Quiet Pavements: A Sustainable and Environmental Friendly Choice

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Paper prepared for presentation
at the Pavement Evaluation, Performance and Management (Poster) Session
of the 2008 Annual Conference of the
Transportation Association of Canada
Toronto, Ontario

Submission Date: May 15, 2008

Acknowledgements: Natural Science and Engineering Research Council (NSERC), Cement Association of Canada (CAC) and Ontario Ministry of Transportation (MTO) for funding the complete research on pavement surface characteristics.

ABSTRACT

Traffic noise is a growing problem, especially for urban areas. The common noise mitigation measures include noise barriers or earthberms that obstruct sound propagation from the roadway to the neighbouring community. Such costly measures are infeasible or ineffective in many urban areas because no actual noise reduction at the source is achieved. Study has found tire-pavement interaction as the major noise contributor at vehicle speed of ≥50 km/h and pavement surface characteristics play an important role in noise generation and propagation. Construction of quieter pavements is therefore considered to be promising technique for economical/sustainable and environmental friendly highway. This paper is intended to provide an overview of what transportation/pavement engineers or highway agencies/ municipalities need to know about the noise for planning, design and construction of quieter roads. The ranges of sound level for typical highway pavement surface courses/textures including some results of quiet pavement research at the University of Waterloo are also presented to aid the practitioners in selecting surface courses or textures of the pavement. Stone Mastic Asphalt (SMA) and whisper grinded portland cement concrete surfaces are shown to be best options considering pavement durability, safety and maintenance issues of roads carrying high volume of traffic. For low volume and low speed roads, double layer porous concrete or porous asphalt are shown to be promising techniques based on study in Europe.

INTRODUCTION

Road traffic noise is becoming a growing concern to residents around the world. Major problems are encountered in dense urban areas near busy roads carrying a high volume of traffic (*1*). Noise, in general, causes annoyance, sleep disturbance, fatigue, high blood pressure, loss of concentration, disturbance in personal recreation, interference with conversation and hearing loss. Survey shows that half of the Canadian are bothered, disturbed or annoyed by noise originated outside their home where the most bothersome type is the road traffic noise (*2*). Traffic noise therefore is an environmental and public health problem. To limit the road traffic noise impact, the Ministry of Environment (MOE) in Ontario recommended physical noise mitigation measures that include construction of noise barrier and earthberm to limit noise level at the outdoor living area, and upgrade building components and install central air conditioning units to reduce noise inside the buildings/houses. Such noise mitigation methods are neither economical nor effective because they can only prevent the noise propagation, but not actually reduce the traffic noise from the source.

Several sources contribute to the overall sound level generated at highway and propagated to the surrounding environment. However, the three main sources of roadway traffic noise are: vehicle engine, aerodynamics, and tire-pavement interaction. Research indicates that noise generated by the interaction between tire and pavement becomes a dominant source when the automobile speeds exceeds about 50 km/h (*3*). Many factors play a role in the generation of sound due to tire-pavement interaction such as tire size, condition and loading, traffic volumes, vehicle type, size, condition and speed, and pavement surface characteristics. Assuming all other factors are constant, the traffic noise levels will vary with variation in pavement surface characteristics such as porosity or texture (*4*). To minimize the tire-pavement noise, and thereby road traffic noise, the pavement surface type and/or the associated texturization are of paramount importance.

This objective of this paper is to provide an understanding of pavement noise, and the fundamental characteristics pertaining to noise generation and propagation mechanisms. The typical sources of highway traffic noise and their individual contribution to overall noise level and the mechanism of tire-pavement interaction and noise generation are described. Different standards/guidelines related to noise mitigation, traffic noise modeling and noise mitigation measures are also presented. The noise and texture measurement techniques are illustrated to assist with the selection of appropriate measurement techniques. Finally, the paper provides examples of quiet pavements including some results from quiet pavement research by Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo, Ontario to aid pavements engineers in choosing the appropriate pavement surfaces during the design of a new pavement or rehabilitation of an existing pavement.

FUNDAMENTALS OF SOUND AND NOISE

Sound and Noise

Sound is what the human ear can hear. Alternatively, noise is unwanted or unpleasant or objectionable sound. The classification of a sound as undesirable i.e. noise or acceptable i.e. not bothering is somewhat subjective. Although, because of subjective nature, it is difficult to determine and quantify which sound is unpleasant, sound from traffic is annoying to most people, and therefore it is considered as the noise (*1*).

A sound source emits acoustic energy that propagates through the air and results in a pressure to a receiving medium. The variation in air pressure above and below the normal atmospheric pressure is termed as the sound pressure, expressed in Pascal (Pa or N/m^2). A young person with normal hearing can detect air pressure variation of as low as 20 μPa, a fractional variation in the order of 2×10^{-10} as compared to the normal atmospheric pressure of 101.3×10^3 Pa. Alternatively, the sound intensity is defined as the continuous flow of sound power at a point on the sound wave propagation path per unit area, and expressed as watts per square metre (W/m^2). For a freely traveling sound wave, the sound pressure at any point is related to the maximum sound intensity as (*5*):

$$p_{rms}^2 = I_{\max} * \rho * c \qquad (1)$$

Where, p_{rms} = root-mean-square (rms) of sound pressure (N/m^2), $I_{\max}$ = maximum sound intensity (W/m^2), ρ = density of air (kg/m^3), C = speed of sound in air (m/s)

The number of complete cycles of oscillation of a sound wave in unit time is called the frequency or pitch of that sound wave, and usually is expressed as the number of cycles per second or Hertz (Hz). It determines how fast the change in air pressure occurs. Sound wave frequencies in the range of 20 Hz to 20,000 Hz can be detected by a healthy human ear. However, the most sensitive frequencies that can easily be detected by the human ear range from 250 Hz to 10,000 Hz (*6*). The tonal quality of a sound is dependent on the frequency spectrum of that sound. In fact, the different frequency spectrums of sound from various sources enable the human ear to detect the differences among the sounds. A low frequency sound is less attenuated with distance and more objectionable or annoying to human. Such noise is therefore a primary concern for traffic and tire-pavement related noise.

Sound Pressure Level (SPL)

A healthy ear can detect sound pressure fluctuations from as low as $2\text{x}10^{-5}$ N/m^2 to about 63 N/m^2 at which the threshold of pain begins. It is difficult to work with or manipulate such large range (*7*). To make sound level measurement practically distinguishable or meaningful, an internationally accepted standard has been developed in logarithm scale for the *SPL*, known as the decibel (dB) taking the threshold of hearing ($2\text{x}10^{-5}$ N/m^2 or 20 µPa) at 1000 Hz (1 kHz) as a reference quantity. In this scale, 0 dB *SPL* (a reference sound level for comparing other sound levels) represents an uncomfortably quiet environment and 140 dB is the loudest sound that generally occurs in the vicinity of a space rocket launching pad. A good environment should have noise levels below approximately 40 dBA (*1*). The *SPL* is expressed as:

$$SPL = 10\log_{10}(\frac{p}{p_0})^2 \qquad (2)$$

Where, *SPL* = Sound Pressure Level (dB), ρ = mean amplitude of the measured sound pressure (N/m^2), and p_0 = mean amplitude of the sound pressure at the threshold of hearing (N/m^2).

It should be noted that although sound intensity and sound pressure are two different qualities, the sound pressure level is analogous to sound intensity level and both of them are expressed in dB.

Loudness and A-weighting Filter

The loudness of a sound depends on both frequency and pressure which is expressed as the phons. At a frequency of 1,000 Hz (1 kHz), the loudness level in phons is numerically equal to the sound pressure level in dB (*8*). For example, a 60 dB *SPL* at 1 kHz will have a loudness level of 60 phons. Since the human ear response to different sound frequencies are not linear, the same *SPL* but at different pure tones (discrete frequencies) will have different loudness levels. Figure 1 shows the equal loudness contours which is developed by International Organization for Standardization (ISO 226-2003) based on research of human ear perception of sound (*9*). As shown is the figure, a 60 dB *SPL* will be perceived as 70 dB (indicated as 70 phons) at 250 Hz which is 10 dB louder than the perceived dB at 1,000 Hz (60 phons). An increase or decrease in *SPL* by 1-3 dB is just perceptible change in loudness for the human ear, while an increase or decrease of 5 dB is a noticeable change. An increase or decrease in *SPL* by 10 dB is perceived as twice or half loud while an increase or decrease in *SPL* by 20 dB is perceived as four times or 1/4 loud (*10*).

To measure the sound or noise level simulating the human hearing sensitivity, a system of frequency filtering and weighting has been developed. The filtering system that best corresponds to human perception is known as "A" weighting filter and the measured *SPL* is known as the A-weighted *SPL*. Tire-pavement or traffic noise, rated as moderate sounds, is always measured with such filtering system. This A-weighted *SPL* is designated as dB(A) or dBA (*1*).

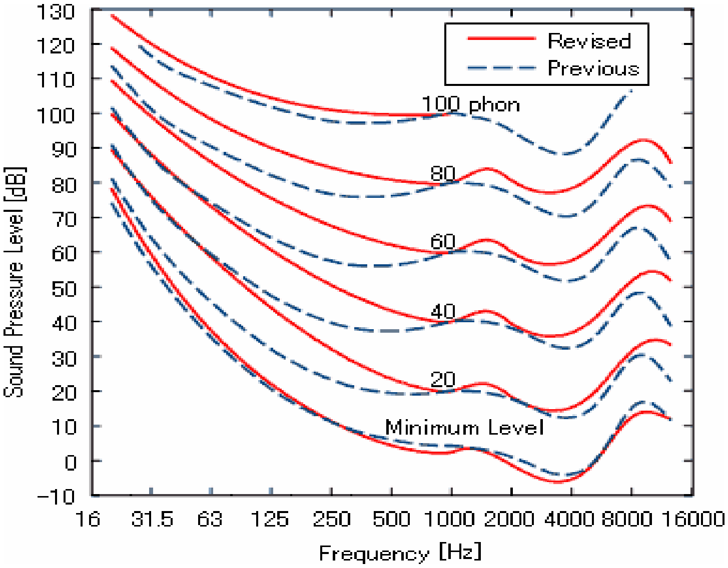


Figure 1. Equal loudness contour for pure tones (*9*).

Addition of Noise (Sound) Level

Two independent sound sources with equal *SPL* result in an equivalent *SPL* which is 3 dB greater than the *SPL* of individual source. Accordingly, doubling the traffic volume with same composition will result in an increase in sound level by 3 dB, the perceptible difference. Equation 3 illustrates the process of adding sounds (the dB levels) from several sources to obtain overall noise level (*10*).

$$SPL_t = 10 * \log_{10}[10^{\frac{SPL_1}{10}} + 10^{\frac{SPL_2}{10}} + 10^{\frac{SPL_3}{10}} + \cdots\cdots\cdots\cdots + 10^{\frac{SPL_n}{10}}] \qquad (3)$$

Where, SPL_t = Total Sound Pressure Level, and SPL_i = SPL from individual source (e.g. individual vehicle) i (i = 1, 2,……..n).

Maximum and Equivalent Noise Levels

Sound from an instant source may be high but diminishes with time and distance. Noise emitted from traffic is continuous but varies in strength over time depending on the time of the day, traffic volume, vehicle types and speeds, weather condition, surface condition, etc. To convert the non-uniform sounds to a meaningful single number, several descriptors are used. The most common descriptors of traffic and tire/pavement noise are: L_{max}, L_{eq} and L_{xx}. Figure 2 graphically show the variation of these three sound levels. L_{max} denotes the maximum level i.e. the loudest sound over the measurement duration and corresponds to the moment when the vehicle is at the closest point to the microphone (93 dB in Figure 2). L_{eq} denotes the equivalent sound level over particular duration of sound measurement, obtained by time-averaging the sound energy during the full measurement duration. It is a common way to express the traffic noise level. For example, L_{eq} *(24h)* of 84 dB means that sound energy is averaged over 24 hours and the average *SPL* is 84 dB. L_{xx} is a statistical descriptor of the measured sound levels and represents the sound level which is exceeded for only XX% of time during the measurement duration. For example, L_{10} *(24h)* of 88 dB indicates that a sound level of 88 dB is exceeded 10 % of the time during the 24-hour period.

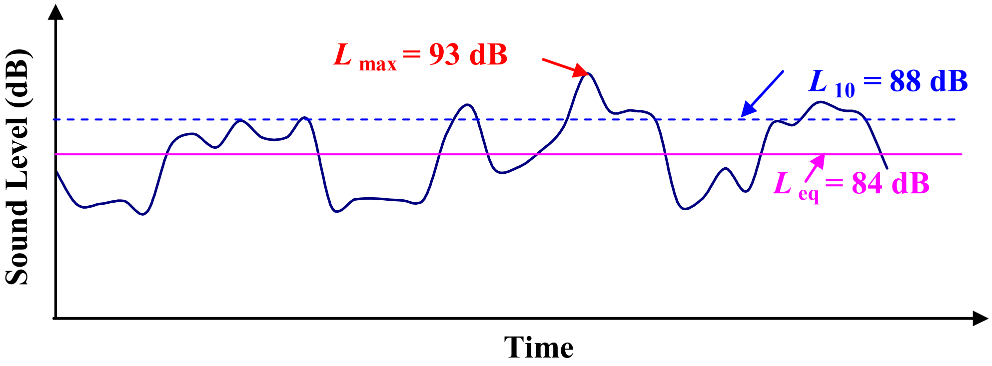


Figure 2. Various noise level descriptors.

Sometimes the 24-hour equivalent noise is computed from noise measurements during different parts within the 24-hour period assigning different weights for noise level during each part. For example, L_{dn} indicates that a 24-hour period is divided into one day (d) and one night (n). To compute the equivalent 24-hour i.e. one day-night level, the night level is increased by 10 dB to account for more severe effects of noise exposure during the night time (*1*). Another metric of sound level is Sound Exposure Level (SEL) which is equivalent to L_{eq} but noise levels are recorded for longer periods of time and normalized for a one second period for comparison.

HIGHWAY TRAFFIC NOISE

The noise from a traffic stream is the combination of all of the sounds produced by the vehicles traveling across a roadway and is received by abutters (community noise) or the travelers (on road or in-vehicle noise). The noise generated by an individual vehicle composed of sounds from three main sources. They are aerodynamic noise, power unit (propulsion) noise, and tire-pavement noise. Aerodynamic noise is produced by wind turbulence around the vehicle as it travels coasting the surrounding air. Power unit noise includes sound generated by fan, engine, exhaust and transmission systems. The tire-pavement noise is the sound generated by the interaction of rolling tire and road surface.

For a given tire, the noise generated by different sources of a running vehicle traveling on a particular road surface depends on the vehicle type and speed. Figure 3 demonstrate the variation of overall vehicle noise level as well as contribution of propulsion and tire-pavement noises at varying speed of a car. As shown in the figure, propulsion noise dominates the overall noise levels at very low speeds and is independent of vehicle speed. As the speed increases and crosses a certain limit, called the cross over speed, the tire-pavement noise becomes the dominant source in overall noise generated by a vehicle. The tire-pavement noise increases linearly with increases in speed. The contribution of aerodynamic noise to the overall exterior noise is not significant at vehicle speeds up to 120 km/h but may be significant for in-vehicle noise (*1*).

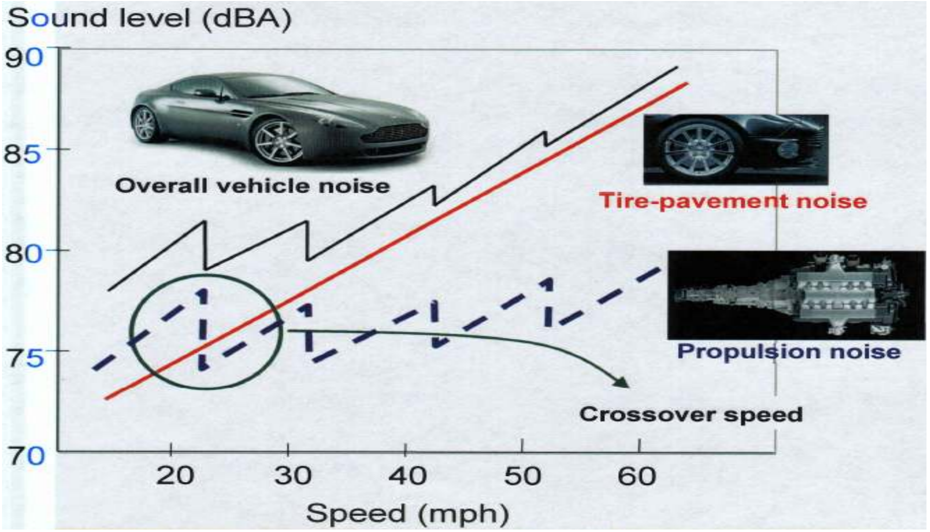


Figure 3. Speed effects on vehicle noise sources and crossover speed (*11*).

The cross over speed at/above which the tire-pavement noise is the dominant source may be taken as a practical threshold to judge the benefit of quiet pavements (*11*). For typical dense graded asphalt or 10-14 mm Stone Mastic Asphalt (SMA) surface, the crossover speeds are shown in Table 1 (*1*). Vehicle type is a significant factor in noise generation. Heavy vehicles are the noisiest vehicles on the road because of their large engine/power system, larger tires, and the fact that they have more tires that causes more tire-pavement interaction. A typical heavy truck is about 10 dBA louder than a typical passenger car traveling at highway speed i.e. a truck can generate sound energy equivalent to ten cars. Accordingly, if a traffic stream contains 10% or more trucks, sound created by the trucks will dominate the overall noise level on the road (*11*).

Table 1. Crossover Speed for Cars and Trucks (1)

Vehicle Type	**Cruising**	**Accelerating**
Cars	15-35 km/h (9-22 mph)	30-50 km/h (19-31 mph)
Trucks	30-50 km/h (19-31 mph)	45-55 km/h (28-34 mph)

The overall noise level will increase by about 2-3 dBA for an increase in vehicle speed of 16 km/h (10 mph). However, traffic volume does not have a significant impact in overall noise level because doubling the traffic volume will result in an increase in overall noise level of approximately 3 dBA. Other operating characteristics that contribute to noise generation, in varying degrees, from the running vehicle include: braking, accelerating, climbing uphill and cornering (*11*).

MECHANISM OF TIRE-PAVEMENT INTERACTION NOISE

The tire-pavement noise depends on the properties of both tire and road surface, and the complex interaction between these two factors. The contribution of the tire depends on the hardness of the tire material, tire age, tire size and tread pattern. The contribution of pavement depends on the pavement surface texture characteristics that include texture amplitude (depth), wavelength, orientation, acoustic absorption and relative stiffness of the surface. In general, the stiffer the tire material and the pavement surface are, the greater the level of noise generated due to their interaction. The important mechanisms of tire-pavement interaction and noise generation are impact, stick and slip, stick and snap and air pumping.

The impact mechanism generates noise through radial (mostly) and tangential vibrations of the tire because of continuous impacts between the rotating tire tread block and pavement surface. It is similar to a rubber hammer striking the pavement surface hundreds or thousands of times per second, depending on the vehicle speed, and each generating sound over a wide range of frequencies. The repetitiveness of the impacts can be reduced by randomization of the tread pattern and pavement surface texture (*3*). Stick and slip occurs as the tire rubber deforms on the pavement surface and periodically slips as the horizontal force exerted by moving tire exceeds the horizontal surface friction. This results in tangential vibration and high frequency noise. Stick and snap is the mechanism of adhesion and release of tire tread block as it rolls on the pavement surface. As a tread block exits from its contact patch, the adhesive force tends to hold the tread block. As the tread block is released due to rolling force, tangential or radial vibration of tire tread block and carcass is produced. The magnitude of such adhesion force, and the resulting vibration and noise depends on the properties of rubber used for tire tread. As a tire tread block enters the contact patch, the entrapped air between the pavement and tire tread is compressed and pumped out. The air is pumped in as the tire tread block leaves the contact patch. This aerodynamic process can generate high frequency sound and the magnitude depends on the tire tread and pavement surface texture patterns as well as the porosity of the pavement (*1*).

The tire-pavement interaction noise described above may be amplified (or reduced) by several other mechanisms such as inefficient radiation of sound energy, smaller tread blocks and other aerodynamic effects. Rough surfaces tend to disperse the sound while porous surfaces absorb the sound from the tire-pavement interface. Tire belt/carcass and sidewall vibrations may also amplify the tire-pavement interaction noise. The inflating air inside the tire itself is also energized by the excitation of the tire due to the interaction with the pavement or other possible mechanism such as tire rotation. This, consequently, causes a distinctive ringing. This sound is better heard inside the vehicle as the vehicle itself tends to further amplify its frequency. Many parameters of tire design and geometry influence the tire-pavement interaction noise. The combined effect of all these design parameters in noise generation varies widely among the tire types because of wide variations in tread geometry, construction, materials and mould shape. In general, the more aggressive the tire tread blocks are, i.e. clearly defined blocks and gaps, the louder the noise. The objectionable tonal frequencies can be minimized with randomization of tread block sizes and/or skewing i.e. angled blocks (*11*).

NOISE CONTROL GUIDELINES

In 1999, the World Health Organization (WHO) published guidelines for community noise to develop public awareness, and provide a guide to environmental health authorities and professionals regarding the impacts of noise on human health. According to the guidelines, L_{eq} of 55 dBA is the threshold of serious annoyance and 50 dBA is the threshold of moderate annoyance based on day criterion. Based on night-time criterion, the threshold of annoyance is L_{eq} of 45 dBA (*12*). The U.S. Federal Highway Administration (FHWA) Policy 23 CFR 772 has provided procedures for abatement of highway traffic and construction noises. Exterior areas are to be given primary consideration when determining traffic noise impacts and needs for noise abatement. Noise abatement is considered only where frequent human uses occur and a lowered noise level would be of benefit. Noise abatement measures must be considered when traffic noise exceeds 67 dBA (L_{eq}) at places of public activities including outdoor of residences, schools, parks, playgrounds, hospitals, etc. (*13*). The MOE has set guidelines for road noise control measures based on sound level to be determined through the Ontario Road Noise Analysis Method for Environment and Transportation (ORNAMENT) (*14*). If the day time L_{eq} is greater than 60 dBA, control measures are required to reduce the level to 55 dBA.

TRAFFIC NOISE MODELING

A number of noise modeling computer software programs are available in North America and elsewhere around the world to predict roadway traffic noise. Ontario and many other Canadian provinces and municipalities use the STAMSON program (an updated version of ORNAMENT), developed by MOE during the 1980's. STAMSON input parameters include: total traffic volume, medium and heavy truck percentages, road grade, distance to the road, and the elevations of the traffic noise source and the noise receiver. The "receiver" position is located at 1.5 m above the ground surface i.e. at ear height level and 3 m off the back wall of a residence (backyard or outdoor living area). For indoor noise, the second floor window is considered the receiver (*14*, *15*). To aid in compliance with policies and procedures under FHWA noise control regulations and measures, the FHWA developed the Traffic Noise Model (TNM) software. The TNM is an advanced computer program used for predicting noise impacts in the vicinity of highways that enables accurate and easy modeling of highway noise, including the design of effective and cost-efficient highway noise barriers.

NOISE CONTROL MEASURES

To control the road traffic noise impact, the MOE has provided guidelines related to traffic noise control measures. The guidelines recommend that physical noise mitigation measures are required if the predicted traffic noise level exceed the acceptable limits. The current certified types of physical mitigations include construction of noise barriers and earthberm to reduce noise level at the outdoor living area. Indoor noise reduction measures include upgrading building components, and installing central air conditioning units in the buildings.

The noise barriers block the sound transmission from roadway to the neighbouring community. Noise barrier or berm, breaking the line of sight between the source and receiver, can reduces the noise level by 5 dBA and each additional one meter height reduces noise by 1.5 dBA (*16*). Barriers are generally very costly and may result in poor road aesthetics. Typical costs for noise barriers are over \$1 million per mile and sometimes as much as \$5 million per mile (*17*). In addition, they results in additional future maintenance expenses. Noise barriers are also impractical and/or inefficient for bridges and mountainous areas, and some urban highways (main noise problem zone) because of access points and intersections that provide escape paths for the sound. Furthermore, in some instances noise barriers may not alleviate rather may actually aggravate the noise exposure by the travelers and passer-by depending on the roadway/barrier geometrics and barrier materials. The mentioned noise mitigation methods are therefore shown to be neither economical nor practical because they can only prevent the noise propagation, but not actually reduce the traffic noise from the source.

ROLE OF PAVEMENT IN NOISE MITIGATION

The pavement surface plays an important role in noise generation and propagation from the tire-pavement interface to the adjacent area/community. Many transportation agencies are investigating the type of pavements which reduce the noise generated due to the tire-pavement interaction. Experience reported from the United States, Europe, and Japan shows that noise-reducing pavement can reduce a significant amount of road traffic sound level. These pavements include rubberized asphalt, open-graded asphalt and stone mastic asphalt. Significant improvement has also been achieved in reducing the tire-pavement noise generated on concrete pavement surfaces through research on surface texturization methods. Longitudinal tining, diamond grinding, exposed aggregate and plastic bristle brushing are indicated to be promising. Other innovative approaches under investigation in Europe are two-layer porous asphalt or concrete pavements.

The noise reduction mechanisms by the pavement itself include acoustic and mechanical impedance. The acoustic impedance largely depends on the system of interconnected voids on the surface i.e. pavement surface type (porous or non-porous) and the pavement surface texture while the mechanical impedance is related to the relative stiffness of the tire and the pavement (*18*). An absorptive surface prevents effective reflection of sound energy and helps to reduce the roadside noise.

Pavement Surface Texture

The irregularities of pavement surface from the smooth horizontal plane surface are known as surface textures. The surface textures are classified into microtexture, macrotexture, megatexture and unevenness (roughness) based on texture sizes as indicated by texture amplitude (depth) and wavelength. The classification suggested by the Permanent International Association of Road Congresses (PIARC) is shown is Figure 4 (*19*). Microtexture refers to surface irregularities with wavelengths of less than 0.5 mm and vertical amplitudes of less than 0.2 mm. Macrotexture wavelengths ranges from 0.5 mm to 50 mm and vertical amplitudes ranges from 0.1 mm to 20 mm. Megatexture have wavelengths in the order of 50 mm to 500 mm and vertical amplitudes of 0.1 mm to 50 mm. Surface irregularities having wavelengths exceeding the megatexture size i.e. 500 mm are called roughness or unevenness. As shown in Figure 4, texture influences several aspects of tire-pavement interaction depending on its size. These include resistance to skidding (especially on wet-weather), tire-pavement noise, splash and spray, rolling resistance, and tire wear.

Texturization Method and Roles

AC pavements surface textures are generally controlled by the asphalt mix aggregate gradation, aggregate type and size. Coarse aggregates with hard and angular fine particles and/or harsh fine aggregates provide good microtexture on asphalt concrete (AC) surface while macrotexture are associated with voids between the stone particles which depends on size, shape and gradation of

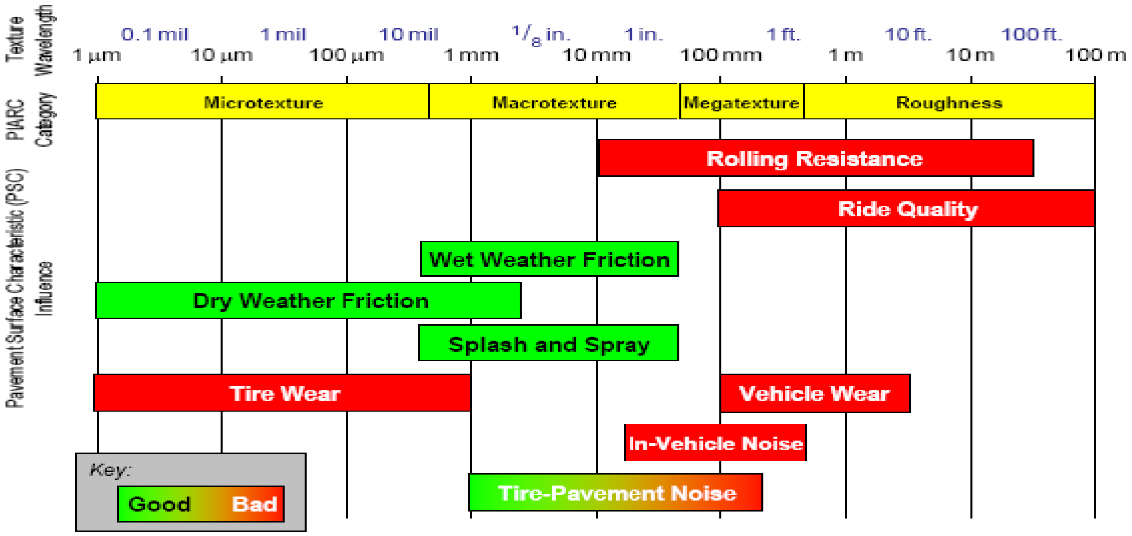


Figure 4. Ranges of texture and anticipated effects (*19*).

coarse aggregate in the mixture. For portland cement concrete (PCC) surfaces, fine aggregate in the mortar mainly contributes to available microtexture while macrotexture are intentionally formed through surface texturization that include small surface channel, indentations or grooves on fresh concrete or cut on hardened concrete in longitudinal or transverse or both directions.

As shown in Figure 4, microtexture and macrotexture are needed for adequate grip to prevent skidding, especially at high speed while macrotexture and megatexture are related to tire-pavement interaction noise with macrotexture having the strongest effect. Texture should be small (<10 mm) and negative (Figure 5) to minimize stab (strike) at and poke (push) into the tire, and thereby minimize the generation of undesirable noise (*11*). Alternatively, pavement surface texture reduces over time due to wear and polish under traffic and environmental effect which may affect the safety because of inadequate surface friction (*20*). A negative texture may reduce the rate of wear and minimize the tire-pavement noise. However, in all cases, the specifying agencies must ensure adequate resistance to skidding over the life of surface course as safety is of paramount importance.

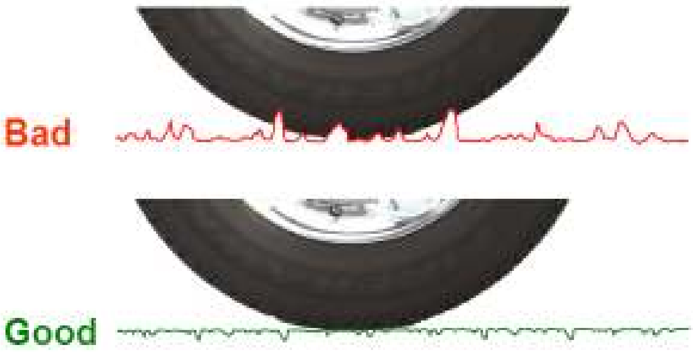


Figure 5. Conceptual schematic of good and bad textures (*11*).

Sound Absorption

Sound absorption is different from sound generation. The sound is generated through complex interactions between the pavement surface and the tire, and depends on the tire characteristics and the pavement surface textures. Alternatively, sound absorption depends on the system of interconnected voids in the pavement mix. For identical surface texture sizes and for a given tire, the noise propagation will decrease as the sound absorption increases. The reduced air compression due to air escaping through the pavement voids may also be helpful in terms of reduced noise generation. An air void content of 15%-20% in the paving mix has been shown to provide sound absorption coefficients of 0.10 to 0.20. However, field measurements show a reduction of tire-pavement noise level of only one to two dBA (*1*). This is probably due to increased textures associated with porous surfaces.

NOISE MEASUREMENT TECHNIQUES

Field Measurement of Tire-Pavement Noise

Several techniques are used to measure the overall traffic noise and tire-pavement interaction noise. However, all these techniques are mainly variations of two basic methods, namely the pass-by (far-field or wayside or roadside) measurement and close proximity (near-field) method. The variations of pass-by method which are commonly used for traffic or tire-pavement noise measurement include Statistical Pass-By (SPB) method and Controlled Pass-By (CPB) method.

In SPB method, noise from random samples of typical vehicles is measured and overall noise level is estimated, called the Statistical Pass-By Index (SPBI). For classification of road surfaces, the microphones are placed usually at 7.5 m (European standard) and occasionally at 15 m (50 ft) (U.S. practice) from the centre line of the travel lane, perpendicular to the direction of travel and at 1.2 m height respect to pavement surface. Measurements are taken for three classes of vehicles: passenger cars, dual-axle heavy vehicles with more than four wheels (bus, coach and truck) and multiple-axle heavy vehicles (trucks with three or more axles and trailers). The composition includes at least 100 passenger cars and 80 heavy vehicles with a minimum of thirty vehicles for each of two heavy vehicle categories. For each pass-by vehicle, under each category, the maximum *SPL* and travel speed are recorded. The SPBI at a reference (normalized) speed is calculated based on the proportion (weighing factor) for each vehicle category and energetic summation of sound levels (*1*). This method relies on normal traffic stream on a particular road, and therefore it can not be used to compare various pavement surfaces at network level as the vehicle combination and their conditions including types and conditions of tires are not comparable for different roads. It is mainly used for determining or predicting overall road side noise level for using in the decision making process for possible noise abatement measures.

The CPB method is similar to the SPB method in terms of the measurement setup whereby a microphone or microphones are placed at specified distance and height with respect to centre line of the test lane. However, in this case, a single test vehicle or a set of test vehicles are driven on reference or test surfaces at specified speed(s) and pass-by noise levels are measured. To compare or qualify the tires, vehicle(s) are mounted with test tire(s) and run on a reference pavement surface. The same idea is used to compare various pavement surfaces using a single vehicle or set of vehicles of different sizes (e.g. car and/or truck but usually cars) mounted with selected or standard tire(s) (*1*). Since the test tire(s) on each vehicle remain the same, this method can be used to compare the roadside noise from different road surfaces. The CPB method is used worldwide to compare pavement surfaces and various surface textures.

The Close Proximity (CPX) method is widely used to compare tires, vehicles and road surfaces for noise. In this case, the microphones are attached in close proximity to the tire, tire-road interface or vehicle engine. For tire and road surface testing, the microphones can be mounted near the tire-road interface of a specified vehicle or mounted near the tire-road interface of special trailer which is pulled by another vehicle. This method enables direct measurement of the tire-pavement interaction noise. An enclosure to microphones is usually provided to curb the noise from other surrounding sources. In addition, the trailer method further minimizes the contribution of the power train and the aerodynamic noise in the measured noise level. A normal tire or standard tire may be used (*1*).

On-Board Sound Intensity (OBSI) Method

The OBSI method is a variation of CPX method developed by General Motors. In this method, the intensity of sound power created due to tire-pavement interaction is measured as opposed to the sound pressure level measured according to the ISO CPX method. The microphones are mounted in close proximity of tire, and therefore it is also called Close Proximity Sound Intensity (CPSI) whereas the ISO CPX method measures the Close Proximity Sound Pressure (CPSP). This method is currently under development in the U.S. for standardization.

In-Vehicle Noise

The intensity of sound pressure inside the vehicle is usually measured by mounting the microphones at ear height of the driver inside the test vehicle.

Measurement of Acoustic Absorption

The common method used to measure the acoustic absorption properties of the pavement layer is the impedance tube method. A cylindrical specimen is mounted at one end and a speaker i.e. sound source is mounted on the other end of the cylindrical tube. A pulse is initiated by an analyzer which is amplified by a sound amplifier that generates a sound in the tube through the speaker. The generated sound is propagated to the specimen that absorbs part of the energy and remaining reflected back. Two microphones capture the incident and reflected wave amplitudes, respectively, which are then used to calculate the absorption coefficient or percentage sound absorption of the material under test. The test specimens may be prepared in the laboratory or obtained by coring from the field.

Another innovative method of sound absorption test of actual in-situ pavement is the portable reverberation chamber. CPATT has developed this method with the help of an acoustic consultant. A small chamber is placed on the pavement surface, a sound is generated in the chamber and the sound decay time is measured using the microphone mounted on the top of the chamber. The delay time is then used to calculate the sound absorption coefficient of the test pavement.

SURFACE TEXTURE MEASUREMENT TECHNIQUES

A number of techniques are used to measure the macrotexture of the pavement surface. The sand patch test is traditional volumetric method. A known volume of sand or glass beads is spread on the pavement surface (in a circle) and the area of the sand circle is used to calculate the mean texture depth. Laser based techniques are available that permits texture measurement in the laboratory as well as in the field. Examples of laser based techniques are Automated Road Analyzer (ARAN), Circular Texture Meter (CTM), RoboTex, etc. ARAN, manufactured by Roadware (Paris, Ontario) can measure the surface texture and roughness along with pavement distress survey at speed of roadway. RoboTex, developed in the U.S., is a six-wheeled remote controlled robot that runs over a road surface at walking speed and captures 3-D texture information.

QUIET PAVEMENT PRACTICES

Quiet Asphalt Pavement Examples

As indicated earlier, the tire-pavement interaction noise largely depends on the pavement surface texture. Therefore, the general requirement for quieter asphalt pavements are to reduce the texture i.e. keep texture as small as possible and avoid positive texture. Quieter asphalt pavements can therefore be constructed with all common mixes such as Dense Graded Asphalt (DGA), Stone Mastic Asphalt (SMA), Open Graded Asphalt (OGA) and Porous Asphalt (PA) provided that the textures are small and negative. Smaller textures can be maintained using smaller maximum size aggregate on the pavement surface. In Europe, a double layer porous pavement (Figure 6) with smaller maximum aggregate size (3 to 4 mm) on top layer is shown to be one of the quietest pavements. This compares to traditional asphalt mixes with 12.5 mm to 19 mm maximum size aggregate (*11*).

Figure 6. Double layer porous asphalt in Netherlands (*21*).

Porous, also known as pervious or permeable, asphalt mixtures consist of open-graded or uniformly-graded aggregates that provide a high air void contents (15% to 25%) in the compacted mix. Generally some polymers and/or cellulose fibres are added to the mix to avoid drain down of the asphalt binder through the pores in the mix during mixing, transportation and placement. The porous pavements have shown promising performance in providing natural drainage and reduction in noise. However, maintenance problem (clogging of voids) and durability as related to freeze-thaw effects, ravelling, fatigue cracking because of low structural capacity and oxidation of binders are major concerns. The noise reduction characteristic also diminishes over time as the voids are being clogged and surface distress appeared.

SMA (Figure 7) has been introduced in the U.S. during 1990 after an AASHTO team's European Asphalt Study Tour and currently being used in several projects in Canada. It is a gap-graded asphalt mixture with intermediate size aggregate missing i.e. the mixture contains larger stones and mastic which is a blend of asphaltic binder and fine aggregates/fillers. The stone rich blend provides close contact with each other and prevents segregation during placement and compaction. The durability is also good. The range of noise level is similar to dense graded asphalt pavements. German specification specifies three different mixes with 11 mm, 8 mm and 5 mm maximum aggregate sizes. AASHTO specification recommended three mixes with 19 mm, 12.5 mm and 9.5 mm nominal maximum aggregate sizes. The MTO (Ontario) specification adopted 12.5 mm and 9.5 mm nominal maximum aggregate size. Finer SMA is quieter, allows smaller lift thickness and reduces water percolation through the pavement.

Figure 7. Stone Mastic Asphalt at CPATT-Waterloo Region Quiet Pavement Test Site

The blending concept of open-graded asphalt such as open-graded friction course, designed for high skid resistance properties, is similar to porous pavement but with lower void contents which are achieved through use of higher finer aggregates. It also provides for noise reduction potential because part of the sound energy is absorbed through the voids in the mix. It has greater durability than the traditional porous pavement but potential durability problems are higher when compared to SMA and dense graded HMA. The noise reducing properties also diminishes over time due clogging of voids and/or deterioration of the surface. Figure 8 shows comparison of Dense Graded HMA (HL 3) and OGFC.

Figure 8. Dense graded HMA (left) and rubberized OGFC (right) at CPATT Test Site

Rubber or polymer modified asphalt mixes have shown to reduce the tire-pavement interaction noise because of higher binder content and lower stiffness which are contributed by the rubber or polymer materials. The rubber modified open-graded asphalts at Region of Waterloo and CPATT quiet asphalt pavement test site has shown to be quieter than the dense HL3 mix with same maximum size aggregates when tested at early ages (maximum 1-year old). However, test after three years of construction showed that SMA is the quietest surface among the four surfaces (Figure 9) at vehicle speed from 80 to 100 km/h while OGFC was shown to be the noisiest surface probably due to clogging of voids. SMA was also shown to exhibit excellent skid resistance with measured ribbed tire skid number of 57 (at 64 km/h). This shows the great potential benefit of SMA mixes as compared to other asphalt mixes.

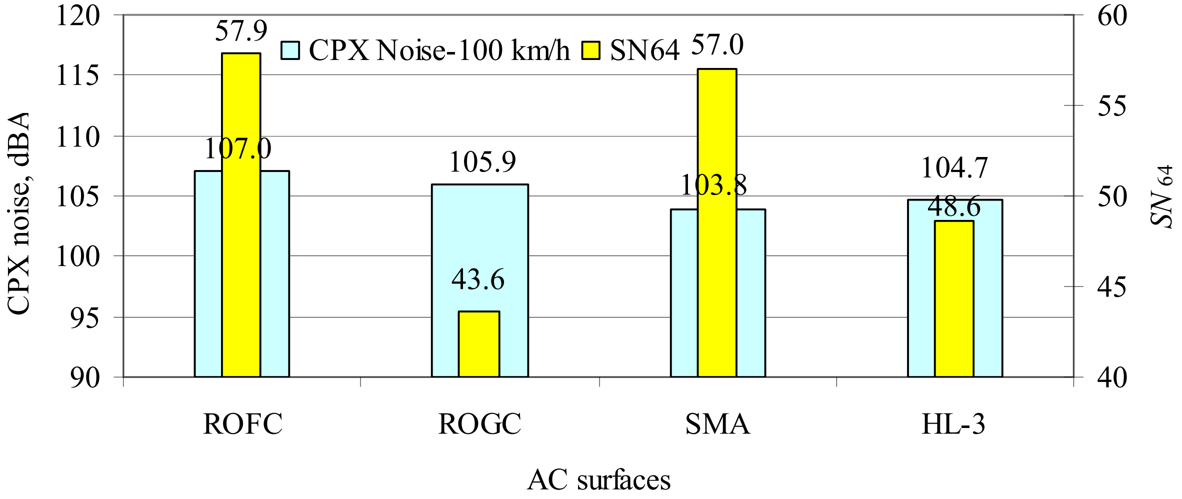


Figure 9. CPX noise and skid resistance of asphalt surfaces at CPATT quiet pavement site.

Quiet Concrete Pavement Examples

Concrete pavements are well known for their high structural durability and stability even under very high traffic. However, noise has been a concern for many decades that impeded the concrete option in pavement construction. A large number of research studies have been devoted worldwide to reduce the noise from concrete pavement surfaces. Among the studied surfaces, burlap and artificial turf drag textures have shown to be the quietest followed by the diamond grounded surface. However, adequacy and longevity of friction performance are concern for drag type textures. Longitudinally tined (Figure 10a) surface has shown to be quieter than transversely tined (Figure 10b) surface. Randomly spaced transversely tined surface has shown to eliminate the noise whine associated with uniformly spaced transversely tined surface.

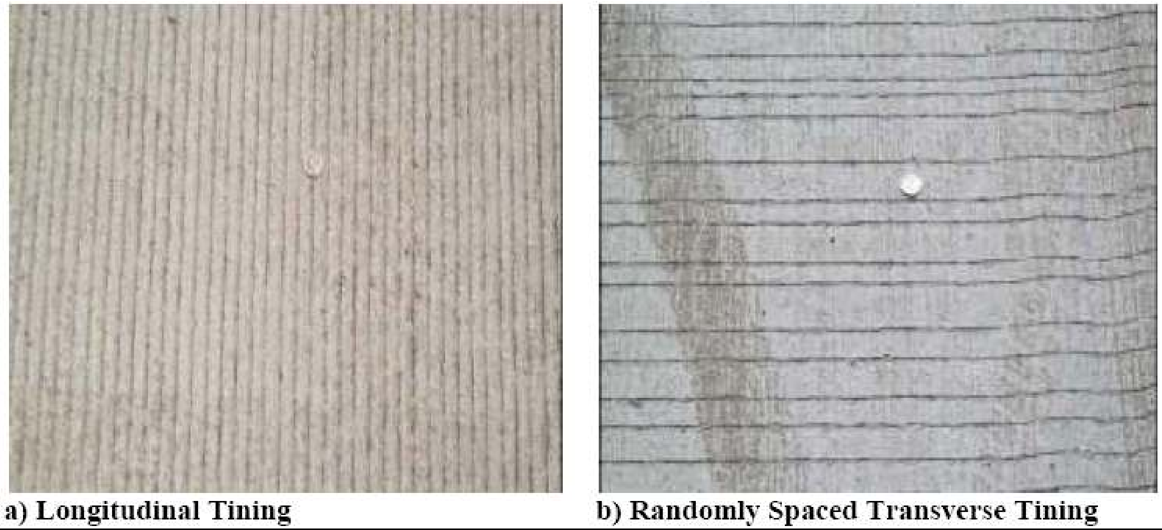
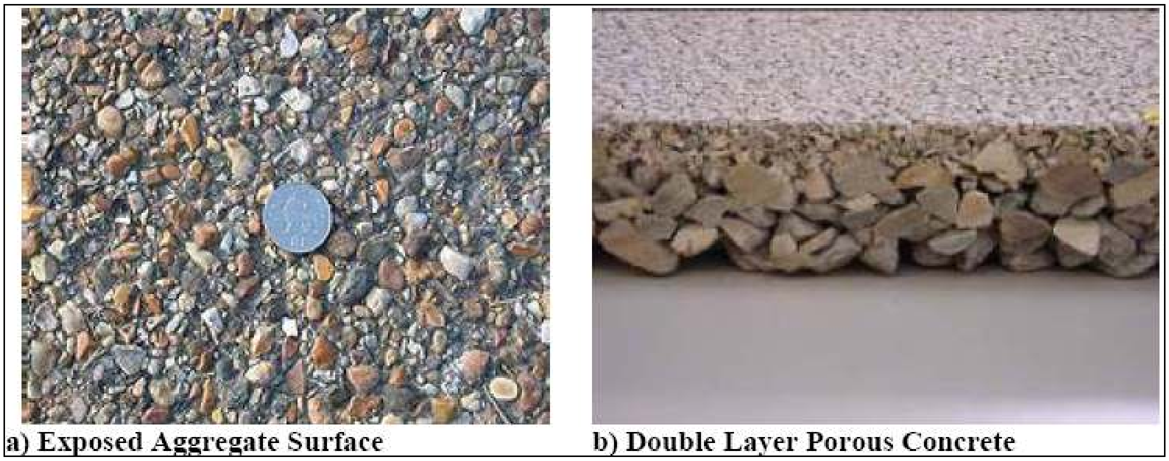

a) Longitudinal Tining **b) Randomly Spaced Transverse Tining**

Figure 10: Longitudinal and transverse tining (*19*).

The State of Arizona has studied a new diamond grinding concept, known as whisper grinding, which produces low textured surfaces and is shown to further reduce the noise (Figure 11). These surfaces were shown to be the quietest and smoothest PCC pavement in Arizona's history (possibly quietest in the whole U.S.). Overall, the CPX noise was 3 dBA lower on newly grinded surface (expected to further reduce after some traffic use) as compared to 19 mm (3/4") spaced longitudinally tined surface while the roughness was reduced by 58% and the surface friction was increased by 27% (*22*).

Figure 11. Whisper grounded surface in Arizona (*22*).

Exposed aggregate surfaces (Figure 12a) are commonly used in Europe. However, they are not as quiet as thought initially. Double layer pervious concrete pavement (Figure 12b) is also used in Europe which is similar in concept with double layer porous asphalt and shown to be quieter.


a) Exposed Aggregate Surface

b) Double Layer Porous Concrete

Figure 12. Exposed aggregate and porous concrete surfaces (*19*).

Sound Intensity Levels for Various Pavements

Figure 13 shows the ranges of sound intensities due to tire-pavement interaction on open graded (OG) and rubberized asphalt concrete (RAC), PCC, and Dense Graded Asphalt (DGA) pavements in California and Arizona. Figure 14 shows ranges of sound intensities on typical European pavements. As shown in the figures, the noise level varies widely even within same pavement group. This indicates that careful selection and construction can provide beneficial noise reduction measure by the pavement itself.

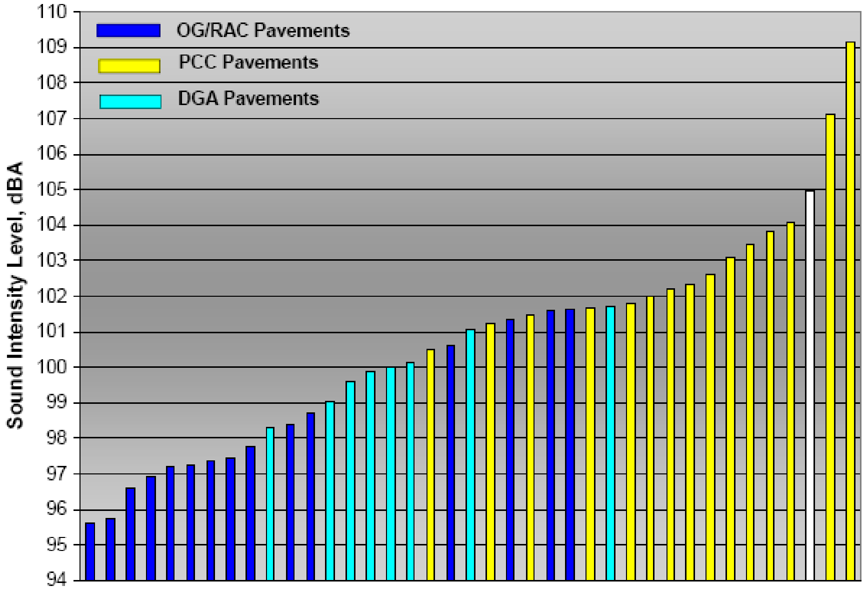


Figure 13. Caltrans data base- California & Arizona pavements noise ranges (*21*).

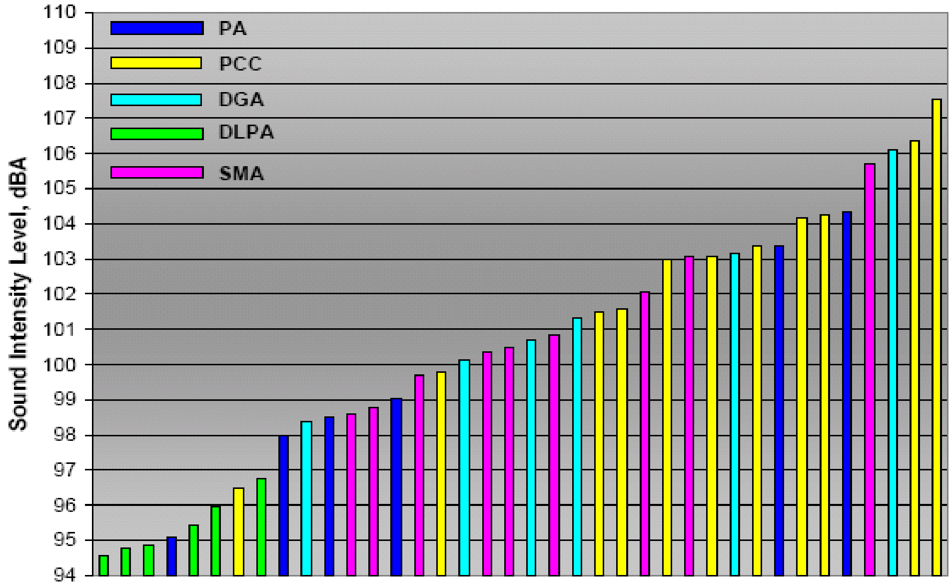


Figure 14. Noise ranges for European pavements at 97 km/h (*21*).

CONCLUDING REMARKS

As the tire-pavement interaction noise depends mainly on the surface macrotexture, it provides the opportunity to play with the pavement surface mixes and/or surface textures to reduce the noise. Examples presented here also showed that techniques are available to reduce the noise without sacrificing the safety and durability. However, careful selection and construction is the key to achieve beneficial noise reduction by the pavement itself.

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