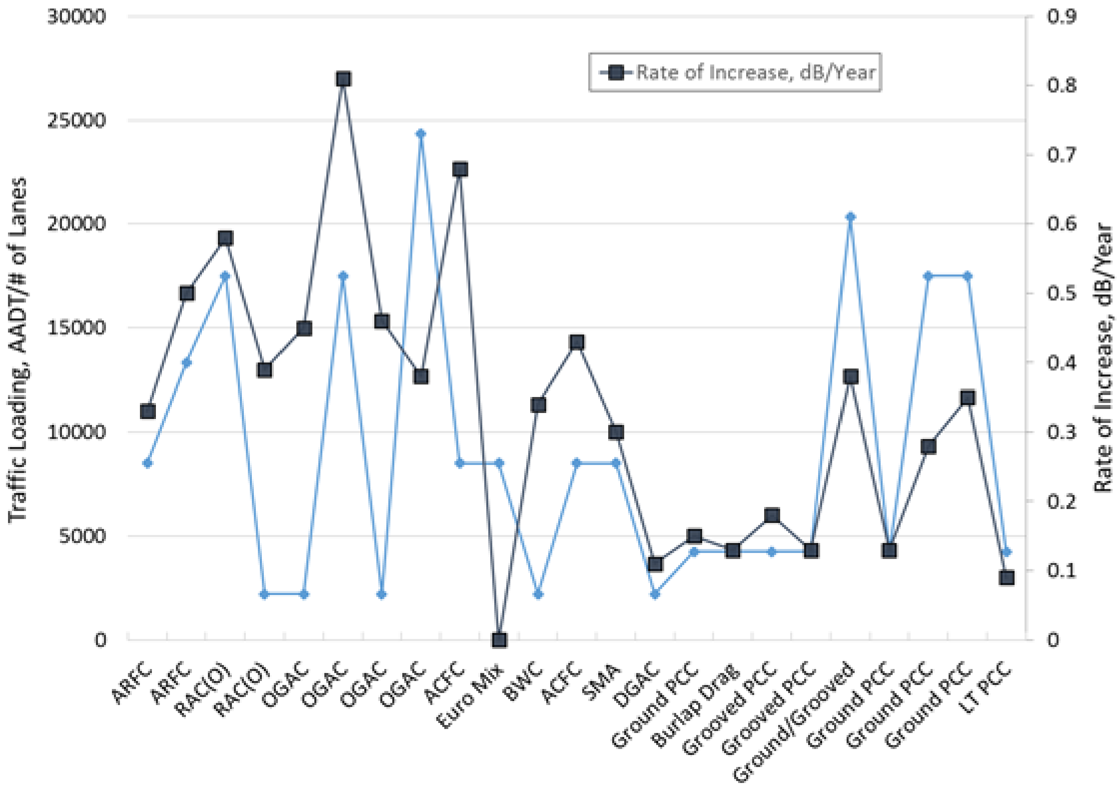


Figure 6-80: Rate of increase and vehicle loading for long-term and smaller repeat studies

6.5 Heavy Vehicles

It is well accepted that the passby noise level produced by heavy trucks at highway speeds is about 10 dB greater than that of light vehicles (Fleming et al. 1996). This means that each heavy truck in the traffic flow contributes the same sound energy as about 10 light vehicles. Noise from truck passbys under cruise conditions is not always reduced by quiet pavements as much as it is for light vehicles. The cause of this difference has been investigated through studies of truck tire behavior and other contributing noise sources such as the truck exhaust noise.

6.5.1 Truck Tires

Starting in 2003, Caltrans partnered with NCAT in a series of pavement acoustic studies at the NCAT testing facility affiliated with Auburn University (Donavan 2006b). The purpose of this study was to determine whether truck tires behave differently than car tires relative to pavement changes. Measuring truck tire-pavement noise source levels is much more challenging than light vehicles and this study provided the first opportunity to use the OBSI methodology to measure truck tire noise levels on an assortment of flexible pavements. The study examined eight pavements with seven truck tires and the Goodyear Aquatred passenger car tire, which was the reference light vehicle test tire at that time. All measurements were taken at the track speed of 45 mph (72 km/h). Figure 6-81 shows the test tires and OBSI average for all eight pavements for each tire. Figure 6-82 shows the overall OBSI levels calculated for each pavement using each of the eight tires.

Figure 6-81: Average OBSI levels for truck tires on eight pavements (passenger car Aquatred in lower left).

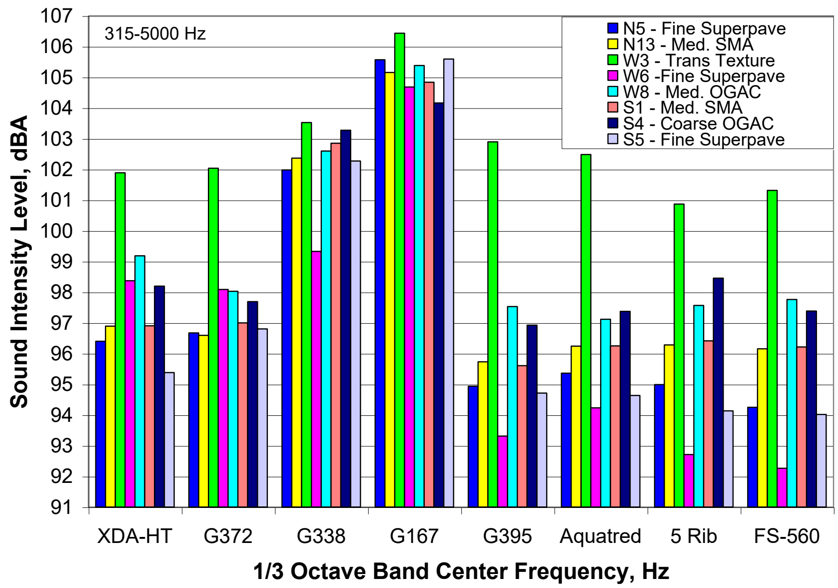


Figure 6-82: Overall A-weighted sound intensity levels for all eight tires on all eight pavements for the frequency range from 315 to 5000 hertz

The test matrix of quiet and loud pavements and quiet and loud tires yielded a number of interesting relationships (Donavan 2007; Rymer and Donavan 2007):

- The total span between quiet and loud tires and quiet and loud pavement was 14 dB. This is similar to the range of OBSI levels measured for all pavements to date using SRTT (see Appendix A and Section 6.1).
- The transversely treaded drive axle tires tended to produce higher noise levels than the longitudinally ribbed tires. Similar patterns in rigid pavement yielded the same results: transversely textured rigid surfaces were louder than longitudinally textured rigid surfaces.
- Levels for transversely textured flexible pavement were consistently high for all tires with a spread of 5 dB. However, when the loudest tire, G167, is excluded, the range was about 2 dB for all tires on this surface. This finding implies that differences in tire design are less important on pavement with significant texture.
- Sound levels for the (longitudinal) ribbed, non-drive axle truck tires (G395, 5-rib, and FS-560) were similar to levels for the passenger car Aquatred, implying that noise generated by less aggressive truck tires was essentially the same as that generated by car tires.
- Excluding the loudest W3 pavement, the traction drive axle tires, G167 and G338, were significantly louder, 5 to 10 dB, than the other truck tires. Similar to transversely textured pavements, transversely patterned treads can significantly elevate roadside noise levels.
- For the loudest tire, the G167, the differences between all pavements were small – only about 2 dB. This implies that aggressive traction drive tires overshadow any pavement differences.

These observations support the assertion that differences in truck tire noise generation could result in both higher passby levels than for cars and in less sensitivity to quieter pavement depending on the tires installed on the truck.

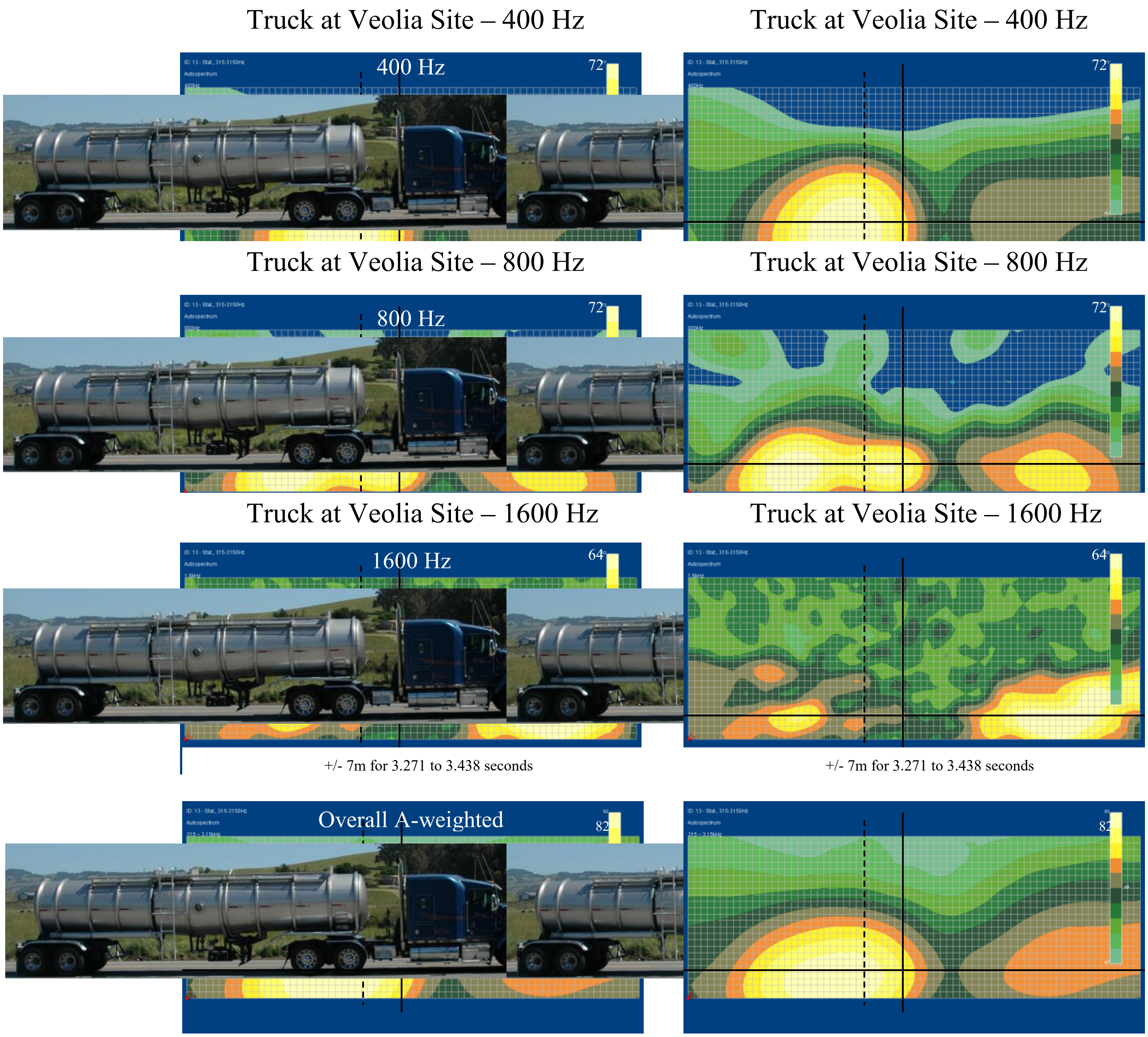
6.5.2 Highway Noise Source Height of Heavy Trucks

The assumption that exhaust noise is a major source for trucks has critical implications in regard to the modeling of traffic noise and abatement. FHWA's TNM (Federal Highway Administration 2017) assigns two sub-source heights to each vehicle type, with source heights of 0 feet and 5 feet (1.5 meters) above the pavement for all vehicles except heavy trucks, and source heights of 0 feet and 12 feet (3.7 meters) above the pavement for heavy trucks. For heavy trucks under cruise conditions, TNM v 2.5 assigns 57% of the sound energy at low frequencies and 46% of the sound energy at high frequencies to the source height 12 feet (3.7 meters) above the pavement, independent of vehicle speed or pavement type. However, it was demonstrated in the early 2000s that tire noise could account for a substantial portion of the 10 dB difference between cars and trucks and that expected reductions in level with pavement depend on the mix of tires used on any specific truck (Rymer and Donavan 2007). The REMEL database reports 2.6% to 5.4% of the energy (depending on frequency) being at 12 feet (3.7 meters) for heavy trucks under cruise conditions (Fleming et al. 1996).

In 2006, Caltrans initiated a study to determine the vertical distribution of noise sources in truck passbys using acoustic beam-forming (Donavan et al. 2008). Acoustic beam-forming was used to visualize the sound radiation of passing trucks under actual highway operating conditions for the purpose of determining the vertical distribution of noise sources and to examine changes in source height with different pavements. A 90-microphone, 7.9-feet (2.4-meter) diameter Brüel & Kjaer beam-forming array was employed to conduct the measurements. Almost 300 individual passby events in the highway environment at three sites of differing pavement were measured and analyzed. Although the study focused on heavy trucks, about 30% of the vehicles evaluated were medium trucks. Some light vehicles, motorcycles, and buses were also assessed.

Figure 6-83 shows a typical example of noise contour plots for a heavy truck at the 400, 800, and 1600 Hz bands and the overall A-weighted level. Note that the color contour SPL scale is variable from plot to plot with the level of the highest (yellow) color noted next to the color bar. The sound level at each 0.66-foot (0.2 meter) increment of height from -0.31 to +1.22 feet (-0.095 to +0.37 meter) above the pavement surface is plotted in Figures 6-84 for the typical truck shown in Figure 6-83, presented for the overall A-weighted level and each one-third octave band between 315 and 3150 Hz. At the lower frequencies (315 and 400 Hz), the maximum deviation with height is on the order of 6 to 8 dB. In the middle frequencies, the maximum deviation increases to about 10 to 15 dB. In the higher frequencies of 2000 Hz and above, the distributions once again flatten due to the side lobes of the beam producing ghost images essentially creating a lower signal-to-noise ratio.

Figure 6-85 shows the overall A-weighted source height distribution, averaged for all heavy truck passby events. As seen in Figure 6-85, the choice of averaging methods has a minor effect on the resultant average, increasing the average level no more than 1 dB at any given source height, with the shape of the profile virtually unchanged.



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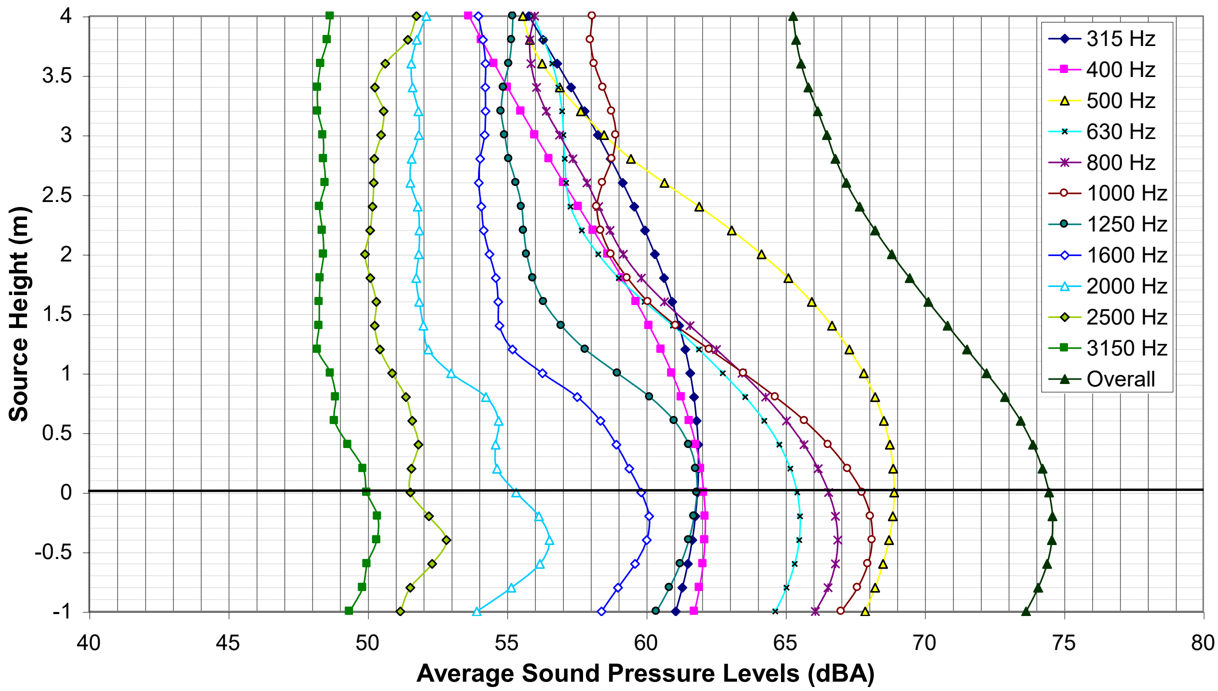

Figure 6-84: Source height distribution for one-third octave band and overall levels of truck from Figure 6-83

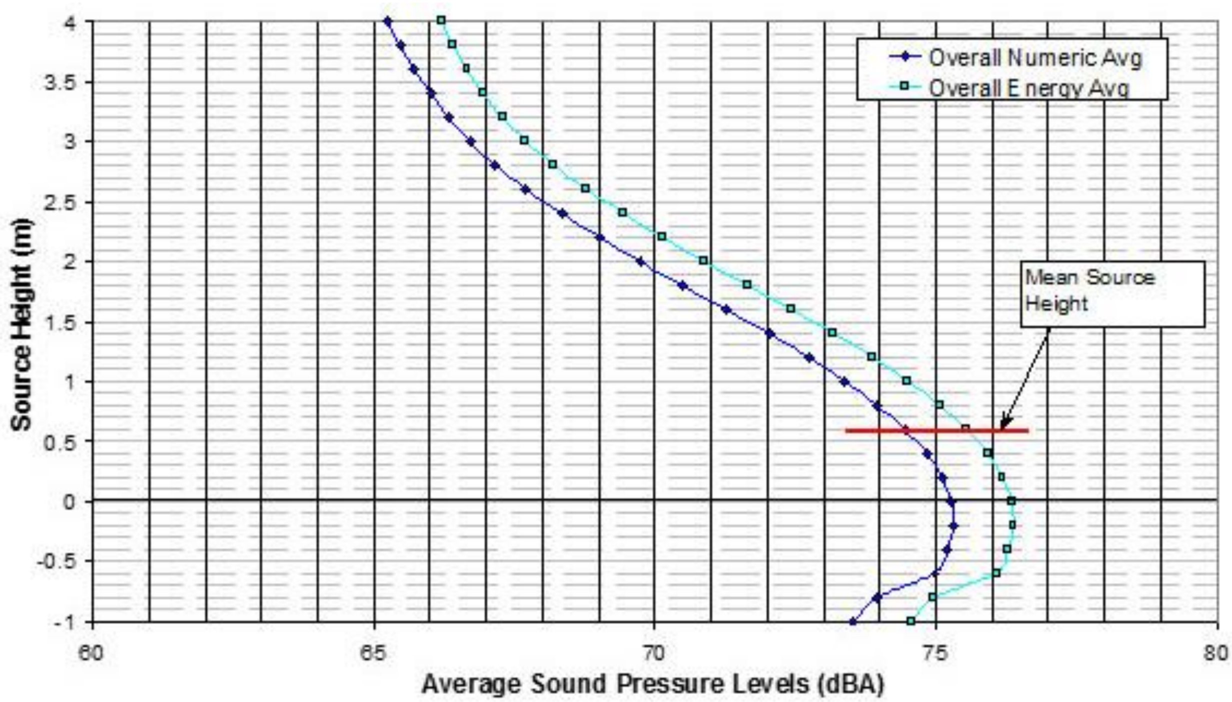

Figure 6-85: Overall A-weighted source height distributions averaged numerically and on an energy basis for all passby events

The results of the Caltrans study indicated that the highest noise source levels generated by heavy truck passby events at highways speeds are at and very close to the pavement surface.

Source levels were found to decrease rapidly with height on an overall A-weighted SPL basis. There was no indication of significant source regions at the exhaust stack height (12 feet [3.7 meters]), as compared with the stronger sources apparent at ground level. At 2.5 feet (0.76 meter) above the road surface, the level is about 5.5 dB lower than the maximum level located at ground level. At 12 feet (3.7 meters), the levels are reduced by about 10 dB relative to ground level. Out of 131 passby events, only one truck indicated appreciable overall noise being generated in the 12-foot height region. This finding is consistent with the sub-source height splits noted in the REMEL database, as described above.

NCHRP Report 635, *Acoustical Beamforming: Mapping Sources of Truck Noise* (Gurovich et al. 2009), also describes the results of acoustical beamforming measurements used for truck noise source mapping. In this study, a 70-plus microphone elliptical array was used. One hundred medium and heavy truck passbys were measured at highway speeds. Of these, 59 heavy truck and 4 medium truck passbys were analyzed in detail, and only 4 heavy trucks exhibited significant noise generation in low frequencies at the exhaust stack height of 12 feet (3.7 meters).

A follow up project, NCHRP 25-45, *Mapping Heavy Vehicle Noise Source Heights for Highway Noise Analysis*, is currently in its final stages of completion. Preliminary results have been released, indicating similar distributions to the Caltrans and NCHRP Report 635 results (Janello 2016). This project included the testing of 20 sites of various pavement types with grade variations ranging from -3% to +3% and speeds ranging from about 30 to 70 mph (48 to 113 km/h). Again, the primary noise source for the vast majority of heavy trucks was found to be tire-pavement noise, with engine and powertrain noise as a secondary source. Some ground-level noise was reflected by the pavement, and some noise, typically about 3 feet (0.9 meter) above the pavement, came through the front wheel well and radiator. Noise from elevated exhaust stacks occurred rarely, with 6 trucks out of 1,289 having levels at the stack equal to or greater than at ground level (0.5%), 23 having levels within 5 dB of ground level (1.8%), and 62 having levels within 10 dB of ground level (4.8%). Vertical noise profiles were largely unaffected by site, vehicle operating conditions, terrain, pavement and region of the country.

6.6 Cost Benefit Analysis of Pavement and Barriers

Barriers are costly to build, but require minimal maintenance and provide a fixed amount of noise reduction over a long period of time. In contrast, quieter pavements can initially be less expensive than barriers, but their noise reduction performance typically degrades with time. Quieter pavement requires shorter rehabilitation cycles to maintain performance, which adds to cost over the life of the project. With the consideration of quieter pavement as an alternative to barriers for highway noise mitigation, a methodology to account for the acoustical performance and life cycle costs of both types of mitigation was needed.

To develop methodologies to account for the acoustic performance and life cycle costs of both types of mitigation measures used separately or in combination, the NCHRP 10-76 project, *Methodologies for Evaluating Pavement Strategies and Barriers for Noise Mitigation*, was completed (Donavan et al. 2013; Donavan 2013c). The study included a method for assessing the life cycle cost of the various options and then applied the method to several case studies based on the noise policies of different states.

6.6.1 Life-Cycle Cost Analysis

A framework with which to compare costs of the two types of noise mitigation was developed using Life-Cycle Cost Analysis (LCCA), a method recommended by FHWA for evaluating pavement design alternatives. LCCA considers the costs of different pavement alternatives in initial construction and the costs of each rehabilitation and maintenance effort over the complete life of the highway project, which can range from 28 to 50 years. The rehabilitation cycle is defined as the time period in which the pavement will deteriorate to the agency's minimum acceptable condition. In the NCHRP 10-76 project, LCCA was expanded to analyze both pavement and barrier strategies for noise abatement. For quieter pavement options, the rehabilitation cycle needs to account for acoustic longevity. Depending on the pavement, the cycle may need to be shortened to assure that an acceptable level of noise reduction performance is maintained throughout the life of the pavement. This would assure that the FHWA criterion of maintaining the noise abatement "in perpetuity" is met (Shrouds 2005). The initial costs for any potential sound walls are added to the appropriate pavement choice. Sound wall maintenance costs such as repairs and graffiti removal are also included in the analysis. For the quieter pavement, the cost of ongoing monitoring of acoustic performance of the pavement using OBSI could also be included in the LCCA.

6.6.2 Acoustical Performance

To go along with the LCCA, prediction of the acoustic performance of the pavement alternatives is needed to complete the abatement analysis. Following the research conducted by the U.S. DOT Volpe Center under FHWA *TNM Pavement Effects Implementation Study* (Rochat et al, 2012) the NCHRP 10-76 project scaled the ground level source strength used in TNM with measured OBSI levels using the SRTT, as prescribed in the AASHTO TP 76-16 test procedure

(American Association of State Highway and Transportation Officials 2016). Through this approach, state highway agencies can input tire-pavement source levels based on their pavement designs and acoustic longevity studies for use in traffic noise predictions. Noise levels resulting from different barrier designs and combinations of pavement alternatives can be predicted, and different scenarios can be evaluated with respect to their noise reduction.

6.6.3 Calculations of Cost and Acoustical Effectiveness for Hypothetical Case

Figure 6-86 shows the cash flow diagrams for two noise abatement options for a hypothetical new freeway project. The hypothetical project was based on a new six-lane highway (three lanes in each direction) with flat terrain and dense noise sensitive receptors. Two different noise abatement strategies were considered: (1) Longitudinally tined rigid pavement with a 12-foot (3.7-meters)-high sound wall, and (2) HMA with an ARFC overlay without a wall. For the rigid pavement option, pavement rehabilitation occurs on a 20-year cycle, which includes diamond grinding the surface. For the HMA option, pavement rehabilitation includes a 2-inch (51 millimeter) HMA dense-graded mill and overlay every 14 years and a 0.75-inch (19 millimeters) ARFC overlay placed every 7 years to maintain acoustical quality. Initial pavement construction costs were estimated based on thicknesses from the Washington State DOT “Pavement Policy Manual” (Washington State Department of Transportation 2010). Barrier construction cost was calculated using the average cost from the FHWA of $27/square foot (0.09 square meter) (Federal Highway Administration 2015). Maintenance-related costs were mostly based on a 1999 report prepared by the Southern Illinois University at Edwardsville for the Illinois DOT (Kay et al. 1999). Both options were analyzed over a 50-year pavement life period.

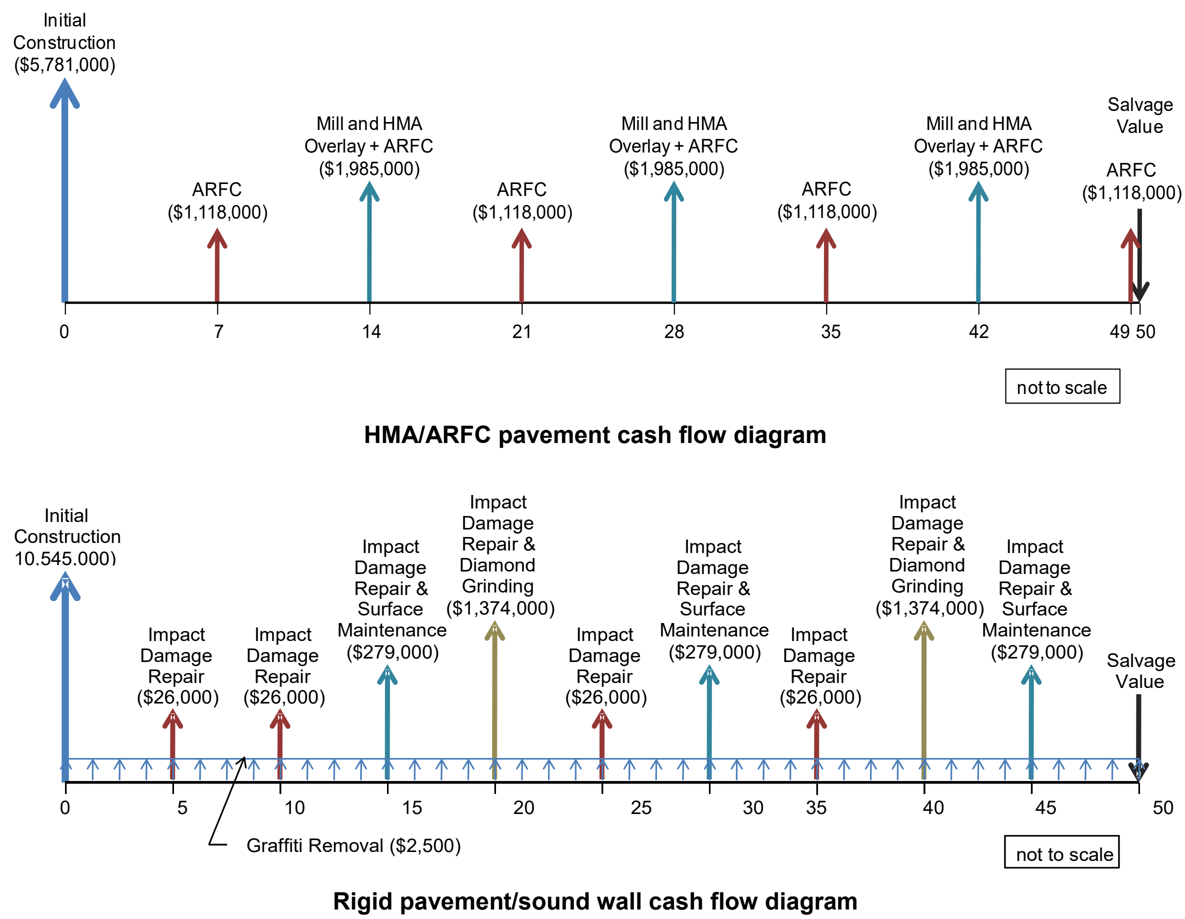

Figure 6-86: Cash flow diagram for the alternatives of HMA and rigid pavement with a sound wall

As shown in Figure 6-86, the total initial construction cost for the rigid pavement alternative is $10,545,000, compared with $5,781,000 for the HMA alternative. After the 50-year lifespan, the rigid pavement option continues to have a higher agency cost, but would have a lower user cost than the HMA/AFRC option because of issues such as increased time transit due to construction and rehabilitation. With changes in the rehabilitation cycle, these costs could vary.

Traffic noise levels at a distance of 100 feet (30.5 meters) from the highway are shown in Figure 6-87 for the HMA/ARFC pavement on a 7-year rehabilitation cycle and rigid pavement on a 20-year rehabilitation cycle with a 12-foot (3.7-meter) high barrier. For comparison, the acoustic performance for rigid pavement with and without a barrier is also shown.

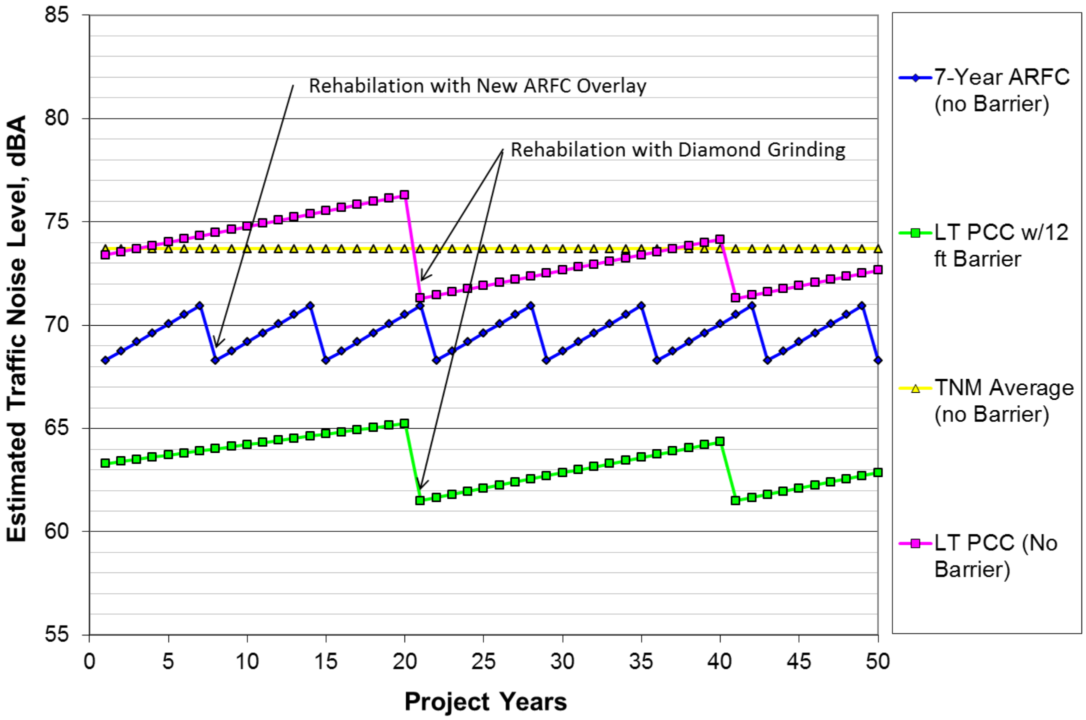

Figure 6-87: TNM-predicted traffic noise levels for LCCA, example case at 100 feet (30.5 meters) for longitudinal tined rigid pavement with and without barrier, ARFC/HMA, and TNM average pavement

Although the HMA/ARFC option would have a lower agency cost, it results in consistently higher sound levels than the rigid pavement with the 12-foot (3.7-meter) barrier and would be considered less acoustically effective. Both noise abatement alternatives initially satisfy a 5 dB improvement criterion compared with the TNM average pavement prediction. However, for the HMA alternative, the 5 dB improvement is maintained only for the first 2 years after the initial project and each rehabilitation. Only the rigid pavement with a 12-foot (3.7-meter) barrier alternative achieves a design goal of 7 dB relative to TNM average pavement. Relative to the rigid pavement case without a barrier, the levels for the HMA/ARFC alternative are 5 to 8 dB lower for the first 20 years of the project. After the rehabilitation grinding of the rigid pavement, the HMA/ARFC alternative provides levels only 0 to 5 dB lower than the rigid pavement without a sound wall would provide.

Using the same LCCA, the acoustic performance of the rigid pavement surface initially textured in transverse tining is shown in Figure 6-88. For this texture, the rigid pavement sound levels during the first 20 years without the barrier range from 5 to 8.5 dB higher than levels with TNM average pavement. The 12-foot (3.7-meter) barrier provides the same insertion loss as it did with the longitudinal texture, providing a feasible and reasonable solution to achieve the design goal. However, the rigid pavement alternative's effectiveness in producing the absolute noise levels is about the same as the HMA/ARFC alternative when averaged over the initial 20-year period. Further, the transverse texture with the barrier does not achieve a 7 dB design goal relative to TNM average pavement.

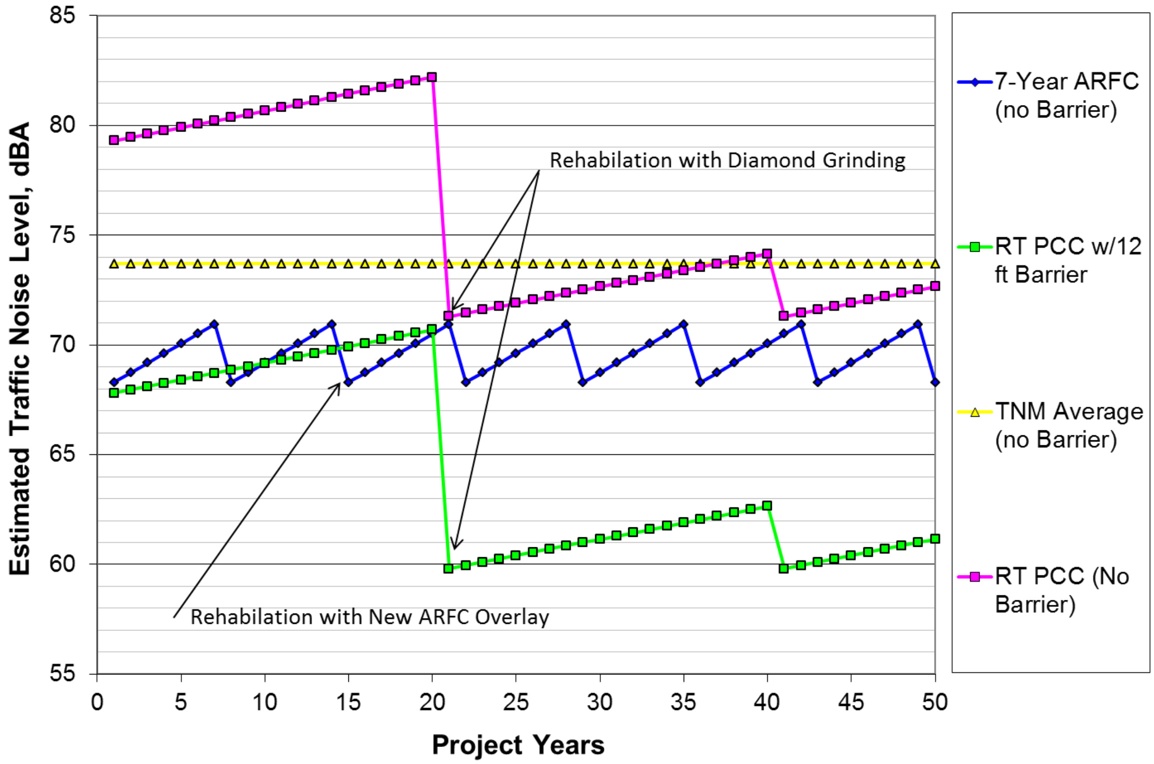

Figure 6-88: TNM-predicted traffic noise levels for LCCA, example case at 100 feet (30.5 meters) for random transverse tined rigid pavement with and without 12-foot barrier, ARFC/HMA, and TNM average pavement

6.6.4 Application of Methods to California Case Study (Lodico et al. 2015)

The methods described above were applied to several hypothetical and state project-based case studies within the NCHRP 10-76 project report (Donavan et al. 2013). In each of these cases, noise abatement options were assessed using the state polices for the corresponding locale (where possible) as well as other states for comparison. The California state project-based example used the proposed addition of one High Occupancy Vehicle (HOV) lane in each travel direction of I-580 over a 13.1-mile (21.1 kilometer) stretch between Dublin and Livermore, California. The total number of travel lanes would be increased from eight to 10 lanes. Although the project was broken into several smaller projects for the purposes of the National Environmental Policy Act review process, this analysis assumed that both eastbound and westbound HOV lanes were to be added as a single project. Out of the 13.1-mile project, three smaller segments were considered in the NCHRP 10-76 project, each with several potential barrier locations. The segment described here, Segment 3, extends from the Vasco Road overpass for about 0.5 mile (0.8 kilometer) to the east and is shown in the aerial photograph of Figure 6-89. The results of the abatement analysis for this example were compared with Caltrans policy (California Department of Transportation 2011).

Figure 6-89: Aerial photograph of California I-580 Segment 3, indicating proposed barrier locations and the number of impacted receptors in parentheses.

Three barriers are proposed: two barriers on the westbound side, W10 and W11, and one barrier on the eastbound side, E11. Barrier W10 is proposed to shield four impacted single-family residences. Barrier W11 is proposed to shield the adjacent park. In addition, residences located north of the park, which are shielded by existing development walls and, therefore, have noise levels slightly below the NAC threshold, would benefit under some of the alternatives. Barrier E11 is proposed to shield a mobile home park with 16 homes.

All eight lanes of the existing pavement are aged longitudinally tined rigid pavement. The additional lanes incorporate a portion of the existing shoulder and a newly constructed pavement to provide the added lanes and shoulders. There are two construction options for the added lanes and shoulders.

1. Rigid pavement (similar to the existing longitudinally tined surface).
2. HMA pavement and all lanes receiving a quieter friction course overlay.

The following pavement alternatives were considered for the LCCA, with the net present value (NPV) results indicated in the parentheses as agency cost per mile. The present value costs are the barrier LCCA costs based on $51.61/square foot (0.09 square meter) (scaled to height and length as needed) plus the pavement present values described in NCHRP Report 738 (Donavan et al. 2013).

1. Added Rigid Pavement Lanes Only (NPV: $3,691,000)
   - Construct additional lanes and shoulders with rigid pavement similar to the surface texture of the existing pavement.
   - The existing pavement is in good condition and does not require rehabilitation at that time.
   - Diamond-grind all lanes (for noise and other considerations) 10 years after the addition of the HOV lanes and every 20 years thereafter.
2. Added Rigid Pavement Lanes, All Lanes Ground (NPV: $5,060,000)
   - Construct additional lanes and shoulders with rigid pavement and diamond grind all lanes to reduce the tire-pavement noise levels.
   - Diamond-grind all lanes on a 20-year cycle thereafter.
3. Added Rigid Pavement Lanes, RAC(O) Overlay (NPV: $4,668,000)
   - Construct additional lanes and shoulders with rigid pavement and overlay all lanes and shoulders with a 1-inch (25.4 millimeters) RAC(O) overlay.
   - Mill the RAC(O) overlay and replace it every 9 years for noise performance.
4. Added HMA Lanes, RAC(O) Overlay (NPV: $5,353,000)
   - Construct additional lanes and shoulders with HMA and overlay all lanes and shoulders with a 1-inch (25.4 millimeters) RAC(O) overlay.
   - Mill the RAC(O) overlay and replace it every 9 years for noise performance.
5. Added HMA Lanes, All HMA (NPV: $5,446,000)
   - Construct additional lanes and shoulders with HMA and overlay existing lanes and shoulders with a 5-inch (127 millimeters) HMA overlay.
   - Mill 2 inches (51 millimeters) of the HMA overlay and overlay it on a 12-year cycle.

Alternative 5 (All HMA) is the most expensive. Alternative 4 (RAC(O) overlay on HMA) provides acoustic performance similar to that of Alternative 3, but at a higher cost. Based on considerations of cost and acoustical uniqueness, Alternatives 4 and 5 were not considered for further analysis.

6.6.4.1 Analysis by Individual Barrier

TNM was used to predict traffic noise levels for the three different pavement alternatives, using the existing longitudinally tined rigid pavement as the reference pavement. Based on TNM noise modeling, the noise levels for the existing longitudinally tined rigid pavement are about 1 dB greater than TNM average pavement. Grinding the rigid pavement lowers the noise level by about 3 dB. The RAC(O) is about 6 dB quieter than the new longitudinally tined PCC and about 3 dB quieter than the ground rigid pavement. Barrier heights ranging from 12 to 16 feet (3.7 to 4.9 meters) were considered, as indicated in Table 6-5, because 12 feet (3.7 meters) was determined to be sufficient to block the line of sight to truck exhaust stacks and 16 feet (4.9 meters) is generally the maximum allowed height in California.

Four impacted receptors were identified in the vicinity of barrier W10. A summary of analysis results for barrier W10 is provided in Table 6-5, which shows the number of benefitted receptors, the predicted noise level range for all impacted receptors, the noise reduction range provided, the total project NPV, the NPV for noise abatement, and the reasonableness allowance calculated for each alternative. In addition, acoustically feasibility, cost reasonableness, and design reasonableness (based on the state policies) are indicated. Effectiveness is a new term, defined in NCHRP Report 738 and shown in Tables 6-5 through 6-7, as the difference in noise reduction between the given alternative and the most acoustically effective alternative (i.e., the alternative that provides lowest overall noise level). The difference is based on the maximum predicted levels for the options being compared. Therefore, an effectiveness of 0 dB indicates the alternative that produces the lowest noise level, and an effectiveness of 4 dB indicates that the given alternative produces 4 dB more noise than the most effective alternative.

Table 6-5: Feasible and Reasonable Requirements Met under Caltrans Policies with Effectiveness and Cost Information – I-580 Segment 3, W10

Pavement Type and Barrier Height	Receptors Benefited (out of 4 Impacted)	Predicted Level Range, dBA	Noise Reduction Range, dB	Total Project NPV ($1000)	NVP for Noise Abatement ($1000)	Reasonableness Allowance ($1000)	Feasible	Cost Reasonable	Design Reasonable	Effectiveness, dB
PCC + 0 feet	0	68-77	0	559	-	-				13
PCC + 12 feet (3.7 meters)	3	66-68	2-9	1,113	554	165	Yes	No	Yes	4
PCC + Ground + 0 feet	0	65-74	3	767	207	-	No	No	No	10
PCC + Ground + 12 feet (3.7 meters)	4	63-67	5-10	1,321	761	220	Yes	No	Yes	3
PCC + RAC(O) + 0 feet	4	62-71	6	707	148	220	Yes	Yes	No	7
PCC + RAC(O) + 12 feet (3.7 meters)	4	62-64	5-13	1,261	632	220	Yes	No	Yes	0

Without a barrier, the traffic noise levels are predicted to range from 68 to 77 dBA, or 2 to 11 dB above the NAC. All abatement alternatives are acoustically feasible except for grinding without a barrier. Only RAC(O) without a barrier is reasonable for cost, but this alternative does not meet the design reasonableness criteria. As a result, none of these alternatives would be considered and no abatement would be proposed.

Thirteen impacted receptors were identified in the vicinity of barrier W11, although some of the alternatives result in seven additional benefitted receptors that were not considered to be impacted. Predicted noise levels at the park behind proposed barrier W11 range up to 78 dBA with the longitudinally tined rigid pavement without the barrier. As shown in Table 6-6, the three alternatives that include barriers are acoustically feasible and meet the design goal of 7 dB, but only two of the alternatives are cost reasonable: Ground +12 feet and RAC(O) +12 feet. An increase in the barrier height up to 16 feet (4.9 meters) for the rigid pavement alternative would not produce additional benefitted receptors and, therefore, continued to not be cost reasonable.

Thus, only the two options with a 12-foot (3.7-meter) barrier and the quieter pavements meet the feasible and reasonable criteria. These two alternatives are nearly equal in effectiveness and NPV for abatement, with the RAC(O) +12-foot (3.7 meter) barrier alternative having a small advantage.

Table 6-6: Feasible and Reasonable Requirements Met under Caltrans Policies with Effectiveness and Cost Information – I-580 Segment 3, W11

Pavement Type and Barrier Height	Receptors Benefited (out of 13 Impacted)	Predicted Level Range, dBA	Noise Reduction Range, dB	Total Project NPV ($1000)	NVP for Noise Abatement ($1000)	Reasonableness Allowance ($1000)	Feasible	Cost Reasonable	Design Reasonable	Effectiveness, dB
PCC + 0 feet	0	64-78	0	629	-	-				9
PCC + 14 feet (4.3 meters)	3	61-70	3-8	1,356	727	165	Yes	No	Yes	3
PCC + Ground + 0 feet	0	62-75	2-3	863	233	-	No	No	No	8
PCC + Ground + 12 feet (3.7 meters)	20	59-68	4-10	1,486	857	1,100	Yes	Yes	Yes	1
PCC + RAC(O) + 0 feet	0	61-74	2-4	796	167	-	No	No	No	7
PCC + RAC(O) + 12 feet (3.7 meters)	20	59-67	4-11	1,419	790	1,100	Yes	Yes	Yes	0

Sixteen impacted receptors were identified in the vicinity of barrier E11. Analysis of Barrier E11, as indicated in Table 6-7, indicates noise levels for the existing pavement without any barrier ranging from 69 to 81 dBA, or 3 to 15 dB above the NAC. All three barrier alternatives meet the feasible and reasonable criteria. In this case, the rigid pavement with the 12-foot (3.7-meter) barrier has the lowest cost, but is the least effective and benefits the lowest number of receptors. The two quieter pavement alternatives with 12-foot (3.7-meter) barriers are nearly equal in effectiveness, number of benefitted receptors, and NPV for abatement, with the RAC(O) +12-foot barrier alternative having a small cost advantage.

Table 6-7: Feasible and Reasonable Requirements Met under Caltrans Policies with Effectiveness and Cost Information – I-580 Segment 3, E11

Pavement Type and Barrier Height	Receptors Benefited (out of 16 Impacted)	Predicted Level Range, dBA	Noise Reduction Range, dB	Total Project NPV ($1000)	NVP for Noise Abatement ($1000)	Reasonableness Allowance ($1000)	Feasible	Cost Reasonable	Design Reasonable	Effectiveness, dB
PCC + 0 feet	0	69-81	0	629	-	-				12
PCC + 12 feet (3.7 meters)	10	66-71	3-10	1,252	623	550	Yes	Yes	Yes	2
PCC + Ground + 0 feet	0	67-79	2	863	233	-	No	No	No	10
PCC + Ground + 12 feet (3.7 meters)	16	64-69	5-12	1,486	857	880	Yes	Yes	Yes	0
PCC + RAC(O) + 0 feet	6	65-76	4-5	796	167	330	Yes	Yes	No	7
PCC + RAC(O) + 12 feet (3.7 meters)	16	62-69	7-12	1,419	790	880	Yes	Yes	Yes	0

6.6.4.2 Analysis of Segment as a Whole

With barriers W11 and E11 located across the highway from each other, the cost of quieter pavement would be shared between the two impacted areas. As a result, a combined hybrid approach can be used for the analysis of the entire segment as one piece. Using one of the two viable options for W11 that includes a quieter pavement directly opposite to the E11 barrier would result in an overall abatement NPV of $1,479,000 for the ground rigid pavement option and $1,413,000 for the RAC(O) option ($233,000 for the cost of grinding or $167,000 for the cost of RAC(O), plus $623,000 each for the two 12-foot (3.7-meter) barriers, W11 and E11). For this case, the reasonableness allowance for the combined 36 benefitted receptors would be $1,980,000 and either hybrid solution would meet the feasible and reasonable criteria.

Another hybrid option would be to apply quieter pavement over the entire segment, including the portion of the roadway adjacent to the single-family residences to the northeast of the Vasco Road Interchange, where barrier E10 was not found to be feasible or reasonable under any alternatives. In this case, extending the total pavement length to 2,275 feet (693 meters) would result in a total abatement cost of $1,667,000 for the RAC(O) option ($421,000 for the cost of RAC(O) plus $623,000 for each of the two 12-foot (3.7-meter) barriers, W11 and E11). The allowance for the new total of 40 benefited receptors would be $2,200,000. This hybrid alternative is feasible, cost reasonable, meets the design criteria, provides benefit for four more receptors in the area, and is the most effective alternative for those shielded by W11 and E11.

6.6.5 Conclusions

The NCHRP 10-76 project report concluded that the FHWA pavement LCCA process could be readily adapted for the purposes of comparing noise abatement that use barriers, pavement strategies, or combinations of both. It also found that the special version of TNM modified to account for pavement based on OBSI data can produce the necessary information to conduct highway noise abatement analysis with current feasibility and reasonableness criteria. Using OBSI acoustic longevity data, the analysis can also be extended to the life cycle of the highway project.

Potential cost savings and impact reduction could be achieved by considering barriers and quieter pavement together. The most effective and cost-efficient alternatives can often involve the use of the quieter pavement alone or with shorter barriers. Further, because quieter pavement effects receivers on both sides of a highway, its use can often benefit more receivers than one barrier alone, particularly when a barrier is only reasonable and feasible on one side of the highway. Where several alternatives with different costs, effectiveness, and benefitted receptors are all found to meet the feasibility, reasonableness, and design criteria, NCHRP Report 738 (Donavan et al. 2013) recommends that developing a rational approach for trading off NPV cost and effectiveness needs to be considered, such as using the cost per benefited receptor for comparing alternatives with different numbers of benefited receptors. Under current policy, quieter pavement alone would not typically meet the design goal requirements, although it offers considerable cost advantages in some cases when compared with the barrier alternatives. As a result, new policies may need to be considered to allow for quieter pavement noise abatement in cases where barriers are not feasible.

More information on this methodology and its implementation is available in the NCHRP Report 738 (Donavan et al. 2013) and from the report of a workshop hosted by the National Academy of Engineering, as published by the Institute of Noise Control Engineering (Institute of Noise Control Engineering 2014).

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6.7 Chapter 6 References

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Chapter 7 Past and Current Quieter Pavement Policy

7.1 Federal Highway Administration (FHWA) Policy

Title 23 Part 772 of the U.S. Code of Federal Regulations (23 CFR 772) requires that for Federal-Aid highway projects, noise analysis must be performed for specific types of projects when potentially impacted receivers are present. This regulation identifies five noise abatement options and requires that the abatement be both feasible and reasonable.

The original *Highway Traffic Noise Analysis and Abatement Policy and Guidance* document, released in 1995, restricted making adjustments for pavement type in the prediction of highway traffic noise levels and using specific pavement types or surface textures as noise abatement measures (Federal Highway Administration 1995). The policy mentions pavement as a possible factor in traffic, but states that "additional research is needed to determine to what extent different types of pavements and tires contribute to traffic noise." Concerns included acoustical longevity and lack of definite knowledge of pavement type and condition.

Following quiet pavement research in the 1990s and input from the general public, FHWA approved ADOT's request for a QP3 in June 2003 (Federal Highway Administration 2017). In 2005, guidance was provided to guide state transportation departments in the development of QP3's and tire-pavement noise research (Shrouds 2005). The intent of QP3's was to "demonstrate the effectiveness of quiet pavement strategies and to evaluate any changes in their noise mitigation properties over time." Consequently, programs were required to collect data and information over a period of at least 10 years.

23 CFR 772 was updated and published on July 13, 2010 for implementation by state agencies one year later (Federal Highway Administration 2011a). The updated version of 23 CFR 772 incorporates some of the information and definitions that were included in the original document. To support this update, the document "Highway Traffic Noise: Analysis and Abatement Guidance" was initially released in June 2010 and revised in December 2011 (Federal Highway Administration 2011b). The revised policy includes changes that affect abatement measures and analysis, but the basic approach remains. The five approved methods of noise abatement remain the same and exclude the use of pavement as an abatement option. In practice, barriers are the primary method of abating traffic noise (National Academy of Engineering 2010). The 2011 guidance allows for the use of any pavement types defined in FHWA TNM in the prediction of existing noise levels. Additionally, the use of pavement types other than FHWA TNM average pavement are now allowed to be considered in future predictions upon approval by FHWA.

In February 2016, FHWA issued *Guidance on Pavement as a Noise Abatement Measure* (Federal Highway Administration 2016). The guidance acknowledges the extensive number of studies that have been conducted over the past decade and the lack of adequate pavement type and texture variables in current noise prediction processes. The concern about acoustical longevity remains, as does a concern over increasing regulatory or procedural requirements to accommodate pavement as noise abatement. In an effort to address these concerns, FHWA intends to continue to evaluate the existing data that makes up the FHWA TNM REMELs and consider ways to integrate new data to increase the accuracy of highway noise prediction. The 2016 guidance encourages highway agencies to research quieter pavement and construct these pavements when appropriate, but continues to restrict the use of quieter pavement as a noise abatement measure under 23 CFR 772. Additionally, in noting that "the inclusion of additional specific pavement types in noise modeling can reduce the under- or over-predictions that can occur from using a national average," the implication is that the use of pavement types other than FHWA TNM average pavement is accepted for the modeling of existing noise levels.

7.2 California Department of Transportation Policy

FHWA approved the Caltrans QPR Plan in November 2006. The goal of the Caltrans QPR is to identify and provide the surface treatments, materials, design specifications, and construction methods that will result in a quieter roadway that is also safe, durable, and cost-effective (California Department of Transportation 2006). The research plan focused on three main elements: flexible pavement, rigid pavement (including bridge decks), and acoustical correlation studies. A tremendous amount of quieter-pavement research followed approval of this plan, the results of which make up the bulk of Chapter 6 of this document.

In 2009, following a few years of research under the Caltrans QPR, Caltrans updated its pavement policy in reference to quieter pavement strategies for noise sensitive areas (California Department of Transportation 2009). The stated Caltrans goal in the policy is to "build and maintain quieter pavements that will sustain traffic noise reduction benefits over time while not compromising on the safety, ride quality, and durability of pavement surfaces."

In compliance with the 23 CFR 772 update in July 2010, as described in Section 7.1, Caltrans released its most recent Traffic Noise Analysis Protocol in May 2011 (California Department of Transportation 2011). Caltrans policy in this document is that although quieter pavement is not listed in 23 CFR 772 as a noise abatement measure for which federal funding may be used, Caltrans is actively researching the benefits of pavement types in reducing tire noise levels to demonstrate the long-term noise abatement characteristics of quieter pavement. The protocol states that "in some special circumstances, Caltrans may consider using State-only funds to pay for quieter pavement to reduce traffic noise."

Chapter 1100 of Caltrans Highway Design Manual, *Highway Traffic Noise Abatement*, released in May 2012, includes objectives for new construction or reconstruction of highways, to limit the intrusion of highway noise into adjacent areas; on existing freeways to limit the noise intrusion to achievable levels within practical and financial limitations; and to limit the noise to the levels specified by statute for qualifying schools adjacent to freeways (California Department of Transportation 2012). The first approach listed in this document is reduction at the source and designers are "encouraged to consider emerging technologies intended to mitigate traffic noise at the source in order to minimize noise emanating from the highway." Quieter pavement is listed as the only example.

The Technical Noise Supplement (TeNS) to the Traffic Noise Analysis Protocol, released by Caltrans in September 2013, provides “technical background information on transportation-related noise in general and highway traffic noise in particular” (California Department of Transportation 2013). Pavement type is listed as a pertinent site condition that can be accounted for in the model. However, TeNS notes that although FHWA policy requires the use of the “average” pavement type for design year traffic noise predictions, alternative pavement types such as DGAC, rigid pavement, and OGAC can be used in the model validation process if actual existing pavements are one of these types of alternative pavements. The use of any pavement type other than “average” for predicting traffic noise levels must be substantiated and approved by FHWA.

Caltrans practice of calibrating noise prediction models allows for optional calibration adjustments for various pavement types (Hendriks 2003). This practice does not mean that quieter pavement is to be used as a noise abatement measure. Rather, the process is used to account for an otherwise unexplained portion of differences between measured and predicted noise results. Without the adjustment for pavement, this difference would have been added anyway, without explaining the cause.

7.3 California Environmental Quality Act

The California Environmental Quality Act (CEQA) requires state, local, and other agencies in California to evaluate the environmental implications of their actions. In addition, California Government Code Section 65302(f) requires that all general plans include a noise element to address noise problems in the community for all of the following sources:

- Highways and freeways.
- Primary arterials and major local streets.
- Passenger and freight on-line railroad operations and ground rapid transit systems.
- Commercial, general aviation, heliport, and military airport operations, aircraft flyovers, jet engine test stands, and all other ground facilities and maintenance functions related to airport operation.
- Local industrial plants, including, but not limited to, railroad classification yards.
- Other stationary ground noise sources identified by local agencies as contributing to the community noise environment.

CEQA does not directly discuss quieter pavement. However, in compliance with State CEQA Guidelines, many jurisdictions have adopted planning policies to allow for quieter pavement as mitigation for noise generated on highways, freeways, primary arterials, and major local streets. Some examples include:

- City of Arcadia General Plan Policy N-2-3 states, “Consider using roadway sound attenuation techniques for resurfacing projects that use ‘quiet’ pavement of noise-reducing rubberized asphalt.”

- City of San Diego General Plan Policy NE-B.2 states, "Consider traffic calming design, traffic control measures, and low-noise pavement surfaces that minimize motor vehicle traffic noise."
- City of Tracy General Plan Policy P3 states, "Pavement surfaces that reduce noise from roadways should be considered as paving or re-pavement opportunities arise."

These policies encourage the use of non-federal funds to pay for quieter pavement to reduce traffic noise on a local level.

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Chapter 8 Best Practices

Quieter pavement is a relative term for any pavement that produces less noise than another from the action of vehicle tires rolling over it (Tire-Pavement Noise Research Consortium 2011). Many people have experienced living near or driving on pavements that are perceived to be loud or quiet. Quieter pavements are not limited to being asphalt or concrete. Rather, either asphalt or concrete can be made quieter through the incorporation of known practices.

As described in Chapter 6, a range in tire-pavement noise levels of about 13 dB has been measured on California highways. With the inclusion of especially quiet test track surfaces and louder pavements on structures, this range extends to about 20 dB. A noise reduction of 13 dB would be considered "attainable" to "very difficult" to achieve using noise barriers, and a noise reduction of 20 dB would be considered "nearly impossible" to achieve using a noise barrier. The design of quieter pavement surfaces is dependent on many factors. The three primary pavement characteristics that have been found to affect tire-pavement noise levels include surface roughness/texture, porosity, and stiffness.

1. Texture: Surface roughness/texture has been found to be one of the major controlling factors in tire-pavement noise generation in frequencies below about 1000 Hertz. In general, smaller aggregate size or texture dimension results in lower noise levels. The remaining texture should be small (less than 5 millimeters) and negative (indenting into the surface rather than abutting upward).
2. Porosity: Pavement porosity has been found to result in significant reductions in the frequencies around 1600 Hz. Porosity is thought to reduce tire-pavement noise through absorption and a reduction in the tire-pavement contact area, especially when in excess of 20% void content. However, more-porous surfaces commonly have larger aggregate, resulting in higher low-frequency noise levels.
3. Stiffness: More flexible pavements, such as rubberized surfaces, can result in quieter noise levels, particularly in the frequencies of 800 Hz and above.

Although controlling the characteristics described above has been found to result in quieter tire-pavement noise levels, it is important to understand that there is often more than one mechanism contributing to the overall sound level. As a result, pavement design must take into account a combination of factors in an effort to produce a quieter surface. The following best practices are recommended for the design of quieter pavement surfaces.

8.1 Quieter Asphalt Concrete Surfaces

The quietest in-service AC surfaces are porous, rubberized, and fine aggregate pavements. Porous surfaces reduce sound, not only at the tire-pavement contact patch, but also as the sound propagates over the sound absorbing pavement surface. Pavements with fine aggregate result in lower noise levels by reducing surface roughness. In all cases, the surface texture should be negative, indenting into the pavement surface. Noise levels of porous and rubberized surfaces have been measured to increase by about 0.3 to 0.6 dB per year, resulting in a recommended rehabilitation period of about 7 to 10 years to maintain acoustic characteristics. Noise levels of DGAC pavements have been measured to increase by about 0.1 dB per year, similar to some rigid pavement surfaces, which may enable a longer rehabilitation schedule for purposes of noise reduction.

8.2 Quieter Rigid Pavement Surfaces

The quietest in-service rigid pavement surfaces have ground and drag textures. Acoustical rehabilitation strategies for existing rigid surfaces typically include grinding of the existing surface or overlaying the surface with a quieter one. The grinding procedures that have produced the quietest surfaces use 0.120-inch (3.0 millimeter) blade spacing or less. Measurements in Europe have also identified porous rigid surfaces, which perform almost as well as their porous flexible equivalents. These surfaces are not yet in use in the United States. Noise levels of rigid pavement surfaces have been found to increase by about 0.1 to 0.4 dB per year, which may enable a longer rehabilitation schedule for purposes of noise reduction then many of their AC counterparts.

8.3 Quieter Bridge Decks

Bridge decks and roadway sections on structure in California have been traditionally paved with rigid pavement surfaces and have included some of the loudest pavements measured to date. Quieter bridge decks generally follow the same strategies as quieter at-grade rigid pavement surfaces, with ground surfaces resulting in the lowest tire-pavement noise levels. Caltrans has recently changed common practice to use longitudinal tining in place of transverse tining for roadways on structure. Longitudinal surfaces typically result in mid-range tire-pavement noise levels, but generally have lower noise levels compared to transverse tining. Bridge expansion joints have also been found to be a primary noise generator, with joint noise becoming more perceptible when the overall traffic noise is reduced through quieter pavement strategies.

8.4 Pavement Joints

Pavement joints produce an audible impulsive sound perceived both inside and outside a vehicle as it is driven on the surface, resulting in an increase in the overall OBSI level of 1 to 3 dB. Potential methods of noise reduction based on theoretical modeling include: (1) narrowing the width of the groove to about 0.125 inch (3.175 millimeters); (2) filling the groove such that the remaining open area is about 0.10 inch (2.54 millimeters); or (3) adding a substance to the groove that increases flow resistance. More research is needed to assess these strategies for in-service roadways.

8.5 Tires

The total span between quiet and loud truck tires has been found to be similar to the span between quiet and loud pavements, about 14 dB. While the acoustic characteristics and ordering between pavements are generally consistent for all tires, louder tires result in smaller ranges in tire-pavement levels between pavements and quieter tires result in larger ranges. This indicates that more aggressive treaded tires would be less sensitive to quieter pavement.

Use of pavement for noise reduction purposes in areas with high use of studded tires and/or chains may not be a viable option. Studded tires and chains in some areas of the United States have resulted reduced acoustical lifespan of quieter pavement surfaces due to the increases raveling of the pavement over a short duration, on the order of a few years.

8.6 Heavy Trucks

The primary noise source for more than 95% of trucks has been found to be tire-pavement noise. This is largely unaffected by site, vehicle operating conditions, terrain, pavement or region of the country. In contrast to these findings, the Federal Highway Administration Traffic Noise Model (TNM v 2.5) currently assigns 57% of the sound energy at low frequencies and 46% of the sound energy at high frequencies to the higher noise source height of 12 feet (3.7 meters) above the pavement.

8.7 Measurement Methodology

The OBSI method of measuring tire-pavement noise levels at-the-source is the preferred method of isolating the effect of the pavement on tire-road noise generation in California. For real-world community noise level predictions, use of a wayside method such as the SIP or CTIM methods, combined with OBSI measurements, is recommended. In the case of porous pavements, it is recommended that both wayside and at-the-source methods are used in conjunction with sound propagation measurements, so as to determine the noise level at the tire-pavement contact patch, as well as the noise reduction achieved as the sound propagates over the sound absorbing pavement surface.

8.8 Cost Benefit Analysis of Quieter Pavement and Noise Barriers

A methodology, *Evaluating Pavement Strategies and Barriers for Noise Mitigation*, is available as NCHRP Report 738. The study developed a method for assessing the life cycle cost of various pavement and barrier options and then applied the method to several theoretical and state-based case studies using the noise policies of different states. Potential cost savings and impact reduction were found to be achieved by considering barriers and quieter pavement together and the most effective and cost efficient alternatives were found to often involve the use of quieter pavement alone or with shorter barriers. Further, since quieter pavement effects receivers on both sides of a highway, its use can often generate more benefitted receivers than just a barrier alone, particularly when the barrier is only reasonable and feasible on one side of the highway. Current policy does not allow for quieter pavement to be used as federally funded noise abatement, so a change in policy would be necessary to turn this method into reality for federally funded highway projects. Federal policy does not preclude road agencies from inventorying their pavements and making informed pavement design decisions to avoid placing loud pavements next to sensitive receivers.

8.9 Inclusion of Pavement Type for Noise Modeling

Using the OBSI measurement procedure, it has been determined that tire-pavement noise is highly correlated to the overall traffic noise levels in the community, especially when traffic is flowing at freeway speeds. While current federal policy restricts the use of quieter pavement as a noise abatement measure under 23 CFR 772, it does note that "the inclusion of additional specific pavement types in noise modeling can reduce the under- or over-predictions that can occur from using a national average". This implies that the use of pavement types other than FHWA TNM average pavement is accepted for the modeling of existing noise levels.

8.10 Determining the Limits of Quieter Pavement Project

Quieter pavement end limits were found to be very sensitive to the absolute OBSI noise level difference between the quieter pavement and the adjoining noisier pavements. End limits were found to be less sensitive to the number of lanes or median width of the roadway cross section and only somewhat sensitive to the distance between the receiver and the roadway and where the quieter pavement terminates. Based on modeling results for a 6 dB difference in level between the quieter and noisier pavements and considering a number of different geometries, a distance of three times the offset distance between the end noise receiver and the center of the nearest lane of traffic is recommended.

Reference

Tire-Pavement Noise Research Consortium. 2011. *Questions and Answers about Quieter Pavement*. Developed under TPF-5(135). January.

Chapter 9 Future Recommendations

Quieter pavement technology has advanced considerably with the research conducted by Caltrans and others, demonstrating a significant range in traffic noise levels between quieter and louder pavements. However, there continue to be areas for which further research could fill in the gaps in existing knowledge or help with implementation. The chapter lists the key areas where further study is warranted, based on the results of the research described in earlier chapters. This list is not intended to be all inclusive.

9.1 Integrating Quiet Pavement into Policy

The NCHRP 10-76 Project provided a comprehensive method for *Evaluating Pavement Strategies and Barriers for Noise Mitigation* (Donavan et al. 2013). The primary hurdle for the inclusion of quieter pavement as a noise mitigation strategy is policymaker acceptance and application into state and federal policy for purposes of noise mitigation under 23 CFR 772. Many policy decisions would need to be made before quieter pavement will be accepted as a mitigation strategy.

1. Defining the pavement age that should be applied within traffic noise modeling for predicting future noise levels.
2. Identifying a method of maintaining funding for pavement rehabilitation for purposes of noise mitigation.
3. Determining pavement life cycle costs that can be applied consistently in all states for use in the life cycle cost analysis.
4. Training of transportation agencies and consultants in the use of quieter pavement strategies for purposes of noise mitigation.
5. Defining a procedure in which noise and pavement engineers can work together to identify the best noise mitigation strategies.
6. Providing a clear definition of *effectiveness*.
7. Integration of quieter pavement into the FHWA TNM (see Section 9.2).
8. Assessment of the federal policy requiring a 7 dB design goal for noise mitigation to be considered reasonable.

Possible solutions for many of these challenges are presented within the report of a workshop hosted by the National Academy of Engineering, as published by the Institute of Noise Control Engineering (Institute of Noise Control Engineering 2014).

9.2 Integrating Research Results into FHWA's Traffic Noise Model

With the advancement of knowledge in quieter pavement and highway noise topics, integration of this knowledge into the FHWA TNM would provide more realistic highway noise predictions.

Suggested refinements include (1) updating the TNM interface to allow for the entering of OBSI data, (2) developing methods for quantifying and incorporating sound-absorbing pavements in TNM, such as including the proper effective flow resistance, and (3) updating TNM to use more realistic truck noise source heights. The first two topics have already been integrated into research versions of TNM, which could be made more user friendly and widely available once policy allows for the use of these features.

9.3 Porous Pavement

Porous pavement is known to reduce traffic noise relative to non-porous surfaces, not only at the tire-pavement contact patch, but also as the sound propagates over the sound-absorbing pavement surface. More research is needed to optimize the tradeoff between porosity and aggregate size in an effort to develop even quieter surfaces that can take both of these parameters into account. Additionally, the inclusion of sound absorbing properties into the FHWA TNM (discussed above) would allow for the prediction of this additional noise absorption in traffic noise modeling. Use of porous surfaces adjacent to the roadway, such as for shoulder construction, may also provide some noise reduction, as has been seen for the ballast used adjacent to railroads (Federal Transit Administration 2006). Finally, developing a rapid, in-situ method of quantifying pavement sound absorption without lane closures or background noise from traffic concerns would add to the understanding of how porosity influences tire-pavement noise.

9.4 Pavement Joints

Pavement joints have been studied theoretically and in a few field studies, resulting in some basic design recommendations. Even fewer studies have been dedicated to bridge expansion joints. Field testing of joints designed within the recommended specifications could result in optimized recommendations with real world applications.

9.5 Pavement Inventory with Pavement Design and Acoustical Specifications

Although the acoustical properties of numerous pavements have been tested, in many cases the specific pavement parameters, such as age, porosity, and aggregate size, were not available to the acoustician. To provide comprehensive design recommendations for quieter pavement surfaces, pavement and acoustical engineers will need to work together to identify and link acoustical results to specific pavement properties and criteria. Much of this could come from the further development and analysis of the pavement inventory provided in Appendix A. Additional information to provide in the appendix could include specific pavement characteristics or inclusion of acoustical properties listed in FHWA's Long-Term Pavement Performance program (Federal Highway Administration 2017). These properties currently include information related to inventory, maintenance, monitoring (deflection, distress, and profile), rehabilitation, materials testing, traffic, and climate.

9.6 European Pavements

Through European pavement testing, two new pavement types of interest were identified; DLPA, which was found to be 1 to 2 dB quieter than the quietest pavements measured in the United States; and a porous rigid pavement, which was found to behave similarly to porous flexible pavement in the United States (Donavan 2006). Further research into these two pavement types may prove to be beneficial in the continued design of quieter pavement surfaces in the United States.

9.7 Parameter Study for SIP and CTIM

Extensive parameter testing for the development of the OBSI measurement method was conducted under the NCHRP 1-44-1 Project (Donavan and Lodico 2011). Similar testing needs to be conducted for the SIP and CTIM methods, focusing on field measurement, modeling, and analysis variability. This testing would allow researchers to compare results more easily and reliably and could result in more optimization of the measurement techniques.

9.8 Project Pavement Inspection Tool

The development of a project pavement inspection tool, which would take into account acoustical and structural properties of the pavement, could help state transportation departments to quantify the construction quality of a pavement, reduce variability within a given segment or pavement type, and identify sections of pavement that have reached the end of their life cycle and are ready for rehabilitation. With the ability to quantify a pavement's acoustical quality, state transportation departments could offer incentives for pavement contractors to improve tolerance and add acoustical pavement performance specifications.

9.9 Develop Even Quieter Pavements

Great advances have been made in the understanding and development of quieter pavement over the past 15 years. The knowledge that has been gained from recent research and development should be used to further advance quieter pavement technology by integrating more innovations and new technology.

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