

An Introduction to Tire/Pavement Noise of Asphalt Pavement

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ABSTRACT

Highway traffic noise is an increasingly important issue in the U.S. As traffic volumes increase, noise levels increase. Simultaneously many communities are seeking to improve quality of life by reducing environmental noise. Thus, highway traffic noise has become an element of the tension between economic development and quality of life.

At freeway speeds for well maintained vehicles, the primary source of traffic noise is tire/pavement noise. Thus, the tire/pavement interface is the primary target of studies to reduce traffic noise. Quieter pavement has been demonstrated in several communities in the U.S. and has been extensively studied in Europe, Japan, and Australia. Based on these case studies, there is evidence that it is possible to construct and maintain pavements that are quieter than typical pavements that are also safe, durable, and cost effective.

This document is written as an introduction to the issues surrounding tire/pavement noise for the technical community and others. The document includes

- A brief introduction to relevant topics in acoustics and noise
- An explanation of the metrics used for describing noise
- A description of how noise is created at the tire/pavement interface
- A summary of the concepts used to create reduced noise pavement
- A summary of tire/pavement noise measurement methods
- An overview of U.S. traffic noise policy

This document is a modified version of the document *An Introduction to Tire/Pavement Noise* (JTRP Report No. , SQDH Report No.) which includes the materials in this document plus discussion of Portland Cement Concrete noise and addition material about tire/pavement noise models. That document also includes a glossary of acoustical terms and an extensive bibliography which are not included here. This document is intended to be introductory, and consequently, the treatment is brief and often cursory. For more detailed discussion, more extensive references are recommended, particularly the *Tyre/Road Reference Book* by Sandberg and Ejsmont.

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1.0 INTRODUCTION

Noise from highway traffic is an environmental problem in both metropolitan and rural areas [BOS, KRUP, MDOT]. The most significant impact of traffic noise is the annoyance it causes to humans and the associated negative effects this annoyance has on the quality of life. However in addition to annoyance, traffic noise may also impact health [WHO], create difficulty with speech communication, suppress real estate values, and cause the stagnation of economic expansion due to public resistance to expanded highway capacity. Without a significant strategy for traffic noise reduction, the type of conflict between economic development and environmental concerns that has essentially stopped airport expansion for the last twenty five year will impact highway expansion. It is essential that reduced noise highway alternatives be identified and utilized to minimize the impact of traffic noise.

Highway traffic noise is generated by four sub-sources of highway vehicles: engine/drivetrain noise, exhaust noise, aerodynamic noise, and tire/pavement interaction noise. As shown in Figure 1.1, for properly maintained automobiles, tire/pavement interaction is the dominant sub-source at speeds above approximately 50 kph (30 mph) [HIBB, SAN1, SAN2, DON2]. For properly maintained trucks that are not using engine compression brakes, the tire/pavement interface noise is similarly dominant but at a slightly higher speed. Pavements that produce less noise for the tire/pavement interface sub-source are an important strategic solution necessary to address future highway noise problems. A comprehensive review of tire/pavement noise was published recently by Sandberg and Ejsmont [SAN2]. This document draws heavily from Sandberg and Ejsmont.

Reduced noise pavement that satisfy transportation agencies' requirements for safety, durability and competitive economics will be developed and

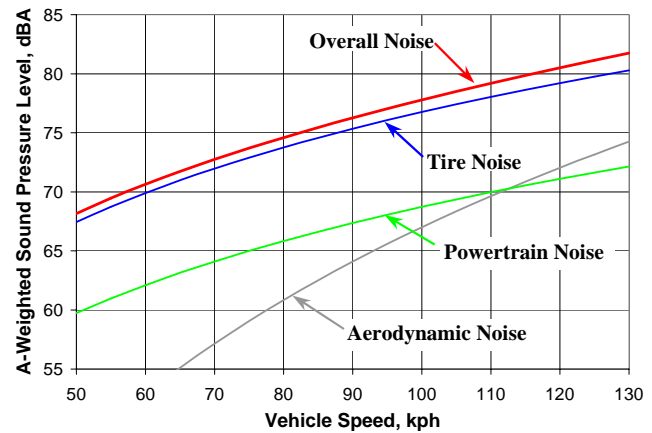


Figure 1.1 Contributions of the various sub-sources of highway traffic noise [DON2]

refined using expertise in pavement design, materials, and acoustics. This document is intended to summarize the state of knowledge of the field, to define terminology, and to serve as a bridge between these disciplines. The document includes sections to describe:

- Relevant topics in acoustics
- Noise metrics used to describe tire/pavement noise
- Tire/pavement noise generation
- Current technology used to develop reduced noise asphalt pavements
- Tire/pavement noise measurement methods
- U.S. traffic noise policy

This document is intended to be an introduction to the subject of tire/pavement interaction noise. It should provide the information needed by the highway engineer to frame important issues. The reader is directed to the references for more comprehensive information as needed.

2.0 RELEVANT TOPICS IN SOUND AND ACOUSTICS

Sound results from small, fast pressure variations in a fluid medium. In the case of tire/pavement noise, the medium is air. Thus, any event resulting from tire/pavement interaction that creates a pressure variation in air will create sound. **Acoustics** is the science of sound and is the broad discipline of the study of the generation, propagation, and reception of sound in all aspects. **Noise** is defined as unwanted sound.

2.1 Sound

Typically sound is created by a vibrating surface, in the manner of a speaker cone, or by aerodynamic forces, in the manner of an air disturbance (e.g., air being moved by a fan). In Figure 2.1, a computer simulation of the sound field from a vibration piston is shown. Vibrating sources are typically referred to as mechanical sources of sound. On the tire, the tread blocks and tire carcass vibrate and create sound directly. Vibrations are also passed to the pavement, wheel, vehicle body, and other structures which vibrate at frequencies in the range of hearing, creating additional sound radiation. Sources that create pressure perturbations using fluid forces are referred to as aerodynamic sources. The dynamic pumping of air in and out of the tread passages of a tire create sound. In addition, the turbulence around the tire and vehicle create sound.

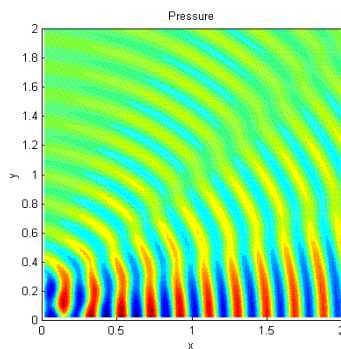


Figure 2.1 Figure illustrating the sound field radiated by a vibrating piston

Since many sources of sound consist of repetitive pressure pulses, it is typical for acousticians to describe sound in terms of frequency. The frequency

content of sound has diagnostic value. It is often possible to correlate the frequency of sound with the frequency of events that occur at the source. For example, tire/pavement noise will be dominated by the frequencies with which tread blocks strike the pavement surface (the so-called tread passage frequency of the tires) and the frequencies with which pavement surface texture variations pass through the tire/pavement interface. This texture related sound is very apparent when uniform transverse tining is used on PCC pavements. The whining sound created is directly related to the spacing of the tining and the speed of the vehicle which determine the frequency that the grooves of the tining process pass through the contact patch.

Frequency content is also useful for understanding the perception of sound. Humans with good hearing can hear sound between 20 Hz (cycles/s) and 20,000 Hz. Sound below 20 Hz (infrasound) or above 20 kHz (ultrasound) is out of the audible range and is typically not a concern for sources of noise. Between 20 Hz and 20 kHz, the sensitivity of hearing varies. The peak sensitivity of the human hearing is between 1000 and 4000 Hz. Noise in this frequency range is most critical when considering strategies for mitigating the effects of noise.

Sound propagates in the form of waves from the sound source at the speed of sound. In air at standard conditions, the speed of sound is 340 m/s (1130 ft/s, 770 mph). The speed of sound is fast enough that the sound created by a close-by event will seem to be coincident with the event. On the other hand, sound is slow enough that a delay is detectable when a source is far away. A typical example is the delay between a flash of lightning in the distance and the sound of thunder. Also, vehicle speed is significant relative to the speed of sound and may cause an increase (approaching) or decrease (departing) in frequency, resulting in an audible Doppler shift.

One of the important characteristic features of sound is its wavelength. The wavelength, or distance between repeating pressure pulses of sound at a given frequency is

$$\lambda = c/f$$

where c is the speed of sound, f is the frequency of sound, and λ is the wavelength. For a frequency of 100 Hertz (Hz) the wavelength is 3.4m (~10 ft.) and for 1000 Hz, the wavelength of sound is 0.34m (~1 ft.). In general, sources must be large relative to a wavelength to be effective radiators of sound. Thus, a woofer must be large to radiate sound effectively at low frequency. Small sources, such as tread blocks, are usually poor radiators of sound at low frequency. The radiation efficiency of small sources is increased if a device such as a horn is brought near the source. These issues can play a significant role in tire/pavement noise.

2.2 Noise

Sound can be either desirable or undesirable. Music is an example of desirable sound. Sound generated by tire/pavement interaction is undesirable and will be referred to as tire/pavement noise. Depending on

amplitude and duration, noise may have a range of effect on humans. At high levels for sustained periods of time, noise can cause hearing loss and adverse health effects such as high blood pressure and hypertension. At more moderate amplitudes, noise can cause speech interference, sleep disturbance, annoyance, and a loss of the quality of life.

In most traffic noise applications, annoyance is the effect of primary concern. Annoyance created by noise is related to the amplitude and frequency of sound as well as other attributes such as its tonality, transient behavior, and duration. Annoyance is also affected by an individual's expectations of the noise exposure. Thus, the quantification of annoyance is complex and varies among a typical population.

3.0 NOISE METRICS

For many applications, the detailed representation of noise in terms of frequency and amplitude is unnecessarily complex. Thus, simplified procedures have been developed to characterize noise. These metrics perform well for broadband noise, such as that from highway traffic. Exceptions occur when annoyance is dominated by specific features of noise, such as tonality, that have been ignored in the measurement of these metrics. Typical noise metrics will be described in this section.

3.1 The Decibel Scale

Noise is typically measured by time-averaging or by capturing the maximum value. The choice between averaging and maximum response is dependent on the nature of the event. For example, the noise from a steady traffic stream is best represented by the use of time-averaging. On the other hand, the sound created by a single automobile passby is better represented by using the maximum pressure.

Humans can hear over a scale of pressure amplitude with a factor greater than 10 million. Additionally, human response to sound pressure is not linear. For these reasons, the amplitude of noise is typically expressed in terms of **sound pressure level** using a logarithmic scale and is reported in decibels (dB) rather than in terms of pressure in Pascals (Pa). The definition of sound pressure level is

$$L_p = 10 \log_{10} (p^2 / p_{ref}^2)$$

where p is the sound pressure of concern and p_{ref} is a reference pressure. The standard reference pressure for sound in air is

$$p_{ref} = 20 \times 10^{-6} Pa$$

which is generally considered to be the threshold of hearing for a human with good hearing. Since decibels are computed from a ratio and do not have units, the reference pressure should always be identified when reporting the sound pressure level.

The sensitivity of the ear is exponential and roughly corresponds to the logarithmic approach used in the decibel scale. The sound level for typical sources, including various transportation noise sources are shown in Figure 3.1.

Under many conditions where the frequency and time characteristics of sound remain similar, humans perceive 10 dB changes in sound pressure level to be one-half or twice as loud. However, a 10 dB increase in level is a factor of ten increase in sound energy. Thus, even a somewhat modest reduction of noise level requires a very significant reduction of sound energy. For example, a reduction of 10 dB, which would be perceived as approximately half as loud would require a 90% reduction of sound energy. This characteristic of human sensitivity to sound can make mitigation challenging.

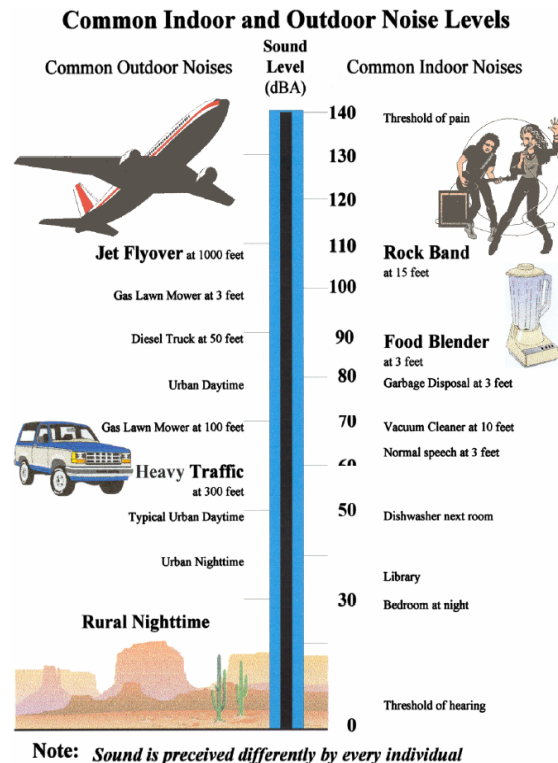


Figure 3.1 The sound pressure level of typical noise sources [ADOT]

3.2 Frequency

The frequency of sound is often referred to as pitch. Humans perceive consecutive doubling of the frequency of sound as equal steps in pitch. Thus, the frequency scale used for description of noise is often expressed in terms of octave bands or one-third octave bands. The center frequencies of these bands are shown in Table 3.1. Each octave or one-third octave band sound pressure level represents the acoustic energy in that frequency band. In some cases, noise measurements are reported in terms of octave band or one-third octave band sound pressure levels rather than in terms of overall level so that the sources of sound can be better understood.

3.3 Weighting Scales

Often, it is desirable to report the effect of frequency and amplitude using a single number metric. To include the frequency related sensitivity of hearing into a single number metric, weighting networks are used. The A-weighting network is an approximation of the sensitivity of the human ear to sound at moderate amplitudes typical of environmental noise. The A-weighting curve is shown in Figure 3.2 and the attenuation factors are shown in Table 3.1. Note the large attenuation applied by the A-weighting

filter for sounds below 500 Hz and above 5000 Hz. Humans are not sensitive to sound in these parts of the frequency range. B- and C-weighting networks are available for weighting sound at higher sound amplitudes than are typical of environmental noise (e.g., industrial noise).

Table 3.1 Band center frequencies for octave bands and one-third octave bands and attenuation factors for A-weighting network

Octave-band center frequency (Hz)	1/3 rd octave-band center frequency (Hz)	A-weighting attenuation factor (dB)
	25	-44.7
31.5	31.5	-39.4
	40	-34.6
	50	-30.2
63	63	-26.2
	80	-22.5
	100	-19.1
125	125	-16.1
	160	-13.4
	200	-10.9
250	250	-8.6
	315	-6.6
	400	-4.8
500	500	-3.2
	630	-1.9
	800	-0.8
1000	1000	0
	1250	+0.6
	1600	+1.0
2000	2000	+1.2
	2500	+1.3
	3150	+1.2
4000	4000	+1.0
	5000	+0.5
	6300	-0.1
8000	8000	-1.1
	10,000	-2.5
	12,500	-4.3
16,000	16,000	-6.6
	20,000	-9.3

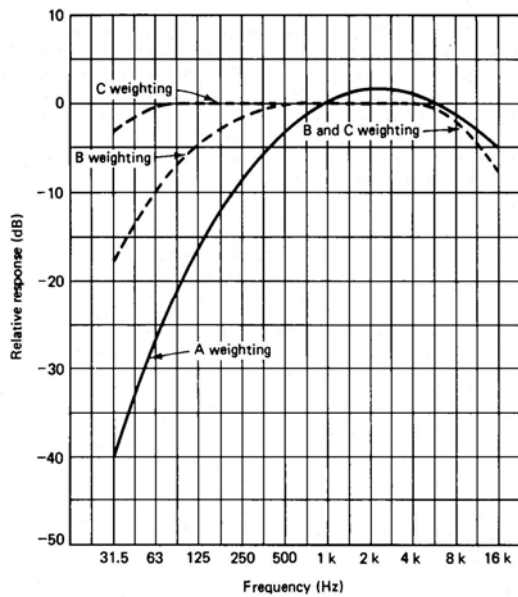


Figure 3.2 A-, B-, and C-weighting filters [IRWN]

3.4 Perception of Noise

The A-, B-, and C-weighting networks were early attempts to incorporate the physiological effects of the hearing system into measurements. These weighting curves are based only on the sensitivity of hearing to steady pure tones. Thus, perception of traffic noise does not always correlate with A-weighted sound pressure level [BILL, KUEM]. For example, there are many exceptions to the conventional wisdom mentioned previously that a 10 dB reduction is perceived as a halving of noise. Such rules of thumb only apply if the temporal and spectral characteristics of the noise stay the same. *Typically if pavement type changes, temporal and*

spectral characteristics change and community perception of sound will not correlate well with sound pressure level difference.

Much more sophisticated understanding of the physiology of hearing is available today and has been incorporated into sound metrics such as loudness [ZWCK, I532]. These metrics correlate better with the perception of the amplitude of sound and are recommended for situations where there is no requirement to use sound pressure level metrics and improved measures of loudness or annoyance is desired. The loudness metric has the additional advantage that it is a linear metric and a reduction of 50% in the metric will be approximately perceived as a 50% reduction.

4.0 TIRE/PAVEMENT NOISE GENERATION

Tire/pavement noise is generated by several sub-sources. The material presented here is a summary of the material presented in a very comprehensive form in the reference, *The Tyre/Road Reference Book* by Ulf Sandberg and Jerzy A. Ejsmont [SAN2]. The figures in this section are from that reference and are reprinted with the permission of the authors.

At the tire/pavement interface, several mechanisms create energy which is eventually radiated as sound. These will be referred to as *source generation mechanisms*. There are also characteristics of the tire/pavement interface that cause that energy to be converted to sound and radiated efficiently. These characteristics will be referred to as *sound enhancement mechanisms*.

4.1 Source Generation Mechanisms

4.1.1 Tread impact

The tire tread blocks travel around the tire as the tire turns. At the entrance of the interface between the tire and pavement (referred to as the contact patch) an impact occurs as the tread hits the pavement as shown in Figure 4.1. The tread impact can be compared to a small rubber hammer hitting the pavement. This impact causes vibration of the tire carcass. If both the tread block and the pavement can be made resilient, the energy created by this impact can be reduced. Randomization of the pavement

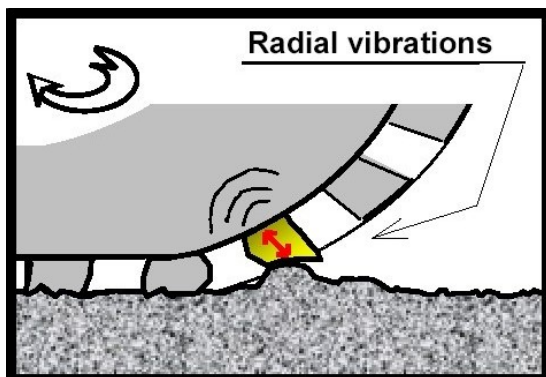


Figure 4.1 Vibration caused by tread block/pavement impact

texture and the tread pattern reduces the repetitiveness of this impact and can change the character of the sound to reduce the annoyance of the sound.

4.1.2 Air pumping

Within the contact patch, the passages and grooves in the tire are compressed and distorted. The air entrained in these passages will be compressed and pumped in and out of the passages as shown in Figure 4.2. Because of air compression effects and air pumping, aerodynamically generated sound is created. This phenomena is similar to sound created by clapping hands.

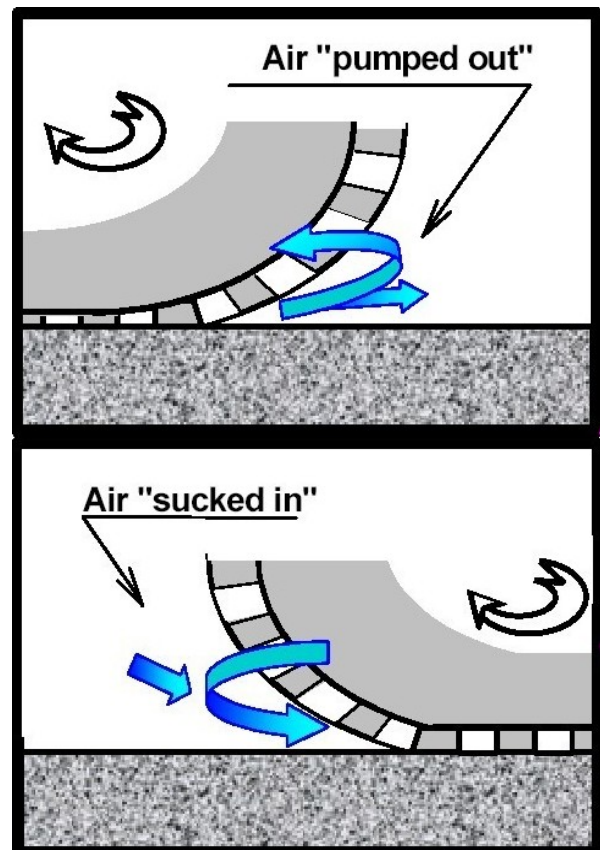


Figure 4.2 Air pumping at the entrance and exit of the contact patch

4.1.3 Slip-stick

Within the contact patch the tread blocks transfer tractive forces from the tire to the pavement for acceleration or braking. In addition, due to the distortion of the tire carcass in the contact patch, the tread block/pavement interface experiences significant horizontal forces. If these horizontal forces exceed the limits of friction, the tread block will slip briefly and then re-stick to the pavement as illustrated in Figure 4.3. This action of slipping and sticking can happen quite rapidly and will generate both noise and vibration. This phenomenon is observed in the gymnasium when athletic shoes squeak on a playing floor.

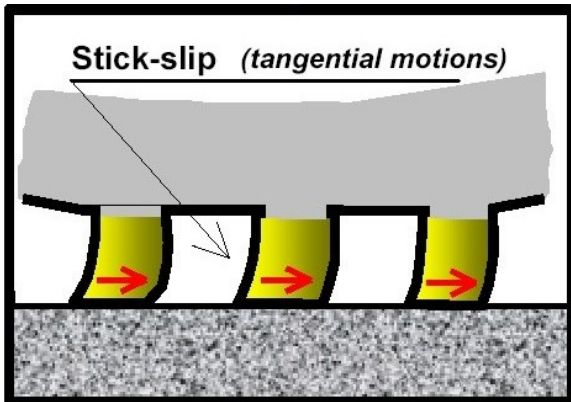


Figure 4.3 Slip-stick motion of the tread block on pavement

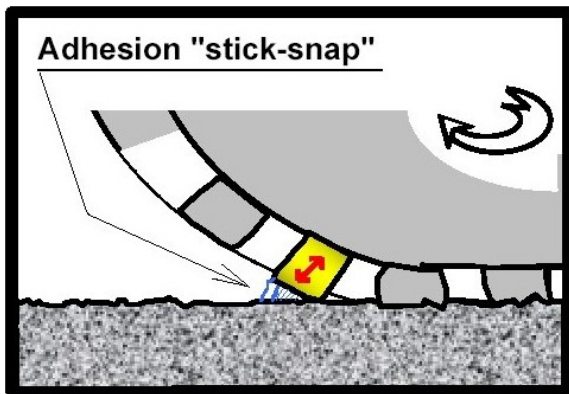


Figure 4.4 Adhesion between the tread block and pavement at the exit of the contact patch

4.1.4 Stick-snap (adhesion)

The contact between the tread block and the pavement causes adhesion between the tread block and pavement. The phenomena can be compared to suction cup behavior. When the tread block exits the contact patch, the adhesive force holds the tread block as shown in Figure 4.4. The release of the tread block causes both sound energy and vibration of the tire carcass.

4.2 Sound Enhancement Mechanisms

In many cases the energy created at the tire/pavement interface is not radiated efficiently. The tread blocks are small and would not be efficient radiators in isolation of the remainder of the tire/pavement system. Also, the air pumping alone would not be a significant source of energy. Several aspects of the tire/pavement system significantly enhance the radiated noise.

4.2.1. Horn effect

The geometry of the tire above the pavement is a natural horn as shown in Figure 4.5, although the shape is not classical and the horn itself is not a desirable shape for a musical instrument. Sound created by any source mechanism near the throat of the horn will be enhanced by the horn.

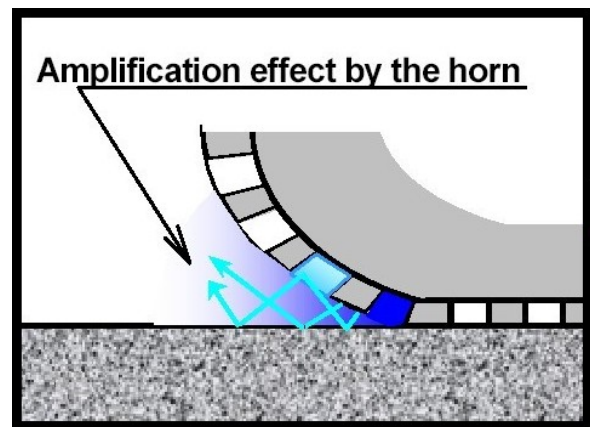


Figure 4.5 The horn effect created by the tire and pavement

4.2.2 Organ pipes and Helmholtz resonators

The tread passages of the tire in the contact patch take on shapes of acoustical systems that enhance sound generation. These include organ pipe resonances that are common in musical instruments and Helmholtz resonances similar to the whistle produced when blowing across an open bottle. These mechanisms are illustrated in Figure 4.6.

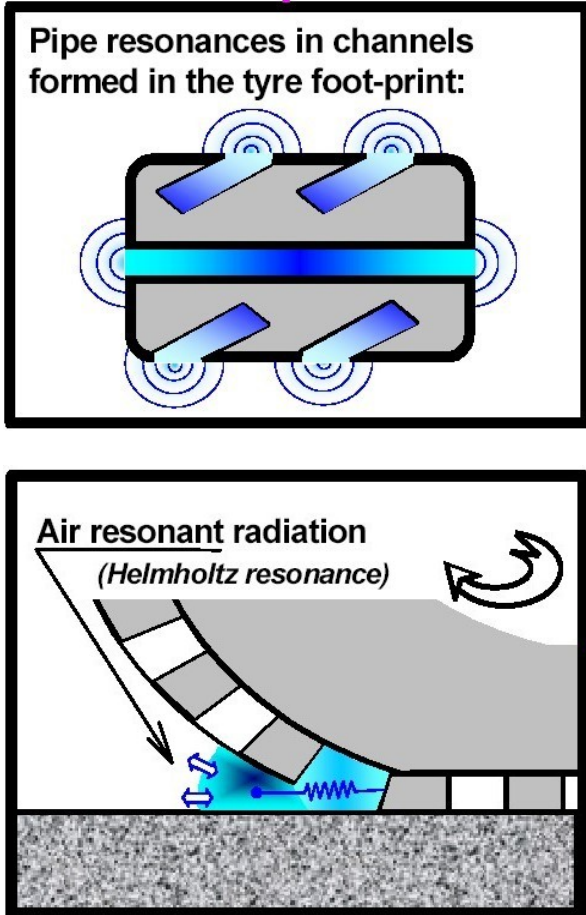


Figure 4.6 Sound amplification caused by organ pipe and Helmholtz resonator geometries within the contact path

4.2.3 Carcass vibration

The vibration energy created at the tire/pavement interface is enhanced 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 create sound which is radiated from the tire carcass. In addition, the tire carcass sidewalls near the contact patch vibrate and radiate sound as illustrated in Figure 4.7.

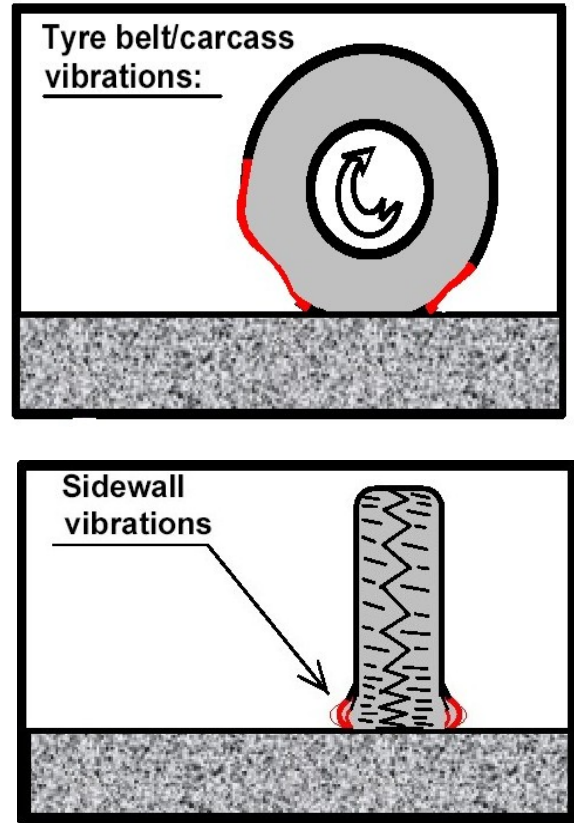


Figure 4.7 Vibration of the tire carcass around the tread band and at the sidewall of the contact patch

4.2.4 Internal acoustic resonance

The air inside the tire, which is used to inflate the tire, is also excited by the excitation of the tire. At certain frequencies associated with the natural frequency of the toroidal enclosure inside the tire, the air inside the tire will resonate as illustrated in Figure 4.8. The response of the air inside the tire is sufficient for these resonances to be audible.

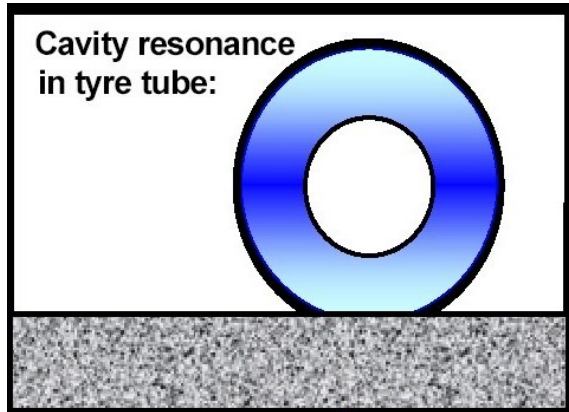


Figure 4.8 Acoustic resonance in the air space inside the tire

4.3 Summary

The tire/pavement noise problem is challenging in several dimensions.

The four tire/pavement source generation mechanisms have all been shown to be important for certain combinations of tire and pavement. Thus, different source mechanisms may dominate the sound generation for different applications making it difficult to develop strategies that would reduce source generation for all cases. In addition, if source

mechanisms are similar in strength, a strategy to suppress one mechanism will not have a dramatic effect on overall noise level because other mechanisms will become dominant.

The enhancement mechanisms further complicate strategies for achieving reduction of tire/pavement noise. The contributions from the various sound enhancement mechanisms are often difficult to distinguish from each other or from the source mechanisms. Thus, it is not always clear which mechanisms are important for various surfaces and conditions. It should also be emphasized that many of the mechanisms for generation or enhancement of sound from tires and pavement are directly integrated with the tire/pavement characteristics required for safety, durability, and cost.

Thus, tire/pavement noise is a challenging problem and methods for improvement are not straightforward. The good news is that significant reduction of noise from the tire/pavement interface has been demonstrated. In the subsequent sections of this document, methods that have been shown to have success will be described.

5.0 REDUCED NOISE PAVEMENT PRINCIPLES

The noise levels of various pavement types reported in the literature normalized to 55 mph at 50 ft. from the center line of the roadway are shown in Figure 5.1 for PCC pavements and in Figure 5.2 for asphalt pavements. These data are a compilation of results reported in papers published since 1996. In the figures the average, maximum and minimum reported levels for any particular pavement are shown. Normalization of this data was done by correcting for speed based on the trends for reference energy mean emission levels used in the Traffic Noise Model [TNM] and correcting for distance using hard site propagation for a line source. Data were not used if sufficient detail was not supplied to make a speed and distance determination or if other variables (e.g., diffraction) were a major concern.

The significant characteristics of these data are:

1. Within any given pavement type there is considerable variation that is believed to be due to either uncontrolled or unreported pavement construction and design variations. It will be important to understand and control these variations in the future.
2. In general, open graded asphalt pavement with small aggregate size is the quietest pavement type.
3. There can be as much as a 9 dB(A) difference for a single pavement type.
4. There can be as much as a 14 dB(A) difference between the noisiest and quietest pavement under similar conditions.

Reduced noise pavements have been built in field test. In 1998, 26 states reported that noise from

various pavement types had been investigated while 29 states reported that changes in standard pavements would be considered for noise control (WAYS). Several countries in Europe and Asia are routinely building reduced noise pavement as part of their national strategy to reduce traffic noise. From this work, certain principles have emerged that appear to be generally true.

In general, reduced noise pavements are based on experimental findings that:

1. surface texture with characteristic lengths greater than 20 mm tends to increase noise
2. surface texture with characteristic length less than 10 mm tends to reduce noise
3. porosity of the pavement tends to reduce aerodynamic noise above 1500 Hz
4. an elastic pavement surface will reduce impact and other mechanical sources
5. better results tend to occur for negative texture (below the surface) than for positive texture (sticking out of the surface)

Other principles are being tested for their general applicability and feasibility and may emerge as better solutions in time. In addition, aspects such as surface friction, splash/spray characteristics, changes with noise emission levels over time, overall durability and overall cost must also be considered when designing for reduced noise pavements.

In the sections that follow, general classes of reduced noise asphalt pavement will be described. The discussion will be limited to pavement solutions that appear to be feasible in the near future.

Noise Levels For Different Cement Concrete Pavement Types (at 50 feet & 55 mph)

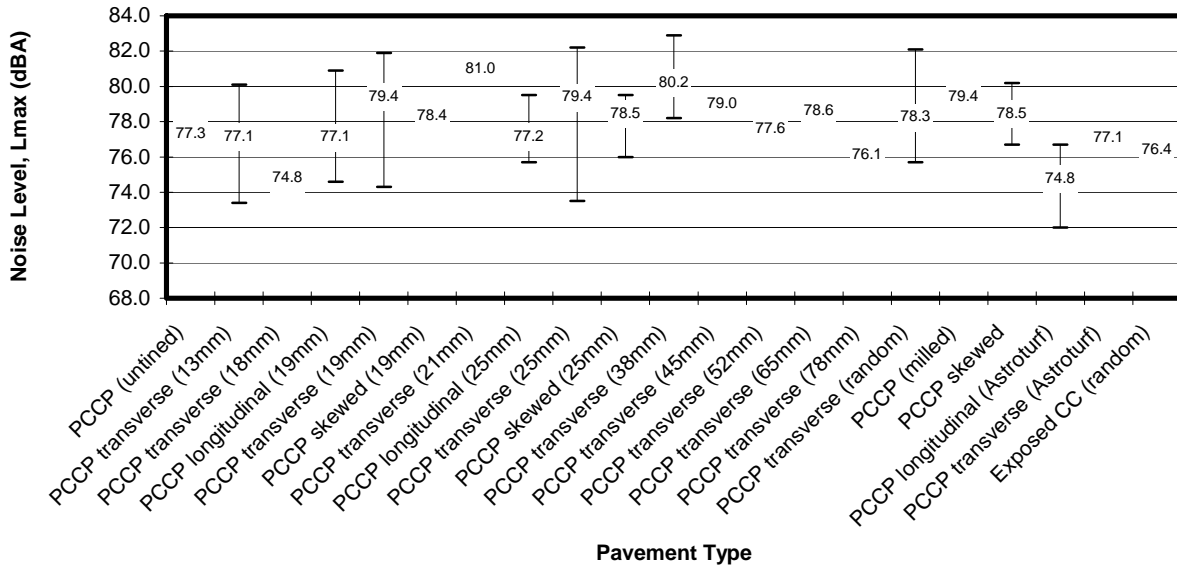


Figure 5.1 Sideline noise measurements of PCC pavements reported in the literature normalized to 50x ft. and 55 mph (courtesy of UCF Community Noise Laboratory, A.E. El-Aassar and R.L Wayson)

Noise Levels For Different Asphalt Concrete Pavement Types (at 50 feet & 55 mph)

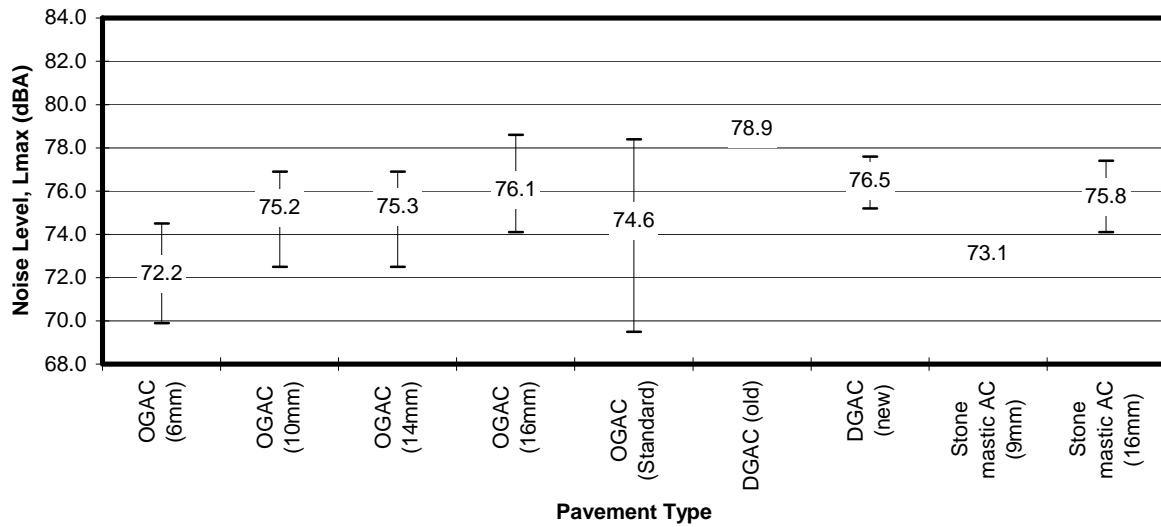


Figure 5.2 Sideline noise measurements of asphalt pavements reported in the literature normalized to 50x ft. and 55 mph (courtesy of UCF Community Noise Laboratory, A.E. El-Aassar and R.L Wayson)

5.1 Porous Asphalt Pavement

Porous pavements are constructed by reducing the amount of small aggregate used in the pavement such that the pavement cannot be tightly compacted. Figure 5.3 shows an example of how porosity occurs in a packed pavement when only large aggregate is used.

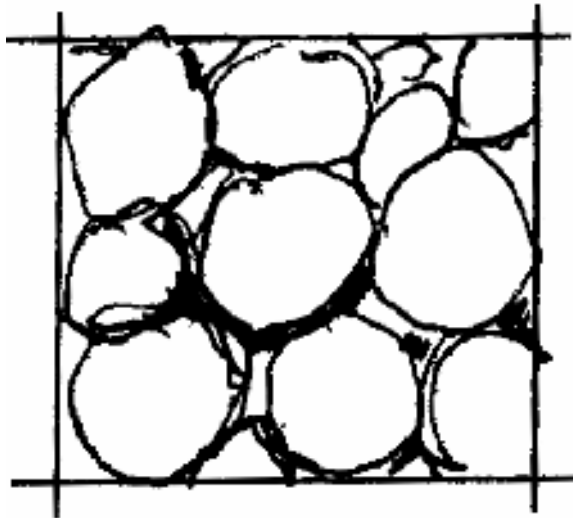


Figure 5.3 Typical structure of porous pavement

In general, porous pavement reduces tire/pavement interaction noise above 1000 Hz. Porosity levels on most installations have been approximately 18-25%. Porosity reduces the strength of the air pumping source mechanism by preventing air compression and reduces the enhancement potential of the horn, organ pipe, and Helmholtz resonator mechanisms.

Porous pavements are also capable of reducing traffic noise by a second property, by absorbing sound. The sound absorption qualities of porous pavements follow the same sound absorption principles as acoustical wall treatments in buildings. But, since tire/pavement noise is generated close to the surface, this absorption effect may not be an important factor for the reduction of tire/pavement noise. However, for trucks and other sources with significant sources under the vehicle body such as engine noise, the added benefit can be significant.

Porous pavements are also highly desirable for reduction of splash and spray. Since water tends to drain, wet friction is also excellent.

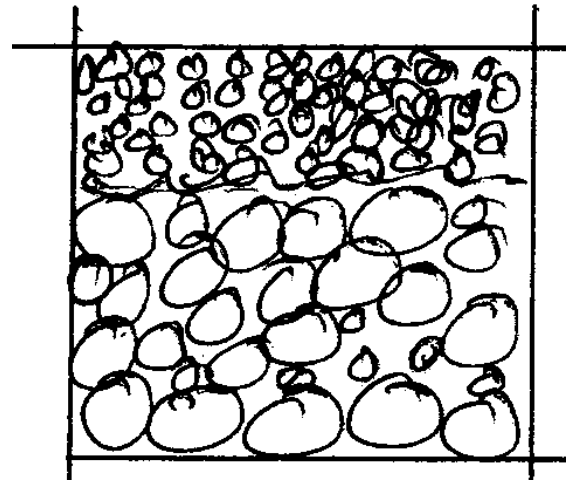


Figure 5.4 Typical structure of a twin layer porous pavement

There is concern about two issues associated with porous pavements. The first is the long term loss of the noise reduction benefit due to clogging of the pores with sand and grit during operation of the pavement. The second is maintenance of skid resistance during icing conditions.

To counter the clogging issue, Europeans have been building twin-layer porous pavements that self-clean better than single layer porous systems. Europeans are also restricting porous pavement solutions to high speed areas which tend to be cleaned by the pumping action of tires across the pavement. An illustration of the concept of a twin-layer porous pavement is shown in Figure 5.4. For this design, the top layer is intended to be a sieve and protect the lower layer from clogging with large grit. The lower layer is highly porous and easily flushed by the pumping action of traffic flow.

Ice control on porous pavements tends to be a challenge for two reasons. First, ice control materials, such as sand and salt, drain through the pavement. These problems can be addressed by pretreating using wetted salt and brine. Porous pavements also cool differently than dense graded pavements and should be treated on a different schedule than dense graded pavements. Due to

winter maintenance concerns and costs, some countries have limited the application of porous pavement to regions where ice formation is not an issue.

5.2 Gap-graded Thin Overlays with Small Aggregate

To circumvent the concerns about porous pavement in low speed applications or where icing conditions are prevalent, Europeans have been developing asphalt pavements with lower porosity (approximately 9% compared to dense graded asphalt pavement in the U.S. with porosity of 5-7%) with small, high quality aggregate. The aggregate typically has top sizes of either 10 mm or 6 mm. Porosity is achieved by using aggregate with certain gap-graded size distribution such that the finished pavement will have a porosity that handles water and grit appropriately. The aggregate will be graded such that very little material in the size range 2-4 mm will be used for 6 mm top sizes or very little 4-6 mm material will be used for overlays with 10 mm top sizes. Overlay thicknesses are from 15 to 25 mm depending on the size of the aggregate used. The small aggregate size tends to produce smooth pavement with very little characteristic texture greater than 20 mm. The porosity, while relatively low, is still effective in reducing high frequency noise.

Typical noise reduction of the pavements with gap-graded, thin overlays with small aggregate has been 3 dB relative to dense graded asphalts. From early test results no reduction in noise benefit has been detected over time. This type of pavement is very similar to small aggregate versions of the Superpave and Stone Matrix Asphalt (SMA) pavement types widely used in the U.S. with some modification of mix design to accommodate the aggregate distribution.

5.3 Texturing for Reduced Noise

Texture is important on all pavements to enhance wet weather friction. Negative texture with characteristic lengths less than 10 mm also tends to reduce noise. However, texture of other sizes and type tends to increase noise, sometimes significantly. Local texture depth of approximately 3 mm (which translates to average texture depths

slightly greater than 1mm) appears to be sufficient to achieve noise reduction effects.

For asphalt pavements the texture is a byproduct of the pavement material and control of texture is achieved by choice of aggregate size, shape, and aggregate size distribution as described in previous sections. Sealants or other techniques to reduce texture and make the pavement smooth at the microtexture scale, will increase tire/pavement interaction noise.

5.4 Poro-elastic Pavement

Our current understanding of the mechanisms of sound generation and enhancement points toward pavement solutions that are mechanically elastic and acoustically porous. Mechanical elasticity helps to reduce the mechanical sources. Acoustically porous pavement helps to reduce the aerodynamic sources, reflections, and acoustical enhancement mechanisms. A few test pavement samples have been developed in an attempt to achieve these ideal characteristics [MEIR]. These pavements are significantly quieter than current pavement technology. However, many of these pavement solutions are not ready for implementation, primarily due to durability limitations.

There has been limited use of asphalt pavement with recycled rubber. These pavements have been developed primarily for the purpose of durability and recycling considerations rather than for noise control. However, some of these pavements have achieved notable noise reductions. It is yet to be determined whether these pavements are truly poro-elastic pavements.

The Arizona DOT has made widespread use of pavement material called Asphaltic Rubber Friction Course (ARFC). [ADOT] This pavement has an open texture and acts like a porous pavement. The recycled rubber is mixed with the binder. These pavements have had some of the lowest measured noise levels of existing surfaces throughout the U.S. This pavement material and similar designs are currently being studied in a long term study to determine whether these pavements will be able to meet cost, safety, and durability requirements in Arizona.

6.0 TIRE/PAVEMENT NOISE MEASUREMENT

In order to evaluate the noise reduction effect of pavement, it is necessary to make reliable acoustical measurements. No single method is possible or practical for all applications. Thus, several methods are used to measure tire/pavement noise [LEE, DON1]. The general approach for each method is described. Details are available in standards and technical papers.

6.1 Statistical Passby (SPB)

Statistical Passby (SPB) methods utilize a random sample of typical vehicles measured one at a time. [18191] The maximum sound pressure level is captured for each passby using a sound measurement

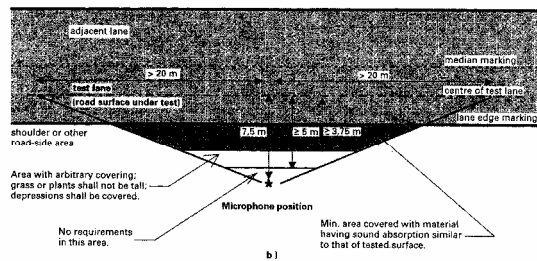
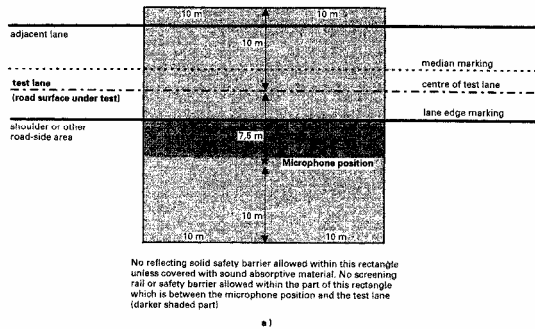


Figure 6.1 Measurement layout for statistical passby measurement [ASTM]

system such as a sound level meter (SLM). The SLM or similar instrumentation is located either 7.5 m (European standard) or 50 ft. (occasional U.S. location) from the center line of the travel lane. The speed and vehicle type of each event is recorded. A statistically significant sample of light and heavy vehicles must be collected. The data is used to compute a Statistical Passby Index (SPBI) which can

be used to compare various pavements. Details of the international standard SPB measurement method are specified in ISO 11819-1 [18191].

SPB methods account for all aspects of traffic noise at the sideline of the highway including engine, exhaust and aerodynamic noise. The method also takes into account the variation that occurs across vehicles of the same type. However, the measurement is not tightly controlled since random vehicles will be involved at different sites. In some cases a paired site method is used, where identical vehicles are measured for each site. For SPB measurements the traffic stream must be such that only a single vehicle passes through the measurement site at a time. The measurement site must be selected to avoid background noise, reflections, or terrain that might affect the measurement. In general, the background noise levels must be 10 dB(A) less than the measured vehicle noise. The method is labor and time intensive, but provides the best available measure of the impact of traffic noise on local highway neighbors.



Figure 6.2 Typical measurement set up for SPB measurement. In this case both 7.5 m and 50 ft. measurements are made (Photo provided by Judith Rochat, U.S. DOT Volpe Center)

6.2 Controlled Passby (CPB)

For controlled passby (CPB) measurements the same measurement setup as SPB is used. For CPB relatively few selected vehicles are driven at a controlled speed past the measurement location. In some cases, to emphasize tire/pavement noise, the vehicle may coast past the measurement point. Pavement alternatives are compared for each vehicle at each speed. No standards currently exist in the U.S. for CPB but the European Union is currently developing a method for EU standardization, and possibly for ISO, based on a French national standard [F119]. In addition, vehicle noise measurement standards of this type, which are used for evaluating vehicles and tires on standard pavements, are available for methodological guidance [I325, I362, S470].

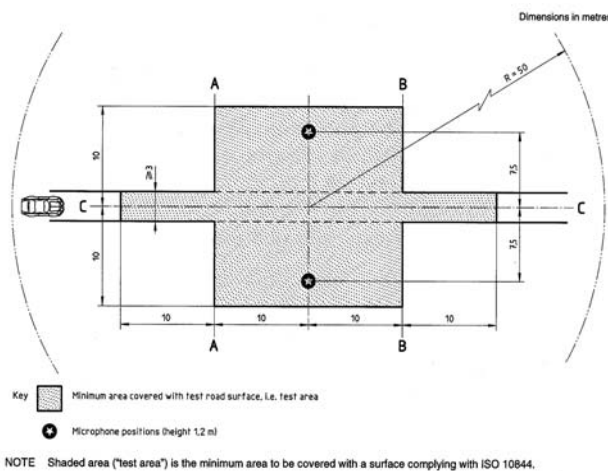


Figure 6.3 Schematic of the layout of a vehicle passby noise measurement [I325]

The CPB method takes less time than the SPB method but does not account for the variation that might occur in vehicles of the same type. The method has the same site limitations as SPB and requires a light traffic density making it more suited to rural or test track conditions.

6.3 Time-averaged Traffic Noise

For conditions of heavy traffic density, neither SPB or CPB can be used to evaluate tire/pavement noise

because vehicle passbys are not sufficiently isolated. For such applications, investigators have used methods of measuring time-averaged traffic noise. For time-averaged measurements, sound pressure is averaged and converted to the equivalent noise level or L_{eq} . To implement time-averaged measurements, an appropriate site is chosen where background noise is at least 10 dB(A) lower than traffic noise and there are no significant reflections or complex terrain. Time-averaged noise as well as traffic speed and vehicle mix are measured. Often meteorological measurements are also made.

For time-averaged methods, traffic mix, traffic volume, speed and meteorological conditions are not controlled. A normalization process based on traffic noise models is used to develop a comparable descriptor of noise at the wayside location. Time-averaged methods are best applied for evaluation of the change of highway noise characteristics of a particular site with time for neutral meteorological conditions. Normalizing the time-averaged data to account for site differences and meteorological conditions is difficult and adds uncertainty to the comparison.



Figure 6.4 Typical measurement setup for a time-averaged sound pressure level measurement (Photo provided by Judith Rochat, U.S. DOT Volpe Center)

6.4 Close Proximity Methods (CPX)

Close proximity methods (CPX) were developed to allow measurement to focus on tire/pavement interaction noise. Details of the CPX measurement procedure are described in ISO/CD 11819-2 [18192]. The measurement is taken on a trailer, as shown in Figure 6.5, using microphones located near the tire. The trailer includes a hood over the microphones such that wind noise is reduced and noise from other traffic is reflected. Thus, this measurement can be made in the traffic stream.

CPX measurements can be made relatively quickly. It is possible to measure tire/pavement noise across a pavement network and to monitor pavement condition using the CPX approach. However, CPX measurements are made with a limited set of tires at one weight. The vehicle variation typical of a traffic stream is not accounted for. The method relies on near field measurements of sound pressure. Particularly at low frequency for highly directive sources, near field measurements can be difficult. In addition, correlation to sideline measurements requires characterization of the path the sound travels between the tire and the sideline position. For sites with sound absorbing pavement, these effects may be significant.



Figure 6.5 Typical CPX trailer measurement (Photo supplied by Doug Hanson, National Center for Asphalt Technology, Auburn University)



Figure 6.6 CPI measurement illustrating intensity measurement positions (Photo provided by Paul Donovan, Illingworth and Rodkin, Inc.)

6.5 Close Proximity Sound Intensity (CPI)

Sound intensity measurement is a more sophisticated measurement of sound than sound pressure. Intensity is the sound power per unit area and is generally a smoother function of position than sound pressure. In addition, intensity measurement is capable of resolving the propagating component of sound in the near field of a source.

CPI measurement is similar to CPX. The intensity probe is mounted near the tire as shown in Figure 6.6. For intensity it is not necessary to shield the probe from wind noise. The measurement can be



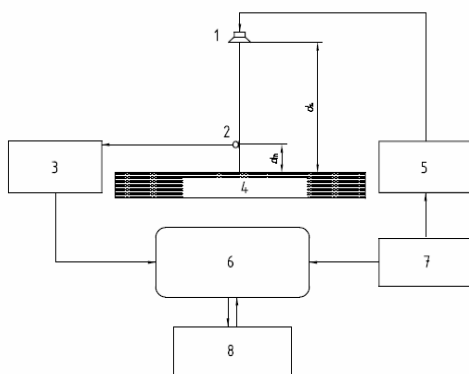
Figure 6.7 Typical mounting of CPI device on a test provided by Paul Donovan, Illingworth and Rodkin, Inc.)

made in the traffic stream at normal traffic speeds. Studies of pavement variation and pavement condition can be made rapidly. However, the CPI apparatus is generally mounted on only a few vehicles. As with CPX, the method does not capture the variation typical of a normal traffic stream.

6.6 Pavement Absorption

Because many of the source and enhancement mechanisms are dependent on the acoustical properties of the pavement, measurement of these properties is important. As previously discussed, the correlation between these measurements and the noise reduction performance of pavements is complex and not fully understood, but as research continues greater understanding will be gained. Thus, recommended practice for measuring pavement acoustical properties is still under development. The current methods in use for measurement of the pavement absorption include:

1. impedance tube methods for laboratory measurement of the acoustical absorption and acoustical impedance of core samples for normally incident sound using ASTM E-1050 [ASTM]
2. methods for measurement of the grazing



- Key
- 1 Sound source
 - 2 Microphone
 - 3 Microphone amplifier
 - 4 Surface under test
 - 5 Loudspeaker amplifier
 - 6 Impulse response time windows and Fourier transform
 - 7 Signal generation
 - 8 Analyser or computer

Figure 6.8 Schematic of *in situ* pavement absorption measurement method specified in ISO 13472-1 (2002)

incident acoustical properties (typically flow resistance which can be related to acoustical absorption) of field samples [ANS]

3. methods for measuring acoustical properties *in situ* for normal incidence using a method referred to as the Maximum Length Sequence [1472]

Other methods are being evaluated but are not currently in use. Potentially, methods of measuring acoustical properties will be useful for augmenting near field data from CPX or CPI with the propagation data needed to predict side line noise levels. Also, if these methods can be refined and correlated with field measurement, it will be possible to use laboratory based optimization of the acoustical properties of pavement before field test cases are built.

6.7 Laboratory Based Measurements

Laboratory based development of tires for all types of mechanical issues, including durability and friction, is done using rolling drums. These drums are made as large as possible to make the surface look as flat as possible and more realistic during testing. Centrifugal forces limit the use of realistic pavement on a rolling drum. To simulate the effects of pavement texture, these rolling drums are often surfaced with replicate pavements made of epoxy. Drums ranging in diameter from 1m to 15m have been used to study tire/pavement noise.

The Tire/Pavement Test Apparatus (TPTA) was developed to allow realistic pavement to be mounted on a stationary ring. The TPTA is shown in Figure 6.9. The pavement diameter is greater than 4 m. Loads up to 1000 lb and speeds up to 30 mph are possible.



Figure 6.9 Tire/Pavement Test Apparatus (TPTA) with PCC samples mounted on the measurement surface

7.0 US TRAFFIC NOISE POLICY

Except for individually approved pilot projects, the Federal Highway Administration (FHWA) currently does not recognize pavement type as an approved noise mitigation strategy for cases where mitigation is required. The stated reasons for the current policy are the limited information available about the safety of reduced noise pavements as well as concern about the consistency of these pavements and the durability of the noise reduction performance of current quiet pavement technology. While this policy does not currently allow a noise reduction benefit to be taken, it does not otherwise restrict the use of noise reducing pavement. Thus, despite the lack of an approved mitigation benefit, many transportation agencies have strong interest in quiet pavement technology to satisfy the public’s growing requests for reduction of traffic noise in locations where community groups are demanding noise reduction even though FHWA levels are not exceeded.

7.1 FHWA Policy and Regulations

The FHWA noise standards for *federal participation in a pavement project* are included in the complete code of Federal Regulation 23 CFR Part 772. These

regulations allow either the time averaged equivalent sound pressure level, L_{Aeq} , or the level exceeded 10% of the time, L_{A10} , to be used as a metric for noise. New highway projects are required to evaluate noise based on the worst hourly traffic noise impact for the existing and design year. *An impact is defined to occur if the prescribed levels listed in Table FHWA are “approached or exceeded” or if a substantial increase in the noise levels occurs.* The noise abatement criteria (NAC) are listed for specific activities. For example, the sound level for the exterior of the activity category B, which includes residences, is 67 dB(A); Leq(h). However, since the standards state that impact occurs when levels “approach or exceed” 67 dB(A), predicted maximum noise levels at 66 dB(A) or less in the various states requires consideration of abatement.

The second impact criterion, a substantial increase, is determined by each state. Substantial noise level increases range from 5 to 15 dB(A) for individual states.

If an impact occurs, abatement must be considered. Proposed noise abatement strategies are evaluated for whether they are “reasonable and feasible”.

Table 7.1: Noise Abatement Criteria (NAC) Hourly A-Weighted Sound Level – decibels: (dB(A))

Activity Category	Leq(h)	L10(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.

Feasibility depends on whether it is possible to implement the abatement. For example, if there are multiple driveways along a roadway, noise barriers are not feasible since large gaps in the barrier destroy the effectiveness of the barrier.

Reasonableness depends on many items. The most important is usually cost. Many states consider reasonableness to include whether a “substantial noise reduction” is achieved and list what is considered substantial. Most states use 5 dB(A). The number of residences where a “substantial” benefit is achieved are counted and used to help determine reasonableness. To be reasonable, the cost of the noise mitigation must not exceed some limit value per residence established by the state multiplied by the number of residences where a substantial benefit will be achieved. If the cost is too great for the benefit achieved, the barrier is not considered to be reasonable.

7.2 Quiet Pavement Pilot Programs

To evaluate potential changes to policy and assist states with quiet pavement programs, the FHWA has implemented a Quiet Pavement Pilot Program. This program is intended to investigate the effectiveness of quiet pavement strategies and evaluate any changes in their noise mitigation properties with time. The programs will collect data and

information for a 5-10 year period. The FHWA requires states participating in the pilot program to:

- Account for documented noise reduction benefits of pavement types by adjusting predicted (modeled) traffic noise levels in the project noise analyses. This may be done by either reducing the number of identified traffic noise impacts or by reducing the height of noise barriers required to mitigate identified traffic noise impacts;
- Include post-construction monitoring for the projects to collect acoustic, texture (macro & micro), and frictional characteristics. Annual monitoring will be performed for five years, possibly longer.
- Document the general public's reaction to the noise reduction capabilities of specific pavement types; and
- Commit to take appropriate actions to provide required noise reduction, if the anticipated pavement noise reduction benefits do not last for the life of the pavement.

The Quiet Pavement Pilot Programs will provide significant data to assist in establishing future noise policy using pavement as an additional tool for noise mitigation.

8.0 CONCLUSIONS

Quiet pavement that is safe, durable (both for sound control and wear) and economical has been demonstrated to be possible with current technology. However, the variation of available materials and construction techniques among the states mean that there is no general guideline available yet for design of quiet pavement. Thus, the highway design engineer will need to select from locally available pavement type and texture that will provide noise reduction using the principles described in Section 5.0. The designer will also need to specify pavement with good surface friction numbers, desirable splash/spray characteristics, and good wear characteristics at reasonable cost.

Many of the issues of quiet pavement are only

partially understood. As effort on the various aspects of quiet pavement proceed, a better understanding of the problem will evolve which will allow more accurate prediction of sound levels, development of lower-noise pavement designs, and direct measurement of the properties affecting noise reductions. The FHWA is encouraging these efforts by states with the Quiet Pavements Pilot Program. At present one state is participating (Arizona) but more are expected in the near future. Other states have quiet pavement programs independent of the FHWA pilot program. Significant effort is ongoing in Europe and Japan. Over the next 5-10 years the body of knowledge about reduced noise pavement will grow substantially such that implementation of quiet pavement will be routine.

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