



APPLIED RESEARCH ASSOCIATES, INC.

# Quiet Pavements Synthesis

October 2023

Task Order/Project No.: BED49 977-07

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## Quiet Pavements Synthesis

**Abstract:** With the expanded infrastructure and increasing traffic levels around residential and community areas around the city, highway noise pollution has been a growing and persisting challenge. Florida department of Transportation (FDOT) finds it necessary to investigate the recent advancements and upcoming research needs in the area of highway noise characterization and the impact of pavements and their effectiveness in reducing highway noise. The main objectives of this study were to find out the recent developments in highway noise, quiet pavements and to better understand the contributing factors, remedies, and the effects of highway noise pollution on the public. This white paper compiled the activities that have been performed during the study. This includes an extensive literature review; analysis of the data collected from FDOT; information collected during interviews with quiet pavement experts from different state highway agencies; and a gap assessment identified through literature review, data analysis and interviews. The main gaps identified in this study were: 1) establishing life cycle cost analysis procedures of noise barriers and quiet pavements; 2) identifying the level of serviceability and noise regulation; 3) understanding the aging of quiet pavements and reduced effectiveness over time; 4) identifying unified methods of quantifying pavement noise; 5) understanding the effect of texture on noise generation; and 6) understanding the friction characteristics of quiet pavements. Moreover, a proposed research roadmap with implementation steps is recommendations to FDOT. It is imperative to continue research and collaboration with experts, research institutions, and stakeholders to ensure the success of the noise mitigation strategy over time.

## 1. Introduction

With the expanded infrastructure and traffic levels around residential and community areas around the city, the importance of minimizing impacts from highway noise pollution has been a growing and persisting challenge. Although it is relative to the perception of different people of what can be considered noise, it can be generally defined as ‘unwanted sound’. Studies have shown that some of the most pervasive sources of noise in our environment are those associated with transportation. Highway noise pollution can have significant impacts on the drivers and the public living close to the highway. Studies have found links between noise pollution and overall mental and physical health, including depression, raised risk of heart attacks among people over 50, risk of obesity, and stress. To reduce noise pollution, Federal Highway Administration (FHWA) policies identify five approved highway traffic noise abatement options (FHWA 2011), with barriers currently being the primary method of abating traffic noise (Lodico and Donovan, 2018). However, while noise barriers are effective, they may not always be the best solution for reducing traffic noise pollution. Barriers can be costly to construct, requiring to be high enough and break the line-of-sight to be effective. Also, in areas with varying terrain and along arterial streets, their effectiveness can be reduced due to the gaps that are required to allow access to driveways and side streets (Lodico and Donovan, 2018).

Several studies have investigated the possibility of using “quiet pavement types” to help abate traffic noise induced at the tire-pavement interface, which can reduce the costs associated with noise barriers. In 2018, Arizona Department of Transportation (DOT) published a comprehensive report summarizing the studies and findings from the Arizona quiet pavement pilot program (Donavan and Janello 2018). In this program, studies were conducted periodically over 10 years to assess the benefits of Asphalt Rubber Friction Course (ARFC). The work involved the use of three types of testing methods to assess the potential of ARFC as a noise abatement measure: Type 1 examined tire/pavement noise at the source; Type 2 examined noise in residential neighborhoods near the freeways; and Type 3 evaluated noise using direct measures of traffic noise adjacent to the freeways. Sound absorption measurements were also made at specific sites at various times throughout the project. Type 1 measurements documented an average initial reduction of 8.7 dBA and an average increase of 0.5 dB/year afterward. The Type 2 measurements revealed an average initial reduction of 5.2 dBA, while the Type 3 measurements showed an average initial reduction of 9.1 dBA and an average increase of 0.5 dB/year. In addition, Caltrans conducted an extensive study to develop a quick, portable, low-cost, and precise pavement acoustic measurement process, which has become an American Association of Highway and Transportation Official (AASHTO) Designation: T 360-16, Standard Method of Test for the Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method (Lodico 2018). In the study, it was found that 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.

In 2009 and 2014, Florida DOT (FDOT) published two reports investigating the sources of and some remedies for highway noise, as well as the equipment and methods used to collect data and perform the analysis to derive conclusions for both the on-board sound intensity (OBSI) method and concurrent wayside sound level measurements for multiple pavement types in Florida. The study provided a detailed assessment of the different noise levels associated with different pavement types in Florida. Moreover, the study investigated the correlation between different pavement variables and noise and concluded that three variables seemed to significantly correlate to noise: mean profile depth, aggregate size, and friction number.

Since then, there have been few, but significant, advancements in the area of highway noise nationally and internationally. With the growing highway network and traffic levels, the issue persists and can lead to significant costs if remedies such as noise barriers are implemented. Moreover, some studies have shown reasonable correlations between pavement characteristics and pavement noise and roadway noise (Kowalski et al. 2016, Teti et al. 2020). However, these correlations vary based on the data set, the measuring systems, and local practices. There is still a need to better understand the impact of various factors on the noise levels at the tire-pavement interface and roadway noise. Accordingly, there is a need to evaluate the advancements in this area of research and practice and reassess the available remedies and factors contributing to highway noise, focusing on the impact of pavement types and surface characteristics as a cost-effective parameter to help reduce highway noise.

## 2. Objectives

With the recent developments in the area of highway noise and the need to better understand the contributing factors, remedies, and the effect on the public. FDOT finds it necessary to investigate the recent advancements and upcoming research needs in the area of highway noise characterizations and the impact of pavements and their effectiveness in reducing highway noise. The objectives of this study were:

- To better understand and identify the potential factors, including pavement surface characteristics, affecting traffic noise and the contribution of these factors to the roadway noise generated by traffic.
- Identify and assess the available methods to reduce roadway noise and the benefits and limitations of the different methods in reference to quiet pavements.

## 3. Methodologies

The study was broadly divided into three tasks – a comprehensive literature review, data analysis with focused group interview to assess the research gaps, developing and providing recommendations through a white paper.

A detailed literature review delivered at the end of Task 1 made it obvious that quiet pavements have the potential in reducing traffic and roadway noise effectively and economically. However, there are major gaps in the literature in assessing the life cycle of quiet pavements and their effectiveness against other traffic noise abatement solutions. In Task 2, the OBSI and roadway data collected by FDOT in previous studies, and focused group interviews with the state highway agencies personnel were used to identify possible qualitative and quantitative benefits of different quiet pavement surfaces. Task 2 also presented an overall gap assessment based on the quantitative analysis and findings from the literature review and interviews.

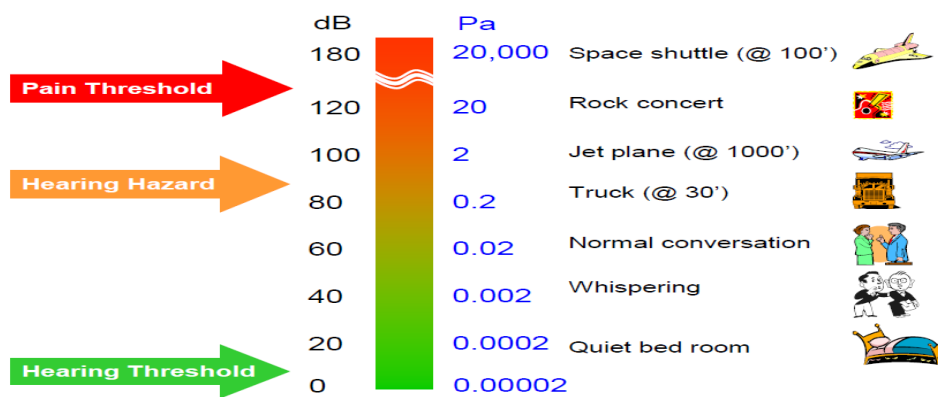
Task 3 includes a detailed summary on the technologies and methods to assess noise, the impact of pavement parameters on noise, and recommendations to FDOT through a whitepaper. The gaps identified through this study were prioritized based on their impact and feasibility. Future research needs and recommendations were also proposed for addressing the identified gaps, outlining research, development, testing, and implementation steps.

## 4. Literature Review

### 4.1 Fundamentals of Traffic Noise

Sound is a pressure wave propagating from the source to the recipient and can be characterized in terms of intensity ( $I$ ), which relates to the square of the pressure ( $P$ ) created by the wave through the relation  $I = P^2/R$ ; where  $I$  is measured in watts/m<sup>2</sup> and  $R$  is the wave impedance of air. For practical reasons, sound intensity is commonly measured in decibels (dB). This is a unit of measurement that indicates the relative intensity of a sound to a standard reference level ( $I_0$ ) on logarithmic scale as illustrated in **Error! Reference source not found.** and Equation 1 (Ohiduzzaman et al., 2016). The zero on the dB scale is based on the lowest sound level that the healthy, unimpaired human ear can detect (Lodico and Donovan, 2018).

$$I(\text{dB}) = 10 \log_{10}[I/I_0] = 10 \log_{10}[P^2/P_0^2] = 20 \log_{10}[P/P_0] \quad (1)$$



**Figure 1. Comparison of sound pressure, sound levels, and common examples**  
(Ohiduzzaman et al., 2016)

Since the dB scale depends on the pressure values, the scale should be modified to account for the human hearing perception, which filters very low and very high frequency components of the sound. To account for the human perception the A-scale has been developed to give a greater weight to the frequency response of the human ear and correlates well with subjective reactions to noise (Hanson and James, 2004). The term dB(A) is used when referring to the A-scale, which is more suitable for characterizing noise levels. **Error! Reference source not found.** presents Different types of outdoor and indoor noise levels on the dB(A) scale associated with various daily activities (Kandhal 2004, Lodico and Donovan 2018, Hanson and James 2004).

**Table 1. Noise Levels Associated with Various Daily Activities.**

Common Indoor and Outdoor Activities	Noise Level (dBA)
Threshold of pain	140
Rock band	110
Jet fly-over at 1000 feet	105
Gas lawn mower at 3 feet	95
Loud shout	90
Diesel truck at 50 feet at 50 mph, food blender at 3 feet, motorcycle passing 50 feet away	85

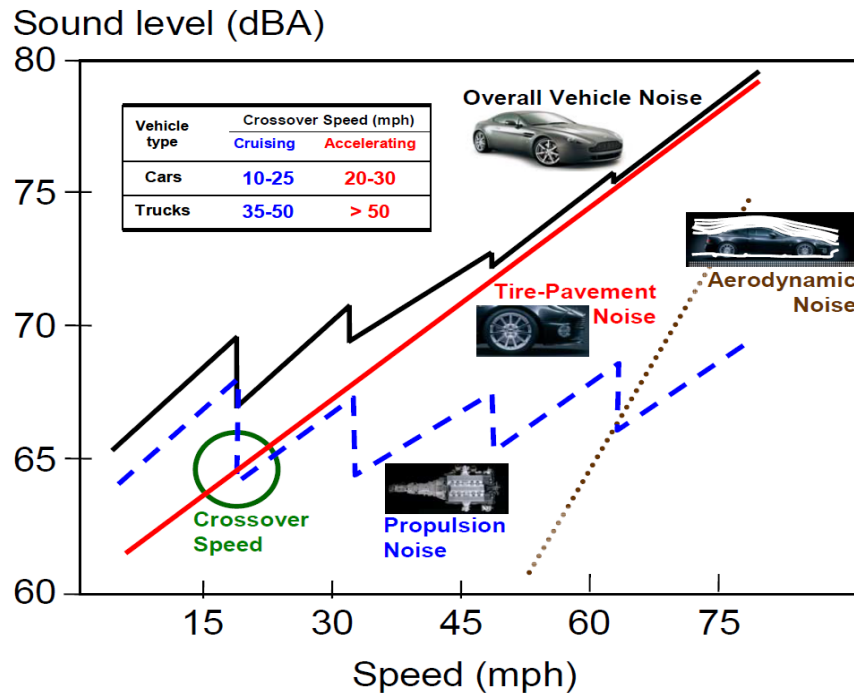
Common Indoor and Outdoor Activities	Noise Level (dBA)
Garbage disposal at 3 feet, car traveling 60 mph passing 50 feet away	80
Noisy urban area, daytime	75
Gas lawn mower at 100 feet, vacuum cleaner at 10 feet	70
Commercial area, normal speech at 3 feet	65
Heavy traffic at 300 feet, normal conversation	60
Large business office	55
Quiet urban daytime, dishwasher next room	50
Quiet urban nighttime, theater, large conference room (background),	40
Quiet suburban nighttime	35
Library	30
Quiet rural nighttime, bedroom at night, concert hall (background)	25
Broadcast/recording studio	15
Lowest threshold of human hearing	0

Depending on the perception of the human ear, the transition from a peaceful environment to a noisy environment is around 50 to 70 dBA. Studies have shown that continued exposure to noise levels in excess of 65 dBA can have negative health effects and noise levels in excess of 80 dBA, which are zones where majority of the traffic related noise lies, can be a hearing hazard (Hanson and James, 2004; Ohiduzzaman et al., 2016). The noise level alongside a freeway can be in the range of 70 to 80 dBA (Kandhal, 2004), which is considered as a primary source of noise pollution (Smit et al., 2016). Highway noise pollution can have significant impacts on the drivers and the public living close to the highway, particularly in urban areas where the population density near major thoroughfares is high and there is a large volume of commuter and commercial traffic. Studies have found links between noise pollution and overall mental and physical health, including depression, raised risk of heart attacks among people over 50, risk of obesity, and stress (Berglund et al., 1999). In addition, traffic noise may create difficulties in speech communication, suppress real estate values, and cause the stagnation of economic expansion due to public resistance to expand highway capacity (Bernhard et al., 2005). Realizing the increasing threat associated with highway traffic noise pollution, the United States Code of Federal Regulations Part 772 (23 CFR 772), "Procedures for Abatement of Highway Traffic Noise and Construction Noise," establishes standards for abatement of highway traffic noise (FHWA, 2011). Although quiet pavements are not included in the recommended traffic noise abatement procedures by FHWA, quiet pavements have been explored by several US and international agencies as will be discussed in the following subsections. This concise but critical literature review focuses on the advancements and gaps in the research and practice areas of quiet pavements. The literature review focuses on assessing the factors contributing to highway noise, such as the impact of pavement type and surface characteristics, and the cost-effectiveness of quiet pavements compared to other remedies.

## 4.2 Tire-pavement Noise Sources & Influences

Traffic noise is usually generated from three distinct sources - propulsion, tire-pavement, and aerodynamics. Propulsion noise dominates the total noise at very low speeds. As speed increases, a crossover speed is reached at which the tire-pavement noise becomes the dominant source. Only

at very high speeds will aerodynamic sources begin to dominate. **Error! Reference source not found.** shows the relative importance of the three primary sources and traffic noise levels at different speeds (Rasmussen et al., 2007).



**Figure 2. Speed effects on vehicle noise sources and crossover speed (Rasmussen et al., 2007)**

Since most highways have prevailing speeds in the middle range, tire-pavement interaction is the predominant source of highway noise pollution. When a tire is rolling on a pavement surface, a number of noise generation mechanisms work in conjunction to generate and amplify noise (Sandberg and Ejsmont, 2002). Noise generation mechanisms can be primarily categorized into two modes. The first one is the structure borne which is directly related to mechanical vibrations of the tires and referred to as source generation, and the second one is air-borne which is related to the aerodynamic phenomena at the tire-pavement interface and referred to as the sound enhancement mechanism. This section will focus on the tire-pavement noise generation mechanisms and other factors that influence and amplifies the generated noise.

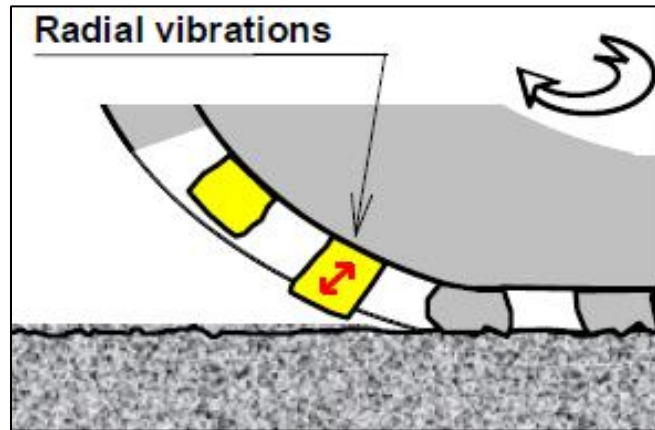
#### 4.2.1 Mechanisms Generating Tire-Pavement Noise

According to different researchers, the following factors are most influential for tire-pavement noise generation mechanism.

##### Tread Impact

This is the first sound mechanism that occurs when tire tread blocks hit the pavement causing vibration in the tire carcass as shown in **Error! Reference source not found.** When rolling tire treads travel circumferentially along the pavement, they individually hit the contact patch of pavement resulting in hundreds or even thousands of impacts each second, with each impact generating sound energy (Lodico and Donovan, 2018). Tire treads vibration is mainly affected by

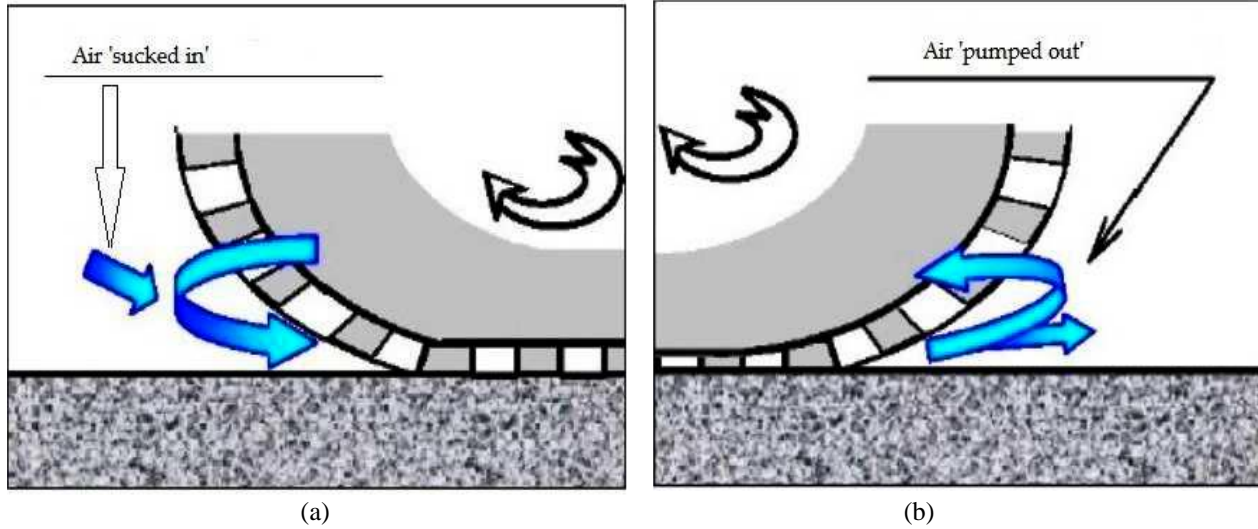
surface macrotexture. This noise mechanism is also affected by the mechanical impedance of pavement but to a lesser extent (Ohiduzzaman et al., 2016).



**Figure 3. Tire tread block/pavement interaction (Sandberg and Ejsmont, 2002)**

### Air Pumping

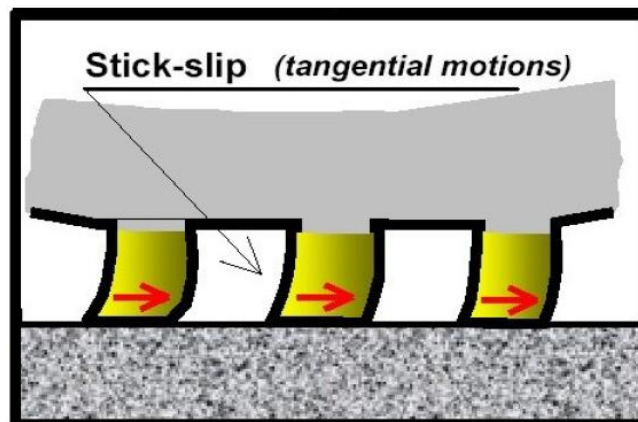
Small air gaps or pockets are located between the tire tread and pavement texture. The air pumping mechanism occurs when air is pumped or compressed at the contact patch between tire and pavement as shown in **Error! Reference source not found.** (Lodico and Donovan, 2018). The entrapped air in the void spaces compresses and is pumped out as the tire loses contact with the pavement. Subsequently, sound is generated aerodynamically due to the air compressing and pumping effect (Ohiduzzaman et al., 2016). This process is similar to clapping or blowing a whistle, where much of the sound that is heard when air is being pushed away quickly through a small opening. The air pumping mechanism is influenced by the porosity and macrotexture of pavement (Ohiduzzaman et al., 2016).



**Figure 4. Air pumping mechanism (a) entrance; (b) exit of the contact patch (Ohiduzzaman et al., 2016)**

### Stick-Slip/Scrubbing

As the tire moves on the pavement surface, the tread blocks will adhere to the surface due to frictional forces and deform. When the horizontal forces due to deformation are greater than the frictional forces, the tread blocks will briefly slip before re-adhering to the pavement, which creates a high frequency sound as illustrated in **Error! Reference source not found.** (Bernhard et al. 2005, Ohiduzzaman et al. 2016, Lodico and Donovan, 2018). This noise mechanism is affected by the texture of all wavelengths whether the surface texture is positive or negative. Temperature has also a great influence on this noise mechanism as tire rubber friction changes with temperature (Rasmussen et al., 2007).



**Figure 5. Stick-slip mechanisms of sound under tread blocks (Rasmussen et al., 2007)**

### Stick-Snap

Sound from this mechanism occurs due to adhesion between tire tread blocks and the pavement surface as shown in Figure 6. The sticking tread block is released at the trailing edge of the contact patch, thus creating vibration which radiated as sound energy This phenomenon can be compared

to a suction cup behavior. This noise mechanism is influenced by both microtexture of surface and temperature. The adhesion mechanism is reduced in wet condition but increased in dry condition (Ohiduzzaman et al., 2016).

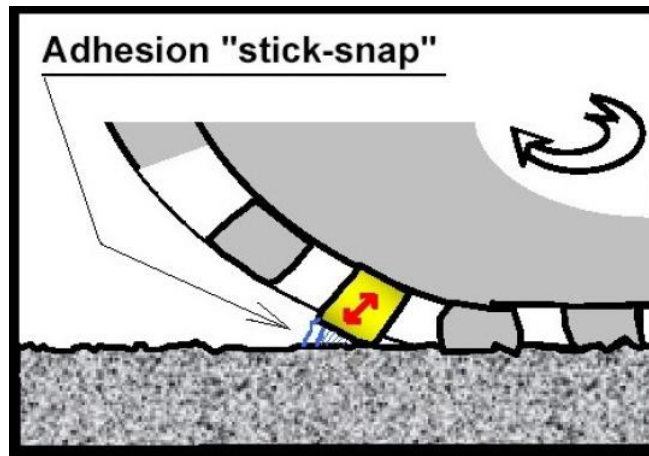


Figure 6. Stick-snap mechanism of sound under tread blocks (Bernhard et al. 2005)

### Acoustical Horn

This is a noise amplification mechanism that works in conjunction with noise source mechanisms. The geometry of a tire and a pavement in contact includes a wedge-shaped segment of open air which is similar to an acoustic horn (Lodico and Donovan, 2018). Multiple sound reflections may occur within this wedge shape segment that can be amplified due to the improved impedance matching between sound in the throat at tire-pavement interface and sound that radiated at the exit of the horn (Ohiduzzaman et al., 2016). This mechanism of natural horn is depicted in Figure 7 (Bernhard et al. 2005). This horn effect is reduced with increasing porosity and sound absorption properties of the pavement surfaces.

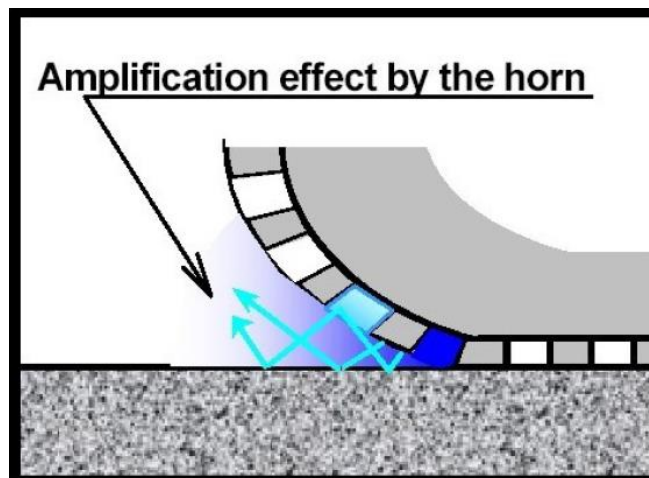
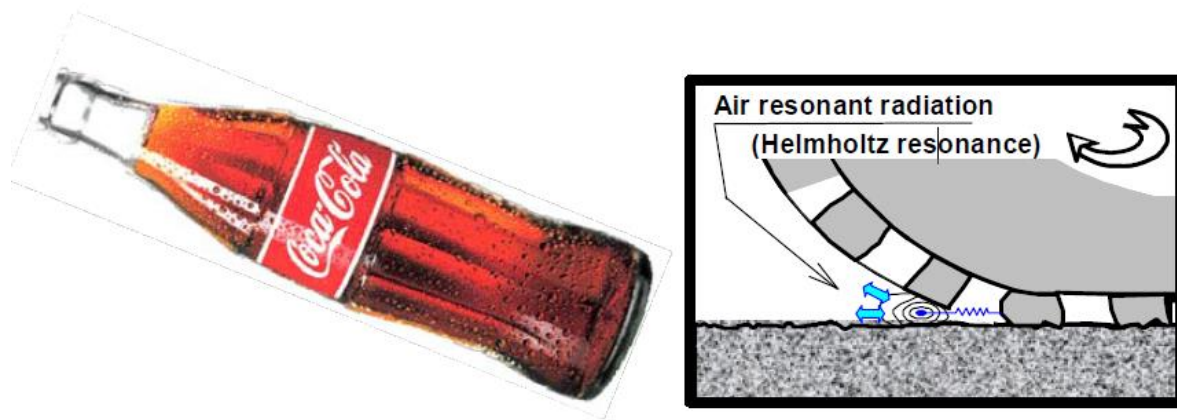


Figure 7. The acoustical horn effect created by the tire and pavement (Bernhard et al. 2005)

## Helmholtz Resonance

This is also a sound amplification process which occurs when a trapped volume of air is connected to the outside air via a pocket. This can be a resemblance to blowing of air across the top of a soda bottle as shown in Figure 8 (Rasmussen et al., 2007). In this mechanism, air in the neck of the bottle vibrates up and down on the pillow of air inside the bottle just like a spring (Lodico and Donovan, 2018), thus amplifying the noise at a frequency unique to that bottle (Ohiduzzaman et al., 2016). A similar geometry can be found close into the wedge of tire and pavement interface. The result is an amplification of some frequencies unique to the geometry of the tire and the pavement. This mechanism primarily amplifies the sound that comes from air pumping. Helmholtz resonance can be reduced by using porous or rough textured pavement as noise can move through the voids of pavement surface (Ohiduzzaman et al., 2016).



**Figure 8. Helmholtz Resonance or “The Pop Bottle” amplification mechanism (Rasmussen et al., 2007)**

## Pipe Resonance

It is a mechanism similar to air blowing across an organ pipe, where the amplified sound is unique to the length of the pipe and the number of openings in the pipe (Lodico and Donovan, 2018). Similar “pipe” geometries can be found as the various grooves and sipes on a tire as illustrated in Figure 9. As the tire rotates, the sipes of the tire tread are deformed forcing air out through these openings. The sound resonance occurs due to opening and closing of sipes while air is transferred through these sipes. Pipe resonance can be decreased by using porous pavement (Ohiduzzaman et al., 2016).

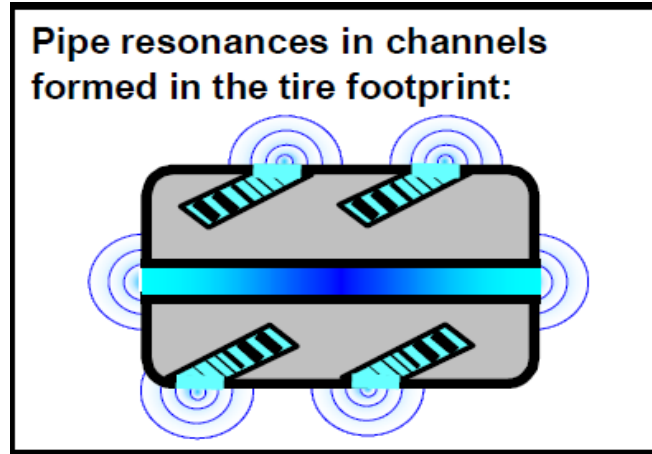


Figure 9. The pipe resonance amplification mechanism (Rasmussen et al., 2007)

### Sidewall /Carcass Vibrations

This amplification process is similar to an electric shaver or vibrating cell phone on top of an upside-down pie plate (Lodico and Donovan, 2018). The vibration energy generated at the tire-pavement interface is augmented by the response of the tire carcass. Vibrational waves propagate in the tread band, which is the structural element of the tire located adjacent to the tread blocks. These waves then create sound which is radiated and amplified from the tire carcass (Figure 10a) (Bernhard et al. 2005). In addition, the tire carcass sidewalls near the contact point vibrate and radiate sound as shown in Figure 10b.

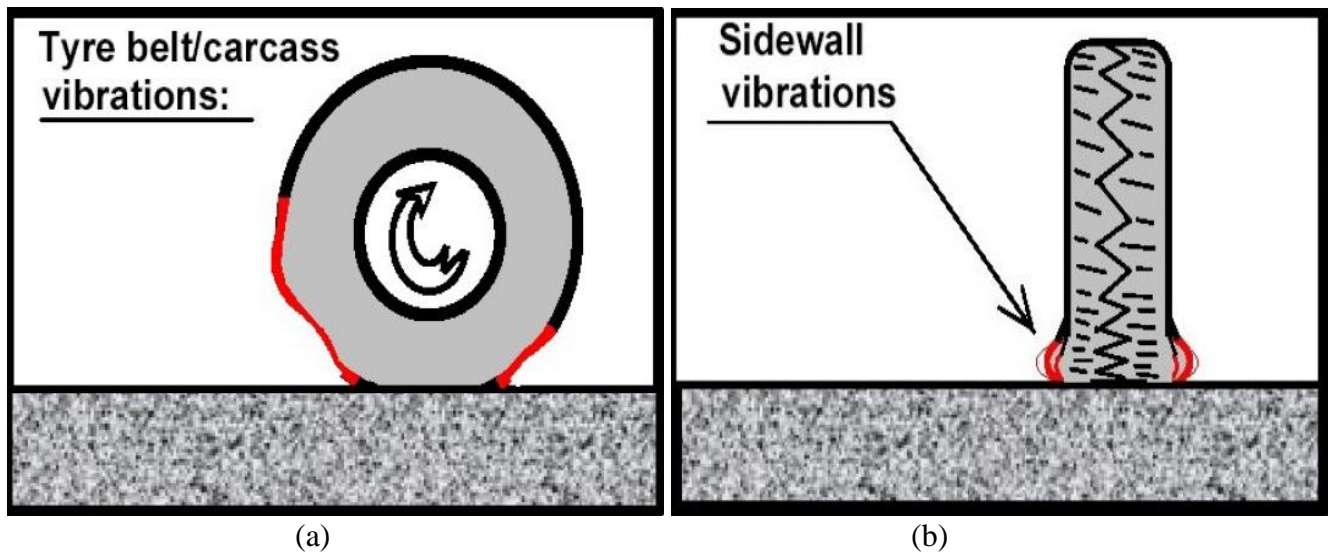
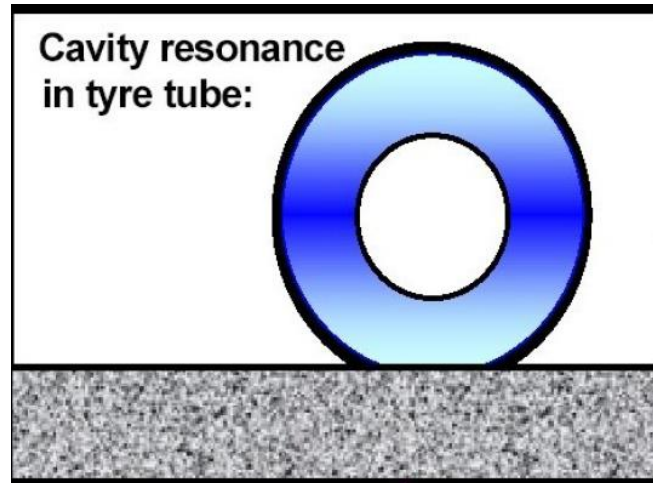


Figure 10. Vibration of the tire carcass (a) around the tread band and (b) at the sidewall of the contact patch (Bernhard et al. 2005)

## Cavity Resonance

When a tire comes in contact with the pavement, the air inside it gets excited and resonates at certain frequencies (Ohiduzzaman et al., 2016) as shown as Figure 11 (Bernhard et al. 2005). This is similar to the ringing sound heard when a balloon filled with air is thumped. This mechanism is more significant for sound inside the car than outside sound, as the vehicle itself tends to further amplify this frequency (Rasmussen et al., 2007).



**Figure 11. Amplification due to acoustic resonance in the air space inside the tyre (Bernhard et al. 2005)**

### **4.2.2 Influential Factors for Tire-Pavement Noise**

There are several factors affecting the noise after it is generated at the tire-pavement interface. Below is a summary of some of these factors and their influence on noise.

#### Effect of distance from source

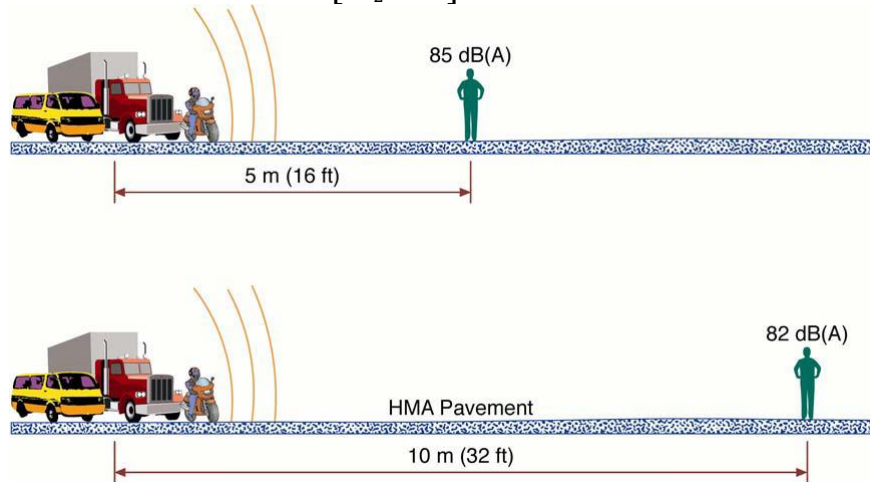
Distance between the source and the receiver is one of the most important factors affecting tire-pavement noise (Smit et al., 2016). According to the inverse-square law of acoustics, sound intensity is inversely proportional to the square of the distance ( $d$ ),  $I$  (watts/m<sup>2</sup>) =  $w_0/4\pi d^2$ ; where  $w_0$  is the power of the wave at the source. For instance, according to Equation 2 for a single point source like a blender, the attenuation factor is 6 dBA when the distance away from the source is doubled ( $20 \log_{10}[1/2] = -6$ ) and is 9.5 dBA at three times the distance ( $20 \log_{10}[1/3] = -9.5$ ).

$$\begin{aligned} I_2(\text{dBA}) - I_1(\text{dBA}) &= 10 \log_{10}[I_2/I_0] - 10 \log_{10}[I_1/I_0] = 10 \log_{10}[I_2/I_1] \\ &= 10 \log_{10} \left[ \frac{1/d_2^2}{1/d_1^2} \right] = 20 \log_{10}[d_1/d_2] \end{aligned} \quad (2)$$

However, roadway noise is considered a line source since noise is transmitted along the entire length of the roadway. For such case, as the distance from the source increases, the noise level decreases at a lower rate compared to single point noise source according to Equation 3 (Smit et al., 2016). For paved surfaces, the attenuation coefficient  $\alpha = 0$ , therefore doubling the distance would result in a 3 dBA reduction in the noise level. Therefore, if a point 16 feet from the center of the noise source (the center of the lane) of the roadway has a noise level of 85 dBA, then a point

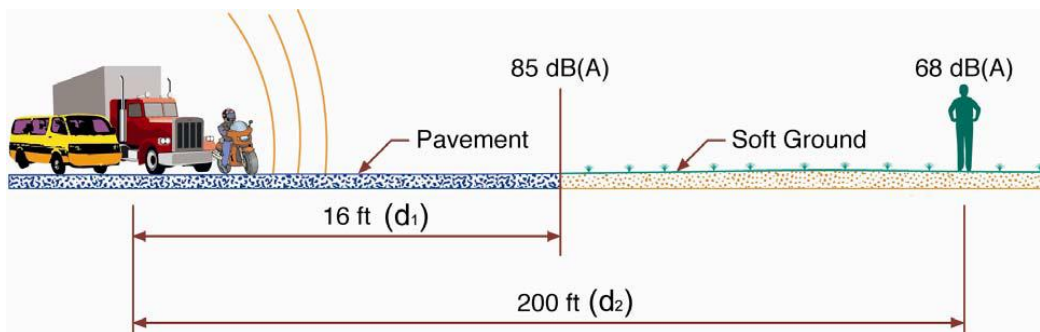
32 feet from the same spot of the roadway would have a noise level of 82 dBA as illustrated in **Error! Reference source not found.** (Hanson et al., 2004).

$$I_2(\text{dBA}) - I_1(\text{dBA}) = 10 \log_{10} \left[ \left( \frac{d_1}{d_2} \right)^{1+\alpha} \right] \quad (3)$$



**Figure 12. Effect of distance on a line noise source over a paved surface (Hanson et al., 2004)**

Attenuation of road noise based on the distance is also affected by the characteristics of the ground adjacent to the road. For example, if the noise level is 85 dBA at the edge of pavement which is at 16 feet (1/2 of a 12-foot lane plus a 10-foot shoulder) from the center of the noise source and a house is 200 feet from the roadway edge with soft ground between the roadway edge and the house, the noise level would be 68 dBA at the house as illustrated in Figure 13. In a rural environment, where the ground between the roadway edge and the receiver is soft and covered with vegetation the noise level would be further reduced due to absorption of the sound into the ground (Hanson et al., 2004).



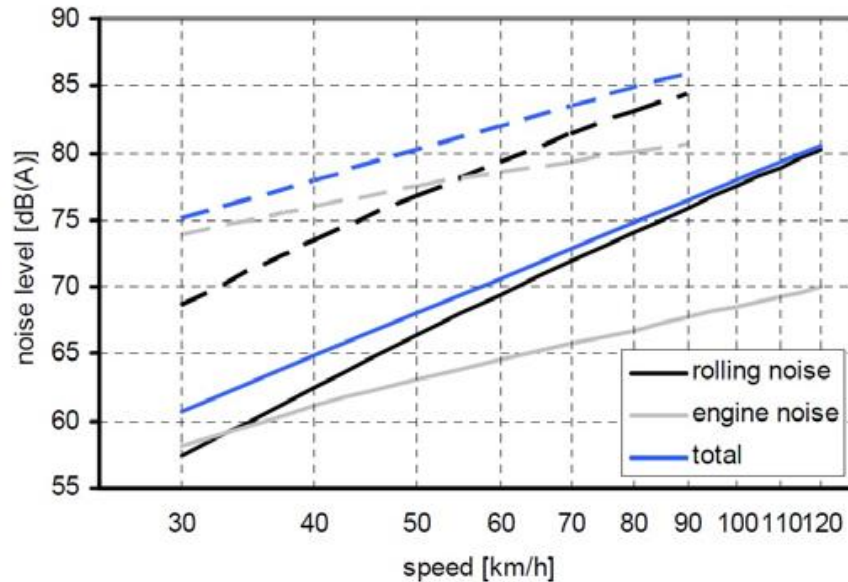
**Figure 13. Effect of distance on a line noise source over soft ground (Hanson et al., 2004)**

### Pavement layer thickness

Pavement thickness had a significant influence on noise reduction of porous pavements as reported by Smit (2008). In his study, Smit evaluated double layer Open-Graded Friction Course (OGFC) and Porous European Mixture (PEM), which performed well compared to the single layer OGFC and PEM pavements.

## Vehicle speed

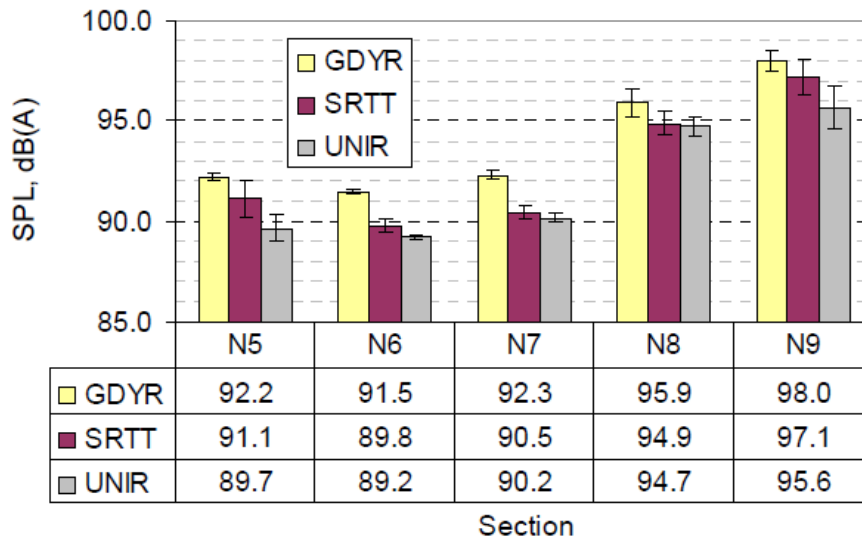
One of the most influential parameters that affect pavement noise is vehicle speed. Noise levels increase with vehicle speed almost all the time as shown in Figure 14. This also shows how tire-pavement or rolling noise is dominant over propulsion or engine noise for speeds of 35 and 50 km/h (20 and 30 mph) or higher for light vehicle (solid line) and heavy vehicles (dashed line), respectively. The contribution of propulsion noise in total traffic noise decreases with the vehicle speed while the share of pavement-tire noise continuously increases. For light vehicles, at a speed of more than 80 km/h (50 mph) propulsion noise is negligible. However, in the case of heavy vehicles the contribution of propulsion noise cannot be neglected even at higher speeds.



**Figure 14. Vehicle engine and road noise with speed (van Keulen and Duškov, 2005)**

## Tire type

Design and types of tires affect the level of noise generated. Road noise levels increase for heavy vehicles like trucks. National Center for Asphalt Technology (NCAT) tested three different tires at the same speed on test track sections constructed with various open-graded mixtures and found difference in noise levels as shown in Figure 15. The tires referred to in this figure are the Goodyear Aquatread, the Uniroyal TigerPaw, and the standard reference test tire (SRTT) and the noise is characterized using the A-weighted global sound pressure levels (SPL) in dB(A) (Smit and Waller, 2007a).



**Figure 15. Effect of tire type on sound levels (Smit and Waller, 2007a)**

### Temperature

Smit and Waller (2007b) investigated the effect of temperature on close proximity noise measurements on a variety of different surfaces, including dense-graded hot mix asphalt (DGHMA), porous friction courses (PFC), and stone matrix asphalt (SMA) at the NCAT test track with average air temperatures ranging from 50 to 85 °F. The temperature-frequency dependency of the sound levels differed for measurements above and below a selected reference temperature of 66 °F (19 °C). Overall, the influence of temperature on measured sound pressure levels (SPLs) was found to be practically insignificant. So, it is concluded that temperature correction of measured sound levels is generally not necessary when testing is done at temperatures ranging from 50 to 85 °F.

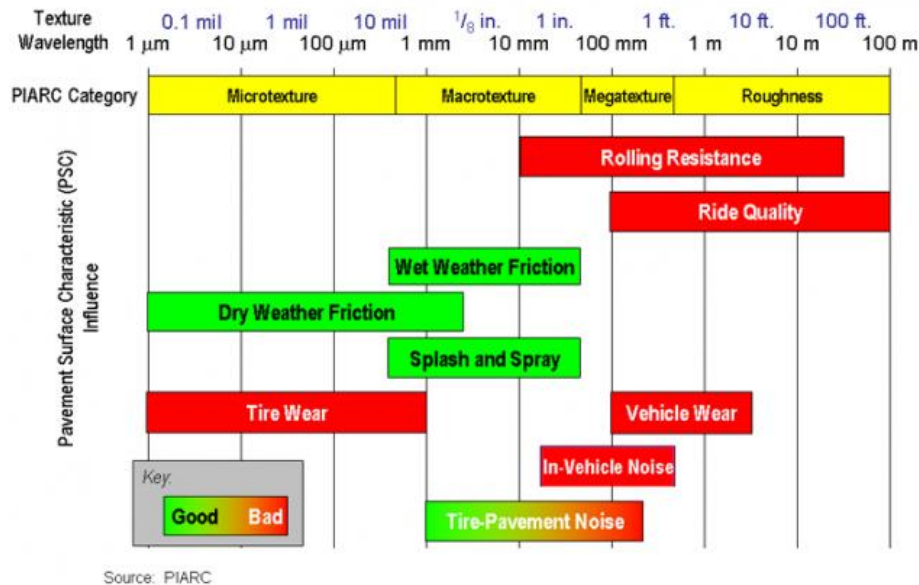
### **4.2.3 Effect of Pavement Surface Characteristics on Noise Generation**

The most dominant set of parameters affecting tire-pavement noise apart from the influence of vehicle speed is that associated with the road surface. The design and construction of the road surface can affect both the generation and propagation of noise (Smit et al., 2016). Studies have shown correlations between measured noise and multiple pavement surface characteristics such as mean texture depth, friction numbers, nominal maximum aggregate size (Wayson et al. 2009; Wayson et al. 2014). The principal factors related to pavement surface characteristics are listed below.

#### Effect of surface texture

Surface texture is generally considered the primary tire-pavement noise generator and has the most pronounced influence on tire-pavement noise, especially for dense-graded HMA and concrete pavements. Texture of a pavement surface can be categorized in terms of wavelengths. Surface macrotexture is defined in the wavelength band between 0.5 to 50 mm (0.02 to 2 in.) while surface megatexture lies in the wavelength band between 50 mm to 500 mm (2 to 20 in.), as shown in Figure 16. Tire-pavement noise is known to be influenced by both surface macrotexture and megatexture as shown in the same figure although it has been found in some literature that even the microtexture of the surface influences friction, which in turn may contribute to the slip-stick

effect at the tire-pavement interface (Smit et al., 2016). It has been also concluded from the research that pavements with very low surface macrotexture can be relatively quieter than other surfaces for truck tires, but opposite trend was found when passenger vehicle tires were used. The wider and deeper truck tire treads is believed to alleviate or reduce air pumping beneath these tires. Higher inflation pressure of truck tires also helps in reducing noise. Therefore, small height unevenness and a short spacing of road asperities are important for reducing truck tire noise. A large amplitude of macrotexture is also important for reducing noise from the wide lateral grooves of truck tires (Smit et al. 2016, Fujikawa et al. 2006).



**Figure 16. Influence of texture on surface characterization (Smit et al., 2016)**

Researchers have deployed different techniques like surface texture profiles based on texture spectrum (Sandberg 1992, Anfosso-Lédée and Do, 2002) and surface profile envelops based on empirical (Meier et al., 1992) and complex models (Klein and Hamet, 2004). Among all these methods surface profile enveloping showed a better correlation of texture and noise spectra (Smit et al., 2016).

### Effect of surface porosity

Porosity of the surface is a measure of the voids in the surface mix that are open to the air. Porous surfaces help to reduce road noise by propagation and sound absorption and increasing the porosity of the surface alleviates the compression and expansion of air trapped in the tire treads. Thus, porosity reduces the noise generated by aerodynamic mechanisms and also helps in diminishing the horn effect (Smit et al., 2016).

### Effect of surface stiffness

Surface stiffness can be referred to as the mechanical impedance of the surface and is also associated with noise generation relating to tire impact mechanisms. A relationship between the mechanical impedance and stiffness was developed (Mingliang, 2013) and it was shown that the mechanical impedance is linearly related to the logarithm of the resilient modulus. So, to lower the noise level an effective way would be to reduce the mechanical impedance is by using low

stiffness materials, such as poro-elastic materials. Conventional HMA mixture cannot produce low mechanical impedance layers but materials with more viscous behavior can provide a greater noise dampening effect, leading to less tire-pavement surface noise. Viscoelastic properties including dynamic modulus and phase angle of the HMA mix were identified as potential pavement noise discriminating parameter. Open and gap graded mixtures with asphalt rubber binder performed quieter than other HMA mix (Biligiri and Kaloush, 2007).

### Effect of surface type

Pavement noise can be generated differently based on the surface type whether it is an asphalt or a concrete pavement. For a HMA pavement noise level depends on the surface texture that can be dictated by the mix design. Whereas, for a Portland concrete cement (PCC) pavement the noise level fluctuates based on the surface finishing or types of tining construction (Smit et al., 2016).

## **4.3 Tire-pavement noise measurement techniques**

Since the early 2000s there is a growing recognition that selective pavement surfaces can be an effective road traffic noise abatement tool. IN addition, there has been a growing need to better understand the noise generation mechanisms as well as accurate measurement of tire-pavement interaction noise (Lodico and Donovan, 2018). The data collected from the measurement techniques will not only be helpful to characterize tire-pavement noise generation for existing and experimental highway surfaces but also will be used in developing and validating traffic noise model (TNM) to predict the future acoustical performance of quieter pavements (Ohiduzzaman et al., 2016). Significant research efforts have been established to develop accurate tire-pavement interaction noise measurement methods and based on these noise measurement techniques can be broadly divided into three categories - wayside noise measurement methods, measuring noise at source (i.e., onboard measurement methods), and laboratory noise measurement methods.

### **4.3.1 Wayside Noise Measurement**

This measurement technique involves measuring the existing traffic, individual roadway vehicles, or control vehicles noise using microphones that are placed at a certain distance from the center line of the driving lane (Ohiduzzaman et al., 2016). Usually, traffic noise from all sources such as tire-pavement interaction noise, aerodynamic noise, and power unit noise are captured by this technique. Below are the most commonly used wayside noise measurement techniques.

#### FHWA Procedure for Highway-Related Noise Measurement

FHWA outlined a detailed pavement noise measurement and analysis instrumentation, site selection, measurement procedures, and data reduction and analysis techniques for highway noise practitioners and researchers across the nation (Lee and Fleming, 1996). The document describes procedures for performing noise measurements in the vicinity of highways. The procedures can be used for establishing an overall sound level for the purpose of assessing noise impact of a nearby highway and quantifying the change in sound levels along a highway segment prior to and upon completion of a project (Lodico and Donovan, 2018). The method involves using 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. Traffic and meteorological data are also collected simultaneously with the noise data collection. Sampling periods are recommended based on the temporal nature of the traffic noise source. This method was meant to be applicable on highways with continuously flowing dense traffic but does not allow for site-to-site comparisons (Lee and Fleming 1996, Lodico and Donovan 2018).

## Statistical Pass-by Method

The Statistical Pass-by Method (SPB) follows an ISO standard (ISO 11819-1) that utilizes a random sample of typical vehicles selected from a traffic stream under constant or nearly constant speed and compares traffic noise on different road surfaces for various compositions of road traffic for the purpose of evaluating the acoustic performance of different road surface types. The method specifies that a roadside microphone should be positioned at 25 ft (7.5 m) from the center line of the vehicle travel lane at a height of 4 ft (1.2 m) above the surface. Statistically significant sample size should be at least 180 vehicles made up of 100 passenger cars and 80 dual/multi-axel trucks. The maximum sound pressure level is captured using a sound level meter for each pass-by event (Ohiduzzaman et al., 2016). The setup is illustrated in Figure 17.

The speed and vehicle type of each event is also recorded. The data are used to compute a statistical pass-by index (SPBI) which is used to compare various pavements. Analyzing the data help to classify pavement surfaces in typical and good condition according to their influence on traffic noise (surface classification) and also to evaluate the influence on traffic noise of different surfaces at particular sites irrespective of the condition and age of the pavement. One limitation of the method is that this method is applicable to traffic travelling at constant speed under free-flowing conditions of 35 mph (50 km/h) and upwards. Individual pass-by events are measured and analyzed statistically (Lodico and Donovan, 2018).



**Figure 17. Wayside pass-by measurement apparatus (Ohiduzzaman et al., 2016)**

## Statistical Isolated Pass-by Method

To be able to examine the effects of various pavement types in the USA with a wayside procedure, elements of the aforementioned methods which are the FHWA procedure and ISO SPB were combined as a new American Association of State Highways and Transportation Officials (AASHTO) standardized pavement noise measurement technique known as Statistical Isolated Pass-by (SIP) method (AASHTO TP-98). SIP method includes measurement of the maximum A-weighted sound pressure levels and vehicle speeds of a statistically significant number of individual vehicle for each desired vehicle classification at a specified roadside location, as shown in Figure 18 (Lodico and Donovan, 2018). This method uses the average pavement data from a national database as a reference in order to compare results. The AASHTO standard supports for placement of two microphones, one is at 25 ft (7.5 m) with height of 5ft (1.5 m) and the other one

at 50 ft (15 m) with height of 12 ft (3.7 m). If there are any site restrictions, either of the defined microphone positions can be used. The standard recommends a sample size of 100 vehicles for each category, with a minimum requirement of 30 vehicles (Ohiduzzaman et al., 2016). However, this process is strictly localized and required large sample size in order to predict long term noise performance of pavements.



**Figure 18. SIP measurement setup statistically (Lodico and Donavan, 2018)**

### Controlled Pass-by Method

The principle of this controlled pass-by (CPB) method is similar to the SPB method but with a relatively small sample size like a single vehicle or a few selected vehicles. In this method, the noise generated from a single vehicle is measured at a constant speed with the engine running at normal condition for the test speed. Only France has adopted a national standard among all the European nations that specifies this method (NF S 31-119-2). The main drawback of this method is that it cannot be used for high traffic levels and hence used less frequently throughout the world (Bernhard et al., 2005). In the USA, Marquette University conducted this type of testing for the Wisconsin Department of Transportation (Kuemmel et al., 2000).

### Continuous-Flow Traffic Time-Integrated Method

With the increasing traffic volume on highways, measuring noise by using SPB, SIP, or CPB is becoming more and more difficult. So, the FHWA procedure was modified, and the Continuous-Flow Traffic Time-Integrated Method (CTIM) was developed 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 procedure contains specifications for both sound 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 ages. A preferred reference position is specified at a distance of 50 ft (15.25 meters) from the center of the near travel lane and at least 5 ft (1.5 meters) above the elevation of the ground surface. Additional positions are described and recommended as needed. Measurements are conducted over a fixed 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 (Lodico and Donovan, 2018). Figure 19 shows a typical CTIM setup.



**Figure 19. CTIM measurement setup (Lodico and Donovan, 2018)**

### **4.3.2 Noise Measurement at the Source**

This technique of measuring noise at the source which is measuring noise near tire is considered to be more accurate than a wayside measurement for isolating the effect of pavements on tire-pavement source noise (Ohiduzzaman et al., 2016). Two types of measurement techniques are used all over the world for noise measurement at the source:

#### On-Board Sound Intensity Method

After the innovation of the sound intensity (SI) technique in the 1970's, different researchers tried to capture the tire-pavement interaction noise which will not be affected by nearby traffic sound or sound from other sources such as nearby industry or construction related noise. Since the SI is a vector quantity, it allows for localizing the noise sources, filtering background noise, and detecting the propagating energy in the acoustic near field. With these traits, it possible to measure the sound within normal traffic conditions by using SI technique. Based on this theory the On-Board Sound Intensity (OBSI) Method was originally developed by General Motors for research purposes only. Later Rasmussen (1990) developed the method using a face-to-face microphone configuration near the leading and trailing edges of a tire contact patch and using time domain approach while analyzing data. Since then, OBSI measurement technique was gradually refined under sponsorship of Caltrans and now standardized under AASHTO TP76-13. The standard (AASHTO TP76-13) specifies two pairs of phase-matched microphones which are placed at both the leading and trailing edges of the tire. If a single pair of microphones is used, then the pair of microphones should be positioned in the leading edge of tire first and complete the valid run. Then the microphones are moved and repositioned to the trailing edge and the procedure is repeated

(Ohiduzzaman et al., 2016). Figure 20 shows the OBSI testing arrangement with two different configurations.



(a)

(b)

**Figure 20. OBSI testing set-up (a) Horizontal configuration (single probe); (b) Vertical configuration (dual probe) (Wayson et al., 2009)**

The OBSI method includes calculating SI levels 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 **Error! Reference source not found.b** 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. 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 (Sohaney, 2011). 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 (Lodico and Donovan, 2018).

Wayson et al. (2009) reported the development and use of OBSI test rig to measure noise and compare it to wayside noise measurements on 22 locations in Florida. The study concluded a general first order approximation between the wayside SPL to OBSI Sound intensity levels as shown in Equation 4.

$$\text{Wayside SPL [dB(A)]} = \text{OBSI Sound Intensity Level} - 32.5 \quad (4)$$

The uncertainty, considering 2.15 standard deviations in the positive and negative direction (practical limits of Gaussian distribution) was  $\pm 3.5$  dB(A) for that first order approximation. In a follow up study, Wayson et al. (2014) included more than 50 test locations to improve the correlation between the OBSI and wayside noise measurements. The study reported that the difference factor  $\Delta$ , which was 32.5 in the first study, is correlated to multiple factors including the friction number (FN), mean profile depth (MPD), and percent aggregate at No. 4 screen (AG4)

as illustrated in Equation 5. This enhancement reduces the uncertainty to a residual standard error of 1.0 dB(A) and improved the  $R^2$  to 0.73.

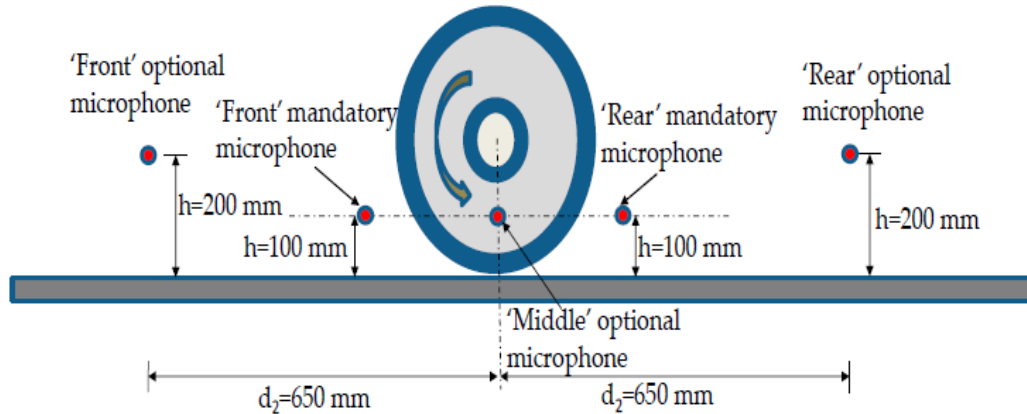
$$\Delta = 32.57 + 0.0349(\text{FN}) + 18.094(\text{MPD}) - 0.0493(\text{AG4}) \quad (5)$$

### Close Proximity Method

The close proximity method (CPX) was originally developed in Europe and defined by ISO standard 11819-2 to measure the tire–pavement noise at the source (ISO-11819-2). In this method, a test tire is mounted within a specially designated trailer that is towed by a passenger car as shown in Figure 21. SPL is measured by two microphones placed at specified points adjacent to the tire. Microphone positions near the test tire according to the ISO Standard (ISO-11819-2) are shown in Figure 22. The microphones are protected from airflow noise contamination by the trailer surrounding the test tire. The measurement is performed along the traffic stream with noise level measured as an average over a certain time interval, usually multiplier of 60 seconds. This method is relatively simple and minimizes affects from noise generated by other traffic due to the position of microphone inside the enclosed chamber. However, this method does not take into account the variation of traffic which is typical for continuous traffic. Manufacturing a specially designed CPX trailer is also costly. In addition, this method is performed with a relatively small set of tires and only one weight is used (Ohiduzzaman et al., 2016). Researchers also compared between the OBSI and CPX systems and preferred the OBSI test method due to slightly better correlation between OBSI and pass-by data and lack of spectral distortion seen in comparing OBSI and pass-by data (Lodico and Donovan, 2018).



**Figure 21. NCAT CPX trailer (Hanson et al., 2004)**



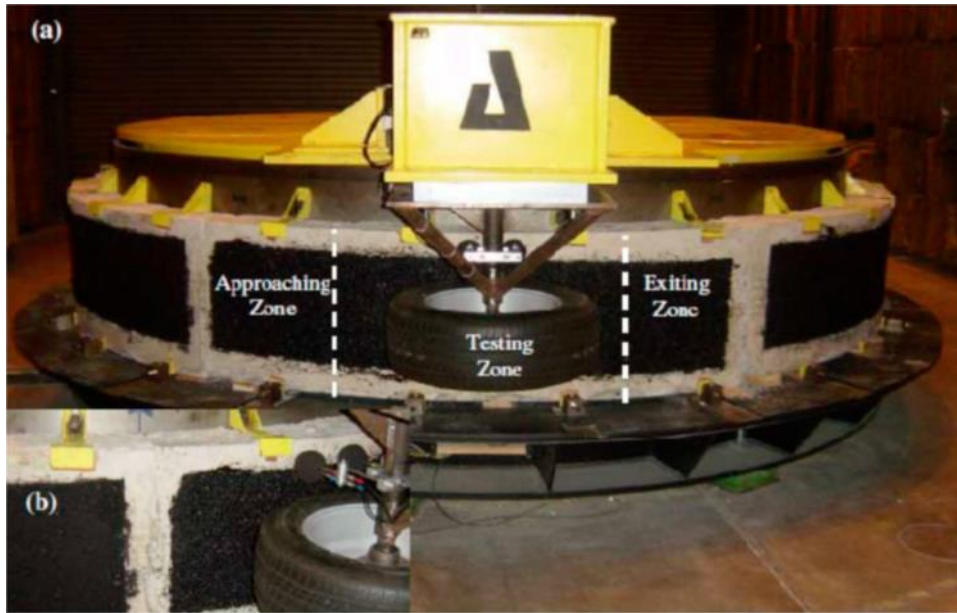
**Figure 22. Diagram showing microphone position according to ISO standard (ISO-11819-2)**

### 4.3.3 Laboratory Noise Measurement Methods

High precision noise measurement technique is required sometimes, especially for research purpose which can be difficult to get from the aforementioned noise measurement methods. The following two methods are often used in the laboratory.

#### Laboratory Drum Method

This method is used in the laboratory to assess tire-pavement interaction noise after isolating small differences in noise emission. The test setup includes a test tire that is mounted on a drum (typical 1.5 m–2.5 m in diameter) and one or more microphones that are placed close to the test tire with positioning similar to that of the CPX method. Test method includes the drum equipped with a surface that resembles an actual test surface to get proper data. This technique can also be used for testing of durability and friction of a pavement. This method does not depend on weather conditions, which is not the case for most of the other field noise measurement testing methods. However, background noise from the drum power unit is an issue and needs special precautions. Figure 23 represents the setup of drum method.



**Figure 23. Laboratory tire-pavement noise testing apparatus (Kowalski, 2007)**

### Acoustic Array Technology Method

This is another source measurement of tire-pavement interaction noise primarily used in the research domain. Measuring sound using acoustic array technology (AAT) can be different based on the basic theory of array procedure which are - Nearfield Acoustical Holography (NAH), temporal array techniques, and an Inverse Frequency Response Function technique (IFRF). NAH employs a 2-dimensional Fourier Transform to compute a 3-dimensional acoustic field inferred from 2-dimensional sound pressure measurements. Temporal array methods sum an array of microphone signals which have been shifted with appropriate source-to-microphone time delays. The IFRF technique reconstructs operating source inputs at discrete locations using the FRFs pre-measured by acoustically exciting at those locations. Each acoustic array technique has its own advantages and limitations which best suit it to particular applications. No one technique is best for all operating test conditions and each method may be modified or further developed (Blough and Wang, 1995).

### **4.3.4 Noise Prediction Models**

One of the goals of highway noise research is to build an accurate and robust model by which state highway agencies and other transportation authorities can properly predict highway traffic noise level. Proper understanding of a noise prediction model requires in-depth knowledge about how different input parameters are measured and how changes in different pavement design parameters can affect the input data for noise prediction models (Dare et al., 2014). In this section, some of the well-known noise prediction models found in the literature are listed and discussed briefly.

### Community Noise Model

The community noise model (CNM) correlates traffic parameters (traffic volume, vehicle speeds and types), sound propagation parameters (distance between source and the observer) and road noise abatement parameters (grade separation, vegetation techniques, using noise barriers, etc.) in order to predict sound pressure levels in the vicinity of the highway (Kugler et al. 1974, Wayson

et al. 1999). Although this model showed good correlation between measured versus predicted results, it did not consider surface characteristics, which is considered one of the main contributors in highway-generated noises (Sirin, 2016).

## Nordic Models

Several Nordic countries (Sweden, Denmark, Norway, Finland and Iceland) introduced a common model in the 1970s for prediction of road traffic noise. This Nordic Model went through several modifications and was commonly adopted as TemaNord in 1996 for all the Nordic countries (TemaNord, 1996). This method gave accurate noise predictions compared to other methods. The main reason is that it included detailed road surface corrections. The addition of road surface corrections encourages the construction of surfaces that give lower traffic noise. However, this model does not give separate surface effects for cars and trucks directly but provides surface effects for mixed traffic. The reference surface was based only on an HMA surface. The latest version of the Nordic model is called Nord2000 (Jonasson and Storeheier, 2000).

## Rasmussen Model

A statistical model of predicting noise level based on the effect of pavement texture was proposed by Rasmussen (2009). In this model, the input data for a 3D texture profile were captured by the RoboTex line laser profiler while noise measurement was performed by using the OBSI method. For each type of pavement texture, a number of sections were included in the analysis. The surface texture characteristics included in the final correlation were the texture levels for third-octave band centered at a texture wavelength of 40 and 50 mm ( $L_{tx,40}$  and  $L_{tx,50}$ ) per ISO 13473-41, texture skew ( $Skew_{tr}$ ) in transverse direction (unitless) per ASME B46.1, and core roughness depth ( $R_{k,tr}$ ) in transverse direction in mm per ISO 13565-2. The final correlation is  $L_{OBSI(Aquatred,97 \text{ kph})} = 91.0 + 0.315(L_{tx,40} + L_{tx,50}) - 1.37 Skew_{tr} - 3.11R_{k,tr}$ . The correlation had a coefficient of determination ( $R^2$ ) of 0.57 and a standard error (SEE) of 0.6 dBA was reported without presenting specific number of pavements used and the range of the OBSI levels.

## Laboratory Noise Model

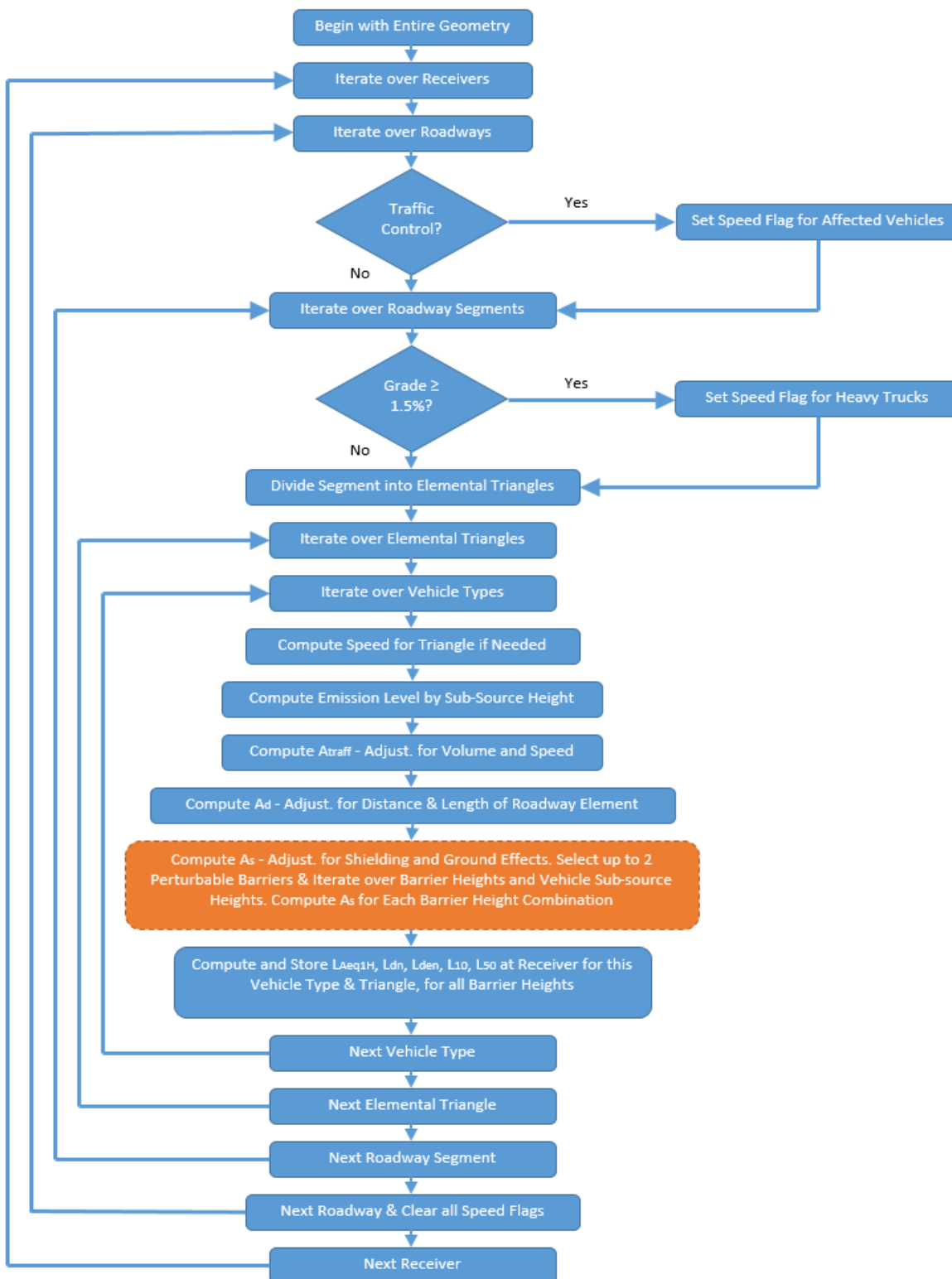
This model was developed based on the input parameters that are collected from laboratory pavement core samples and not from field test sections. The input parameters were mean profile depth (MPD) and airflow resistivity that were collected from the laboratory-controlled environment, so they are less influenced by environmental conditions (Reyes and Harvey, 2011). This model is one of the very few models where prediction of one-third octave band frequency data can be done. Although no standard error was reported for predicted noise, it presented a low coefficient of determination (Sirin, 2016).

## Tyre-Road Interaction Acoustic Simulation Model

Finite element and boundary element modelling methods were attempted by various researchers. Among them the Tyre-Road Interaction Acoustic Simulation (TRIAS) model was developed by Roo et al. (1999). It is a purely physical model that can predict tire vibration and noise emission. Two sub-models were developed later by following the TRIAS model which are Road Design Acoustic Simulation (RODAS) model, which generates the physical road surface characteristics (texture, porosity and sound absorption) from the material composition (aggregate size, binder content and layer thickness). The other sub-model is acknowledged as TYDAS (TYre Design Acoustic Simulation), which simulates model inputs from known tire parameters (Sirin, 2016).

### FHWA Traffic Noise Model

The traffic noise model (TNM) was developed by the U.S. Department of Transportation FHWA to predict noise levels in the vicinity of highways. It is mandatory to use the model in federally funded projects to determine whether noise barriers are needed (Menge et al., 1998). The preliminary version (TNM v1.0) has some limitations such as exhibiting similar relationships for two different types of pavements (Burge et al., 2002) and validation issues. TNM v2.5 addressed all the issues and a validation study showed good agreement on average between measured and predicted data (Rochat and Read, 2013). However, the site bias such as pavement type was affecting the prediction of sound level by TNM v2.5 (Rochat and Fleming, 2004). Later the FHWA TNM v2.5 was modified for research purposes to incorporate pavement effects. In the FHWA TNM v2.5, two sound sources are used to describe vehicle noise each vehicle type, with the lower-height source representing tire-pavement interaction noise. In this special version of the FHWA TNM v2.5, the lower source is isolated and adjustments due to pavement effects have been applied in the calculations for each one-third-octave band. Researchers compared the measured and predicted noise level for three surfaces, which include open graded rubberized asphalt, longitudinal tinned PCC and transverse tinned PCC. Results show that pavement-adjusted spectral shapes match more closely to measured spectra which indicated pavement effects can be incorporated in the FHWA TNM model by using an OBSI adjustment to the tire-pavement sub-source (Sirin, 2016). The only drawback of the FHWA TNM v2.5 was it was validated only for one type of car test tire therefore it is not fully representative for all vehicles and tire types of roads. Version 3.0 was released in the December of 2019 and an upgrade to that version TNM v3.1 was released very recently in 2022. The new upgrades include XML libraries, improved geospatial alignment, and optimized barrier analysis to incorporate cost (Hastings, 2019 and 2021). A simplified flow chart of the TNM computations is presented in Figure 24.



**Figure 24. High-level Flow Chart of TNM Computations with Horizontal Geometry Components are in Blue with Solid Outlines. Vertical Geometry Components are in Orange with Dashed Outlines. (Hastings, 2021)**

## 4.4 Noise Abatement Techniques

Current FHWA policy requires state highway agencies to conduct a highway traffic noise study early in the planning process before undertaking any major highway improvements. If the predicted highway traffic noise levels cause an impact, the highway traffic noise study must consider highway traffic noise abatement measures to reduce the highway traffic noise levels. Then if an FHWA-approved highway traffic noise abatement measure is determined to be feasible and reasonable, the highway agency must incorporate the noise abatement measure in the project design. The FHWA approved highway traffic noise abatement measures include creating buffer zones, constructing noise barriers walls, planting vegetations, installing noise insulation in buildings, private fencing and managing traffic. With the exception of noise insulation, the highway agency must maintain the noise abatement measure in perpetuity (FHWA, 2011).

On the other hand, researchers from the US and internationally have suggested that it is possible to design and build pavement surfaces that will provide low noise roadways, so-called quieter pavements. It has been demonstrated that modification of pavement surface type and/or texture can result in significant tire-pavement noise reductions. Highway agencies around the world have found that the proper selection of the pavement surface can be an appropriate noise abatement procedure. Specifically, it has been identified that a low noise road surface can be built at the same time considering safety, durability and cost using one or more of the following fundamental approaches (Smit et al., 2016):

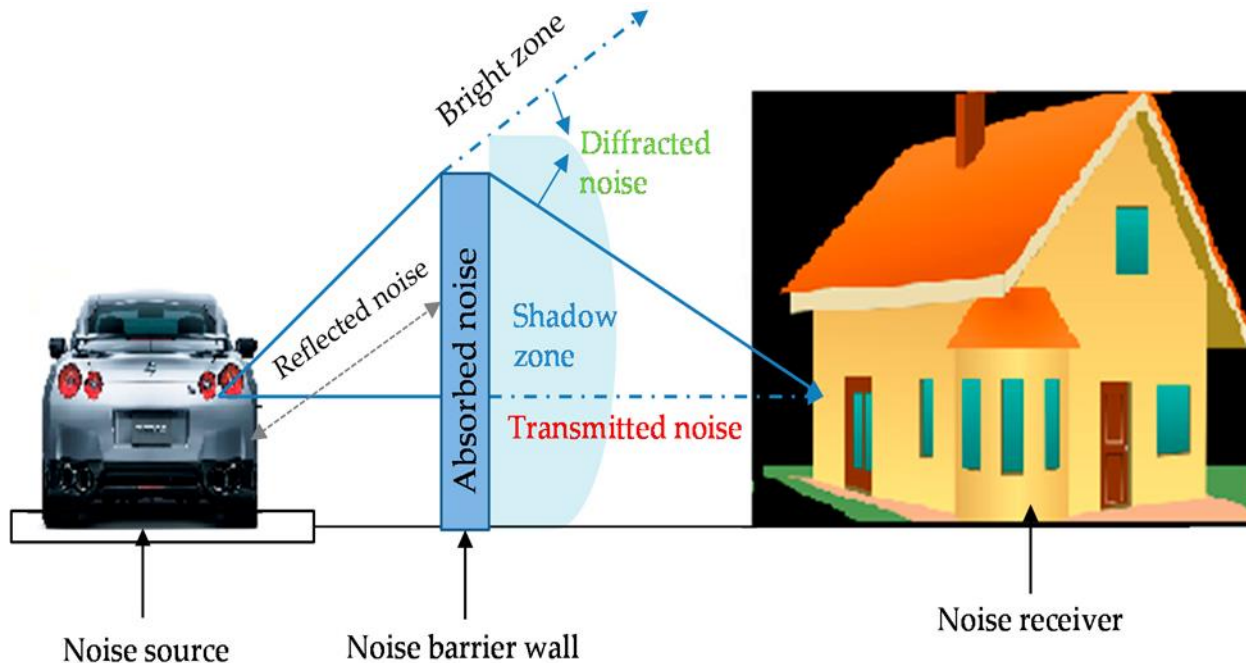
- A surface with a smooth surface texture using small maximum size aggregate
- A porous surface with a high air void content
- A pavement-wearing surface with an inherent low stiffness at the tire/pavement interface

### 4.4.1 FHWA Recommended Noise Abatement Techniques

#### Noise Barrier Wall

Noise barrier walls are one of the most commonly used mitigating solutions for noise abatement for a highway facility. It is also the only required noise abatement technique that should be considered while undertaking any Federal or Federal-aid projects. These are solid obstructions constructed between the highway and the receivers along the highway. Effective noise barriers can reduce noise levels by 10 decibels, cutting the loudness of traffic noise in half. When a noise barrier wall is placed in between noise source and receiver, it creates an acoustic ‘shadow zone’ which perceives a reduction of noise level (FHWA, 2011). Some part of the noise is also absorbed by noise barrier wall and some part of it reflected back to the highway. Still some portion of noise is transmitted and diffracted over barrier wall which reached to the receiver as shown in Figure 25. Generally, the noise reduction of barrier walls depends on the height of the wall and its placement between receiver and source. The thickness of barrier walls also plays an important role in noise reduction (FHWA, 2011). Noise barrier walls can be broadly divided into three major categories (Ohiduzzaman et al., 2016):

- Earthen berms along the road
- Solid vertical walls
- Combination of earthen berm and solid vertical walls



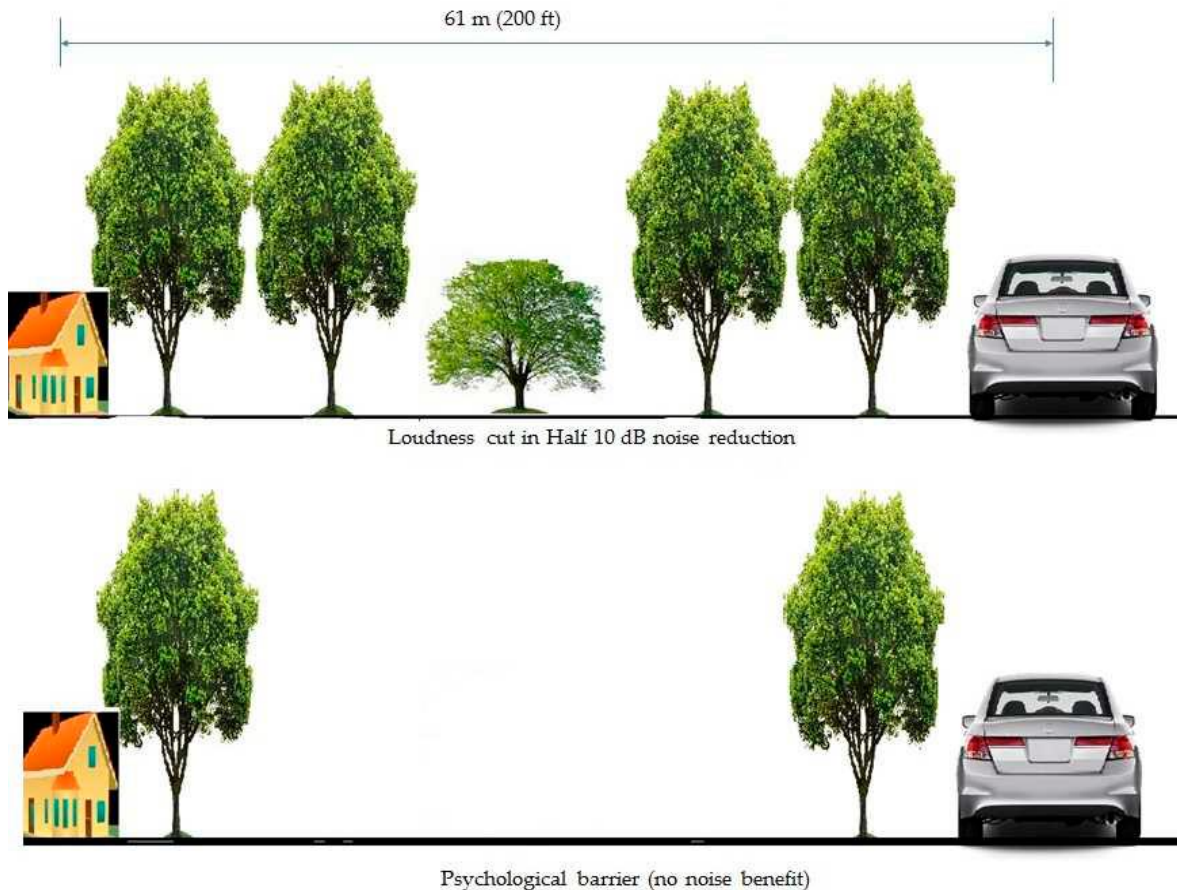
**Figure 25. Schematic showing noise distribution due to barrier wall (Ohiduzzaman et al., 2016)**

Earthen berms along the highway are less expensive, attractive due to its natural appearance and are environmentally friendly. However, they require large amount of land acquisition which is difficult nowadays. Solid vertical barriers can be constructed of wood, brick, concrete, steel, transparent materials etc. Concrete barrier wall is commonly used in various parts of world due to effectiveness in noise reduction. But it is also associated with a number of practical limitations such as high construction cost which may be up to 2.1 million dollar per mile making them less cost effective for low population areas (Hanson et al., 2004), emission of CO<sub>2</sub> during construction time and throughout the service life, location restriction like intersections or hilly areas, , and high acoustic reflectivity with limited sound absorption capability which may cause serious discomfort to drivers and passengers (FHWA 2011, Ohiduzzaman et al. 2016). Sometimes it is suggested to plant vegetations in between vertical wall and road so that noise can be dispersed before and after reflection from the noise barrier.

### Vegetation Technique

The reduction of sound due to vegetation can be achieved by the processes of reflection, scattering and absorption of noise. Amount of noise reduced through the process is dependent on the height of the trees and width of the vegetation belt. Noise abatement from vegetation is primarily dependent on the height of the trees and width of the vegetation belt. Generally, noise reduction tends to increase with tree height up to 32–40 ft, after that, any increase in tree height has an adverse effect on noise reduction. FHWA (2011) demonstrated that almost 10 dBA noise reduction can be achieved by providing 200 ft (61 m) dense vegetation. However, from a practical point of view, vegetation that wide is difficult to plant along the road. An effective vegetation belt is also dependent on the location of it between receiver and source. The vegetation belt is more effective when it is placed either relatively close to a noise source or close to the area to be protected. It is less effective when placed midway between the source and receiver. Usually, many years are

required for vegetation to mature to be effective; hence FHWA does not consider it as an effective noise abatement technique. Nevertheless, FHWA still encourages plantation of trees along highways because it provides favorable psychological effects to humans in addition to its environmental benefit. Figure 26 shows noise effectiveness and psychological effects of vegetation (Ohiduzzaman et al. 2016, FHWA 2011).



**Figure 26. Effectiveness of vegetation in noise reduction (Ohiduzzaman et al., 2016)**

### Buffer Zone

Buffer zones are underdeveloped, unused open spaces which are used to increase the distance between a highway and nearby neighborhoods. It has been seen that if the distance between the noise source and receiver increases, resulting noise will be reduced at the receiver. Therefore, FHWA (2011) sometimes recommends using a buffer zone as a noise abatement technique. When state highway agencies purchase land or development rights in addition to the normal right-of-way, they can prohibit any further construction in close proximity of the highway. Furthermore, it increases aesthetic beauty of the road which is always desirable for road users. Nonetheless, in this current economic situation, it is very difficult to acquire buffer areas because of excessive expense of land. In addition, in many cases personal land and dwellings close to highway borders already exist, and hence creating buffer zones is often not feasible (Ohiduzzaman et al., 2016).

## Private Fencing

Boundary walls or fencing around a house are generally provided for security and privacy reasons. These can provide a visual screen between source and receiver, although they may not provide noise benefit to inhabitants. Similar to vegetation, these walls or fences may provide psychological relief but should not be considered as an effective noise abatement procedure (FHWA, 2011).

## Insulating Materials

Insulating material and structures are very effective in reducing noise. So, for public or non-profit organizational structures such as places of worship, schools, hospitals, libraries, etc., sometimes use of insulation materials is considered by highway authorities. However, this noise benefit policy is exclusively reserved for public property only. As for private structures, owners are responsible for installing/constructing noise proof insulation. Also, air conditioning is usually required in conjunction with the insulating materials since proper noise reduction will be achieved only with closed windows; hence the overall cost of the project increases a lot. Therefore, use of insulating materials as a noise abatement method is less practiced by the transport authorities (Ohiduzzaman et al., 2016).

## Traffic Management

FHWA (2011) recommends that traffic management can be used as an effective method in reducing noise. There are a number of possible ways to use traffic management such as prohibition of trucks using certain streets and roads inside a residential zone, permission of trucks using roads and streets only during the daytime, providing efficient traffic planning and traffic lights to smooth movement of traffic, and reducing the highway speed limit if possible, which requires an approximate 20 mph decrease of speed to be effective. Most transportation authorities in the world are using traffic management as a noise abatement measure because of its effectiveness, as well as it being inexpensive (Ohiduzzaman et al., 2016).

### **4.4.2 Quiet Pavements Technique**

Researchers from all parts of the world especially Europe have shown that a modified pavement surface or mixture type has the potential to be used as an effective noise abatement technique for highways. Therefore, a large number of pavement surfaces have been constructed using modified mixture or surface properties following three major techniques to reduce tire-pavement interaction noise (Sandberg and Ejsmont, 2002):

- Optimized surface texture. Pavement surfaces with lower positive macrotexture can help reducing noise but there should be a balance or alternative textures (such as negative textures and enhanced microtexture) between surface texture smoothness and friction to ensure safety.
- Higher air voids mix so that air can move through the interconnecting voids and minimize the ‘horn effect’ mechanism.
- Softer pavement similar to the stiffness tire so that some of the tire deflection can be minimized. However, softer pavements can lead to additional complications related to pavement performance such as rutting.

In this section some of the most commonly used modified mixture /surface types to achieve quieter pavement are discussed.

## Noise Reduction on Asphalt Pavement

### *Porous asphalt pavement*

Although porous pavements are quite familiar since the 1960's due to their increased skid resistance in wet conditions, improved water draining capacity, and endurance against fatigue and rutting, the noise reduction benefits of porous asphalt were discovered in the mid-1980's (Crocker et al., 2004; Sandberg and Ejsmont, 2002). Generally, to call a surface porous it should have more than 10 % air voids and an open-graded friction course (OGFC) must have air voids greater than 15%. A number of researchers specified that an OGFC surface reduces noise significantly (3 dBA to 5 dBA) compared to a dense graded asphalt (DGA) surface (Sandberg and Ejsmont 2002, Hanson et al. 2004, Donovan and Rymer 2003, Hanson and Waller 2006). The air trapped between the tire and the pavement surface moves to void space available within the porous surface, thus reducing the 'horn effect' of noise amplification. Additionally, it provides increased sound absorption capability, which in turn reduces noise. However, the air voids should be interconnected to be able to damp the noise (Sandberg and Ejsmont 2002, Hanson et al. 2004). On the contrary, Wayson et al. (2009) reported in their study that among 22 locations in Florida OGFC with ground tire rubber showed the highest noise intensities.

Use of an OGFC can also be problematic as dirt and dust from the environment can enter the void spaces and clog the surface. At wet condition, these pores are 'self-cleansed' under high-speed passing wheel (Sandberg, 2009). The process of clogging is accelerated on less travelled roads and at lower vehicle speeds, the pores of the surface are consistently filled by fine particles due to passing wheels. This reduces the noise benefit of these porous surfaces. An early study by Bendtsen (1998) demonstrated initial noise reduction of around 4 dBA by using a porous surface compared to a DGA surfaces. However, researchers observed noise reduction of 1 dBA after 7 years in comparison with a DGA surface. Sandberg (2009) reviewed porous surfaces around the world and concluded noise benefit of porous surface diminished at a rate of 1 dBA per year in relation to DGA surface. The rate of noise reduction increases at low speeds and especially in areas where there is a large amount of dirt in the vicinity. In addition, these surfaces are at least 50% more expensive in comparison with DGA surface over life cycle (Ohiduzzaman et al., 2016). Figure 27 shows the surface texture comparison of porous and dense asphalt surfaces.

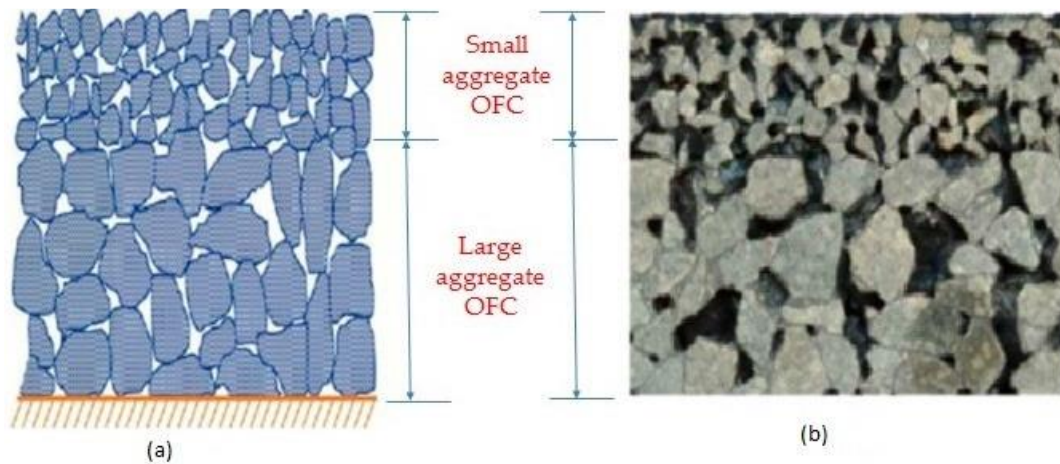


**Figure 27. Surface texture of (a) porous asphalt; (b) dense asphalt (EAPA, 2007)**

### *Double layer porous surface*

This concept is mainly practiced by European countries to counter the problem of clogging in porous pavement (Faure et al., 2000). The structure of a double layer porous pavement consists of a top layer that is filled with finer mixes (with 1/4-inch maximum aggregate size) whereas the

bottom layer is filled with a thick highly porous mixture (with 5/6-inch maximum aggregate size) for acoustic absorption, as shown in Figure 28. A newly constructed double layer porous surface is capable of reducing noise up to 6–7 dBA compared to a DGA or Stone Mastic asphalt (SMA) (Sandberg, 2009). The noise reduction of double layer porous surface is due to the combination of two mechanisms. Firstly, small sized aggregates at the top layer produced smooth surface which minimizes the texture impact of tires. Secondly, the thicker underneath layer consists of coarse aggregate which has higher void content with increased sound absorption (Ohiduzzaman et al., 2016). The noise benefit of these porous surfaces diminished with age, but at a slower rate (Sandberg, 2009). However double layer porous surface is expensive compared to single layer porous surface or conventional DGA surface and generally have reduced life cycle due to raveling of aggregates from the top layer (Goubert et al., 2005).



**Figure 28. Double layer porous pavement concept (a) schematic diagram; (b) cross section of real pavement (Bendtsen and Larsen, 2011).**

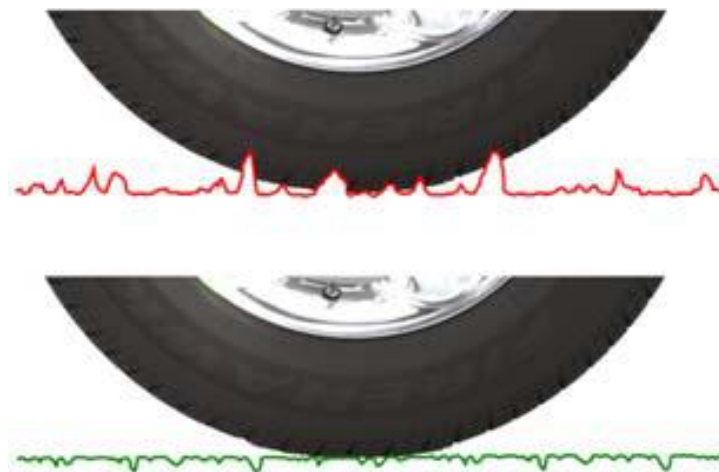
### *Asphalt rubber friction course*

Asphalt rubber friction course (ARFC) was first developed in Arizona to resist cracking and is proposed in limited studies to counter traffic noise when compared to some PCC pavements. In this surface, the binder is mixed with crumb rubber granules of 0.5–2.0 mm. The proportion of crumb rubber is 10% weight of total binder content which is generally twice of polymer modifier used in a porous asphalt surface (Sandberg, 2009). Arizona Department of Transportation (ADOT) placed an ARFC surface on the existing PCC surface and conducted noise study on it by using OBSI testing method (Aspro, 2005). Figure 29 represents a picture of the ARFC surface.



**Figure 29. ARFC surface on Arizona Freeway (Ripke et al. 2005)**

Sandberg (2009) explained noise reduction of ARFC surface is due to combination of number of factors. Firstly, the surface texture of ARFC has negative profile due to small maximum aggregate size. As illustrated in Figure 30, a surface with negative texture shows more troughs with flat ridges at the high elevation, while a surface with positive texture includes more peaks out of the surface. Secondly, ARFC surface has lower stiffness due to excess amount of binder and rubber content hence, the impact between tire tread and pavement becomes less which reduces noise. Lately, Tehrani (2014) performed a review of rubberized HMA surfaces used for noise abatement technique and summarized that addition of rubber decreases noise level about 2 to 3 dBA compared to a HMA surface and 4.5 to 6 dBA compared to a PCC surface. However, as observed for other modified surface or mixture, noise benefit of crumb rubber bitumen is also diminished with time (Ripke et al. 2005, Tehrani 2014). Despite the results reported in the studies, the comparison was done against pavements with higher noise levels.



**Figure 30. Positive (top) and negative (bottom) texture (Smit et al., 2016)**

## *Asphalt overlays*

Thin asphalt layers (TAL) are usually a gap graded high quality aggregate asphaltic mixture with layer thickness varying from 10 mm to 30 mm depending on the nominal maximum size of aggregates (Sandberg et al., 2004). In these mixtures, moderate percentages of sand and modified polymer binder are also added. The air void content of these mixtures varies from 15% to 25%. Initial noise reduction of TAL surfaces varied between 0.9 and 6.9 dBA for passenger car depending on the maximum aggregate size and surface type. For multi-axle truck, the initial noise reduction of TAL surfaces is less significant compared to passenger car (Ohiduzzaman et al., 2016). TAL is less expensive as an in-service pavement maintenance procedure and has a low initial construction cost; it is therefore widely used for roads with heavy traffic in Europe (EAPA, 2007). However, as observed for other porous surfaces, noise benefits of TAL surfaces decrease with age and also due to raveling of aggregates under heavy traffic (Sandberg et al., 2011). Therefore, it is very difficult to use these TAL surfaces at places where heavy vehicles exert high shear forces on the surface layers.

## *Stone mastic asphalt*

Stone mastic asphalt (SMA) surfaces are porous with 20% porosity. It is usually a gap-graded mixture with an aggregate skeleton of relatively coarse aggregates filled with mastic of asphalt, filler, and fine aggregate (EAPA, 2007). Since SMA has a relatively open surface texture that reduces the air pumping mechanism, it also reduces noise. Research conducted in Finland showed that SMA surface with 5 mm aggregate size showed an initial noise reduction of 3 dBA and 5 dBA at vehicle speed of 30 mph and 80 mph, respectively in comparison with original pavement (Valtonen et al. 2012). However, after one year, noise increased significantly due to the wearing on SMA surface. SMA surface is generally more expensive compared to conventional DGA surface because of higher binder content and high-quality aggregates (Ohiduzzaman et al., 2016).

## Noise Reduction on Concrete Pavement

Concrete pavement surfaces are in general noisier than asphalt pavements and the efforts to reduce their noise focused primarily on the surface finish or tining that is applied to improve friction and skid resistance (Smit et al., 2016).

## *Diamond grinding concrete*

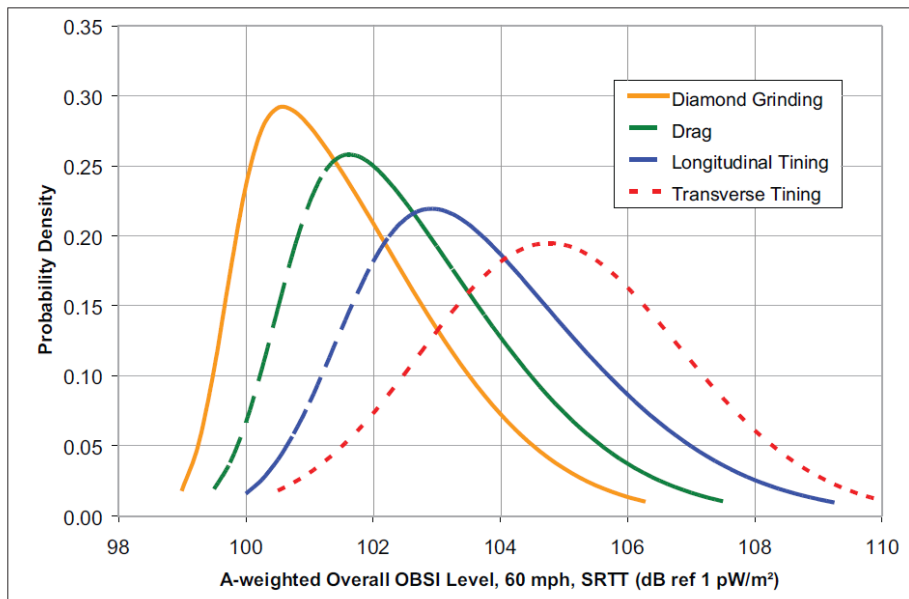
Diamond grinding is a concrete restoration technique in which the surface is ground by small sawblades to create a narrow and fine longitudinally grooved surface (Rasmussen et al, 2008), as shown in Figure 31. Diamond grinding of either new or old concrete pavements provides a smooth ride and enhance friction that consequently reduces noise. Initial noise reduction after grinding the surface is about 1–2 dBA compared to a DGA surface and 3–5 dBA in relation to a transverse tinned concrete surface (Sandberg 2009, Rasmussen et al, 2008). Diamond grinding pavement is quite durable except it is susceptible to wear from studded tire especially in winter. However, the initial noise benefits of this surface decreases with time due to polishing of aggregates (Sandberg 2009, Rasmussen et al, 2008).



**Figure 31. Diamond-ground surface in Texas (Smit et al., 2016)**

### *Drag surfaces*

Drag surfaces like burlap and artificial turf are considered one of the quietest concrete pavements next to diamond-ground surface. The National Concrete Pavement Technology Center (CP Tech Center) of Iowa State University, FHWA, American Concrete Pavement Association (ACPA), and a consortium of State Highway Agencies formed a partnership in 2004 to lead the research effort of identifying the quieter concrete pavement options that do not compromise safety. As part of this effort, over one thousand pavement test sections throughout the US and Canada have been tested for noise, texture, friction, and smoothness. The database has allowed for characterizing noise level distributions for concrete pavements as illustrated in Figure 32 (Rasmussen et al. 2007, Rasmussen et al. 2010).



**Figure 32. Normalized distributions of OBSI noise levels for conventional concrete pavement textures (Rasmussen et al. 2010)**

## *Longitudinal and transverse tining*

Longitudinal tining can also be used to produce quieter pavements. However, some longitudinal tining has also been found to be loud. To ensure a quieter surface, a higher standard of quality control is required, especially when texturing. There must also be a compatibility between the mix, speed of placement/texturing, and the texturing technique, which must be identified in advance. Research suggested that minimizing periodic deposits of concrete displaced by the tining process, reducing vibrations of the paver and texture cart may also help constructing quiet concrete pavement with longitudinal tining (Rasmussen et al. 2007, Rasmussen et al. 2010).

Transverse tined concrete pavements are considered as the loudest and when tined with a uniform spacing, they can contain a “whine” that increases the annoyance even further. Quieter transverse tined pavements are possible but are often found to have a short spacing between the tines – nominally 12 mm or less. Furthermore, randomizing this short spacing can minimize the potential for “whine”. Even with this nominal spacing, however, the potential remains for constructing an objectionable pavement in terms of noise. Both material compatibility and quality control issues must be addressed to help overcome this (Rasmussen et al. 2007).

## *Next generation concrete surface*

Next Generation Concrete Surface (NGCS), shown in Figure 33, are constructed using a combination of diamond grinding and grooving to reduce noise levels while maintaining sufficient tire-pavement traction. Scofield, L. (2020) indicated that NGCS has been in service for 12 years and has been constructed in 15 states and three countries by 2020. Guada et al. (2012) reported that NGCSs were found to be quieter than the conventional diamond grinding, with an average OBSI values ranging from 99.5 dBA to 101.7 dBA, with an average of 100.8 dBA, compared with a range of 100.6 dBA to 104.7 dBA, and an average of 102.8 dBA measured on the conventional diamond grinding. Between 2011 and 2015 the Virginia DOT constructed pilot projects to evaluate both AC and Concrete Quieter Pavement Technologies. As of June 2015, the NGCS concrete surface continued to have a noticeable (approximately 4 dB) advantage over the standard concrete finish (transverse tining) and a 1 dBA advantage over the conventional diamond grinding (Scofield, L. 2020).



**Figure 33. Photo of Next Generation Concrete Surface (Scofield, 2020).**

## European Practices for Noise Reduction Through Quiet Pavement

FHWA, AASHTO, and National Cooperative Highway Research Program (NCHRP) sponsored a scanning study of quiet pavement systems used in Europe to reduce traffic noise. The countries participated in the study- Denmark, France, Italy, the Netherlands, and the United Kingdom have policies requiring consideration of quiet pavement and have conducted extensive research on quiet pavement technology (Gibbs et al, 2005). In this section some practices followed by these countries to maintain quiet pavements are discussed.

### *Denmark*

The Danes have measured noise stability on several experimental pavements for several years and concluded that the drainage asphalt (DA) with the smallest chip size (8 mm) and the highest percentage of built-in voids (over 22 percent) had the best noise reduction (3 to 4 dB) and retained its porosity. Single- and double-layer porous mixes and thin surfacing have also been used as noise-reducing pavement mixes. The porous mixes showed the greatest potential to reduce noise by more than 3 to 5 dB but have experienced performance problems like clogging and durability. The thin mixes are more cost effective and appear to be more durable but provide only limited noise reduction like 1 to 3 dB. The Danes have also completed three case studies in which they compared the cost of porous asphalt, noise barriers, and sound insulation for three road categories: city street, ring road, and freeway. They concluded that compared to noise barriers and façade insulation, porous asphalt gives a much higher noise reduction per invested Euro (Gibbs et al, 2005).

### *The Netherlands*

Researchers from Netherlands conducted a comparison between dense graded asphalt concrete, single-layer porous asphalt (PA), two-layer porous asphalt (TLPA), and thin top layer known as Microflex. Among them TLPA was quieter at all speeds tested (20 to 80 mph), as much as 4 dB quieter than the next best mixes (thin layer and porous single layer) at high speed (80 mph), and as much as 9 dB quieter than conventional dense-graded asphalt. TLPA, therefore, is especially recommended for the main highway system where traffic speeds are higher and sound reduction the greatest. The Dutch also concluded that the porous mixes do not perform as well as conventional dense mixes when there is more braking, acceleration, and turning, or wringing actions, as might be expected in urban areas. Based on these considerations following application classifications are recommended: PA or TLPA for national highways, and thin top layer for city streets. Aggregate size, void structure, binder properties, skid resistance, and mix durability are all considered critical mix properties for these mixes. Porous mixes have the greatest potential to reduce noise by more than 3 to 5 dB (at greater than 20 to 35 mph). On the other hand, the thin mixes are more cost effective and appear to be more durable but provide only limited noise reductions (1 to 3 dB). However, the thin single-mix layers work better in urban (low-speed) conditions than the two-layer pavement systems. Although porous pavements are slightly more expensive, they produce a 50 percent cost efficiency compared to the same reduction of noise by barrier. Current barrier costs are estimated at EUR400 to EUR500 per square meter. The high costs are associated with the extensive foundation structural support needed in the Netherlands (Gibbs et al, 2005).

### *France*

France has separated structural and surface characteristics and using some techniques like best-quality aggregates, adjustment of pavement dressing to noise characteristics, and using smaller grain size for getting quieter pavements. very thin (2-to-3-cm) and ultrathin (1.5-cm) mixes were

also developed to improve the surface characteristics such as skid resistance and noise. After much experimentation, the French have found that the 0/6-mm extreme gap mix is most effective at reducing noise and increasing skid resistance. The noise-reducing mixes are usually considered sacrificial layers and are not given any structural value in pavement design. However, the French estimate that these mixes have about half the modulus of dense graded mixes. Gap graded mix seems to increase raveling potential, but the addition of 7 to 10 percent sand mortar has helped resist raveling. The wearing course is replaced within 10 to 15 years. The French also placed PA on one continuously reinforced concrete pavement (CRCP). Lightweight aggregates (expanded clay) have been used for skid resistance in areas with few good natural aggregates. These synthetic aggregates may provide slight improvements in noise reduction. Rubber has been used in the mix binder and has reduced noise by up to 1 additional dB. The optimum rubber content is 1 to 2 percent rubber. Rubber has also been used in the very thin mixes (Gibbs et al, 2005).

### *Italy*

In Italy About 35 percent of the road (1,868 km) was surfaced with PA by the end of 2003, but most of this PA is composed of 0/16 mm aggregate size. The new formula tends toward a smaller maximum aggregate size of 0/11 mm or perhaps even 0/8 mm to achieve quieter pavements. The porous mixes are specified to achieve a minimum of 23 percent air voids, and most are constructed at about 30 percent air voids (Gibbs et al, 2005).

### *United Kingdom*

In the UK, Paving contracts are required the use of quiet surfaces, but contractors are allowed to decide what type of surfacing products to use for the roads they build. More than 32 approved proprietary surfacing systems meet safety and noise requirements. The approval process is known as the Highway Product Approval System (HAPAS). To obtain HAPAS approval, the product must be proven to perform in an extensive range of quality tests, including skid resistance, drainage, and durability, with an optional test of noise generation. In addition, the products must perform in situ as indicated during HAPAS testing for at least 3 years. The British are considering an extension to this warranty period. If the product does not meet the specified minimum noise or skid requirement during the warranty period, it is removed and replaced. If it fails other requirements, the product may be permitted to remain in place at no pay. Noise-reduction properties are compared to the performance of hot rolled asphalt (HRA) using a noise prediction algorithm. To obtain approval as a quiet pavement mixture, it must provide at least a 2.5 dB noise reduction in compared to HRA. The British has also experimented with exposed aggregate concrete (EAC), which was reported to achieve a 3 dB reduction compared with a standard brushed finish with minimum texture (1.2 mm). The British also reported a 10 percent cost increase using EAC surface. Thin-layer bituminous surfacing have replaced EAC as a more cost-effective way to reduce noise. Current policy does not allow concrete pavement to be used as the finished surface. Any new concrete pavement is considered a supporting base with a required quiet pavement surfacing. Even so, 40 percent of new roads are CRCP (almost exclusive use of CRCP in England) with a thin surface layer. The public has responded favorably to the use of noise-reducing surfaces and is especially impressed by improvement in ride comfort (Gibbs et al, 2005).

## 4.5 Research Gaps

This extensive literature review study showed that considerable progress has been made in several aspects of mitigating tire-pavement interaction noise. However, some areas of design and construction of quieter pavement are not properly addressed yet. Accordingly, considerations should be given to the following issues.

- Noise regulations are not uniform from one agency to the other. Furthermore, intervention for noise abatement can be biased with limited objective measurements and procedures. Research is needed to identify public impact in pass-by noise, potential for interior noise, and noise generated at the tire. Close proximity noise includes a shorter list of mechanisms. It may therefore, constitute a good benchmark and help systematic study.
- Repeatability and reproducibility of standard close proximity and pass-by noise measurements is still unclear. The reported noise levels in different literature are often the average of several measurements, but the level of scatter is rarely listed. Before policy is written that is based on these results, the noise differences should be considered in light of the level of repeatability of the measurement.
- Very few studies have been done that directly relate the texture power spectrum to the noise power spectrum (Eberhardt 1985). This is partly because detailed measurements of texture profile were previously difficult to obtain. This omission in the understanding of the relationship between texture and noise may hinder the development of new concepts for delivering quiet pavement with high friction. Further, defining the relationship between short-duration rough features (i.e., faults, opened joints) and acoustic traces may help improve the consistency of noise measurements.
- The mechanisms of noise generation at the tire road interface are well understood, and their relative influence on roadside noise has been studied very carefully. Although the mechanisms that affect the propagation of noise to the roadside are also studied, their influence appears as uncontrolled external variables in most studies. Little information is available about the effect of mix design, aggregates, and surface texture on noise propagation. In part, this is because these effects are masked by the influence of direct tire/road contact in pass-by noise measurements. Further, access to pavements with similar surface texture but controlled changes in mix design and aggregate type are very rare and should be investigated.
- Traditionally, noise prediction models have been developed using a reference pavement (either a national average or standard pavement type) in order to predict noise impacts and determine abatement measures. Recent research showed the contribution of pavement effects on noise prediction can be incorporated in noise models. For the FHWA TNM, further work is needed to incorporate a broad range of pavements into the model.
- Porous pavement is widely accepted as a low noise surface. However, researchers hypothesize that the voids of this surface fill with dirt over time, which in turn increases noise. Therefore, additional investigation is needed to evaluate the clogging effect on the noise properties of the mixtures.
- Only a small number of studies have been done that measured the changes in noise on pavements with age. One study observed a decrease in noise on concrete pavements over the first seven years, then an increase afterward (Chalupnik, 1992). Another study found an increase in noise on porous asphalt of 2.9 dBA over seven years (Poelmans 1994). The limited amount of information on the effect of pavement wear on noise shows that it may

be significant. Furthermore, the changes in noise level reported with time are as large as the differences in noise level that are often used to justify selecting one surfacing or texturing alternative over another (Karamihas and Cable 2004).

- Surface friction of a pavement is a key safety issue. In general, tire-pavement noise and pavement surface friction appears to be inversely correlated. Therefore, more research is needed in order to optimize these two conflicting pavement properties.
- Various factors affected the tire-pavement interaction noise as reported in literature. Of them, temperature plays an important role in generating tire-pavement noise. The literature survey showed that the highest air temperature used in previous studies is limited to 95 °F (Rochat, 2010). Donovan and Lodico (2011) conducted a study on precision and bias of OBSI testing (which is the basis of current AASHTO standard) and restricted temperature for noise testing within 20 to 100 °F. However, in some regions especially in the Southwest, temperature often exceeds 100 °F during summertime. Therefore, a comprehensive testing program incorporating a wide range of temperatures is needed to evaluate the temperature effect on tire-pavement noise.
- According to the study performed in Florida (Wayson et al., 2014) there is a tremendous data base established in Florida and more complete analysis is needed. More specifically the study concluded six analysis needs including additional testing on other mixes and continue evaluating frequency spectra changes with changes in mix of the surface texture.

The main objective of this section was to present the literature review and document the recent developments in the area of highway noise and the to better understand the contributing factors, remedies, and the effects of highway noise pollution on the public. This review will help in better understanding and identifying the potential factors, including but not limited to pavement surface characteristics and tire-pavement interaction, affecting traffic noise. Available methods to reduce wayside noise were also investigated from previous research and the benefits and limitations of the different methods in reference to quiet pavements was also discussed.

This review showed that tire-pavement noise is influenced by a number of factors. Of them, pavement surface types play an important role in generation of tire-pavement noise. Generally, asphalt concrete (AC) surfaces produce less noise compared to PCC surfaces. OGFC surfaces are the quietest among AC surface types. While transverse tinned is the loudest and diamond grooving is the quietest surface within PCC surface types. It is evident from the literature review that acoustical performance of pavement diminishes with aging especially for porous AC surfaces. Therefore, long term monitoring is needed to build quieter pavement that will maintain noise benefits over time. It is recognized in the literature that tire-pavement interaction noise can be correlated to the pavement's material characteristics. However, limited number of research focuses in this area. Hence a systematic research program is required to gain better understanding of long-term noise behavior of pavements.

## 5. Data Analysis and results

In this task, the research team collected data from several previous studies conducted by FDOT. The studies included two phase On-Board Sound Intensity (OBSI) and wayside noise measurements on different pavement sections in Florida. Noise measurements were collected for concrete pavement joints, rumble strips and thermoplastic pavement markings, and some turnpike segments. After careful evaluation of all the data, the research team has decided to work only on the two-phase noise measurements (Wayson et al., 2009 and 2014) on quiet pavements as this was the only study directly related to the surface characteristics of pavements as a noise mitigation strategy.

OBSI and wayside data was collected from 22 pavement sections during phase I and additional 32 sites were included during phase II of the study. Since the draft American Association of State Highway and Transportation Officials (AASHTO) standard (AASHTO TP 76-13) was undergoing revisions at the time of data collection, all the OBSI testing was performed at a speed close to 55 mph. Some data was also collected at a speed of 60 mph. The important steps of sound data collection through OBSI included finding tangent and dry pavement sites for testing, setup of testing equipment on a level surface, and using the microphones in pairs. During Phase I and II, ten second durations were used for data collection. At each location, a minimum of six runs were made at a speed close to 55 mph. So, the pavement length tested over at least a ten second time period resulted a test section length of approximately 800 feet at each pavement site (Wayson et al., 2009 and 2014).

The data was then rearranged, sorted, and divided into six surface types to examine the effect of the surface characteristics to reduce wayside noise generated by traffic. Average OBSI and wayside noise levels of these six surface groups along with their corresponding texture and friction data is presented in Table 2.

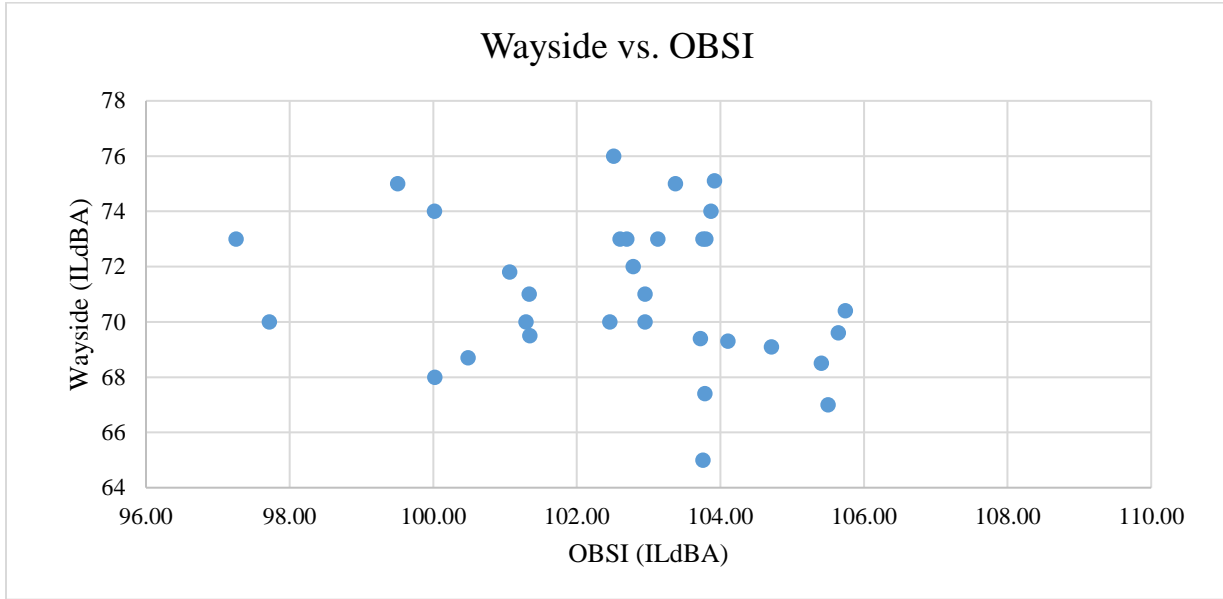
**Table 2. Six Surface Types Analyzed in the Study**

Surface Type	No. of Sections	OBSI (ILdBA)	Wayside (ILdBA)	MPD (inches)	Skid Number (Ribbed Tire @ 50 mph)	Skid Number (Smooth Tire @50 mph)
Open Graded Polymer Modified	24	103.79	71.59	0.063	38.64	36.98
Open Graded Asphalt Rubber	21	102.46	71.55	0.062	32.82	34.68
Thick Open Graded Polymer Modified	2	102.13	NA	NA	NA	NA
Dense Graded with GTR	8	102.02	69.15	0.021	48.95	25.05
Dense Graded Polymer Modified	2	101.91	66.85	0.018	44.00	28.30
PCC Surface	11	103.53	73.50	0.016	37.30	27.30

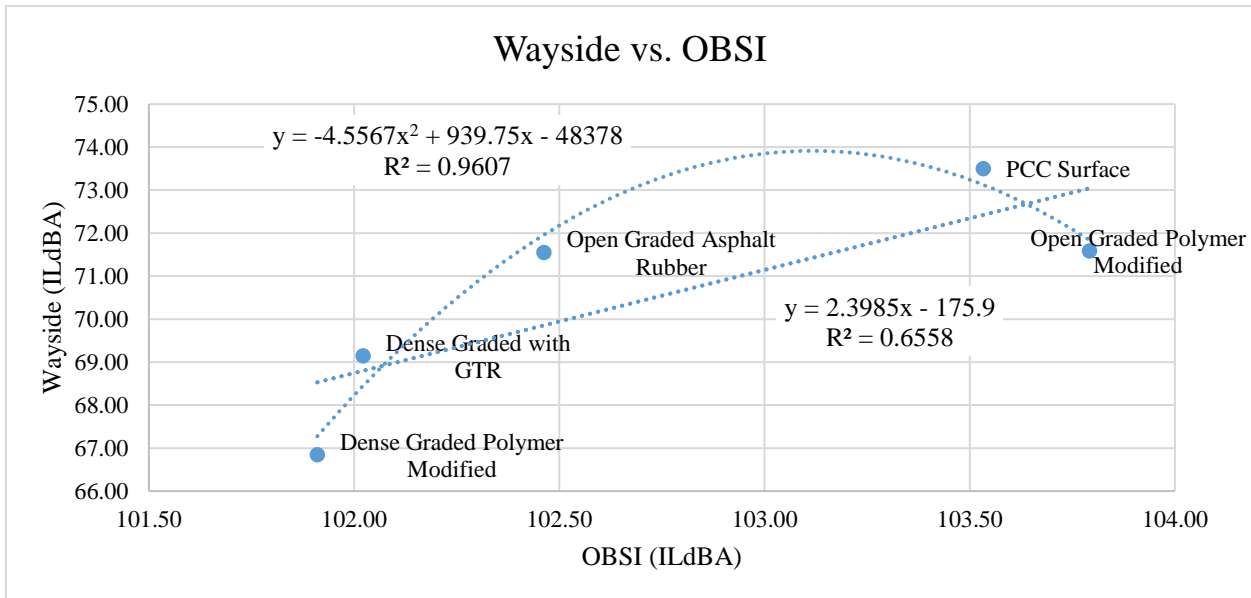
### 5.1 Correlation Between Wayside and OBSI Noise Levels

The noise levels obtained from five different surface groups (wayside measurements were not collected on thick open graded polymer modified surfaces) were compared to check if the two methods are correlated to each other. The scatterplot presented in Figure 34 did not show any

meaningful correlation between the OBSI and wayside noise levels. Therefore, average values of all the surfaces were compared and showed in Figure 35.



**Figure 34. Relationship Between OBSI and Wayside Noise Levels**



**Figure 35. Relationship Between OBSI and Wayside Noise Levels (Average Values for all the Surfaces)**

Figure 35 indicates that OBSI and wayside noise levels are correlated. Initially, a higher correlation was found with a 2<sup>nd</sup> degree polynomial relationship. However, since a second order polynomial does not have intuitive physical interpretation it was considered as an overfitting model. Hence, a linear regression model was fitted to present the relationship between OBSI and wayside sound levels. The correlation was also tested for different individual surfaces. However, no clear trends were observed for individual surface type. FDOT also found a consistent difference between the

OBSI and wayside noise levels and proposed a first order approximate method (Equation 6) to approximate wayside sound levels if OBSI measurements are made.

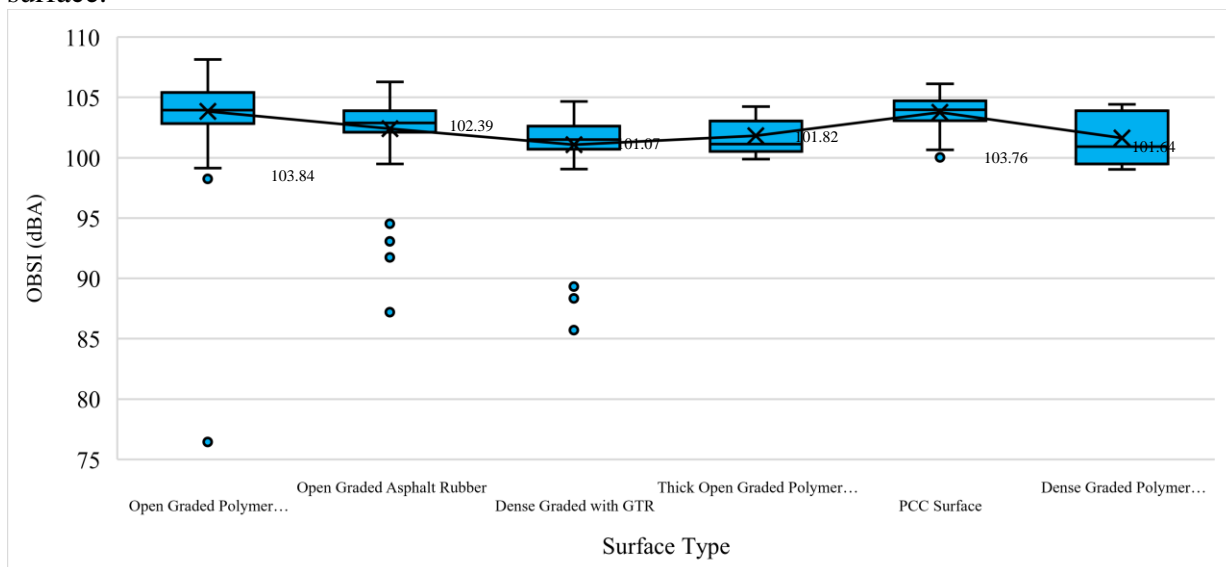
$$\text{Wayside SPL [dB(A)]} = \text{OBSI Sound Intensity Level} - 32.5 \quad (6)$$

The standard deviation of this model was  $\pm 3.5$  dB(A) (Wayson et al., 2014).

State agency representatives that participated in the interviews also mentioned that there is good causal relationship between the OBSI and wayside noise levels. Field validation is recommended to identify the most effective relationship between these different noise measurement systems.

## 5.2 OBSI on different types of Surfaces

OBSI data collected on different pavement surface types was compared to investigate which surface was the quietest. To examine the effect of surface type on the OBSI sound level in detail, box and whisker plots were graphed with all the OBSI data collected during phase I and II of the study. The plot is presented in the Figure 36. The average values of OBSI measured on different surfaces is also presented in the Figure 36 (Average values are labeled). The loudest sections from Figure 36 are open graded polymer modified surface and Portland Cement Concrete (PCC) surface.



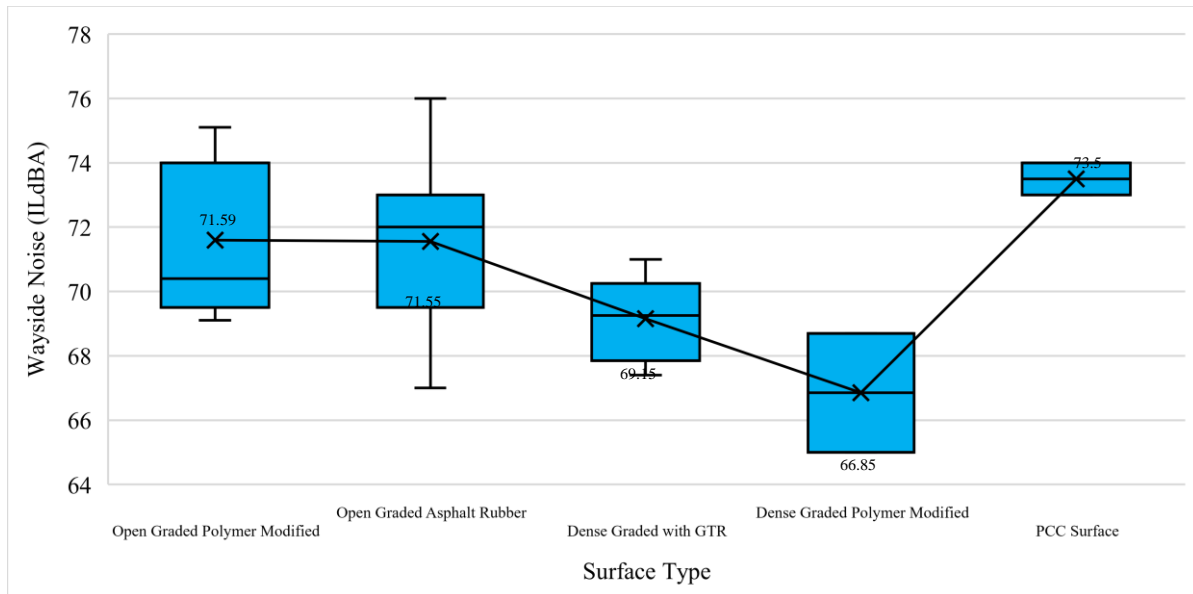
**Figure 36. Range and Median of OBSI Noise Level Measured on Different Surfaces**

Dense graded asphalt surfaces are conventionally believed to be louder pavements. However, dense graded surface modified with ground tire rubber (GTR) and polymer are the quietest sections. Since the age of these pavement sections has not been provided and included in the analysis, it may be that some dense graded sections were relatively newer and quieter than the aged open graded surfaces. FDOT performed a limited aging study on four sections during phase II and found that the effectiveness of these pavement sections is decreasing at a rate of 0.2 to 0.3 dBA per year (Wayson et al., 2014). This finding corroborates the claim that rubber modified asphalt surfaces can be quieter. It should be noted that Caltrans has been using rubberized asphalt as an approved quiet pavement surface since 2009 (Caltrans quiet pavement bulletin, 2009).

Figure 36 indicates that PCC and open graded polymer modified surfaces are the loudest according to the median values. Nevertheless, it is observed that open graded surfaces can be the quietest for individual sections as the range of these two surfaces can be stretched down to 99 dBA. The outliers (defined as measurements  $\pm 1.5$ \* interquartile range from the median) also suggest that some of the quietest sound levels were collected from open graded surfaces. Rubberized dense graded performed best in context of median and range of OBSI values. So, there are variabilities and overlapping results between different pavement surfaces. The reason behind these variabilities can be the design of the pavement, surface deterioration, or the age of pavement. Any of the single factors can have a significant impact on the noise level performance of these pavement sections.

### 5.3 Wayside Noise Levels on Different Surface Types

Wayside noise levels showed similar pattern as the OBSI as presented in Figure 37. Dense graded polymer modified and dense graded GTR modified surfaces were the quietest. PCC surface was the loudest. One factor that may result in the high variabilities of the open graded mixes is sample size. Out of the 22 sites where sound level was measured during Phase I, 16 pavement sites were constituted with open graded mixes. Phase II included total 32 sites, where 26 were open graded mixes. Since nearly 80 percent of the pavement sites are open graded surfaces, sound level measurement can be affected by the design of the pavement, surface deterioration, or the age of pavement etc.

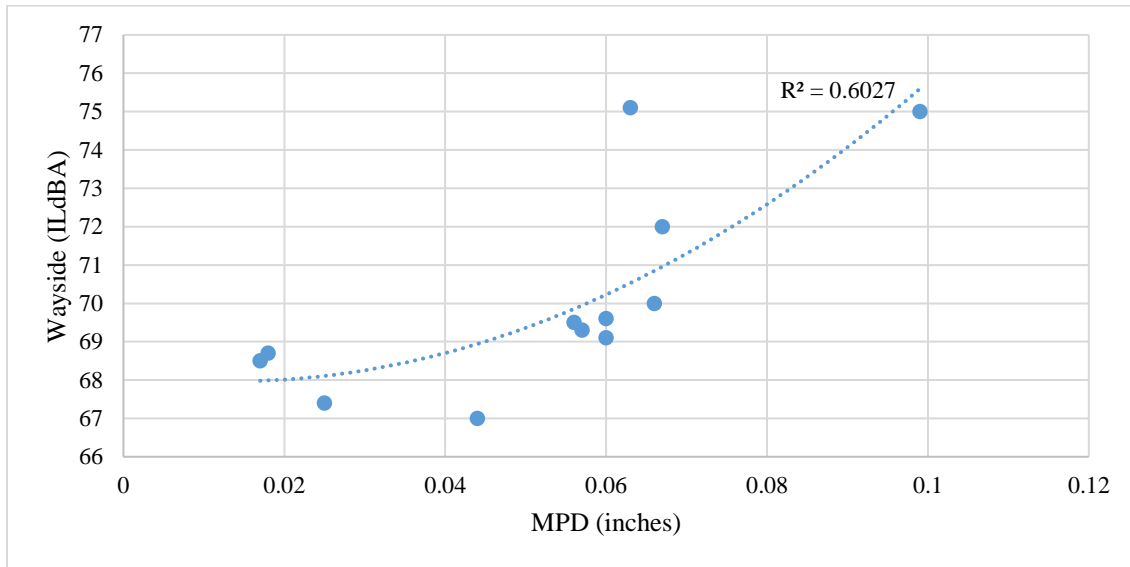


**Figure 37. Range and Median of Wayside Noise Level Measured on Different Surfaces**

### 5.4 Effect of Surface Texture on Sound Generation

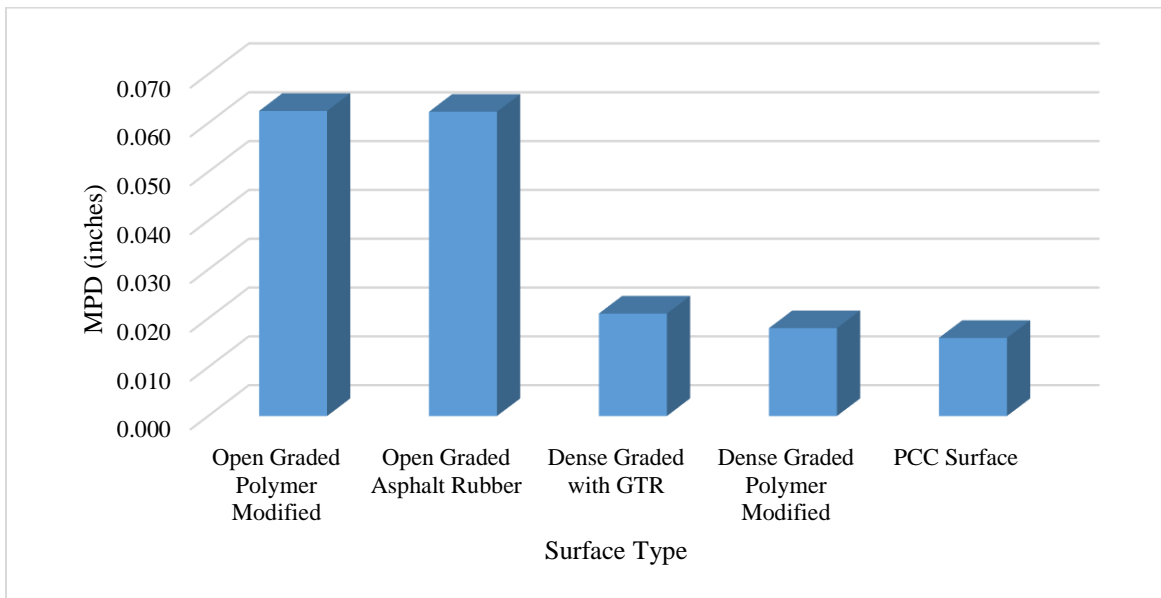
Surface texture is believed to be one of the significant contributing factors in reducing noise using quiet pavements. From the literature review it was noted that noise generation is augmented by the macrotexture and megatexture of the pavement surface. The texture data collected from FDOT was mean profile depth (MPD) which is an indicator of pavement macrotexture. OBSI noise level

data did not show a significant correlation with MPD, but wayside noise level increased as the MPD value increased (Figure 38). FDOT also had same conclusion (Wayson et al., 2014).



**Figure 38. Relationship Between Wayside Noise Level and Mean Profile Depth**

MPD was also plotted against different surface types in Figure 39.

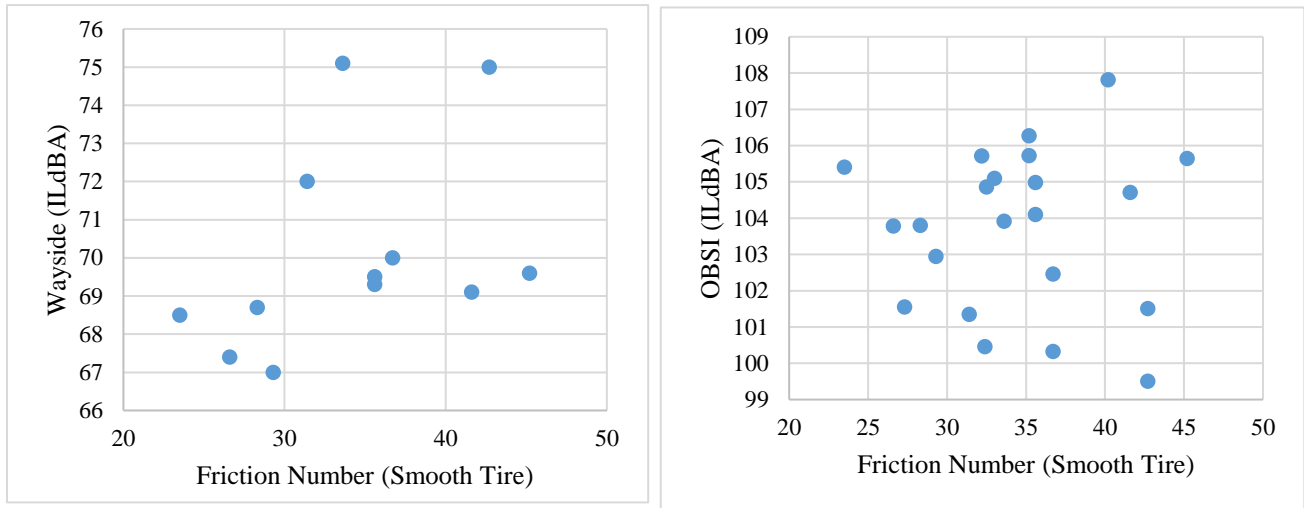


**Figure 39. Mean Profile Depth of Different Surface Types**

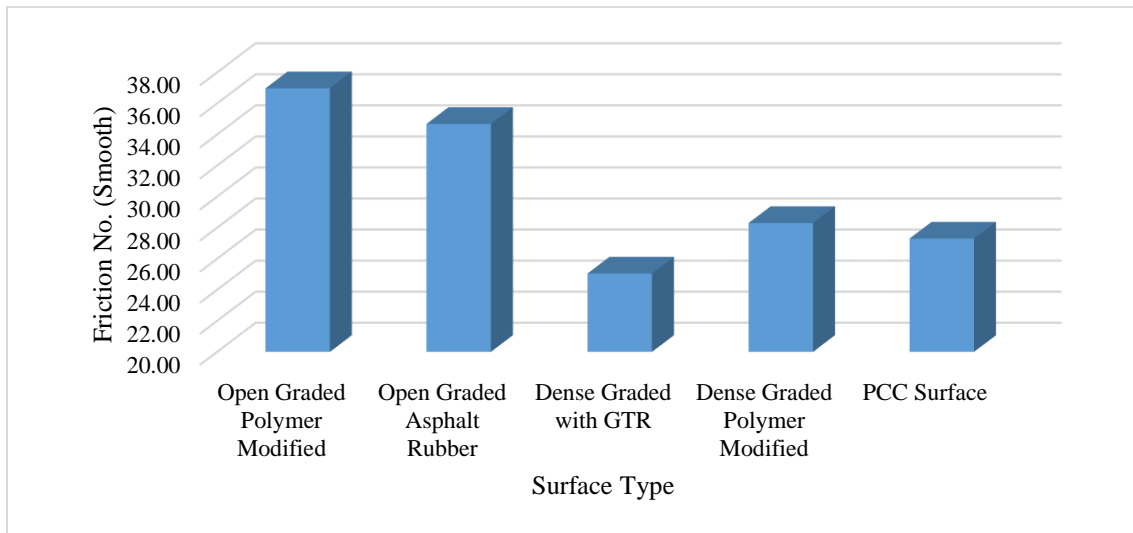
From Figure 39, it is obvious that polymer and rubber modified open graded mixes have much higher MPD than the dense graded mixes. So, high macrotexture can be correlated to the open graded sections being louder, that was also seen from the trend of wayside noise level (Figure 38).

## 5.5 Surface Friction of Different Pavement Surface Types

The friction data provided by FDOT was in form of Friction Number (FN). FN correlates to both microtexture and macrotexture. Friction data was collected with both smooth and ribbed tires. FN was compared with both OBSI and wayside noise levels as shown in Figure 6. No specific trend was observed, for both the sound levels. FN based on the surface types was also plotted and presented in Figure 40 and 41. Same conclusions were also drawn by FDOT (Wayson et al., 2014).

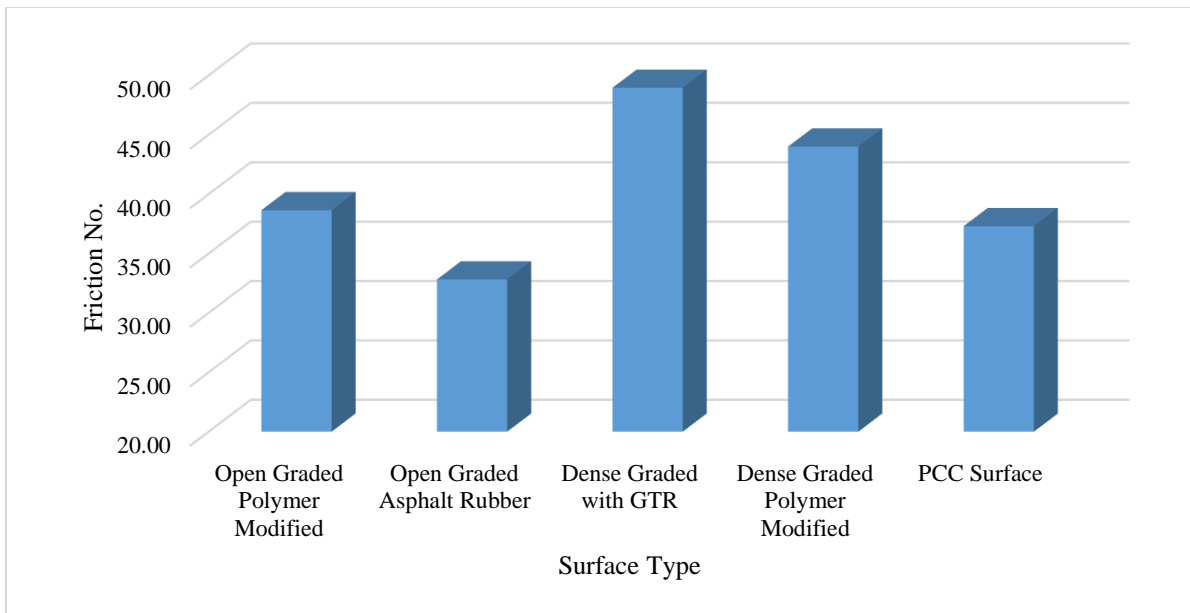


**Figure 40. Relationship Between Sound Pressure Level and FN**



**Figure 41. Friction Number Generated by Smooth Tires on Various Surface Types**

Open graded surfaces have higher friction with smooth tires. For ribbed tires, dense graded and PCC surfaces showed higher friction (Figure 42), although open graded surface friction numbers did not change significantly for smooth and ribbed tires. Similar findings were observed during the field-testing assessment conducted by FDOT to measure the level of precision of the locked-wheel testers (Choubane et al., 2006).



**Figure 42. Friction Number Generated by Ribbed Tires on Various Surface Types**

Texture and friction data analysis indicates that complete road-tire sound generation mechanism can be correlated to both microtexture (FN) and macrotexture (MPD). Therefore, texture and friction characteristics need to be explored in more details to completely understand the impact of pavement surface characteristics on noise generation mechanisms. Furthermore, open graded surfaces are slightly louder than smoother rubber and polymer modified dense graded surfaces. Accordingly, caution should be taken to balance between the quieter pavement and lower friction values if verified. (Wayson, 1998).

## 6. Focused Group Interviews

In Task 2, ten state highway agencies were selected, based on the literature review. The personnel involved with the quiet pavement research were contacted for an interview. Five out of the ten agencies agreed and participated in the interviews, namely, Arizona Department of Transportation (ADOT), Caltrans, New Jersey Department of Transportation (NJDOT), Texas Department of Transportation (TxDOT), and Washington Department of Transportation (WSDOT). Nine questions were asked during the interview regarding the effectiveness of quiet pavements compared to other noise abatement strategies such as noise barriers. The interview also aimed at understanding the major contributing factors in reducing noise using quiet pavements, life cycle assessment, and long-term performance of quiet pavements. The complete list of the questions is provided in the Appendix A of this report. Responses from these interviews is summarized in Appendix B. Outcomes from these focused group interviews are discussed in this section.

### 6.1 Noise Measuring System Used by the Agency

All five agencies stated that they are using OBSI as primary pavement noise measurement technique. Caltrans are the developer of this method and has formulated an AASHTO standard for OBSI (AASHTO T 360-16, 2020). Wayside measurements are also used by NJDOT and ADOT. TxDOT uses sound pressure meter for routine level sound measurements. Close Proximity Method (CPM) is another method used by Caltrans and ADOT.

## 6.2 Correlation Between Different Systems

According to all the participating agencies, OBSI has very good correlation with other methods. So, OBSI method alone can be used to monitor sound pressure levels of pavements.

## 6.3 Effectiveness of Quiet Pavements

All the five participants agreed that quiet pavements are effective and can reduce noise to some extent. Caltrans believe quiet pavements are more effective than noise barriers as they can reduce the noise up to 5 dBA only for the receptors directly behind the wall and the effectiveness greatly diminishes after 200 feet from the wall, which is known as the wall's 'acoustic shadow' zone (Figure 43). Whereas quiet pavements can reduce the noise levels by 6-10 dBA on both sides of the highway and works at greater distances such as 500 feet or more, far beyond any acoustic shadow zone of a noise barrier. The agency also believes quiet pavements keeps the money in pavement whereas noise barriers need additional \$2M/mile/side of the road.

WSDOT stated that their quiet pavement can reduce noise levels by at most 4 dBA. NJDOT also found the effectiveness of quiet pavements in the similar range (3-4 dBA). They got the best result from asphalt rubber modified open graded friction course (OGFC). Although TxDOT did not provide noise reduction values, the agency believe that quiet pavements are effective because it can reduce the noise from source compared to the noise barriers which is not effective behind the acoustic shadow zone. ADOT reported that their quiet pavements are capable of reducing noise levels by 5-11 dBA with an average reduction of 8.2 dBA. Asphalt Rubber Friction Course (ARFC) overlay worked as the best quiet pavement option for the agency.

## Source – Path – Receptor

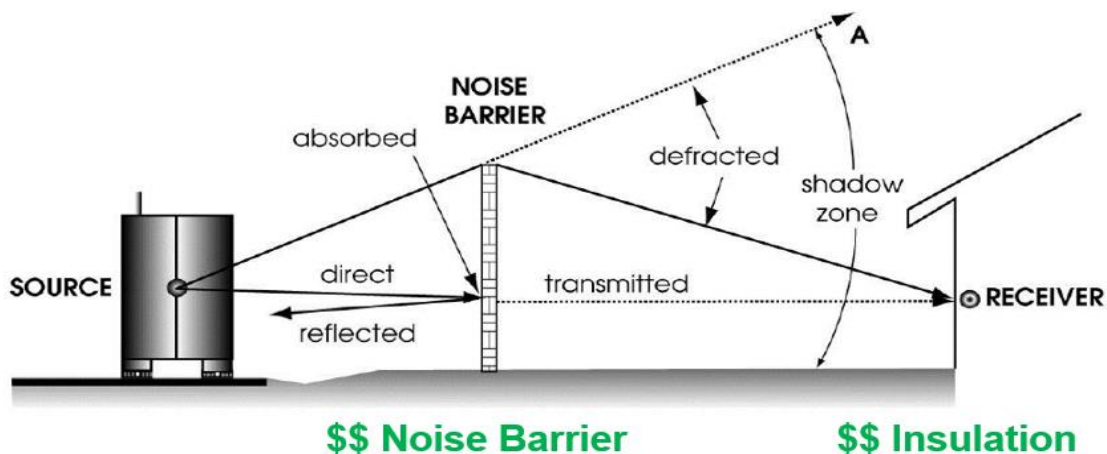


Figure 43. Working Principle of a Noise Barrier (Source: Caltrans)

## 6.4 Public Perception of Quiet Pavement

Public perception was specified as 'positive' by the participating agencies. People notice while driving over a quiet pavement or living beside one. NJDOT said people in the hilly areas had complains about the effectiveness of noise barriers and quiet pavement was appreciated by most of them. TxDOT reported people think noise barriers are aesthetically unpleasant, especially when vandalized by graffiti.

## 6.5 Effectiveness of Quiet Pavement over Time

The fact that effectiveness of quiet pavements reduce over time is supported by all participating agencies. In the colder regions like Washington and New Jersey, freeze-thaw durability is the main reason. In Washington, studded tires are legal during winter and open graded surfaces get affected by these winter tires and lose the effectiveness of sound reduction, sometimes only after one winter cycle. Caltrans, TxDOT, and ADOT all reported raveling of larger size aggregates and subsequent clogging is the primary reason that quiet pavements loss their sound reduction capacity within 2-3 years after construction. Caltrans believe rigid pavement with quiet surface measure lasts longer while TxDOT said OGFC and Permeable Friction Course (PFC) can perform well approximately 5-7 years before they need to be replaced. Rigid pavements with diamond grinding are considered quiet surface in Texas and these start to lose effectiveness after 2-3 years of construction. TxDOT indicated that maintenance activities like resurfacing were periodically performed to restore the effectiveness of these quiet pavement surfaces. Resurfacing to restore the effectiveness of quiet pavement is a practice specified by TxDOT only. TxDOT has also been using high performance thin overlay mixes and these surfaces are providing excellent noise reduction for up to seven years before resurfacing is needed, meaning acoustics properties outlived the life of the pavement. ADOT reported they have seen an average decrease of effectiveness by 0.5-0.6 dBA per year.

## 6.6 Major Contributing Factors in Reducing Noise Using Quiet Pavements

Different states have different opinion regarding the contributing factors that are crucial in reducing noise using quiet pavements. Table 3 has all the factors listed. Nevertheless, surface texture and aggregate size are the two most important factors for reducing noise, according to most of the agencies.

## 6.7 Texture as a Parameter to Model Noise

All the agencies measure texture as a part of their routine pavement management activities, although no one tried to explore the effect of texture on pavement noise. Caltrans explored the effect of surface texture in some limited research activities, but no conclusive findings were reported.

## 6.8 Life cycle assessment of Quiet Pavements

Only Caltrans performed a research study that involved some life cycle assessment of quiet pavements (Donavan et al., 2013). The study included consideration of both the initial and future costs of maintaining a specified level of noise reduction performance over time. Two options were evaluated- new Hot-Mix Asphalt (HMA) pavement with 1-inch ARFC overlay and new longitudinally tined PCC pavement. The PCC pavement option included use of a 12 ft high concrete noise wall. It was found in the analysis that quieter pavement alternatives can be both feasible and cost reasonable in some situations even under current state agency criteria. The LCCA results from this study is presented in the Table 3.

**Table 3. Summary of Deterministic LCCA Results for the Primary HMA and PCC Alternatives**

Total Cost	Alternative 1: HMA (7-year overlay cycle)		Alternative 2: PCC (with barriers)	
	Agency Cost (\$000)	User Cost (\$000)	Agency Cost (\$000)	User Cost (\$000)
Undiscounted sum	\$15,249.71	\$66.34	\$14,334.00	\$31.47
Salvage value	\$958.29	\$9.53	\$0.00	\$0.00
Present value	\$9,623.79	\$24.81	\$11,846.04	\$9.88
Equivalent uniform annual cost	\$447.99	\$1.15	\$551.44	\$0.46

From the LCCA presented in Table 3 it can be concluded that the quiet pavement option, which is HMA pavement alternative, yields a lower present value and Equivalent Uniform Annual Cost (EUAC) of agency costs. Also, the present values would be lower for a longer rehabilitation cycle. For example, a 9-year overlay cycle for the HMA pavement alternative would lower the present value even more (Donavan et al., 2013). However, the life cycle cost analysis (LCCA) performed has some limitations as the pavement section used was hypothetical average pavement sections from FHWA traffic noise model (TNM) and rehabilitation cost needed for degradation of quiet pavements over time was not considered. Lack of real-world project data like level of noise reduction achieved with a specific pavement design, acoustic longevity of different types of quiet pavement design, quiet pavement rehabilitation cycle, and acoustic performance of the anticipated rehabilitation, was also an issue while performing the LCCA. According to the agency rehabilitation cycle time and the project life of quiet pavements along with collaboration between pavement engineers and environmental engineers is prerequisite of LCCA comparison between noise barriers and quiet pavements. At the same time robust input data is needed to be collected from various quiet pavement projects because LCCA are only as good as the input data. On the other hand, WSDOT and NJDOT think noise barriers are long term solutions as flexible and rigid quiet pavement surfaces need frequent resurfacing; although no actual comparisons were made by these agencies. TxDOT indicated the importance of assessing the life cycle cost of noise barriers compared to quiet pavements, as noise barriers sometimes need to be replaced and reconstructed.

### 6.9 Recognition of Quiet Pavement as a Noise Mitigation Strategy

As of now, ADOT, Caltrans and NJDOT has officially recognized quiet pavements as a noise mitigation strategy. In fact, ADOT was one of the first to implement a quiet pavement program initiative back in the early 2000s. Other two agencies said they are still following FHWA guidelines for noise abatement strategies.

### 6.10 Trade-off Between Noise and Friction in Context of Quiet Pavements

Caltrans did some preliminary research on the friction condition of quiet pavement surfaces using the Skid abrader equipment and observed some subtle and interesting shifts in the pre and post pavement spectra. Detailed research is necessary to obtain more information about how friction level of quiet pavement changes with time. Other agencies did not perform any specific research although NJDOT stated OGFC perform great under wet weather friction. TxDOT also thinks same but according to the agency their PFC loss friction rapidly over time.

## 7. Research Gaps

For the gap assessment, the research team combined the findings from the data analysis, focused group interview, and the findings from literature review, to identify the gaps under each topic as listed below.

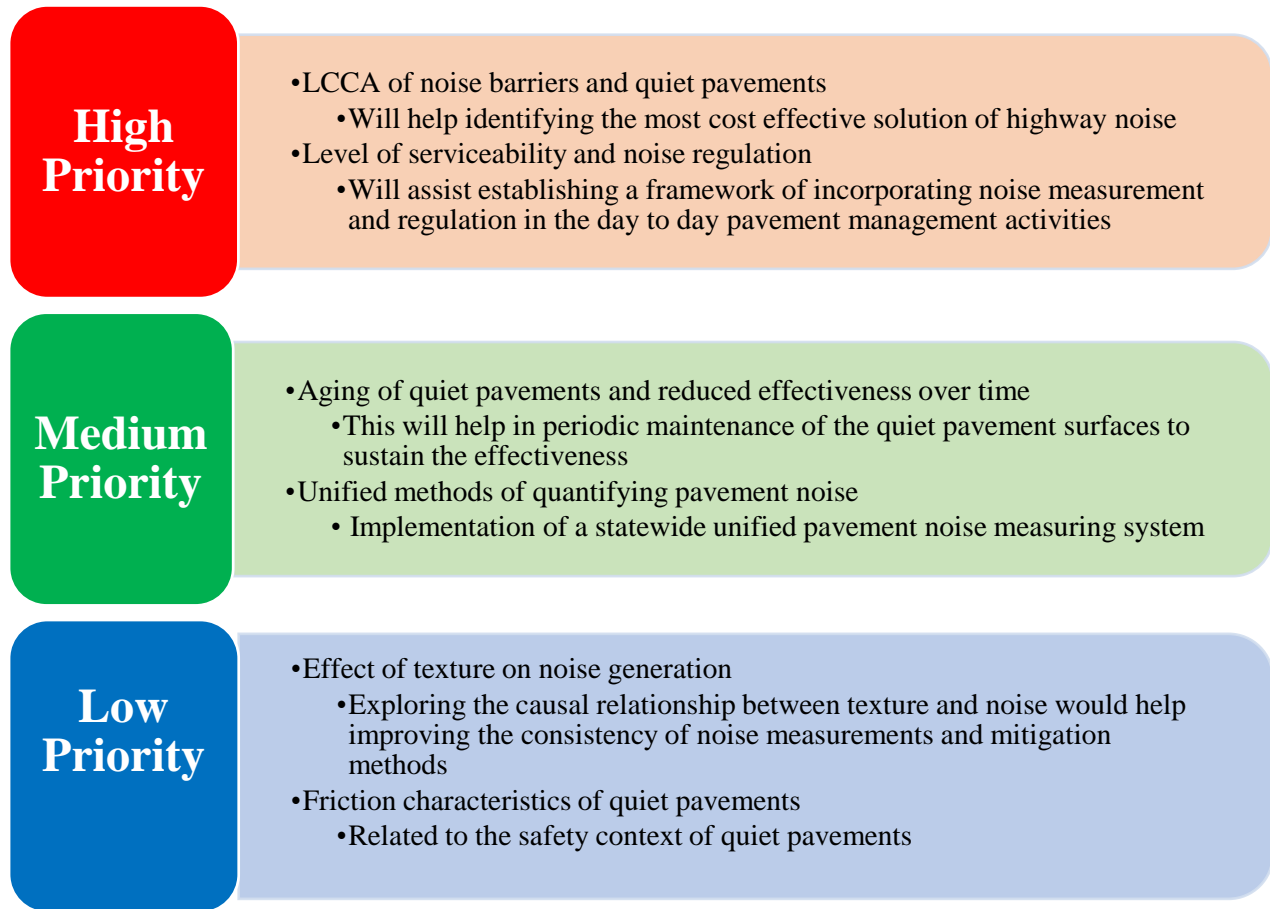
- **LCCA of noise barriers and quiet pavements:** To determine the most effective and sustainable traffic noise abatement technique, the state highway agencies need to be knowledgeable about life cycle cost of the mitigation strategies. This is applicable for both noise barriers and different quiet pavement options. There is a lack for proper documentation and comparisons between noise barriers and quiet pavements considering maintenance and rehabilitation cost of pavement surfaces opposing to the maintenance and replacement cost of noise barriers. Distance of the effective zone, the number of people benefitting from noise abatement, site elevation all this interconnected factor needs to be considered while selecting a noise mitigation strategy. Absence of proper financial assessment is the primary reason that noise reductions by the quiet pavement surfaces are not considered as an effective noise abatement technique by the FHWA Office of Environment and Natural Resources (FHWA-HEPN). Despite that, FHWA provides a well-established pavement rehabilitation process which would periodically replace loud worn-out pavements, so serviceability in terms of noise mitigation will not diminish. The framework presented in the NCHRP 738 can be a starting point of evaluating economic and acoustic performance of pavement and barrier noise abatement options (Donavan et al., 2013).
- **Effect of texture on noise generation:** Almost all the research studies performed on the quiet pavements emphasized the effect of surface texture on noise generation and mitigation. Macrottexture and megatexture, and potentially microtexture, can affect the noise generation characteristics of pavement at different noise spectrum. MPD of pavement surfaces showed some promising correlations. Hence detailed measurements of texture profile using handheld scanners or high-speed texture profilers may open some new horizons that can ultimately help improve the consistency of noise measurements and mitigation methods.
- **Aging of quiet pavements and reduced effectiveness over time:** There is significant evidence that aging makes quiet pavement surfaces ineffective over time. Raveling of open graded asphalt pavements and subsequent clogging of voids are believed to be the primary reason for reduced efficiency of flexible quiet surfaces. On the other hands texture attained through diamond grinding or simple burlap drag on rigid surfaces help to mitigate noise compared to longitudinal/transverse tinning but also diminishes rapidly after some point of their service life. Raveling of asphalt pavement is a very well researched topic but how the raveling of open graded surfaces affects the noise generation needs additional investigation. Similarly, changes in tinning or texture of rigid pavement surfaces over time needs to be studied and used to justify selecting one surfacing or texturing alternative over another.
- **Level of serviceability and noise regulation:** State highway agencies need to prioritize assets to regulate noise pollution and keep the pavements serviceable against highway noise to some extent. Right now, there is no standardized procedure of assessing highway noise at the network level and most of the times noise evaluations are done after complains received from the locals. A framework of periodic noise level measurements on different

functional classes would be helpful in creating an acoustic database which can be beneficial in a multipurpose way. Pavement is a state DOT's primary product and having an acoustic index of different pavement noise levels can be a very handy tool for addressing noise complaints.

- **Unified methods of quantifying pavement noise:** It was identified from the literature review that different agencies use different methods to quantify sound pressure levels. OBSI method is an AASHTO standard procedure which has been used by different agencies in research and routine applications. Level of repeatability and reproducibility of OBSI measurements are fairly high. Correlations with other highway noise measuring system are reported satisfactory by most of the highway agencies. Agencies should consider moving forward with a unified pavement noise measuring system which will not only be beneficial in setting benchmark for noise mitigation strategies but also work as a data repository for future research and implementation activities.
- **Friction characteristics of quiet pavements:** Tire-pavement noise and pavement surface friction appears to be inversely related and therefore there could be a trade-off between noise and friction. Friction is a key safety factor, and more research is needed to verify the correlation and quantify potential balanced characteristics that maintain both properties.

### 8. Recommendations

In this study a comprehensive assessment on quiet pavements was performed through literature review, expert interviews, and existing data analysis to identify areas where quiet pavement technology needs improvement or further research. Some gaps are identified to help Florida DOT in understanding the feasibility and effectiveness of quiet pavements as a noise abatement strategy in Florida. Figure 44 presents the main gaps identified based on their impact and feasibility to help FDOT in understanding the status of quiet pavement in reducing highway noise and upcoming research needs.



**Figure 44. Prioritization of Gaps in the Area of Quiet Pavement**

Based on the identified gaps and level of priority, the research team is also recommending FDOT to develop a roadmap that will be beneficial for addressing the identified gaps, outlining future research needs, testing required to assess the effectiveness of quiet pavement technology, and developing an improved traffic noise abatement program. A proposed roadmap with recommended implementation steps is presented in Table 4.

**Table 4. Proposed Roadmap with Recommended Implementation Steps for Addressing the Identified Gaps**

Implementation Steps	Stage 1 – Immediate Activities	Stage 2 – Near or Short-Term Activities	Stage 3 – Future or Long-Term Activities
1. Define desired level of service for pavements against highway noise	Review existing noise regulations, determine the level of service required for quiet pavements	Monitor compliance with regulations, Collect data, Update highway noise regulations based on research and data analysis	Regularly monitor and adjust noise regulations
2. Unified method of quantifying pavement noise	Evaluate the suitability of existing methods, Train FDOT staff on standardized measurement methods like OBSI	Develop or adopt a standardized noise measurement, Conduct research on emerging measurement methods	Regularly maintain the measuring equipment and update measurement methods
3. Develop LCCA models for different noise mitigation strategies	Gather cost and additional (effective zone radius, number of people benefitted) data for noise barriers and quiet pavements, Compare the cost-effectiveness of various options	Conduct LCCA for different noise abatement options, Integrate LCCA into planning and funding of projects where highway noise can be an issue	Continuously update LCCA models
4. Monitoring and maintenance of Quiet Pavements	Assess the condition and effectiveness of existing quiet pavements in Florida, Implement maintenance activities as needed	Develop maintenance plans for different quiet pavements	Invest in research and development for durable quiet pavement materials and sustainable technologies
5. Identify texture and friction requirements for noise reduction	Review existing pavement surface texture and friction	Research and select suitable quiet pavement textures, Evaluate the performance of different textures	Establish a quiet pavement surface monitoring and maintenance program

It should be noted that this proposed roadmap is a general guideline, and the specific steps and activities may vary depending on the unique needs, resources, and regulatory framework of FDOT. It is crucial to collaborate with experts, research institutions, and stakeholders to ensure the success of the noise abatement program over time.

### 9. Conclusions

The main objectives of this study were to find out the recent developments in the area of highway noise, quiet pavements and to better understand the contributing factors, remedies, and the effects of highway noise pollution on the public. This white paper compiled the activities that have been performed during the study. This includes an extensive literature review; analysis of the data collected from FDOT; information collected during interviews with quiet pavement experts from different state highway agencies; and a gap assessment identified through literature review, data analysis and interviews. Findings from this analysis was used to prioritize gaps and develop a roadmap as recommendations to FDOT.

## References

- AASHTO T 360-16. *Standard Method of Test for Measurement of Tire-Pavement Noise Using the on-Board Sound Intensity (OBSI) Method*, American Association of State and Highway Transportation Officials, Washington, DC, USA, 2020.
- AASHTO TP 76-15. *Standard Method of Test for Measurement of Tire-Pavement Noise Using the on-Board Sound Intensity (OBSI) Method*, American Association of State and Highway Transportation Officials, Washington, DC, USA, 2013.
- AASHTO TP 98-13. *Standard Method of Test for Determining the Influence of Road Surfaces on Vehicle Noise Using the Statistical Isolated Pass-by (SIP) Method*, American Association of State and Highway Transportation Officials, Washington, DC, USA, 2013.
- Anderson, K., Uhlmeyer, J., Russell, M., and Weston, J. *Evaluation of Long-Term Pavement Performance and Noise Characteristics of the Next Generation Concrete Surface*, Report No. WA-RD 767.1, Washington State Department of Transportation, Olympia, Washington, 2011.
- Anfosso-Lédée, F., and Do, M-T. Geometric descriptors of road surface texture in relation to tire-road noise. *Journal of the Transportation Research Board*, Vol. 1806:160–167, 2002.
- Aspro; Silence in Arizona. *Official Journal of the Institute of Asphalt Technology*; Institute of Asphalt Technology: Bathgate, UK, 2005.
- Bendtsen, H. Drainage asphalt and noise reduction over a long period. In Proceedings of the *Euro-Noise1998*, Munich, Germany, 4–7 October 1998.
- Bendtsen, H., and Larsen, E. Two-layer porous pavements and noise reductions in Denmark. In Proceedings of the *Inter-Noise*, The Hague, The Netherlands, 27–30 August 2001.
- Berglund, B., Lindvall, T., Schwela, D. H. World Health Organization (WHO). Occupational and Environmental Health Team. *Guidelines for community noise*. World Health Organization, 1999.
- Bernhard, R., and Wayson, R. L. *An Introduction to Tire/Pavement Noise of Asphalt Pavement*. 2005.
- Biligiri, K. P., and Kaloush, K. E. Influence of pavement material properties on tire / road surface noise. *Journal of the Transportation Research Board*, 2007.
- Blough, J., Dumbacher, S., Hallman, D., and Wang, P. Source Identification Using Acoustic Array Techniques, From the Proceedings of the *SAE Noise and Vibration Conference*, Vol 2, pp 1023-1035, Traverse City, MI, May 1995.
- Burge, P., Travis, K., and Rado, Z. Transverse-tined and longitudinal diamond-ground texturing for newly constructed concrete pavement: A comparison. *Journal of Transportation Research Board*, 2002.

- Chalupnik, J. D., and Anderson, D. S. *The Effect of Roadway Wear on Tire Noise*. Final Report. Washington State Transportation Commission, 1992.
- Choubane, B., Holzschuher, C., and Gokhale, S. *Precision of Smooth and Ribbed Tire Locked Wheel Testers for Measurement of Roadway Surface Friction Characteristics*, Florida Department of Transportation, Tallahassee, FL, 2006.
- Crocker, M., Hanson, D., Li, Z., Karjatkar, R., and Vissamraju, K. Measurement of acoustical and mechanical properties of porous road surfaces and tire and road noise. *Journal of Transportation Research Board*, 2004, 1891, 16–22
- Dare, T., McDaniel, R., Shah, A., and Bernhard, R. *Hot Mix Asphalt Surface Characteristics Related to Ride, Texture, Friction, Noise and Durability*; Report No. MN/RC 2014-07; Minnesota Department of Transportation, Saint Paul, MN, USA, 2014.
- Donavan, P. R., Pierce, L. M., Lodico, D. M., Rochat, J. L., and Knauer, H. S. *Evaluating Pavement Strategies and Barriers for Noise Mitigation*, NCHRP Report 738, National Cooperative Highway Research Program, Washington, D.C. 2013.
- Eberhardt, A. C. 1985. *Investigation of the Tire/Pavement Interaction Mechanism Phase I and II*. Final Report. FHWA contract DTRS5681-C-00002.
- European Asphalt Pavement Association (EAPA). *Abatement of Traffic Noise—The Arguments for Asphalt*, EAPA, Brussels, Belgium, 2007.
- Faure, B., Hamet, J.F., Kestemont, X., Luminari, M., Quaresma, L., and Sandulli, D. *Traffic Noise and Road Surfaces: State of the Art*, Belgian Road Research Centre, Brussels, Belgium, 2000.
- Federal Highway Administration (FHWA). *Highway Traffic Noise: Analysis and Abatement Guidance*, FHWA-HEP-10-025, U.S. Department of Transportation, Washington, D.C., 2011.
- Fujikawa, T., Koike H., Oshino, Y. Tachibana, H. Road texture for abating truck tire noise generation. *Internoise*, 2006.
- Gibbs, D., Iwasaki, R., Bernhard, R., Bledsoe, J., Carlson, D., Corbisier, C., Fults, K., Hearne, T., McMullen, K., Newcomb, D., Roberts, J., Rochat, J., Scofield, L., and Swanlund, M. *Quiet Pavement Systems in Europe*, Office of International Programs, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2005.
- Goubert, L., Hoogwerff, J., The, B., and Hofman, R. Two-layer porous asphalt: An international survey in the frame of the Noise Innovation Programme (IPG). In *Proceedings of the Inter-Noise 2005*, Rio de Janeiro, Brazil, 7–10 August 2005.
- Guada, Irwin M., Arash Rezaei, John T. Harvey, and David Spinner. *Evaluation of grind and groove (next generation concrete surface) pilot projects in California*. Report No. UCPRC-RR-2013-01, California Department of Transportation, 2012.

- Hanson, D. I., James, R. S., and NeSmith, C. Tire/pavement noise study. NCAT Report 04-02, National Center for Asphalt Technology, Auburn University, Auburn, AL, 2004.
- Hanson, D. I., and James, R. S. *Colorado DOT Tire-Pavement Noise Study*, Report No. CDOT-DTD-R-2004-5, Colorado Department of Transportation: Denver, CO, USA, 2004.
- Hanson, D., and Waller, B. *2005 Colorado DOT Tire-Pavement Noise Study*, Report No. CDOT-2006-18; Colorado Department of Transportation: Denver, CO, USA, 2006.
- Hanson, I., James, S., and NeSmith, C. *Tire-Pavement Noise Study*; National Center for Asphalt Technology, Auburn, AL, USA, 2004.
- Hastings, Aaron L. Traffic Noise Model 3.0 - Technical Manual, FHWA-HEP-20-012, U.S. Department of Transportation, John A Volpe National Transportation Systems Center, Cambridge, MA, 2019.
- International Standard ISO 11819-1. *Acoustics-Method for Measuring the Influence of Road Surfaces on Traffic Noise. Part 1: The Statistical Pass-by Method*, International Organization for Standardization, Geneva, Switzerland, 2005.
- International Standard ISO-11819-2. *Acoustics-Measurement of the Influence of Road Surfaces on Traffic Noise. Part 2: Close-Proximity Method*, International Organization for Standardization, Geneva, Switzerland, 2000.
- Jonasson, H., and Storeheier, S. *Nord 2000: New Nordic Prediction Method for Road Traffic Noise*; SP Report 2001-10, Swedish National Testing and Research Institute (SP), Boras, Sweden, 2001.
- Kandhal, P. S. *Asphalt Pavements Mitigate Tire/Pavement Noise*, Hot Mix Asphalt Technology, 2004.
- Karamihas, S.M., and Cable, J. K. Developing Smooth, Quiet, Safe Portland Cement Concrete Pavements, FHWA Project DTFH61-01-X-0002, U.S. Department of Transportation, Washington, DC, 2004.
- Klein, P., and Hamet, J-F. *Road texture and rolling noise - an envelopment procedure for tire road contact*. Technical Report LTE 0427, INRETS, 2004.
- Kowalski, K. *Influence of Mixture Composition on the Noise and Frictional Characteristics of Flexible Pavements*. Ph.D. Thesis, Purdue University, West Lafayette, IN, USA, 2007.
- Kuemmel, D., Sonntag, R., Crovetti, J., Becker, Y., Jaeckel, J., and Satanovsky, A. *Noise and Texture on PCC Pavements-Results of a Multi-State Study*, Report No. WI/SPR-08-99, Wisconsin Department of Transportation, Madison, WI, USA, 2000.
- Kugler, B., Commins, D., and Galloway, W. *Highway Noise; a Design Guide for Prediction and Control*, National Cooperative Highway Research Program, Report 174; Transportation Research Board, National Research Council, Washington, DC, USA, 1974.

- Lee, C. S. Y. and Fleming, G. G. *Measurement of Highway-Related Noise. Section 4: Existing-Noise Measurements in the Vicinity of Highways*. FHWA-PD-96-046. U.S. Department of Transportation, Volpe National Transportation Systems Center, Acoustics Facility, Cambridge, MA, 1996.
- Lodico, D., and Donovan, P. *Quieter Pavement: Acoustic Measurement and Performance*, Report CTHWANP-RT-18-365.01.1, California Department of Transportation, Sacramento, CA, 2018.
- Menge, C., Rossano, F., Anderson, G., and Bajdek, C. *FHWA Traffic Noise Model, version 1.0: Technical Manual*, Report No. FHWA-PD-96-010 and DOT-VNTSC FHWA-98-02, U.S. Department of Transportation, Washington, DC, USA, and John A. Volpe National Transportation Systems Center, Cambridge, MA, USA, 1998.
- Li, M. *Tyre - Road Noise, Surface Characteristics and Material Properties*. PhD thesis, Delft Technical University, Netherlands, 2013.
- Li, Mingliang, Wim van Keulen, Emiel Tijs, Martin van de Ven, and André Molenaar. "Sound absorption measurement of road surface with in situ technology." *Applied Acoustics* 88 (2015): 12-21.
- Ohiduzzaman, M., Sirin, O., Kassem, E., and Rochat, J. L. *State-of-the-Art Review on Sustainable Design and Construction of Quieter Pavements —Part 1: Traffic Noise Measurement and Abatement Techniques*, Sustainability, 8, 742, Multidisciplinary Digital Publishing Institute (MDPI), Basel, Switzerland, 2016.
- Poelmans, F., et al. *Continuously Reinforced Concrete with Noise Reducing Surface for the Reconstruction of the E313 (A13) Motorway in Hasselt, Belgium*. In *Seventh International Symposium on Concrete Roads*, Austria, pp. 119-124, 1994.
- Rasmussen, R. *Pin-point noise sources on vehicles during pass-by using intensity technique*. In *Proceedings of the International Tire-Road Noise Conference*, Gothenberg, Sweden, 8–10 August 1990.
- Rasmussen, R., Bernhard, R. J., Sandberg, U., and Mun, E. P. *The Little Book of Quieter Pavements*, FHWA-IF-08-004, Federal Highway Administration, Washington, DC, 2007.
- Rasmussen, R., Garber, S., Fick, G., Ferragut, T., and Wiegand, P. *How to Reduce Tire-Pavement Noise: Interim Better Practices for Constructing and Texturing Concrete Pavement Surface*, Research Report Pooled Fund TPF-5(139), National Concrete Pavement Technology Center, Ames, IA, USA, 2008.
- Rasmussen, R. *Measuring and modeling tire-pavement noise on various concrete pavement textures*. *Journal of Noise Control Engineering* 2009, 57, 139–147.
- Rasmussen, R., Garber, S., Sohaney, R., Wiegand, P., and Harrington, D. *What Makes a Quieter Concrete Pavement?* Tech brief, National Concrete Pavement Technology Center, Iowa State University, Ames, Iowa, 2010.

- Rasmussen, R., Sohaney, R., Wiegand, P., and Harrington, D. Measuring and Analyzing Pavement Texture. Concrete Pavement Surface Characteristics Program. National Concrete Pavement Technology Center; Iowa State University, Institute of Transportation, Tech Brief, January 2011
- Reyes, C., and Harvey, J. A method for prediction sound intensity noise levels using laboratory pavement cores. In Proceedings of the *Noise-Con*, Portland, OR, USA, 25–27 July 2011.
- Rochat, J., and Fleming, G. Addendum to Validation of FHWA’s Traffic Noise Model® (TNM): Phase 1, Report No. FHWA-EP-02-031 Addendum and DOT-VNTSC-FHWA-02-01 Addendum, U.S. Department of Transportation, Washington, DC, USA, and Volpe National Transportation Systems Center: Cambridge, MA, USA, 2004.
- Rochat, J., and Read, D. Effective flow resistivity of highway pavements. *Journal of Acoustic Society of America*, 2013, 134, 4710.
- Roo, F., Gerretsen, E., Hoffmans, W., and Doelman, N. Dutch tire road noise emission model-adjustments and validation. In Proceedings of the *Inter-Noise*, Fort Lauderdale, FL, USA, 2–4 December 1999.
- Sandberg, U., and Ejsmont, J. *Tire-Road Noise Reference Book*, Informex, Kisa, Sweden, 2002.
- Sandberg, U., Kragh, J., Goubert, L., Bendtsen, H., Bergiers, A., Biligiri, K., Karlsson, R., Nielsen, E., Olesen, E., and Vansteenkiste, S. *Optimization of Thin Asphalt Layers—State of the Art Review*; Project: ERA-NET ROAD; European National Road Administrations: Brussels, Belgium, 2011.
- Sandberg, U. *Low noise road surfaces. a state-of-the-art review*. Technical report, Swedish Road and Transport Research Institute, Sweden, 1992.
- Sandberg, U. *The Global Experience in Using Low-Noise Road Surfaces: A Benchmark Report*, Report Made in Response to ‘Hong Kong Environmental Protection Department’ Project No. AN 06-004, Hong Kong Environmental Protection Department: Hong Kong, China, 2009.
- Scofield, L. *Development and Deployment of the Next Generation Concrete Surface*. Moving Advancements into Practice (MAP) Brief, 2020.
- Shatnawi, S. *Quieter Pavement Bulletin*, Division of Pavement Management, State of California Department Of Transportation, Sacramento, CA, 2009.
- Sirin, O. State-of-the-Art Review on Sustainable Design and Construction of Quieter Pavements —Part 2: Factors Affecting Tire- Pavement Noise and Prediction Models. Sustainability, 8, 692, Multidisciplinary Digital Publishing Institute (MDPI), Basel, Switzerland, 2016.
- Smit, A., and Waller, B. *Sound pressure and intensity evaluations of low noise pavement structures with open graded asphalt mixtures*. NCAT Report 0702, National Center for Asphalt Technology, Auburn University, Auburn, AL, 2007a.

- Smit, A., and Waller, B. *Air Temperature Influence on Near-Field Tire-Pavement Noise*. Transportation Research Record, 87th Annual Meeting CD ROM, Paper No. 08-0389, 2008.
- Smit, A. F. *Synthesis Of NCAT Low-Noise HMA Studies*, NCAT Report 08-01, National Center for Asphalt Technology, Auburn University, Auburn, AL, 2008.
- Smit, A. F., Trevino, M., Zuniga, N. G., Buddhavarapu, P., and Prozzi, J. *Selection and Design of Quiet Pavement Surfaces*. Report FHWA/TX-16/0-6819-1, Texas Department of Transportation, Austin, TX, 2016.
- TemaNord. *Road Traffic Noise-Nordic Prediction Method*, Report 1996:525; Nordic Council of Ministers, Copenhagen, Denmark, 1996.
- Sohaney, R. Experiences with CDOT's Quiet Pavement Research Program, Presented in *23rd Annual Road Profile Users' Group (RPUG) Meeting*, Stateline, NV, 2011.
- Van Keulen, W., and Duškov, M. *Inventory study of basic knowledge on tyre/road noise*. IPG Report DWW-2005-022, Delft, the Netherlands, 2005.
- Von Meier, A., Van Blokland, G. J., and Descornet, G. The influence of texture and sound absorption on the noise of porous road surfaces. In *PIARC 2nd International Symposium on Road Surface Characteristics*, pages 7– 19, 1992.
- Wayson, R., Chovarelli, M., and MacDonald, M. Testing the AAMA community noise model. In *Proceedings of the 78th Transportation Research Board Annual Meeting (CD)*, Washington, DC, USA, 10–14 January 1999.
- Wayson, R., MacDonald, M., and Martin, A. *Modeling of Quieter Pavements in Florida*, Florida Department of Transportation, Tallahassee, FL, 2009.
- Wayson, R., MacDonald, M., and Martin, A. *On-Board Sound Intensity (OBSI) Study*, Florida Department of Transportation, Tallahassee, FL, 2014.
- Wayson, R. *Relationship Between Pavement Surface Texture and Highway Traffic Noise*, Synthesis of Highway Practice 268, National Cooperative Highway Research Program, Washington, D.C. 1998.

## Appendix Appendix A - Focused Group Interview Summary

Questions	Caltrans	WSDOT	NJDOT	TxDOT	ADOT
1. Noise measuring system used by the agency?	Developer and user of OBSI.	OBSI.	Did wayside. Using OBSI now	Sound Pressure Meter (Routinely) OBSI (research)	OBSI, CPX and Wayside.
2. Good correlation between different systems?	Compared OBSI and CPX. They were well correlated.	Correlated well with other states.	Did some research with Rutgers	Good correlation between two	OBSI has strong correlation with all methods
3. Effectiveness of quiet pavements?	Noise Barriers - 5 dBA only for receptors directly behind the wall. Effective for approximately 200 feet. Quiet Pavements - can reduce noise levels by 6 to 10 dBA on both sides of the road and work at much larger distances (500 feet plus) from the roadway.	Quiet Pavements - can reduce noise levels by at most 4 dBA.	Quiet Pavements - can reduce noise levels by 3- 4 dBA. Best - Asphalt Rubber Modified OGFC.	Much effective. Noise barriers are not effective behind the acoustical shadow zone. On the other hand, quiet pavement reduces the noise from the source.	ARFC is effective. Can reduce noise levels by 5-11 dBA with an average reduction of 8.2 dBA.
4. Public perception of quiet pavement?	People want noise reduction whatever the means possible	Great, people noticed. Residents appreciated.	Public prefer noise barriers. People complain about noise barriers in hilly areas.	Positive perception. People can feel the results. Residents have some aesthetic complains about the noise barriers. Cleaning of Graffiti is also a problem.	ARFC provided significant reductions in noise at the wayside of the freeways
5. Effectiveness of quiet pavement over time and if any studies have been undertaken to assess the reduction of efficiency over time?	Raveling reduces effectiveness of flexible pavements. Rigid pavement lasts longer. Some long-term studies are undertaken.	Effectiveness lasts for only 2-3 months. Freeze-thaw is the main reason. Studded tire is also responsible.	Effectiveness reduces over time.	OGFC/PFC - Clogging is an issue. Voids reduced. Perform well 5-7 years and then they need to be replaced. Rigid with DG is quieter. After 2-3 years they start to lose effectiveness. Thin overlay mixes are very effective. After 6-7 years they stay quiet. The acoustics properties outlived their life.	Reduced efficiency over time. Effectiveness decreases by 0.5-0.6 dBA per year.

## Quiet Pavements Synthesis

Questions	Caltrans	WSDOT	NJDOT	TxDOT	ADOT
6. Major contributing factors in reducing noise using quiet pavements?	Surface texture, aggregate size, and air voids are the primary pavement variables. A 'negative' surface texture with air voids is the quietest pavement. Next Generation Concrete Surface (NGCS) is the quietest rigid surface proposed by Caltrans which is formed by optimizing surface texture and air voids and noise as control parameters.	Air voids.	Texture, Raveling.	Absorption of sounds - Flexible Texture - Rigid pavement. Burlap drags and DG is helpful. Other factors are Pavement age, Aggregate size, traffic level.	Texture.
7. Has texture been used as a contributing parameter to model noise? If yes, what texture measurement techniques have been incorporated?	Yes. A variety of texture measurement approaches were used.	Profilers used but not for quiet pavement. Longitudinal tinning/ Diamond grooving are effective for rigid pavements.	Yes, Lasers are used.	No, CTM and sand patch is used for texture measurements only.	Yes, MPD with outflow meter.
8. Any life cycle assessment of quiet pavements compared to noise barriers?	Yes, NCHRP 738. Quieter pavement alternatives can be both feasible and cost reasonable in some situations (even under current state agency criteria).	No, flexible quiet pavement will need frequent repaving. Rigid may perform better. But after 2-3 years diamond grooving is not effective.	Noise barriers provide long term solution. Resurfacing needed every 10 years for quiet pavement.	No actual study. But very much needed. How much people get benefit, maintenance needed over time. Sometime barriers need to be replaced because of construction.	None.
9. Recognition of quiet pavement as a noise mitigation strategy?	Yes, Caltrans issued a District Director Memorandum about selecting quieter pavement options near noise-sensitive receptors.	No. Stopped testing	Yes, Finer graded like thin overlay and SMA are being used now.	No, follow FHWA guidelines.	Yes.
10. Trade-off between noise and friction in context of quiet pavements?	This was tested with Skid abrader equipment and some subtle and interesting shifts were observed in the pre and post pavement spectra.	No, frictions are not measured on quiet pavement sections.	Have not experimented. OGFC is great for wet weather friction	No, with time PFC loss friction.	None tested

## Appendix - B Interview Questions

1. Which systems does your agency use to measure noise and have you found good correlation between the different systems?
2. Based on the work done in your state, how effective are quiet pavements compared to noise barriers in reducing noise?
3. How is the public perception when using quiet pavement compared to noise barriers, do they feel more comfortable with noise barriers even if quiet pavement provided the intended noise reduction?
4. Did you notice reduction in effectiveness of quiet pavements over time? Did your agency perform any studies to assess the reasons in reduced efficiency?
5. What do you think are the major contributing factors in reducing noise using quiet pavements? The available studies provide a wide range of correlations, but we are interested in the engineering analysis that explain the causes.
6. If you used texture as a contributing parameter to model noise, what texture measurement techniques have been most effective?
7. Did you assess the life cycle of quiet pavements and compared that to the life cycle of noise barriers?
8. Does your agency recognize quiet pavement as a noise mitigation strategy?
9. Have you investigated the trade-off between noise and friction and are there strategies to mitigate that trade-off if present