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Delaware Hot Mix Asphalt Pavement Noise Study

By

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DELAWARE HOT-MIX ASPHALT PAVEMENT NOISE STUDY

Chapter 1

INTRODUCTION

1. Introduction

Traffic and pavement noise constitute environmental noise pollution that is of much concern. They can have adverse effects on the health of humans, reduce real estate values and create difficulties in speech communications. It can also have a negative impact on sleep patterns and cause general annoyance. Traffic noise has been studied in much of Europe and Asia and various strategies have been tried to create quieter pavements and to reduce general noise generated by the tire/pavement interaction. According to Iwao and Yamazaki (1996), tire/road pavement noise is only second to engine noise as shown in Figure 1.1.

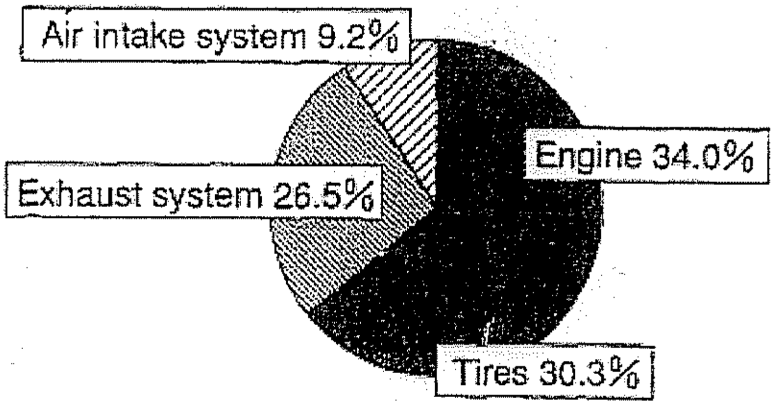


Figure 1.1. Proportions of various noise sources (after Iwao and Yamazaki, (1996))

Certain types of asphalt pavements have been known to reduce tire/pavement interaction noise. A typical example is porous asphalt pavement.

The state of Delaware, like other states in the USA and many parts of the world, faces problems with annoying noise from tire/pavement interaction. It is a challenging problem since the noise is generated from a complex combination of various sources and mechanisms. When one source of noise is reduced, the other sources become pronounced. That is, it is difficult to separate the sources and deal with them in isolation. This presents a formidable problem, but which problem needs to be solved to ensure quieter pavements, and more enjoyable residential neighborhoods that abut busy streets and freeways.

The present report discusses tire/pavement interaction noise of hot-mix asphalt (HMA) pavements for the state of Delaware. Chapter 2 gives background of sound and noise, and a review of the literature for pavement noise. Chapter 3 presents a laboratory testing program for various Delaware Department of Transportation (DelDOT) HMA mixes, while chapter 4 gives results and data analysis. Conclusions and recommendations are presented in chapter 5.

2. Statement of the Problem

The state of Delaware has previously used Stone Matrix Asphalt (SMA) and Open Graded Friction Course (OGFC) for flexible pavements. OGFC had mainly been used for rehabilitation of dense-graded pavement surfaces by placing a 1-inch topping of OGFC. Even though current research has shown that OGFC pavements produce lesser tire/pavement interaction noise, problems encountered with this maintenance method regarding rapid deterioration after the planned life of the OGFC had passed caused DelDOT to discontinue the method. At present, DelDOT uses superpave HMA mixtures for flexible pavements.

Pavement noise is a known issue within the pavement research community, and even among the general public. Noise barriers have been used to cut off much of the noise generated by passing traffic for residential neighborhoods near freeways and busy streets. A major part of the noise from passing vehicles is generated at the tire/pavement interface, and much research has been directed at reducing this type of noise. In response to the problem of pavement noise, DelDOT initiated a proposal to study and evaluate noise generated from DelDOT Superpave HMA mixtures, and possibly compare it with noise from DelDOT SMA and OGFC.

3. Objective

The objective of the present study is to evaluate the noise produced by the tire/pavement interaction of hot-mix asphalt (HMA) pavements. The evaluation will cover DelDOT Superpave HMA mixtures, SMA, and OGFC. The evaluation is intended to help the Delaware Department of Transportation (DelDOT) develop quieter pavements in the state of Delaware through better testing methods for the acoustic properties of DelDOT superpave mixes.

4. Research Approach

Much research has been done in the area of pavement noise, especially in Europe and Asia. Certainly, there has been some research also done in the USA. However, the state of Delaware still wants to ensure quieter pavements by conducting comparative testing on the mixes used in Delaware and in other states.

Thorough coverage of the background and review of the literature will be conducted to know what has been done, and is being done in HMA pavement noise. Focus will be on the different types of HMA pavements and their effect on pavement noise, the parameters that are involved in tire/pavement noise generation, and current pavement noise testing methods. In order to understand pavement noise, general background will be given on sound and noise, propagation of sound and the factors that affect the generation and propagation of sound.

Information gained from the background study will help in developing a strategic laboratory testing program directed at unraveling the critical parameters involved in, and that enhance, pavement noise production. Some case studies will also be explored.

Chapter 2

BACKGROUND AND LITERATURE REVIEW

2.1. Introduction

In order to understand the mechanisms that generate tire/pavement interaction noise there has to be an exploration of the background of sound and noise, and the means by which they are generated and propagated. Knowledge of this background would be needed to do a thorough literature review of tire/pavement interaction noise on HMA pavements.

The following background and literature review are intended to help with developing a better understanding of the influence of HMA pavement type on tire/pavement noise, as well as the parameters that contribute to the phenomenon. The effect of the produced noise on nearby residential neighborhoods (that is, the effect on humans) and the ways by which such noise is being mitigated will also be reviewed. The current Federal Highway Administration (FHWA) noise policy will be discussed in addition.

2.2. Relevant Terms

There are three main relevant terms when studying noise: Sound, noise, and acoustics. Sound may be defined as mechanical energy or pressure vibrations that are transmitted as waves through a fluid medium, and that can be heard by the ear. Noise is unwanted sound. This means, noise is relative to the listener. Certain sounds may be noise to one person but pleasant to others, depending on whether it is wanted or unwanted by the listener.

Acoustics is the science of sound, studying scientifically the properties of sound. The mechanics of the noise generated from HMA pavements as vehicles travel on them, including the measurement of sound, are governed by acoustics. Emphasis is placed more on what causes HMA pavement noise in this report. The following section discusses sound and noise.

2.3. Sound and Noise

Sound is produced by pressure variations in a fluid medium. Mechanical vibrations produce mechanical sounds. A vibrating string, or a vibrating surface would produce mechanical sounds. Sound can also be produced aerodynamically. A moving vehicle generates additional sound by "cutting" through the air; the movement of air around the vehicle generates aerodynamic sound.

Generally, humans can hear sounds in the frequency range of 20 Hz – 20,000 Hz. Sound above 20,000 Hz is called ultrasound, and sound below 20 Hz is called infrasound. Within this range, hearing ability varies. Women can hear some sounds above 20,000 Hz. Human peak hearing sensitivity are around 1,000 Hz to about 4,000 Hz. This implies that any studies on noise would benefit from focusing on this frequency range.

Just as waves, sound may be described in terms of frequency, speed, wavelength, period and amplitude. Frequency is the number of complete cycles per unit time; speed is the speed of the waveform as it passes through a fluid medium; wavelength is the distance between two repeating points on a waveform; period is the time required for a complete cycle; and the amplitude is the maximum displacement of the waveform.

Noise, as indicated earlier, is unwanted, undesirable or harmful sound. Vehicles moving along a highway generate much undesirable sound from interaction with the road pavement. The adverse effects noise can have on humans depend on the frequency and duration of the sound. High frequency noise for long sustained periods can cause loss of hearing. Steady low-energy noise (low amplitude) may cause problems with speech communication, disturb sleep and generally lower the quality of life.

2.4. Sound Concepts and Definitions

Some definitions have already been mentioned, including frequency, speed, wavelength, period and amplitude. There are still further concepts and definitions that are important in the study of noise. These are discussed as follows.

2.4.1. Human Perception of Sound and The Decibel Scale

The sound pressure range experienced in practice is large and varies from as low as 10^{-5} Pa to as high as 10^{3} Pa; the threshold of pain is about 100 Pa. Between the two extremes of audible sound, human perception of sound or noise exhibits a logarithmic behavior, and therefore, this range necessitates a logarithmic scale of measurement. Table 2.1 illustrates this nature of sound perception by the human ear using changes in noise level.

Table 2.1. Subjective effect of changes in noise level (after Barber, 1992)

Change in Level	Subjective Effect
3	Just perceptible
5	Clearly perceptible
10	Twice as loud

The unit of sound is the decibel (dB), which is a ratio between two quantities. The bel is the fundamental unit (after Alexander Graham Bell), and it is defined as the base 10 logarithm of the ratio of two powers. The decibel is 0.1 bel.

According to Table 2.1 humans perceive sound twice as loud when the change in sound is about 10 dB, and therefore, four times as loud when the change is 20 dB. Humans judge the relative loudness of two sounds using approximately the ratio of their mean square pressures. Therefore, the quantity used for measuring sound pressure, the sound pressure level (in dB), is given by

$$L_P = 10\log_{10}\frac{\overline{p^2(t)}}{p_{ref}^2} = 20\log_{10}\frac{p_{rms}}{p_{ref}}, \tag{1}$$

where p_{ref} is a reference pressure of 20 μPa, which is the reference pressure used for sound propagation in air. It corresponds to an rms (root mean square) pressure of a pure tone at 1 kHz, which is just audible for the average young human. 1 kHz, thus, corresponds to a sound pressure of level of 0 dB. Furthermore, according to equation (1), a sound pressure level of 0 dB does not necessarily imply an absence of sound; it may mean the sound level is equal to the reference sound level. Table 2.2 gives typical sound pressure levels from various sources.

The A-weighting procedure corrects for the logarithmic nature of the human perception of sound. Therefore, sound is most commonly measured in dB(A), with the 'A' indicating A-weighting.

Table 2.2 Typical RMS pressure fluctuations and their sound pressure levels (rough approximations) (After Fahy and Walker, 1998).

	P_{rms} (Pa)	L_{p} (dB re $2\times10^{-5}\,Pa$)
3 m from jet engine	200	140
Rock concert	20	120
2 m from pneumatic hammer	2	100
Vacuum cleaner	0.2	80
Conversational speech	0.02	60
Residential area at night	0.002	40
Rustling of leaves	0.0002	20
Threshold of hearing	0.00002	0

2.4.2. Propagation of Sound

Sound or noise perception due to tire/pavement interaction depends on the propagation of sound and the factors that affect the propagation. The parameters of sound that are apparent will be velocity and wavelength. Noise from tire/pavement interaction travels through air, and hence, will be affected by wind and directional effects; these factors can cause attenuation of sound in air.

The velocity of sound in air at 20°C (68°F) is approximately 340 m/s. It is higher in liquids and solids.

Attenuation of sound depends on temperature, humidity, and frequency, even though the effect of temperature is small. It is a common observation that sound travels faster in fog, perhaps due to the stillness of the air in fog. Table 2.3 provides the attenuation of sound in air depending on frequency and humidity. It is easily observed that the intensity of sound seems to increase downwind in windy conditions, and decreases upwind. In these conditions, attenuation of sound is not easily predictable; therefore, it is always advisable to measure sound in still air conditions.

Table 2.3 Attenuation of sound in air (dB/km) (after Barber, 1992)

Frequency (kHz)	Relative Humidity (%)					
	0	10	20	40	60	80
1	0	12	6	4	4	3
2	1	40	19	10	9	8
4	3	110	68	32	23	20
16	41	280	460	380	270	210

Sound with velocity, v, and frequency, f, has a wavelength given by

$$\lambda = \frac{v}{f} \tag{2}$$

The radiation of sound in air from a source to a receiver obeys the inverse square law. That is, the intensity of sound at the receiver varies with the square of the distance from the source.

Directivity will affect the propagation of sound, especially during measurement of sound. Even though sound sources generally radiate sound more in one direction than other directions, the actual radiation pattern can be complex. Furthermore, the radiation is affected by the presence of reflective surfaces near the source. This suggests that measuring sound should be a three-dimensional work, in which contours of sound pressure levels are generated from a three-dimensional array around the source (Barber, 1992). Figure 2.1 shows a schematic of sound pressure level contours.

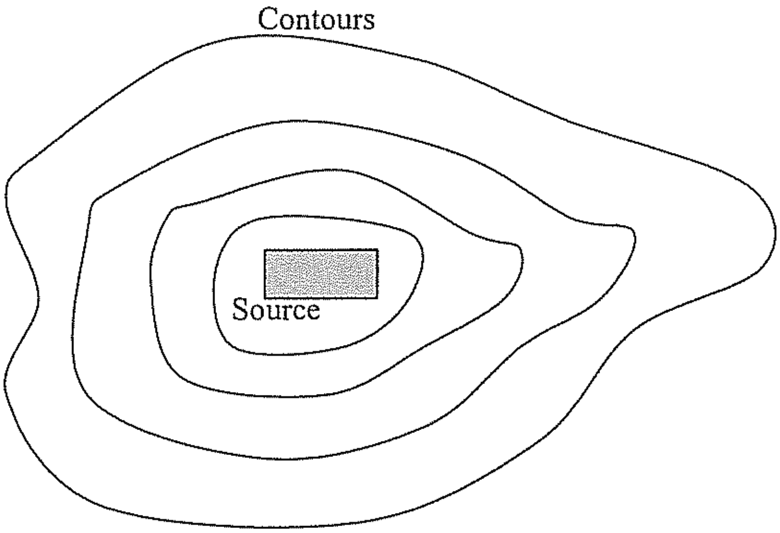


Figure 2.1 Sound Pressure Level Contours

Sound sources acting incoherently (i.e., unrelated) cannot be added arithmetically. For instance, the decibel value of sound source A cannot be simply added to that of sound source B to get (A + B) dB. The nature of the decibel scale requires that the decibel values be converted back to the corresponding sound energy, where values can be arithmetically added or subtracted. The final value is then converted back to the decibel scale. Usually, a table of values is used to combine decibel values. A typical table is provided on the FHWA's Website, which is given in Table 2.4

Table 2.4 Decibel addition approximation (from FHWA Website)

When two decibel values differ by (dB)	Add to higher value (dB)	Example
0 to 1	3	50 + 51 = 54
2 to 3	2	62 + 65 = 67
4 to 9	1	65 + 71 = 72
10 or more	0	55 + 65 = 65

If more than two decibel values have to be added together, first rank them from lowest to highest. Then add them two at a time to get the final result.

2.5. Traffic Noise

Traffic noise is basically a combination of the noise directly from the vehicles, aerodynamic noise, and noise from the interaction of the vehicle's tires and the pavement. Noise that emanates directly from the vehicle includes noise produced by the engine, the drivetrain and the exhaust system. It follows that the older the vehicle the higher the chances of it producing higher noise levels. In addition, vehicles that are not well maintained may tend to be noisy. The type of vehicle also affects the noise levels; general observation indicates that trucks and buses produce more noise than cars do. The average speed of traffic may also contribute to general traffic noise by increasing aerodynamic noise due to the air turbulence around the vehicle as it travels. While cruising vehicles may not necessarily produce a lot of noise, accelerating to a certain cruising speed generates more noise from the revving of the engine.

2.6. Generation of Tire/Pavement Noise

Noise is generated from passing vehicles and from the interaction of the tires with the pavement surface. Even though noise is generated from the engine, drive train, and the exhaust system, a large part of the noise generated from traffic is that from the tire/pavement interaction. Transportation agencies have leverage mostly on the pavement characteristics; the vehicle tires generally depend on the driving public. Therefore, the proceeding noise generation mechanisms will mostly cover the influence of the characteristics of the pavement rather than the tire.

Tire/pavement noise may be divided into three: Tire structural vibrations, aerodynamic processes around the tire and tire/pavement interface, and interaction of the tire surface in contact with the surface of the pavement. Although there are two main categories of noise generation, there are also processes that either amplify or reduce the sound generated. Table 2.5 summarizes these mechanisms.

Table 2.5. Tire/road noise generating mechanisms (after Sandberg and Ejsmont, 2002, pp. 98; Used with permission from publisher)

Generation Mechanisms	Vibrational (structure-borne)	1	Impact Mechanism (mostly radial vibrations)	1A	Tread Impact: Impact of tire tread blocks or other pattern elements on road surfaces, causing radial and to some extent also tangential vibrations in the tire tread and belt, spreading to the sidewalls
				1B	Texture Impact: Impact of road surface texture on the tire tread, also causing radial and to some extent also tangential vibrations in the tire tread and belt, spreading to the sidewalls
				1C	Running Deflection of tire tread at leading and trailing edges, giving tire belt/carcass vibrations
		2	Adhesion Mechanism (mostly tangential vibrations)	2A	Stick/slip tread element motions relative to the road surface, causing tangential tire vibrations, also called "scrubbing" (might give excitation to 3C and/or 3D)
				2B	Rubber-to-road stick/snap (adhesive effect); giving either tangential or radial vibrations
	Aerodynamical (air-borne)	3	Air Displacement Mechanisms	3A	Air turbulence; turbulence around tire due to the tire displacing air when rolling on the road, and air dragged around by the spinning tire/rim
				3B	"Air-pumping"; air displaced into/out of cavities in or between tire tread and road surface, without necessarily being in resonance
				3C	Pipe resonances; air displacement in grooves ("pipes") in the tire tread pattern amplified by resonances, so-called $\lambda/2$ resonators (may also be seen as a special case of 3B)
				3D	Helmoltz resonance; air displacement into/out of connected air cavities in the tire tread pattern and the road surface amplified by resonances (may also be seen as a special case of 3B)
Related Amplification or Reduction Mechanisms		4	The Horn Effect	4	The curved volume between the tire leading and trailing edges and the road surface constitute something similar to an exponential horn used to amplify sound
		5	The Acoustical Impedance Effect	5A	Communicating voids in porous surfaces act like sound absorbing material, affecting source strength
				5B	Same, but affecting sound propagation to a far-field receiver
		6	The Mechanical Impedance Effect	6A	The road surface gives more or less reaction to tire block impacts depending on dynamic tire/road stiffness proportions
				6B	Some tire vibrations may be transferred to the road surface, possibly radiating as sound (speculation)
		7	Tire Resonance	7A	Belt resonances (mechanical resonances in the belt)
				7B	Torus cavity resonance (resonance in the air column of the tire)

2.6.1. The Impact Mechanism

Noise is generated from the tire/pavement interaction by the impact of the tire tread on the road surface. This action sends radial vibrations through the tire. The contact area of the tire on the pavement has a leading edge and a trailing edge (Figure 2.2).

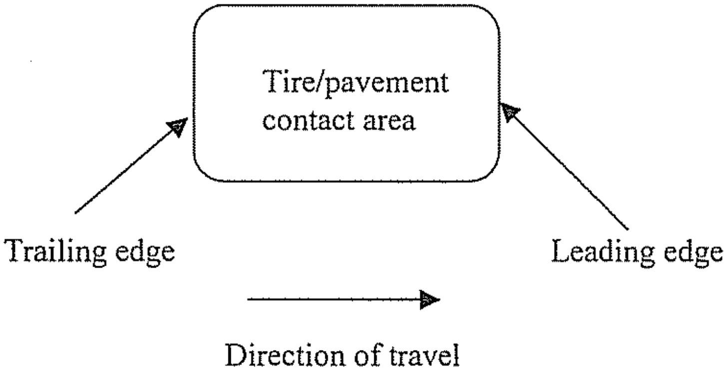


Figure 2.2 Schematic of Tire/Pavement Contact Area.

When the tire rolls or travels along the pavement, the tread elements that reach the leading edge of the contact patch are pushed in towards the tire's center of rotation, and are again pushed out when they reach the trailing edge. The tread blocks and tread band absorb these impacts or hammerings since the road is incompressible, which consequently produce noise vibrations.

Iwao and Yamazaki (1996) measured the inertance level (acceleration/exciting force) at the tread area (excitation point) and the sidewall area when the center of the tread surface is excited. High vibration levels were found in the frequency range of 500 Hz to 800 Hz at the sidewalls, and in frequencies over 800 Hz at the tread area. The authors also found that at 50 km/h sound pressure levels were higher for smooth tires

(tires with no tread) than for treaded tires for frequencies over 1 kHz on an asphalt pavement even though it was not the case when testing was done on a chassis dynamometer (Figure 2.3).

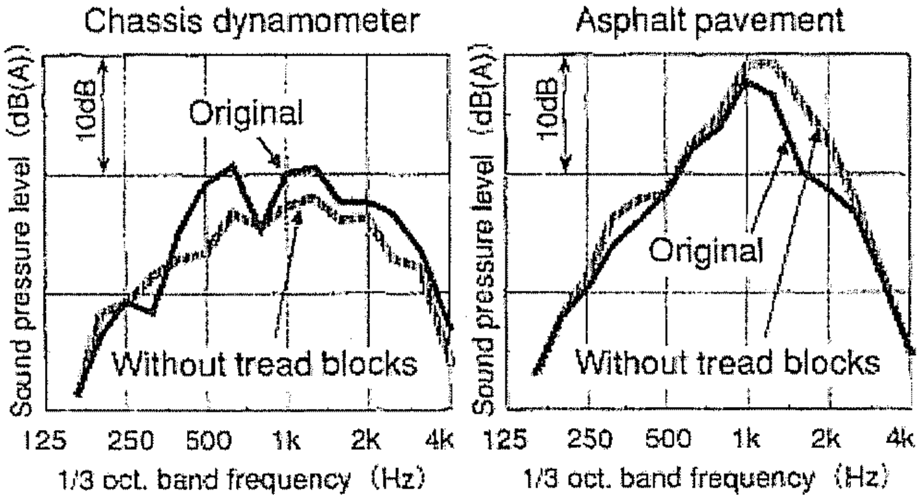


Figure 2.3 Tire noise spectrum (50 km/h) (after Iwao and Yamazaki (1996))

They estimated that excitation from the road roughness might be the cause of the higher vibrations because of a reduction of dynamic stiffness tire surface where the tread used to be. Figure 2.4 shows a schematic of the test and plot of the results.

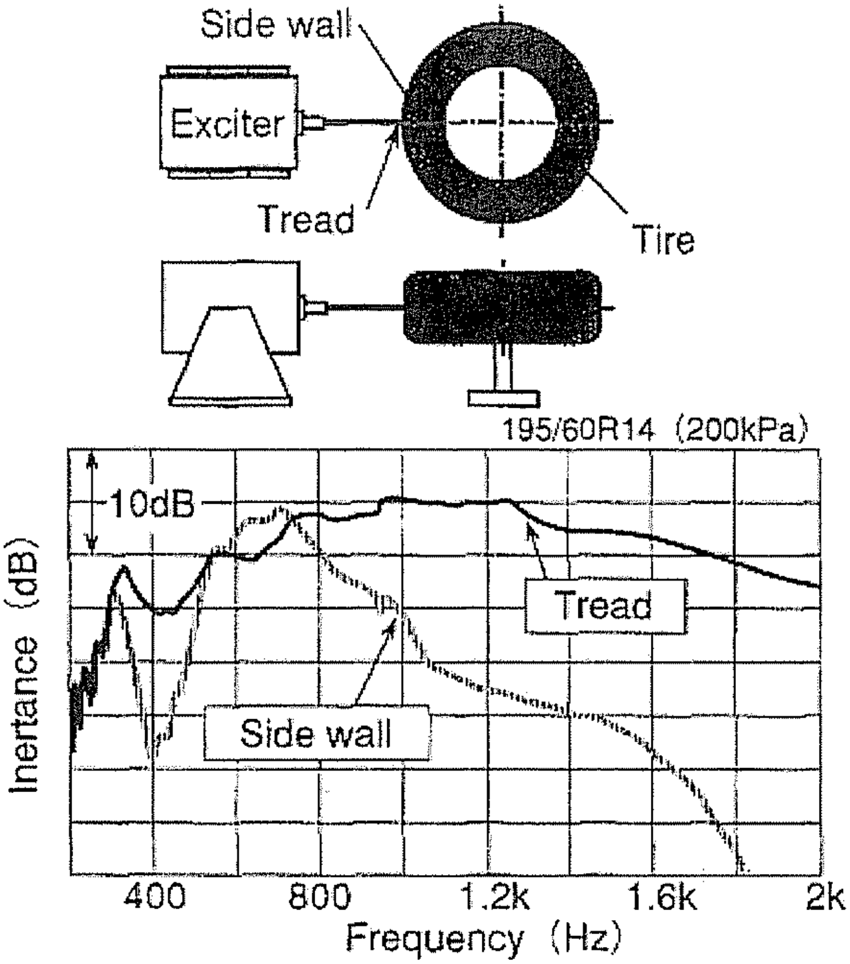


Figure 2.4 Dynamic characteristics of tire vibration (after Iwao and Yamazaki (1996))

2.6.2. Effect of Pavement Surface Texture on Noise

Pavement surface texture influences pavement noise depending on the noise frequency. Low-frequency pavement noise (tread impact mechanism) increases with texture amplitude for texture wavelengths in the range 10-500 mm; high-frequency pavement (air displacement mechanism) noise decreases with texture amplitude for texture wavelengths in the range 0.5-10 mm. Furthermore, the nature of the tire treading also affected the noise generated. Smoother tread patterns enhanced the low-frequency mechanism while rougher tread patterns enhanced the high-frequency mechanism (Sandberg and

Descornet, 1980). Recently, Fujikawa et al. (2005) did a parametric study on the influence of road roughness on pavement noise using a tire/road contact model. The parameters used are explained in the road profile schematic shown in Figure 2.5.

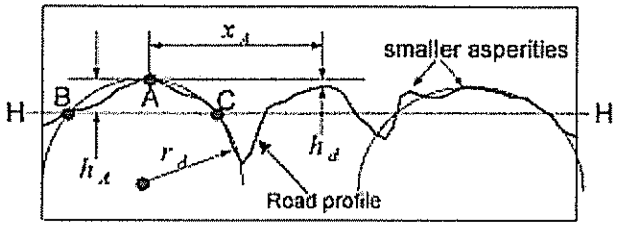


Figure 2.5. Road Roughness Parameters Obtained From Road Profile (after Fujikawa, et al. 2005).

A horizontal plane, H-H divides the profile into two halves. The half above H-H would represent the road asperities, following the observation that the actual contact area between the tire tread the pavement is less than 50 percent of the nominal contact area. The parameters in Figure 2.1 are defined as follows.

h_A = asperity height;

h_d = asperity height unevenness, which is the asperity height difference between two adjacent asperity peaks;

x_A = asperity spacing, which is the distance between two adjacent asperity peaks;

r_A = asperity radius, which is the radius of the arc formed approximately by points A, B, and C.

The contact model used is detailed in the paper. A number of conclusions were drawn in the paper, including

- Asperity height alone does not significantly affect tire/pavement noise; asperity height unevenness, however, is an essential parameter in tire/pavement noise generation, which suggests that high-quality road surface finish is important in mitigating noise from this parameter;
- Asperity spacing is an important parameter in reducing pavement noise when smaller spacing is used. The authors inferred that two-layer drainage asphalt pavements with smaller grains more effectively reduce noise than the usual drainage asphalt pavements.
- Smaller asperity radii reduce pavement noise even though on a smaller scale than spacing and height unevenness.

2.6.3. Friction- and Adhesion-Related Mechanisms

Two phenomena that partly govern noise generation are the stick-slip and stick-snap mechanisms (Sandberg and Ejsmont, 2002). The two mechanisms depend on friction and adhesion on the pavement surface. Longitudinal and tangential stresses build up at the tire/pavement interface as the tire travels along the pavement surface. These stresses give rise to the two phenomena mentioned above. Both stick-slip and stick-snap mechanisms occur mainly at the trailing edge of the tire/pavement contact area.

When the forces generated at the tire/pavement interface momentarily exceed frictional forces, the tire "slips" back and re-locks ("sticks") in position as friction quickly recovers. This slip-stick motion can repeat frequently causing the tire tread to vibrate tangentially and release noise. This suggests that better skid resistance on asphalt pavements can mitigate noise from the stick-slip mechanism. However, the mechanism will also produce increased noise with an increase in friction, especially for high frequencies. Therefore, a fine balance needs to be determined for skid resistance and stick-slip to effectively mitigate noise.

A "sticky" surface on a very smooth surface can generate adhesive forces at the contact area as the sticky surface lifts off the smooth surface; consider a person walking on a clean and smooth floor with "sticky" rubber shoe soles. For the sticky surface to lift off successfully from the smooth surface, it has to "snap" because of adhesion. A similar phenomenon occurs at the tire/pavement interface, called the stick-snap mechanism. A superior pavement surface finish is desirable. However, the stick-snap mechanism may also be pronounced. To reduce stick-snap, pavement microtexture has to be increased, but also considering the effects of stick-slip. It is a delicate interplay of pavement surface characteristics, stick-slip, and stick-snap that needs careful study for quieter pavements.

2.6.4. Aerodynamic Considerations

Airflow through the passages created by the contact of the tire tread and the pavement surface can produce audible sounds. Some of the processes that create this type of noise are discussed as follows.

2.6.4.1. "Air Pumping"

As the vehicle tire travels along the pavement surface, pockets of air are pumped in and out of the tire tread grooves near the tire/pavement contact area. At the front of the contact area air is compressed and pushed out into the atmosphere; at the back of the contact area air is expanded and sucked into the tire tread grooves and the grooves within the pavement surface. It is to be noted that the contact area (or the tire/pavement interface) consists of grooves or passages formed because of the nature of the two touching surfaces (contrast it with two smooth surfaces touching). These passages act as conduits for air that flows through the contact area. The variations in these conduits create variations in the airflow, producing vibrations in the air. The vibrations can be heard as sound. This phenomenon is known as "air pumping". The vibrations occur because there are insufficient "escape routes" for the air into the atmosphere. Sufficient escape routes (or ventilation) would have to be created within the contact area to mitigate this type of sound. Pavement engineers have used drainage asphalt pavements, which provide some measure of ventilation to mitigate this type of sound.

2.6.4.2. Helmholtz Resonance

Resonance can amplify sound produced by air pumping. When a cavity is "leaving" the contact area at the trailing end (back of contact area), the volume in the cavity acts as a spring while the air between the tread and the pavement surface acts as a mass. The mass-spring system results in radiated sound as the cavity moves away from the contact area. This phenomenon is called the Helmholtz resonance, which amplifies the sound from air pumping.

2.6.4.3. The Horn Effect

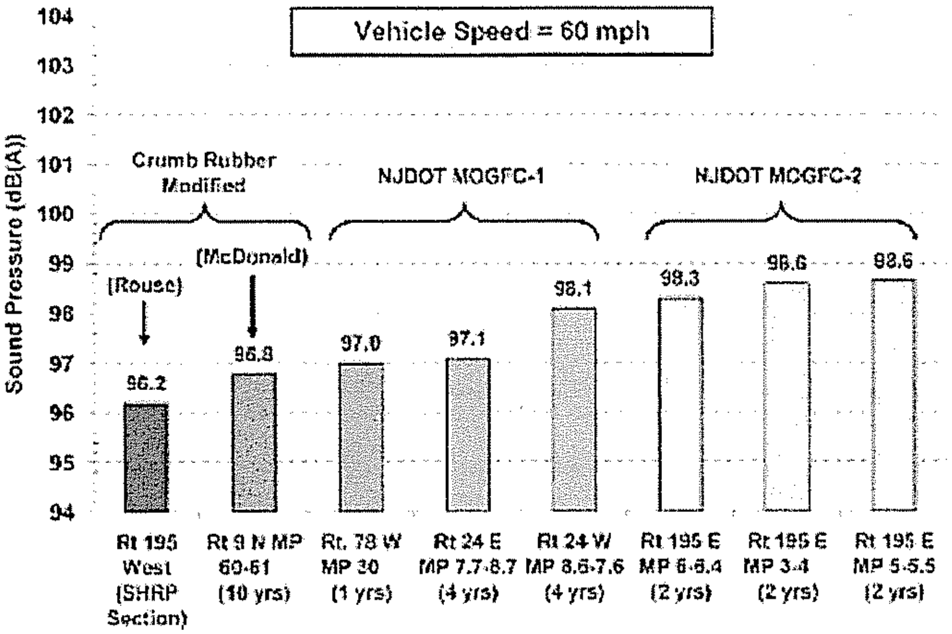
The shape formed by the tire and the surface of the pavement around the leading and trailing edges of the contact area resembles an acoustical horn. The throat of this horn is at the leading and trailing edges of the contact area, so that the farther away from the throat, the wider the horn becomes. This horn is able to amplify the sound radiated through those edges of the contact area.

2.7. Types of Hot-Mix Asphalt Pavement and Their Noise Characteristics

Bennert et al. (2005) used the Close Proximity Method (CPX) to investigate the influence of pavement surface type on tire/pavement-generated noise in New Jersey, USA. The HMA pavement types tested included the open-graded friction course (OGFC) with and without crumb rubber, dense-graded asphalt (DGA), stone-mastic (stone matrix) asphalt (SMA), NovaChip®, and microsurfacing slurry mix. The authors had three objectives, two of which are given below:

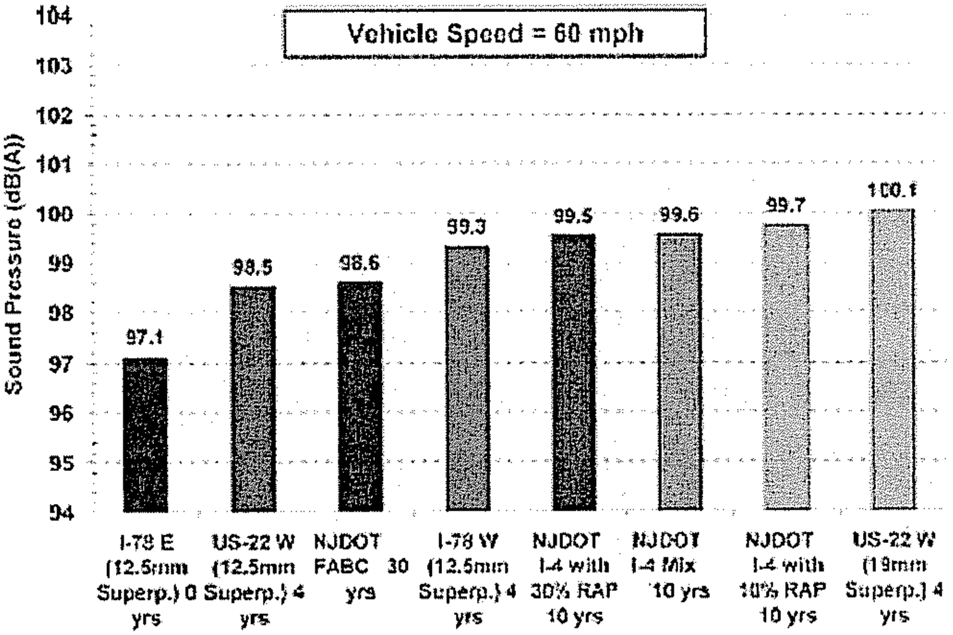
- The influence of pavement surfacing materials on tire/pavement noise;
- The effect of vehicle speed on tire/pavement noise.

60 mph was the vehicle speed used for testing. Three of the DGA's were Superpave mixes: 9.5 mm, 12.5 mm, and 19 mm Superpave mixes. The results for the effect of the various HMA surface types on noise are given as follows in Figures 2.6 to 2.9.



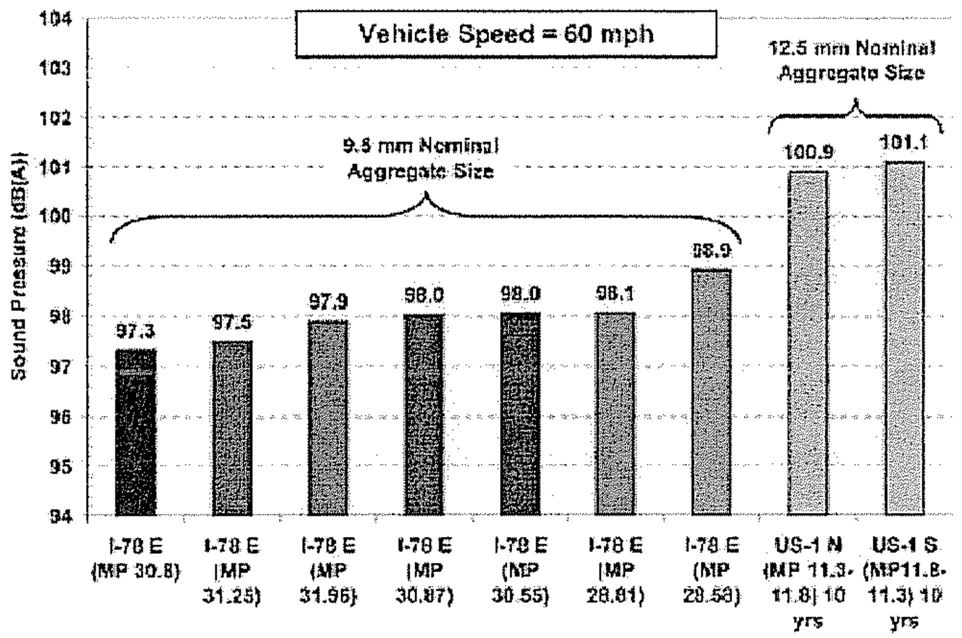
60 mph = 96.5 km/h

Figure 2.6. Sound Pressure Results for OGFC (after Bennert, et al. 2005)



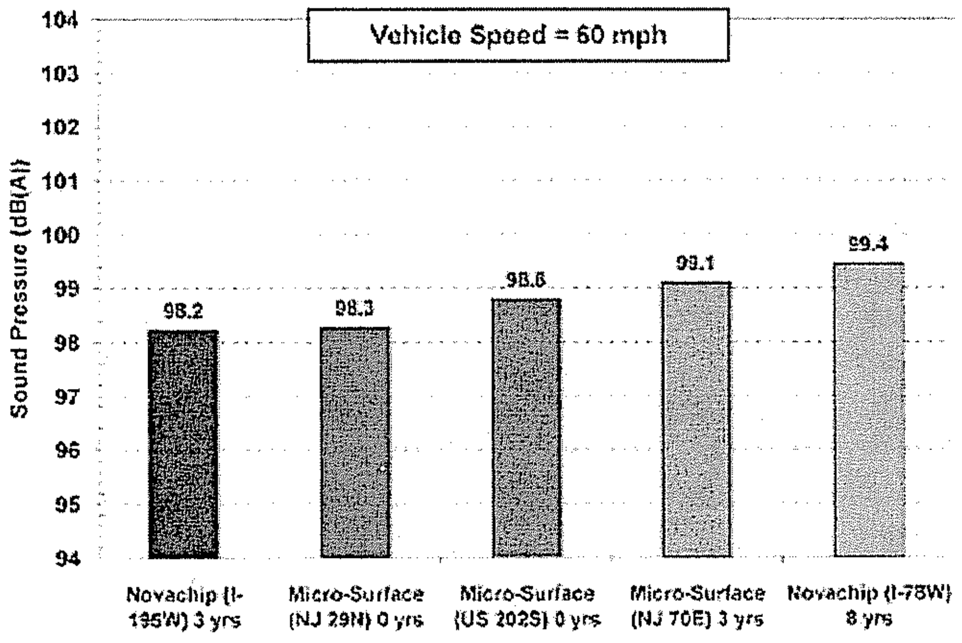
60 mph – 96.5 km/h

Figure 2.7. Sound Pressure Results for DGA (after Bennert, et al., 2005)



60 mph = 96.5 km/h

Figure 2.8. Sound Pressure Results for SMA (after Bennert, et al., 2005)

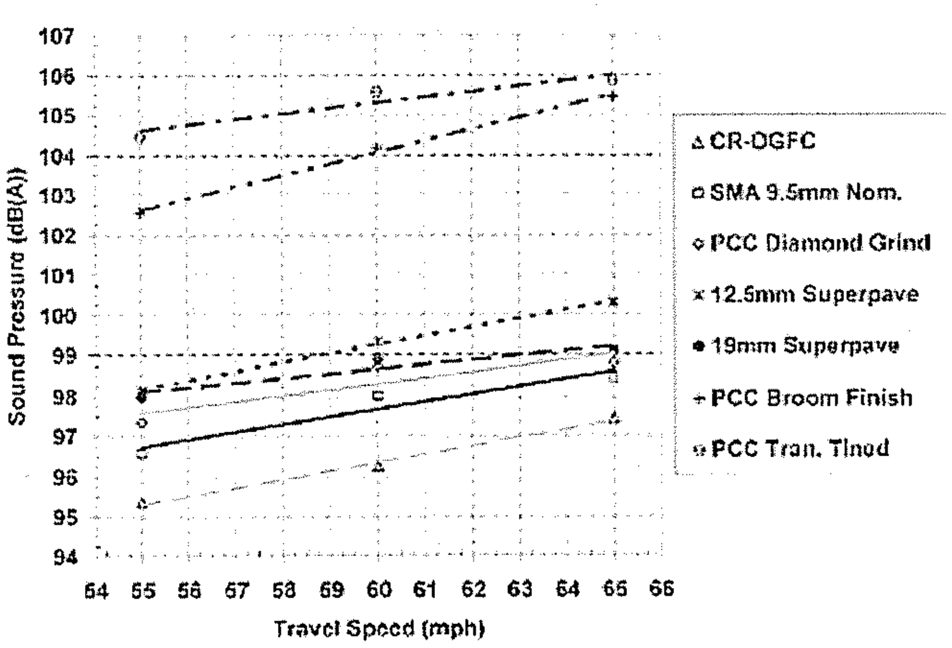


60 mph = 96.5 km/h

Figure 2.9. Sound Pressure Results for NovaChip and Micrsosurfacing Slurry (after Bennert, et al., 2005)

The OGFC modified with crumb rubber produced the least noise; they had finer aggregate gradations than the usual OGFC used in New Jersey, however. Even though the OGFC had the overall least levels of noise, the noise level of the DGA's also reduced with reducing nominal aggregate size. The 12.5-mm Superpave mixes generated less noise than the 19-mm Superpave mixes; the 9.5-mm SMA generated less noise than the 12.5-mm SMA mixes.

Regarding the effect of vehicle velocity, Bennert et al. (2005) measured pavement noise for velocities of 55, 60, and 65 mph. Figure 2.10 illustrates the effect of vehicle speeds on pavement noise for various types of pavement.



1.0 mph = 1.6 km/h

Figure 2.10 Effect of Vehicle Speed on Pavement Noise (after Bennert et al. 2005)

A parameter, "noise gradient", was defined as change in noise versus change in speed; it has units of dB(A) per mph. Usually, increasing traffic speeds increase tire/pavement noise. Pavements with lower noise gradients have lower tendencies of producing increased pavement noise as speeds increase. On the average, the HMA mixes had noise increases per mph (noise gradients) as given in Table 2.6.

Table 2.6. Average noise gradients with variable speeds for different HMA mixes (after Bennert, et al., 2005)

Pavement Surface Type	Number of Sections	Noise Gradient (dB(A) per mph)
OGFC	8	0.16
DGA	13	0.20
SMA	7	0.17
NovaChip®	1	0.15
Microsurfacing	2	0.28

Even though NovaChip had the lowest noise gradient (0.15 dB(A)), only one section was tested. In contrast, eight sections of OGFC were tested and they had an average noise gradient of 0.16 dB(A). Therefore, unless more sections of NovaChip are tested, OGFC's are probably better at reducing pavement noise.

In earlier pavement noise studies (Sandberg and Descornet, 1980; Descornet and Sandberg, 1980), open-graded asphalt pavements (porous pavements) were found to reduce pavement noise. This phenomenon was related to the sound absorption capacity of porous pavements as opposed to dense-graded asphalt pavements; sound absorption coefficient and sound propagation over the road surface were two important parameters that affected the generation of pavement noise. Recently, Golebiewski et al. (2003) used similar parameters (sound exposure and the road surface coefficient) to develop a model that predicted pavement noise of porous pavements.

Hanson and Waller (2005) evaluated the noise characteristics of Minnesota pavements. The authors refer previous noise studies on pavements in various states by the National Center for Asphalt Technology (NCAT) that presented average noise values of four HMA types (Hanson, et al., 2004). Table 2.7 shows the average values. A low-noise road surface was defined as one with a noise level of about 94 dB(A) when measured with a CPX trailer.

Table 2.7. HMA pavement types with average characteristic noise levels (after Hanson and Waller, 2005)

HMA Pavement Type	Average Noise Level (dB(A))
Open-Graded Mixes (fine gradation)	93
Stone-Matrix Asphalt Mixes	96
Open-Graded Mixes (coarse gradation)	97
Dense-Graded HMA	97

Regarding the testing done in Minnesota, four HMA pavement types tested at 60 mph produced average noise levels as given in Table 2.8.

Table 2.8. Average noise levels for Minnesota HMA pavement types (after Hanson and Waller, 2005)

HMA Pavement Type	Average Noise Level (dB(A))
NovaChip	98.2
Microsurfacing	99.6
HMA (mostly Superpave)	98.4
Macrosurfacing	99.1

From the results, the authors concluded that the noise levels on Minnesota roads were similar to noise levels found at other states, with an average noise level for HMA pavements as 98.6 dB(A).

2.8. Measures to Reduce Traffic and Tire/Pavement Noise

Much research is being done in the area of highway-related noise in recent years. The annoyance produced by highway noise has been a catalyst for the development of various measures aimed at reducing overall highway noise. Some of the measures include building an obstruction between the noise source and the receiver (obstructing the path of the propagated sound), increasing the distance propagated-sound would have to travel, and reducing the noise directly at the source. Some noise-reducing measures are discussed in the following.

2.8.1. Noise Walls/Barriers

Noise walls or barriers have been traditionally used to cut off highway-related noise from abutting residential areas. Long and high walls are needed to effectively mitigate noise from highways, but the walls are expensive to build; it is estimated that a mile of wall costs about U.S.$1.25 million (Kandhal, 2004). Considering about 400 feet of wall length is needed for every 100 feet beyond the wall that the last house is located, the noise wall quickly becomes ineffective for streets that have a lot of driveway entrances.

2.8.2. Porous Asphalt Pavements

The prohibitive cost of noise barriers necessitated efforts into finding alternative methods of noise mitigation from highways. Porous pavements, such as the OGFC, are being explored for tire/pavement interaction noise mitigation. Porous pavements absorb much of the noise generated at the tire-pavement interface thereby reducing the overall highway noise.

2.8.3. Better Vehicles With Low Engine Noise

Vehicle manufacturers are continually building quieter vehicles and using that attribute as a strong selling point when advertising the vehicle. The leverage the manufacturers have is on the engine and drivetrain noise, and to some extent the tire noise (much more dependent on the tire manufacturer.) Much as everything is being done to develop quiet vehicles, if tire/pavement noise is not dealt with very little progress is going to be made in mitigating overall highway noise since tire/pavement noise is a major contributor.

2.9. Measurement of Tire/Pavement Noise

The main methods for measuring pavement noise are (Sandberg and Ejsmont, 2002):

- The Controlled Pass-By (CPB) method;
- The Statistical Pass-By (SPB) method;
- The Close-Proximity (CPX) method (formerly known as the Trailer method);
- The Coast-By (CB) method.

All four methods primarily compare the factors that influence the generation of tire/pavement noise. However, they do not cover the same sources of noise. Whereas the CPB and the SPB methods both consider power unit noise, tire/pavement noise, and sound propagation over the pavement surface, the CPX and CB methods mostly measure only tire/pavement noise.

The International Standards Organization (ISO) and the FHWA (Lee and Fleming, 1996) have guidelines regarding site characteristics, weather conditions, types of sound-measuring instruments and placement of sound-measuring instruments, vehicles types, and vehicle speeds. Basically, they are general procedures for measuring highway-related noise.

2.9.1. The Controlled Pass-By Method

A selected small number of vehicles are driven through a chosen pavement test section, cruising at a constant speed. Sound-measuring instruments are set up at both sides of the road at a specified distance from the centerline of the driving lane. The location of the instruments is varied along the same test section for an average value of the measured sound. The result could be compared with results from other test sections.

2.9.2. The Statistical Pass-By Method

The Statistical Pass-By method (SPB), unlike the CPB, uses an actual traffic stream. Sound-measuring instruments are set up on the side of the road according to approved specifications. Vehicles passing by that have constant speeds are selected; the specific speed range and the number of vehicles to be included in the test depend on the specifications being followed. The sound from different types of vehicle can be measured and tabulated accordingly. Statistical analyses are then used to assign noise values to the road for certain speeds and vehicle types.

2.9.3. The Close Proximity Method

The Close Proximity method (CPX) measures the sound generated by a reference tire running on a pavement. The reference tire could be one of the four tires under an actual vehicle (it does not need to be a special vehicle). Sound-measuring instruments are mounted on the tire, close to the pavement to measure the noise from the tire/pavement interaction as the vehicle travels at a specified constant speed. The sound-measuring instrument is usually in an enclosure to shield it from other sources of sound that might affect the sound from the tire/pavement interaction. The CPX method is usually used for light vehicles only. Therefore, if the percentage of heavy vehicles in a traffic stream is less than 10 percent, it implies light vehicles generate most of the noise, and the CPX method would be a good choice to measure the noise.

2.9.4. The Coast-By Method

The Coast-By method (CB) is essentially similar to the CPB method, with the only difference being the engine is switched off in the CB method. The vehicle is driven at a constant speed. When it is about to enter the test section the engine is switched off and the gear is immediately put in neutral. The vehicle is then allowed to roll through the test section while the sound from the tire/pavement interaction is measured.

2.10. Pavement Noise Policy

The Federal Code of Regulations Part 772 (23 CFR 772), "Procedures for Abatement of Highway Traffic Noise and Construction Noise," provides criteria for noise abatement on highways, and all highways that conform to this regulation are deemed to satisfy FHWA noise standards. In addition, the FHWA also has a noise abatement policy and guidance document, "Highway Traffic Noise Analysis and Abatement Policy and Guidance."

The noise abatement measures provided in 23 CFR 772 do not directly mention mitigation measures by pavement surface type. However, it states that if the measures proposed are not economically or practically feasible the highway agency may propose other abatement measures that would need to be approved by the Regional Federal Highway Administrator. This would probably indicate that highway agencies might pursue noise mitigation measures related to pavement surfaces. Although possible, the FHWA noise abatement policy does not recognize noise abatement benefits from adjustment of a pavement surface. Exactly, it states, "It is very difficult to forecast pavement surface condition into the future. Unless definite knowledge is available on the pavement type and condition and its noise generating characteristics, no adjustments should be made for pavement type in the prediction of highway traffic noise levels." While the document recognizes the success of OGFC asphalt pavements in mitigating pavement noise, it does not endorse OGFC since any noise reduction benefit is lost within approximately 6-12 months when the voids fill up and aggregates become polished. Again, the document emphasizes that, "The use of specific pavement types or surface textures must not be considered as a noise abatement measure." Other proposed ways of mitigating traffic noise are traffic management, land-use, and noise barriers.

Despite the FHWA not recognizing the use of specific pavement types in mitigating traffic noise, some highway agencies are still interested in investigating how modification of the pavement surface can reduce tire/pavement interaction noise. A case in point is the Arizona DOT's placement of an OGFC asphalt rubber mix on U.S. 60 between Tempe and Mesa; residents living along that section appreciated the reduced noise from the highway (Kandhal, 2004).

The FHWA noise abatement document suggests that more research is needed to present a stronger case for using pavement surface type for noise mitigation. In the meantime it provides a Noise Abatement Criteria (NAC) for various activities, which are given in Table 2.9. While these criteria give a general guidance, any noise abatement strategy should not just seek to meet the criteria, but should seek to substantially abate noise.

Table 2.9. Noise Abatement Criteria (NAC): Hourly A-Weighted Sound Level in Decibels (dBA)* (After Highway Traffic Noise Analysis and Abatement Policy and Guidance, 1995).

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

* Either $L_{eq}(h)$ or $L_{10}(h)$ (but not both) may be used on a project.

Definitions for notations used in Table 2.9 are as follows (23 CFR 772).

L_{10} = The sound level that is exceeded 10 percent of the time (the 90th percentile) for the period under consideration.

$L_{10}(h)$ = The hourly value of L_{10}.

L_{eq} = The equivalent steady-state sound level which in a stated period of time contains the same acoustic energy as the time-varying sound level during the same time period.

$L_{eq}(h)$ = The hourly value of L_{eq}.

2.11. Summary

The preceding has been an overview of the background of noise, noise generation, and noise propagation. In addition, human perception of sound is discussed, which is needed to understand the effect of asphalt pavement noise on humans. Various means by which noise is generated from tire/pavement interaction are discussed as well as certain asphalt pavement types and their noise characteristics. Historically, Open-Graded Friction Course (OGFC) asphalt pavements have been known to effectively mitigate asphalt pavement noise better than other HMA types.

Although, there is no explicit policy that recognizes noise mitigation by adjusting the characteristics of pavement surfaces, some transportation agencies are still exploring ways by which such noise mitigation may be achieved. Meanwhile, there are Federal policies regarding other ways of mitigating traffic noise, such as noise barriers, land-use, and traffic management.

Chapter 3

PREVI0US FIELD AND LABORATORY TESTING

3.1. Introduction

The following chapter presents field and laboratory testing of asphalt pavement noise performed in Delaware and other states, including, but not limited to, New Jersey, Minnesota, and Texas. The National Center for Asphalt Technology (NCAT) has also performed some testing in various states that will be discussed.

The present chapter discusses mainly the types and characteristics of the asphalt pavements tested, and the measurement methods used rather than the results obtained even though few results may be mentioned in passing.

3.2. New Jersey Study

The State of New Jersey tested five types of hot-mix asphalt (HMA) pavements (Bennert, et al. 2004): Open-Graded Friction Course (OGFC), Novachip, Micrsosurfacing, Stone-Matrix Asphalt (SMA), and Dense-Graded Asphalt (DGA). In all, 30 different sections were tested using the NCAT Noise Trailer, which uses the Close-Proximity Method (CPX) to measure tire/pavement noise. The choice of the measurement method was influenced by a number of CPX advantages, including (Bennert, et al. 2004):

- The ability to measure pavement noise at almost any site;
- The ability to check for compliance with a noise specification for a surface;

- The ability to check for a pavement surface's maintenance condition;
- More portable than the Statistical Passby Method; it requires little set-up.

The above advantages notwithstanding, some questions were still asked of the CPX method regarding suitability for New Jersey pavements. Some of the questions included the number of passes allowed per noise value and the effect of large variations in measurement, the effect of OGFC mixes on noise measured by the NCAT Noise Trailer because of the microsurfacing used by the NJDOT, and the effect of aging on tire/pavement interaction noise.

3.2.1. Open-Graded Friction Course

In the report by Bennert et al. (2004), a total of eight OGFC test sections were analyzed. There were four general types of OGFC:

- Crumb Rubber Modified OGFC mix using the Rouse procedure, which uses an 80-mesh crumb rubber particle size (AR-OGFC (I-195));
- Crumb Rubber Modified OGFC mix using the McDonald procedure, which uses a 40-mesh crumb rubber particle size (AR-OGFC (Rt 9));
- The New Jersey Department of Transportation (NJDOT) modified OGFC (MOGFC-1);
- The New Jersey Department of Transportation (NJDOT) modified OGFC (MOGFC-2) – MOGFC-1 is coarser than MOGFC-2.

The preceding four types of OGFC were distributed among the eight test sections in the report as follows (age is included):

- Route 24 E. (MP 7.5 to 9.7) – MOGFC-1 (4 years old)

- Route 24 W. (MP 9.7 to 7.5) – MOGFC-1 (4 years old)
- Route 195 E. (MP 1 to 7) – MOGFC-2 (2 years old)
- Route 195 W. (MP 10) – OGFC with Crumb Rubber – SHRP site (10 years old)
- Route 78 W. (MP 30: bridge deck) – MOGFC-1 (1 year old)
- Route 9 N. – OGFC with Crumb Rubber (10 years old)

Figure 3.1 gives the gradations of the OGFC test sections.

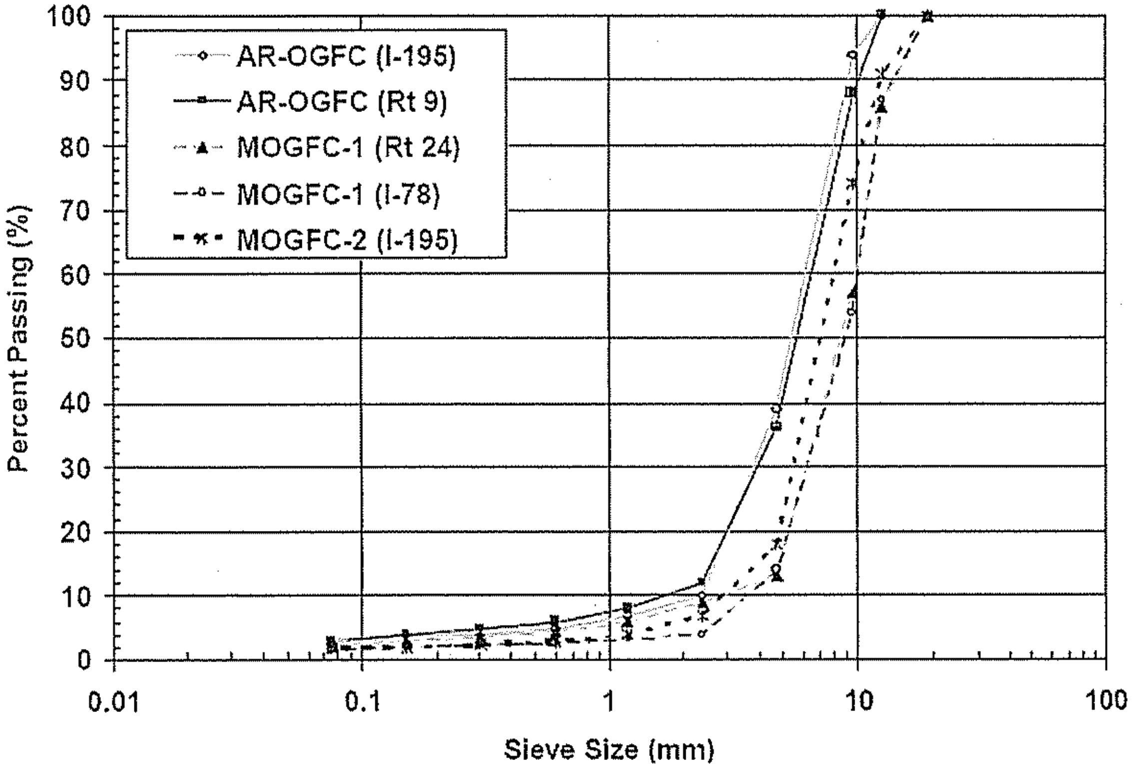


Figure 3.1. OGFC Pavement Surface Gradations for New Jersey Study (After Bennert, et al. 2004)

During testing, it was realized that there were variations in the noise measurements even within the same test section, some by as much as 0.3 dB(A), and a difference in measurement of about 1.0 dB(A) for two sections that were almost identical in characteristics and age, which was attributed to a possible change in air voids or material gradation.

3.2.2. Novachip® and Micro-surfacing

Material properties for Novachip and micro-surfacing were not provided in the report by Bennert et al. (2004). However, the micro-surfacing mix used by NJDOT is typically used in higher traffic volume areas.

The descriptions of the test sections are as follows.

- Novachip
  - Route 78 W. (MP 17 to 18) (8 years old)
  - Route 195 W. (MP 1 to 5) (3 years old)
- Micro-surfacing
  - Route 70 (3 years old)
  - Route 202 S. (MP 26 to 27)
  - Route 29 S. (MP 27 to 26)

3.2.3. Stone-Matrix Asphalt

Bennert et al. (2004) did not provide the material properties for Stone-Matrix Asphalt or Stone-Mastic Asphalt (SMA). The test sections are described as follows.

- Route 1 N. and S. (MP 11.3 to 11.8)
- Route 78 E. and W. (roadway and bridge decks) (MP 23.1 to 30.8)

3.2.4. Dense-Graded Hot-Mix Asphalt

The Dense-Graded Hot-Mix Asphalt (DGA) is the most common HMA type used by the NJDOT (Bennert, et al. 2004). The mixes analyzed in the noise study were from the Marshall design method and the Superpave design method. Most of the test sections for DGA were located on Route 195 West, which is part of the Strategic Highway Research Program (SHRP) test site. The descriptions of the test sections are given as follows.

- Route 22 W. (MP 31.7 to 34.3) – 12.5mm Superpave mix (4 years old)
- Route 22 W. (MP 34.3) – 19mm Superpave mix (4 years old)
- Route 78 W. (MP 31 to 42) – 12.5mm Superpave mix (4 years old)
- Route 78 E. (MP 31 to 42) – 19mm Superpave mix (5 years old)
- Route 78 E. and W. (MP 23.1 to 30.8) – 12.5mm Superpave mix (less than 1 year old)
- Route 195 W. – SHRP Test Sections (mostly NJDOT I-4 and I-4 with RAP) (10 years old)

3.2.5. Repeatability of NCAT Noise Trailer CPX Test

The repeatability of the CPX test was evaluated using 33 test sections. It was found that the longer the test section the better the reliability of the test. This observation comes from Figure 3.2, in which standard deviation (in dB(A)) is plotted against test section length (in miles.)

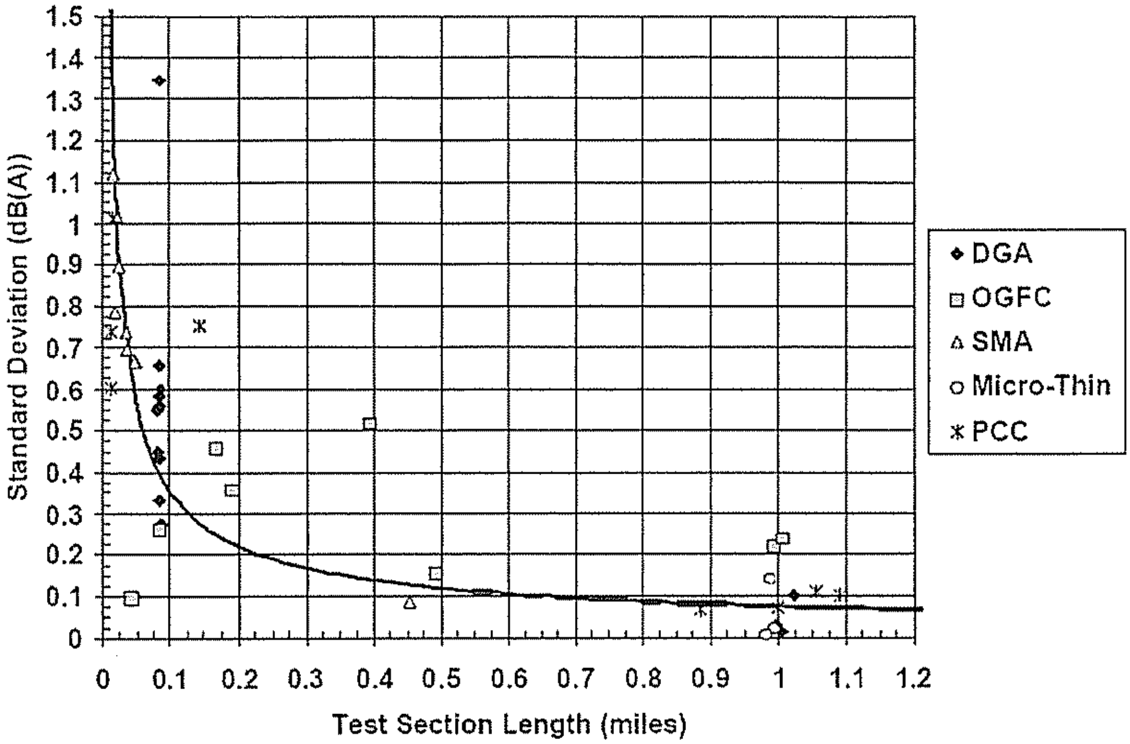


Figure 3.2. CPX Test Method Repeatability Evaluation (After Bennert et al. 2004)

3.3. Minnesota Study

The pavement noise study in Minnesota was done using the NCAT Noise Trailer. Twelve asphalt pavement sections of various types were tested on Minnesota highways, and nine sections at MnRoad (Hanson and Waller, 2005). No material properties were presented in the report. However, the section locations were given. Testing was done at 60 mph on the highways, and at 60 mph and 45 mph at MnRoad. Two types of tire were used for testing "to provide a better representation of the tire/pavement noise levels for each surface type," according to the authors. Table 3.1 and Table 3.2 give the test sections and results for Minnesota highways and MnRoad respectively.

Table 3.1. Sections and Test Results on Minnesota Highways (After Hanson and Waller, 2005)

Highway	Direction	Surface Type	Start	End	Average Noise Level (dB(A))
I-35	S	NovaChip	17	16	100.3
I-90	W	HMA-Superpave	227	226	99.3
I-35	N	HMA-Superpave	44	45	99.7
I-35	S	HMA-2361	45	44	99.4
US 14	W	MacroSurfacing	155	154	99.1
ST 52	S	HMA-Superpave	91	90	97.7
I-494	W	HMA-12.5mm Superpave	65	66	96.7
I-494	W	NovaChip	68	69	96.6
ST 36	E	Microsurfacing	Victoria St.	4	98.2
I-394	E	HMA-12.5mm Superpave	5	6	97.8
ST 60	E	Microsurfacing	33	34	101.0
I-394	E	NovaChip	6.3	7.5	97.7

Table 3.2. Sections and Test Results for MnRoad (After Hanson and Waller, 2005)

Cell	Surface Type	Noise Level	
		45 mph	60 mph
3	HMA	96.0	100.2
4	Macrosurfacing	93.6	97.8
16	Macrosurfacing	94.6	99.0
20	Macrosurfacing	91.5	95.6
26	HMA	94.0	97.0
35	HMA	95.3	98.5

3.4. Texas Study

McNerney et al. (2000) reported a pavement noise study conducted in Texas. The method used for roadside noise measurement was adopted from the ISO Standard 10844, and the method for the onboard noise measurement was similar to the ISO draft standard, ISO/CD 11819-2, "Method for measuring the influence of road surfaces on traffic noise – Part 2: The close-proximity method." Test results from ten asphalt pavements were reported, and are given in Table 3.3. The descriptions of the asphalt pavements presented in the report are as follows. One control section of aged dense-graded asphalt pavement tested at the beginning and end of the testing series; one aged dense-graded asphalt pavement section in the SHRP (SHRP LTTP section 480001); one new dense-graded asphalt pavement section; one new asphalt test section of coarse matrix high binder (CMHB), which is an experimental mix, and whose properties are similar to the SHRP mix with similar aggregate gradation and about 7 percent air voids; one asphalt pavement with transverse saw-cut grooving on Runway 13R/31L at Austin Robert Mueller Airport; two microsurfacing asphalt pavements, one in Corpus Christi and one in Austin; one chip seal surface, which is constructed by spraying on a thick seal coat and then grade 4 stones, approximately 0.32 to 0.40 in. (8 to 10mm) in diameter, and then placing and rolling into the seal coat; two novachip pavements, one 4-year old and one only months old.

The test plan used by the authors is given below.

- One speed, 100 ± 2 kph (62 ± 1.2 mph)
- One vehicle with single-axle trailer
- One tire type, Michelin LTX OWL P21575SR15
- Wind conditions less than 8 kph (5 mph)
- No significant grade
- Microphone height at roadside 1.5m (4.8 ft)
- Microphone distance from roadside 7.5m (24 ft)
- Dry pavement
- Tire pressure 221 kN/ms (32 psi)
- Weight on axle 7493 N (1,700 lb)
- No other vehicles within 60 m (200 ft) of test vehicle
- No traffic barriers or curbs present unless noted
- The terrain behind the microphone was relatively unobstructed and nonreflective

Table 3.3. Asphalt pavements considered for noise testing (after McNerney et al., 2000.)

Pavement Type	Pavement Location	Test Date
Typical TxDOT Asphalt Pavement – New	Loop 1604 – San Antonio	1/22/97
Typical TxDOT Asphalt Pavement – Aged	MoPac @ Braker – Austin	1/26/97
TxDOT Asphalt Pavement with Microsurfacing	MoPac @ 45th – Austin	1/26/97
Grooved Asphalt Pavement	Robert Mueller Airport Runway 13R/31L	11/20/96
Chip Seal Pavement	SH 16 northwest of Helotes	1/22/96
TxDOT Coarse Matrix High Binder Asphalt Section	S. MoPac – 3 mile section south of Slaughter Lane – Austin	11/13/96
Novachip – New	So. Padre Island Dr. – Corpus Christi	3/2/97
Novachip – Aged	US 281 just south of SH 46 – San Antonio	1/10/97
TxDOT Asphalt Pavement with Microsurfacing	So. Padre Island Dr. – Corpus Christi	3/2/97
Control Section – Decker Lane	Decker Lane – Austin	2/21/97

The results of the noise study for roadside and onboard measurements are presented in Table 3.4.

Table 3.4. Results of noise study in Texas (after McNerney, et al, 2000)

Pavement	Roadside Data Rankings (dBA) (Average)	Onboard Data Rankings (dBA)	
		135° location Mic	180° location Mic
Novachip (aged)	79.5	100.8	101.7
Microsurfacing (MoPac @ 45th)	80.1	102.3	104.0
Coarse Matrix High Binder	80.7	101.8	104.0
Asphalt (new)	81.5	102.9	105.0
Novachip (new)	81.6	104.4	106.6
Microsurfacing (Corpus Christi)	82.5	105.0	107.6
Asphalt (aged, MoPac @ Duval)	83.1	107.2	109.7
Chip Seal (Grade 4)	84.4	104.4	106.1
Asphalt (aged, Decker Lane)	84.4	104.5	107.2
Asphalt (grooved)	86.0	105.5	108.8

3.5. National Center for Asphalt Technology Study

The National Center for Asphalt Technology (NCAT) is testing as many asphalt pavements as possible throughout the United States to determine the noise characteristics of different HMA pavement types in order to develop some kind of design manual to be used by DOTs and other agencies interested in building low-noise HMA pavements.

Recently, the NCAT conducted noise tests on asphalt pavements in various states including Alabama (both on Alabama roads and at the NCAT test track), Nevada, Arizona, Texas and Colorado (Hanson, et al., 2004). Testing was done on OGFC's, DGA's, and SMA's using the NCAT CPX Noise Trailer. Even though the testing program seemed extensive, the results were considered preliminary and that additional research was needed to corroborate the results.

3.5.1. Open-Graded Friction Course

OGFC pavement data was provided in the report. One table gave OGFC gradations and air voids to analyze the effect of air voids on pavement noise; the values are given in Table 3.5. Another table gave OGFC gradations for pavements that were evaluated for the effect of gradation on pavement noise; the values are given in Table 3.6.

Table 3.5. OGFC gradation, air voids, and noise level data (after Hanson, et al. 2004)

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

Table 3.6. Gradations of OGFC's tested for effect of gradation on noise (after Hanson, et al. 2004)

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

Notes: [1] from specification ranges
[2] from cores

3.5.2. Dense-Graded Asphalt

The majority of the 46 different pavement surface types that make up the NCAT test track are DGA. The material properties of the DGA's were not provided in the report by the authors. However, the properties are provided on the NCAT test track Website (http://www.pavetrack.com/construction.htm).

Analyses performed on the DGA's included the effect of mean particle depth on noise level, effect of fineness modulus on noise level, and the effect of air voids on noise level.

3.5.3. Stone-Matrix Asphalt

The study mentions testing done on SMA's in Maryland, Colorado, New Jersey, and Virginia. Average pavement noise levels depended on the SMA mixes; noise levels generally increased with increase in maximum aggregate size of the mix. Table 3.7 gives the results of mix, location, and noise levels as provided in the report.

Table 3.7. Pavement noise levels for SMA mixes tested (after Hanson, et al., 2004)

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

3.6. Delaware Study

3.7. Summary

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