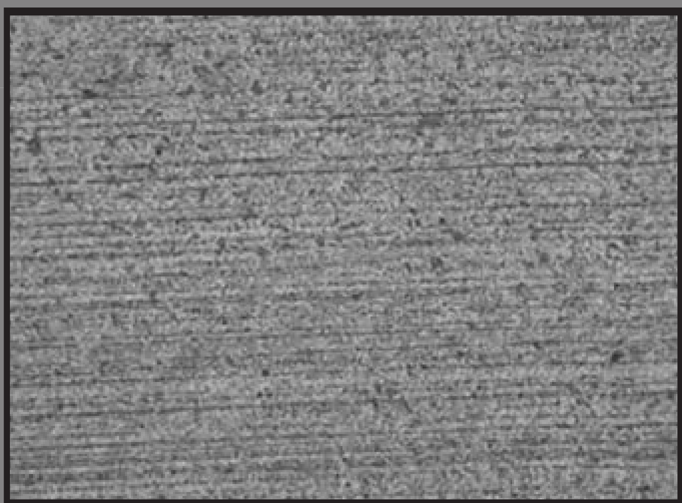
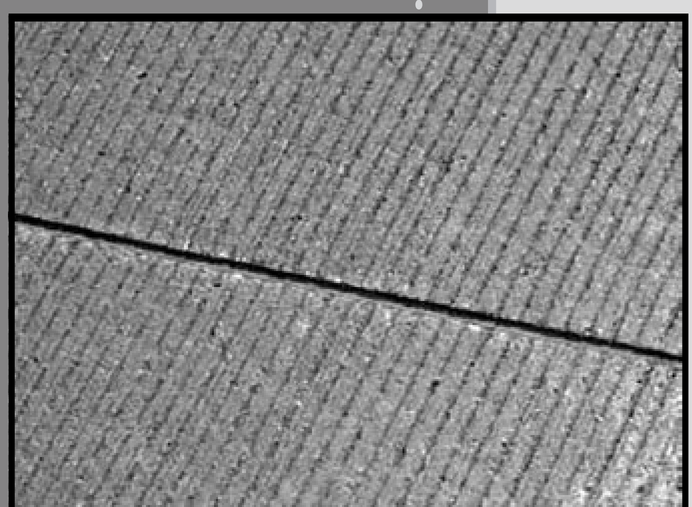
ENGINEERING BULLETIN

Pavement Surface Characteristics:
A Synthesis and Guide





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AMERICAN CONCRETE PAVEMENT ASSOCIATION

Pavement Surface Characteristics – A Synthesis and Guide

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ABSTRACT: This report presents an overview of the major aspects of tire-pavement interaction as they relate to highway noise, safety and economics. The many sources of sound in the highway environment are described and the perception and measurement of noise are discussed. The measurement of roadway friction and the impact of pavement texture on highway safety are described. Techniques for controlling sound from the highway environment are also discussed, including the use of noise walls and barriers and the management of pavement surface characteristics. The noise, safety characteristics and cost-effectiveness of traditional and newer concrete pavement materials and surface textures, including turf drag, longitudinal tining, exposed aggregate, porous concrete, diamond grinding and others, are described and documented through summaries of studies from around the world. Techniques for balancing noise, safety, economics and other factors in the selection of pavement surface type and texture are also reviewed.

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Foreword

This publication is for anyone concerned about pavement surface characteristics. It is both a synthesis of existing technology and a guide for decision-making.

To compile this resource, the author, Mark Snyder, gathered information from around the world, synthesizing volumes of research reports, field and laboratory studies, statistical data, and other technical information. In presenting this compilation, we offer an *unprecedented depth and breadth* of information about the broad spectrum of pavement surface characteristics, their importance, and how those features relate to one another.

Why are surface characteristics so important? In any discussion about surface characteristics, safety is clearly the most important aspect to road users. But emerging issues are also linked to surface characteristics, with examples being tire-pavement noise, vehicle wear, ride quality, fuel efficiency, and more.

In the past, pavement engineers focused mainly on imparting skid resistance to concrete pavements, so texturing for safety became the single focal point. Among the host of other related issues that have come to the forefront, tire-pavement noise is currently a primary consideration for many agencies. Few would argue, however, that it should be the defining issue for specifying a quality pavement system, particularly when issues such as safety, cost and structural durability must always be considered.

A new age of concrete pavement surface characteristics is dawning. It will be marked by a paradigm shift away from single issues and toward optimizing pavement surfaces, which is to say *striking the right balance of desired properties*.

This revolution will require a commitment to achieving better texturing consistency during construction, which, in turn, must be backed by education and training. That means more than just relegating the responsibility to a machine operator and an inspector; it means involving everyone whose decisions or actions affect the pavement surface. We envision that this revolution in surface texturing also will require automated equipment and better process controls to reduce texturing variability.

"Pavement Surface Characteristics: A Synthesis and Guide" is not the *final* word in the evolution of pavement surface characteristics. It is a comprehensive resource that represents the best "point-in-time" information available and presents the concrete pavement industry's perspectives on the rapidly changing technology.

Gerald F. Voigt, PE
President & CEO
American Concrete Pavement Association

Chapter 1. Introduction

Traffic noise levels are a growing concern to residents worldwide, particularly in urban areas where there are higher population densities near major roads which, in turn, carry greater volumes of traffic.[1] High traffic volumes can result in unacceptably high sound levels for people outside the vehicles, as well as for those within.

Many sources of sound contribute to the overall level of sound that is generated in the highway environment, including:

- pure vehicle sources (e.g., mechanical sounds from the engine, drive train and exhaust, as well as onboard equipment, such as refrigeration units in heavy trucks);
- aerodynamic effects, such as those that result from the passage of air around the vehicle and through the vehicle (e.g., into radiator and engine air intakes); and
- the interaction of vehicle tires and the pavement over which they travel.

The noise produced by tire-pavement interaction is generally the largest individual source at vehicle speeds of more than 20 mph for cars, and more than 30 mph for trucks.

Many factors are involved in tire-pavement interaction and the resulting generation of sound, including tire design, size, condition and loading, vehicle speed and pavement texture. If all other factors are held constant, traffic noise levels will vary mainly with the different physical characteristics of the pavement surface, such as porosity or texture, and not the pavement material, such as concrete or asphalt. In other words, pavements constructed using different materials but with identical surface characteristics will generate nearly identical sounds when subjected to identical traffic streams. No paving material is inherently superior when it comes to reducing tire-pavement interaction noise.

PERCEIVING THE PROBLEM

Outside of the vehicles, overall sound levels depend upon the distances to the sources, the presence of blocking barriers and reflecting surfaces, environmental conditions (e.g., wind direction and speed, temperature, etc.) and many other factors. Inside any given vehicle, overall sound levels depend upon the frequencies and levels of sound generated by the different sources and the ability of the vehicle to filter, block or "cancel" those sounds (through insulation, suspension characteristics, etc.).

Measured sound levels, both inside and outside of a vehicle, vary with the measurement approach (including the equipment used, the distance to the source, analysis techniques and other factors). Furthermore, sound measurements do not reflect everyone's perceptions of noise because people have differing sensitivities to the same pitches and intensities of sound. Traffic noise that is very irritating to some people might not bother others at all. Furthermore, an environment with an overall lower level of sound might be perceived to be louder or more irritating if it contains certain frequencies of sound that are missing from an environment with a higher overall level of sound. Therefore, it's not enough to simply compare total levels of sound to determine the "less noisy" of two pavement textures; frequency content and other factors must also be considered.

It is clear that the problems of general highway traffic noise, tire-pavement interaction noise, noise measurement and user perceptions of noise are extremely complex.

THE NEED FOR NEW PAVEMENT NOISE SOLUTIONS

Historically, the most common approaches to highway noise mitigation have involved the use of noise walls and berms to block or deflect sound from nearby receptors. More recently, special asphalt concrete overlays have also been used to reduce the generation of noise at the source. These approaches are often expensive (either initially, as in the case of noise walls, berms and certain types of overlay materials, or in the long term due to increased maintenance costs, as is the case with some asphalt concrete overlays). They may also provide only limited or temporary relief for nearby residents (and little or no relief for drivers, in the cases of noise walls and berms). The bottom line is that noise walls, berms and asphalt overlays are often not the most cost-effective solutions to the problem of highway noise.

Of much greater concern is the potential for decreased travel safety that often accompanies changes in asphalt pavement surface texture and profile over time. It is clear that new solutions are needed for the problem of pavement noise.

PAVEMENT SURFACE TEXTURE ALSO AFFECTS SAFETY

Pavement texture plays an important role in roadway safety issues. There are more than 1 million deaths and 50 million injuries annually on highways and roads all over the world, with more than 40,000 deaths and 3 million injuries annually in the U.S. alone.[2] Research indicates that about 14 percent of all crashes occur in wet weather, and that 70 percent of these crashes are preventable.[3]

Two primary causes of wet weather crashes are 1) uncontrolled skidding due to inadequate surface friction in the presence of water (hydroplaning), and 2) poor visibility due to splash and spray. Pavement surface texture characteristics play an important role in both of these safety-related phenomena. Inadequate friction contributes to many accidents in dry weather as well, especially in work zones and intersections, where unusual traffic movements and braking action are common.

It follows that good surface texture can prevent many of these accidents, thereby reducing the numbers of deaths and serious injuries. Pavement engineers must select surface textures that reduce the potential for hydroplaning at higher speeds while providing sufficient surface drainage so that splash and spray are minimized.[4]

NOISE AND SAFETY MUST BE CONSIDERED TOGETHER

While many types of surface texture are effective at reducing noise-related problems, pavement engineers must recognize the effects of those textures on pavement friction and safety. FHWA recommends that neither safety nor durability be sacrificed for the sake of reducing noise that may be neither significant nor persistent. Specifically, both FHWA guidelines and the 1993 AASHTO Guide on the Evaluation and Abatement of Traffic Noise recommend that the designer should never jeopardize safety to obtain a reduction in noise.[4] The latest FHWA technical advisory states that "tire/surface noise should be considered when specifying pavement and bridge surfaces" but that "safety considerations are paramount".[5]

CONCRETE SOLUTIONS

Research and experience have resulted in the development of guidelines and techniques for minimizing the tire-pavement noise associated with traditional concrete pavement surface textures (i.e., tined and drag-textured pavements). Surface texture modification (e.g., diamond grinding) is an effective solution for significantly reducing concrete pavement-tire interaction noise for existing pavements. In addition, new pavement types and surfaces (e.g., porous concrete and exposed aggregate surfaces) and other innovations are being developed to reduce the noise generated at the tire-pavement interface while providing safe and durable travel surfaces.[6] Although these "silent roads" (as they are sometimes called) often have higher initial construction costs than conventional pavements, their use can sometimes reduce or eliminate the need for (and cost of) noise barriers and negate the need for (and cost of) periodic overlays.[7] These and other newer concrete pavement options are discussed in more detail later in this document.

THE PAVEMENT ENGINEER'S CHALLENGE

The selection of the best pavement type and surface texture for a given location is a complex problem that requires consideration of several factors that are often competing, including noise, safety, durability and cost considerations. When concrete is selected as the material of choice, the challenge to the pavement engineer is to design, specify, and construct a durable concrete pavement system that balances noise considerations with the need for adequate surface friction and splash/spray characteristics (safety), surface texture (and overall) durability for long-term noise mitigation, safety, and good life-cycle costs. This report describes techniques for rationally making pavement type and surface selections in consideration of these factors.

Chapter 2. Characterizing Pavement Texture

DEFINITIONS OF SURFACE TEXTURE

Pavement surface texture influences many aspects of tire-pavement interaction, including wet-weather friction, tire-pavement noise, splash and spray, rolling resistance, and tire wear.[8] Overall pavement surface texture includes the contributions of many surface features with different combinations of texture depth (amplitude) and feature length. These features include the contributions of aggregate texture and gradation, pavement finishing techniques, and pavement wear, to name just a few. Different texture characteristics (i.e., combinations of texture depth and wavelength) have different effects on tire-pavement interactions. Therefore, it is important to be able to classify pavement texture in a way that is useful in interpreting the effect of the texture on pavement performance characteristics.

In 1987, the Permanent International Association of Road Congresses (PIARC) proposed the following categories of pavement surface characteristics based on their amplitude (depth) and wavelength: *microtexture, macrotexture, megatexture and unevenness (roughness)*.[9] Each of these categories is described below, and the specific influence of each category on tire-pavement interaction is illustrated in Figure 2.1.

Microtexture

Microtexture is defined as texture having wavelengths of 0.0004 in. to 0.02 in. (1 μm to 0.5 mm) and vertical amplitudes less than 0.008 in. (0.2 mm).[9] In concrete pavements, this very fine texture is typically provided by the fine aggregate (sand) in the mortar.[11]

Good microtexture is usually all that is needed to provide adequate stopping on dry concrete pavements at typical vehicle operational speeds and on wet (but not flooded) concrete pavements when vehicle speeds are less than 50 mph (80 kph). When higher vehicle speeds are expected, good microtexture *and* macrotexture are generally required to provide adequate wet-pavement friction.[4]

Microtexture is not generally considered to be a factor in the development of pavement noise or splash and spray.

Macrotexture

Macrotexture refers to texture having wavelengths of 0.02 in. to 2 in. (0.5 mm to 50 mm) and vertical amplitudes ranging from 0.004 in. to 0.8 in. (0.1 mm to 20 mm).[9] Macrotexture plays a *major* role in the wet weather friction characteristics of pavement surfaces, especially at higher vehicle speeds. Therefore, *pavements that are constructed to accommodate vehicles traveling at speeds of 50 mph (80 kph) or faster require good macrotexture* to help prevent hydroplaning.[4]

In concrete pavements, macrotexture is most commonly produced through small surface channels, grooves, or indentations that are intentionally formed in plastic concrete or cut in hardened concrete to allow water to escape from beneath a vehicle's tires.

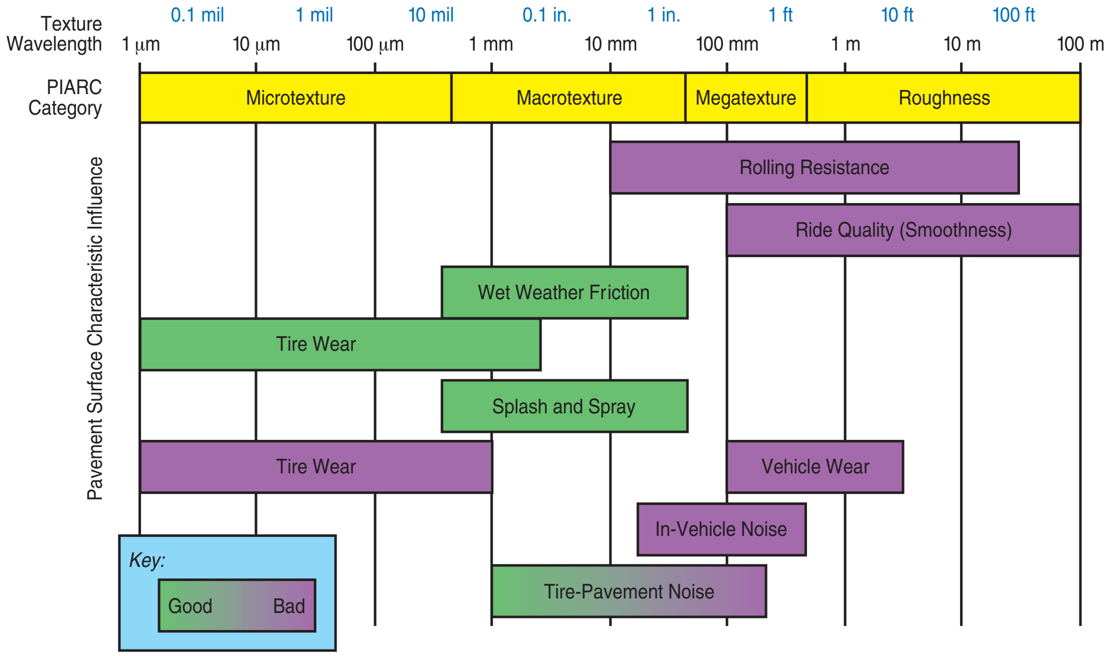


Figure 2.1. Illustration of PIARC pavement surface characteristic classifications and their impact on pavement performance measures.[10]

This allows more flexibility to the engineer to address macrotexture than with asphalt pavement in which macrotexture is a result of asphalt mixture characteristics, such as aggregate grading and liquid asphalt content and bleeding. It is also important to note that the purpose of the grooves or tine channels is for macrotexture and not for draining water from a concrete pavement surface, which is addressed by the pavement cross-slope.

In addition to providing wet weather friction, macrotexture is the pavement surface characteristic that has the strongest impact on tire-pavement noise and splash and spray (see Figure 2.1). The impact of macrotexture on pavement friction and noise (both interior and exterior) is strongly influenced by the type of surface texture selected (e.g., transverse tining, longitudinal tining, turf drag, exposed aggregate, etc.) and its design details (e.g., width, depth and spacing of surface grooves, regularity of spacing, direction of texture, etc.).[12]

Megatexture

Megatexture comprises texture with longitudinal wavelengths of 2 in. to 20 in. (50 mm to 500 mm) and vertical amplitudes ranging between 0.004 in. to 2 in. (0.1 mm to 50 mm).[9] This level of texture is typically the result of poor construction practices, local settlements, or surface deterioration. Megatexture can cause vibration in tire walls, resulting in in-vehicle noise and some external noise. It also adversely affects pavement ride quality and can produce premature wear of the vehicle suspension (i.e., tires, shock absorbers and struts).[12]

Megatexture is rarely measured or considered directly; it is defined primarily to provide a continuum between macrotexture and unevenness (roughness).[12]

Unevenness or Roughness (Smoothness)

Pavement unevenness (roughness) is defined as surface irregularities with wavelengths longer than the upper limit of megatexture (> 20 in. [500 mm]). Wavelengths in this range have an impact on vehicle dynamics, ride quality, and surface drainage.[12] Unevenness is generally attributed to the environment (i.e., temperature and moisture effects) and/or construction practices and load-induced deformations in any pavement layer.[12] Unevenness does not significantly affect tire-pavement noise.

Pavement engineers and contractors generally do not consider unevenness (roughness) to be a traditional component of surface texture, but it is clearly a pavement surface characteristic that influences ride quality and may contribute to user annoyance and perceptions of noise.

MEASUREMENT OF SURFACE TEXTURE

Research shows that pavement surface texture characteristics can strongly affect both vehicle operations and the surrounding environment by impacting both highway safety and ambient sound levels (noise). As a result, much attention has recently been focused on the direct measurement of surface texture characteristics, especially macrotexture, which is the characteristic most strongly associated with many aspects of pavement-tire friction and sound emissions.

There are several different methods for measuring surface texture, but the results of these methods are sometimes difficult to compare directly (although correlations and conversion equations have been developed). Some commonly used measures and measurement methods are described below.

Mean Texture Depth (MTD)

The mean texture depth (MTD) is a measure that is determined using the traditional volumetric method (commonly referred to as the "sand patch test" or ASTM E 965). The volumetric method originally required the use of a special tool to spread a specified volume of specially graded Ottawa silica sand (passing the No. 50 sieve, but retained on the No. 100 sieve) on the pavement in a circular motion (see Figure 2.2). In recent years, the Ottawa silica sand in this test has been replaced with manufactured glass spheres because the glass spheres can be spread more uniformly than the Ottawa sand and because the glass spheres can be produced commercially by many manufacturers. The MTD is calculated by dividing the known volume of sand or spheres by the area of the roughly circular patch computed using the average of four equally spaced diameters.[8,13]

Figure 2.2. Photo of original "sand patch" test using Ottawa silica sand and spreading tool.[14]

Acceptable levels of MTD vary widely among highway agencies and often depend upon expected vehicle speed and other factors. For example, an FHWA Technical Working Group recently recommended that concrete surfaces have an average MTD of at least 0.03 in. (0.8 mm), with a minimum of 0.02 in. (0.5 mm) for any individual test, to achieve adequate surface friction.[4] New Zealand, Quebec and South Australia require intervention when MTD levels fall below values ranging from 0.015 to 0.035 in. (0.4 to 0.9 mm) on higher speed roadways. Great Britain has had a goal of providing an MTD of 0.06 in. (1.5 mm) on their newly constructed concrete pavements.[8]

Mean Profile Depth (MPD)

In the past decade, advances in laser technology and computational power have led to the development of systems that measure pavement longitudinal profile at highway travel speeds. The data from these systems can be used to compute the mean profile depth (MPD).

The MPD is computed by analyzing 4-in. (100-mm) segments of the collected profile data. Each segment is divided in two and the average of the highest profile peaks in each half is computed; the MPD is then computed as the average of all individual segment peak averages. A more detailed description of the MPD computation method is presented in ASTM E-1845.[16]

It is widely believed that the MPD is the best parameter for estimating macrotexture for the prediction of wet pavement friction.[16,17,18]

Profile Measurement Equipment

One specific example of a high-speed laser-based system for measuring pavement macrotexture and determining MPD is the Road Surface Analyzer (ROSAN). The ROSAN system comprises a van equipped with laser sensors mounted on the vehicle's front bumper (see Figure 2.3) and can accurately measure pavement profiles at speeds up to 70 mph (112 kph).[8]

MPD can also be measured using the Circular Texture Meter (CTMeter), a portable device (shown in Figure 2.4) that uses a laser to measure the profile of a circle with a circumference of 35 in. (890 mm).[19] The circular profile is then divided into 8 arc segments of 4.4 in. (110 mm) and the mean profile depth (MPD) of each arc segment is computed according to standard ASTM and ISO practices.[16,18] All eight segment mean depths can be averaged to produce the most accurate estimate of MPD at each test location. The CTMeter can also compute the Root Mean Square (RMS) texture depth of each segment.[20]

Figure 2.3. Photo of Road Surface Analyzer (ROSAN).[30]

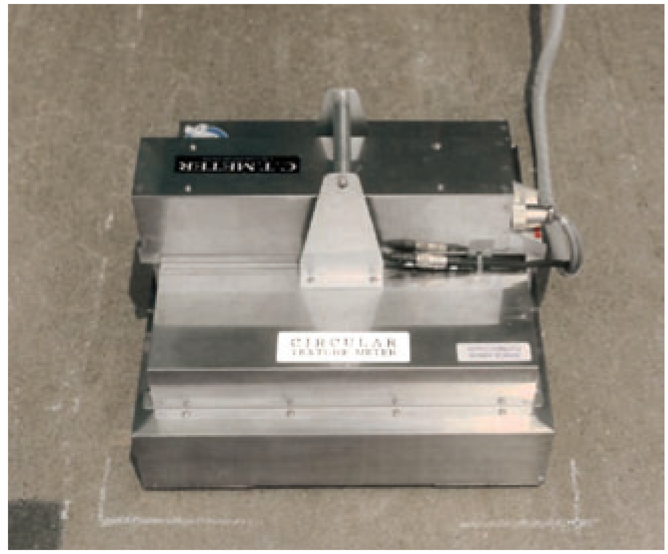


Figure 2.4. Photo of circular texture meter (CTMeter).[21]

Robotic Texture Measurement System

In 2005, an innovative robotic texture measurement system called RoboTex (see Figure 2.5) was developed for a study[166] sponsored by the American Concrete Pavement Association, Iowa State University and the Federal Highway Administration. Built around a line laser sensor and fixed atop a remote-controlled robotic chassis, RoboTex is capable of sampling over 100 points across a 4-in. (100-mm) wide laser line at 1000 Hz as it travels down the road under its own power at approximately 1.6 ft/s (0.5 m/s). The result is a three-dimensional pavement texture measurement with a spatial resolution of about 0.0006 in.^{2} (0.4 mm^2) and a height resolution of 0.39 mil (0.01 mm). The 3D measurement technique inherent with RoboTex identifies the subtleties in texture that lead to the differences in a surface's noise character. This differentiates it from two-dimensional texture profiles that result from using a single-point laser device.

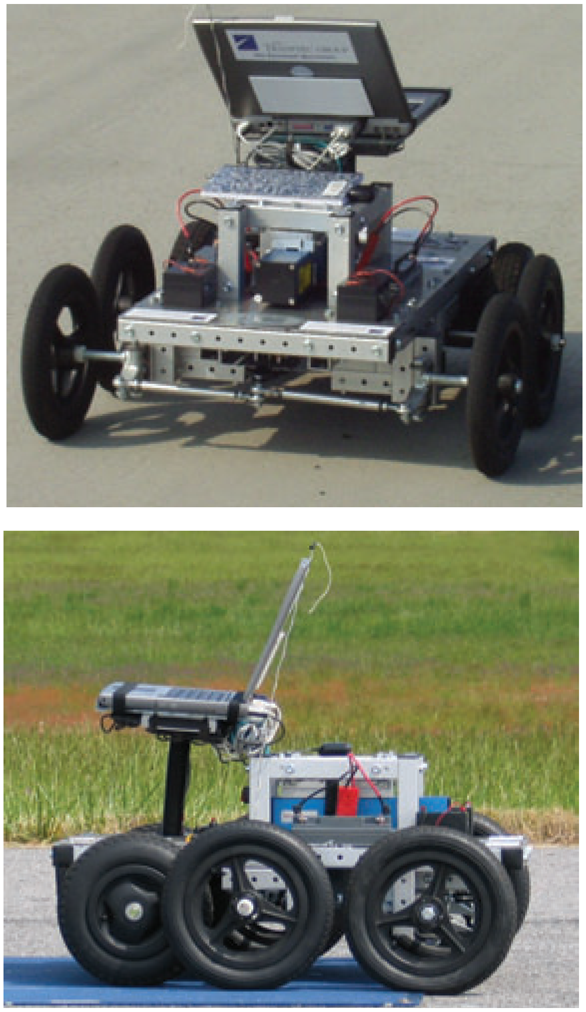


Figure 2.5. Robotic Texture Measurement Device (RoboTex). Photo courtesy of Dr. Robert Otto Rasmussen, P.E., Vice President & Chief Engineer, The Transtec Group, Inc., Austin, TX.[166]

Other Methods of Texture Measurement

Many other methods of texture measurement have been proposed for both general and specific applications and they are described in various publications. For example, ISO 13473-1 describes a method for obtaining a single value that represents macrotexture, and ISO 13473-2 presents several additional techniques (including spectral analysis).[18,23] ISO 13473-3 provides specifications for road surface profilometers that operate in the macro- and megatexture ranges.[24]

A comprehensive state-of-the-art report on road surface texture, including measurement methods and equipment, was prepared by Sandberg in 1997.[25]

Chapter 3. Fundamentals of Roadway Noise and Pavement Texture

DEFINITIONS OF NOISE AND SOUND

What is Sound?

To understand sound and noise requires an understanding of both the physics of sound and how humans respond to it.

Sound is acoustic energy that results from variations in air pressure and density that travel through air in longitudinal waves that radiate from sources at a speed of about 770 mph or 1100 ft/s (340 m/s) – the speed of sound. Our ears react to the strength (amplitude) of these waves, as well as to the speed of their variation (frequency), and translate those characteristics into sound volume and pitch, respectively.

The variations of air pressure above and below normal ambient atmospheric pressure are expressed in units of Newtons/m^2 or Pascals (Pa). Typical human hearing is sensitive over a very wide range of pressures: from 20μPa (20 x 10^{-6} Pa) to approximately 20 Pa. Sound *power* (intensity) is proportional to the square of the sound pressure, so the working range of the human ear is from about 10^{-12} to 1 watts/m^2 – a range of 12 orders of magnitude – without risking serious hearing damage and pain. Figure 3.1 presents a table of sound intensity levels for typical sound sources.

Since sound pressure and power *values* occur over ranges covering many orders of magnitude, it is often impractical to work directly with these numbers in a way that conveys the significances of differences between typical values. For example, if a linear scale is used to measure all of the sounds that can be heard by the human ear and if that scale ranges from 0 to 1, most sounds that we hear in daily life would be recorded on that scale between 0.00 and 0.01. It would be difficult to discriminate between sounds in our daily life using this linear scale.

To overcome this problem, sound pressure *level* is computed as a function of sound pressure using a logarithmic scale:

$$SPL = 10 * \log (p/p_{ref})^2 \qquad \text{(Eq. 3.1)}$$

where:

SPL = sound pressure level, in decibels (dB),

p = sound pressure in Pascals, and

p_{ref} = reference sound pressure = 20 x 10^{-6} Pa (the threshold of human hearing).

The resulting scale, which is also illustrated in Figure 3.1, has a lower limit of 0 (the threshold of human hearing) and is theoretically open-ended at the top, although most people are not commonly exposed to sound levels in excess 100 dB. This scale has the convenient property that an increase or decrease in SPL of 10 dB is *perceived* by humans as a doubling or halving (respectively) of loudness. It also has the property that 1 dB is smallest difference in pure tone (i.e., single frequency) SPL that human hearing can distinguish under *ideal* circumstances.[1] Under less-than-ideal circumstances, it is

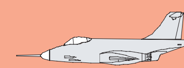
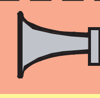
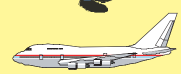
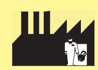
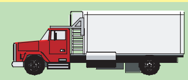
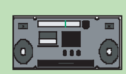
Effects	Sound intensity ratio: (rel. hearing threshold)	A-weighted SPL in dB:		Typical sound source at this level
Serious hearing damage	100 000 000 000 000	**140**		Space rocket launch, in vicinity of launch pad
Hearing damage and pain	10 000 000 000 000	**130**		Jet engine (25 m distance)
				THRESHOLD OF PAIN
Hearing damage after short exposure	1 000 000 000 000	**120**		Air-raid alarm (5 m distance)
Serious hearing damage hazard	100 000 000 000	**110**		Rock music concert, close to stage
Hearing hazard	10 000 000 000	**100**		Jet plane take-off (300 m)
Some hearing hazard	1 000 000 000	**90**		Noisy industrial hall
Health effects	100 000 000	**80**		Heavy truck, 70 km/h (10 m distance)
Some health effects Severe annoyance	10 000 000	**70**		Car, 60 km/h (10 m distance)
Annoyance	1 000 000	**60**		Normal conversation (1 m distance)
Some annoyance	100 000	**50**		Quiet conversation (1 m distance)
Good environment	10 000	**40**		Subdued radio music
	1 000	**30**		Whispering (1 m distance)
	100	**20**		Quiet bedroom
	10	**10**		Rustling leaves
Uncomfortably "quiet"	(reference)	**0**		Anechoic room for sound measurements
				HEARING THRESHOLD

Figure 3.1. Illustration of typical sound levels (dB) and sound intensity ratios for common sounds (from Sandberg and Ejsmont, 2002 (Ref. 1); used with permission).

generally accepted that 3 dB is the smallest difference that most people can distinguish.

Addition of Sound Sources

There are generally many sources of sound in any given environment, especially in the highway environment. When it is desirable to add the effects of sound from two or more independent sources (such as multiple tires or vehicles) to determine an overall sound level, it is first necessary to convert the contributing levels back to their corresponding measures of sound power, add them, and then convert the combined power value back to the logarithmic measure of sound level. This can be done using equation 3.2:

$$dB_t = 10 * \log\left[10^{\frac{\{dB_1\}}{10}} + 10^{\frac{\{dB_2\}}{10}} + n + 10^{\frac{\{dB_n\}}{10}}\right] \quad \text{Eq. 3.2}$$

where:

dB_t = the total noise level, and

dB_1, dB_2, and dB_n = the noise levels of individual sources 1, 2 and n, respectively.[26]

Using this equation, it can be seen, for example, that the combined effect of two independent sounds of 65 dB each will result in an overall sound level of 68 dB (rather than a simple sum of 130 dB), as shown in Figure 3.2.

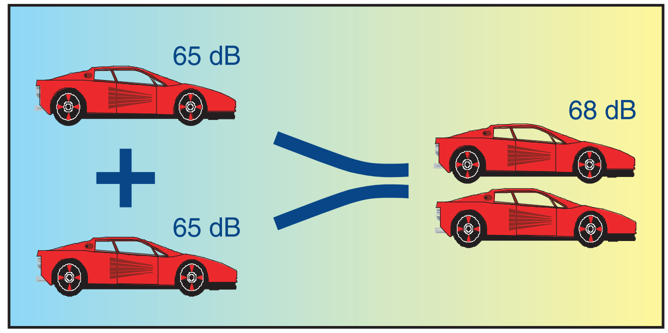


Figure 3.2. Illustration of the result of adding sound from independent sources (from Sandberg and Ejsmont, 2002 (Ref. 1); used with permission.

Considered another way, one practical implication of this relationship is that a doubling of the traffic flow on a given highway facility (holding traffic composition constant) will result in an increase in sound level of about 3 dB (see Figure 3.3), which is near the limit of human ability to perceive the difference under typical conditions.

The discussion above applies strictly to the addition of "pure tone" sounds rather than "broadband" sounds containing a range of frequencies, because different frequencies are perceived to have different intensities, as is discussed in the next section. The *general* principles described above do apply to broadband sounds, however.

Figure 3.3 Doubling traffic flow (with constant composition) increases sound by about 3 dB.

Human Perception of Sound and the "A-weighting" Filter

Human hearing is not equally sensitive to sound of all frequencies. A person with good hearing can typically hear sounds in the frequency range 20 Hz to 20 kHz. Our hearing is typically most sensitive to the frequency range 2 kHz to 5 kHz and is especially insensitive to low frequency sound. It can be said that human hearing includes a physiological filter that weights sounds according to their frequency. This weighting also depends upon the sound pressure, so the filter is highly nonlinear.

These facts are illustrated in Figure 3.4, which presents the "equal loudness contours" of ISO 226, which are based on research concerning the human perception of sound.[27] Note, for example, that a 1000 Hz sound at a sound pressure level of 80 dB is perceived as 80 dB, while a 20 Hz sound at the same 80 dB sound pressure level is perceived as less than 20 dB. It takes an actual sound pressure level of more than 110 dB for that 20 Hz sound to be perceived at the 80 dB level.

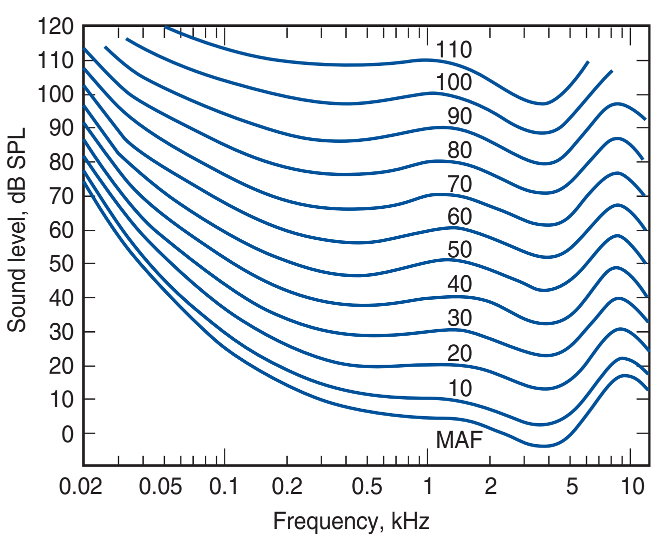


Figure 3.4 Normal equal-loudness contours for pure tones.[28]

Measures of sound and studies of its impact on humans must reflect this relationship. Thus, sound pressure signals are often filtered and/or weighted to produce values that imitate human hearing. Many weighting filters have been developed for this purpose, and the one that is generally considered to correspond best to the human perception of sounds is called the "A" filter. The "A" filter, which is shown in Figure 3.5 with two less commonly used filters, can be seen to be similar to the inverse of the equal loudness contours presented in Figure 3.4. When a sound pressure level is processed through the "A" filter, it is called an "A-weighted sound pressure level" and is expressed in units of dB(A) or dBA. Most studies of highway traffic-related sound are conducted using A-weighted sound pressure levels. The dBA filter accurately represents frequency sensitivities for people with good hearing.

What is Noise?

Noise is simply unwanted or unpleasant *sound*. Sound doesn't become noise until it is perceived by someone (or something) that is disturbed by it. Thus, the term "noise" is a subjective assessment of a sound that can be defined and quantified objectively, as described previously.[1]

Using these definitions, it is interesting to note that traffic generates only sound – no noise or unwanted sound – in areas where humans (and other creatures) are not affected. And it is possible that there are a few people in populated areas who actually *like* the sound of traffic and tire-pavement interaction; these people would hear sound but would not consider it to be noise. However, most people prefer to not hear highway-related sounds at *any* significant level and consider them to be "noise" in almost any setting. For this reason, highway-related sounds are generally referred to as "noise" throughout this synthesis. Nevertheless, it is important to remember the fundamental difference between noise and sound.

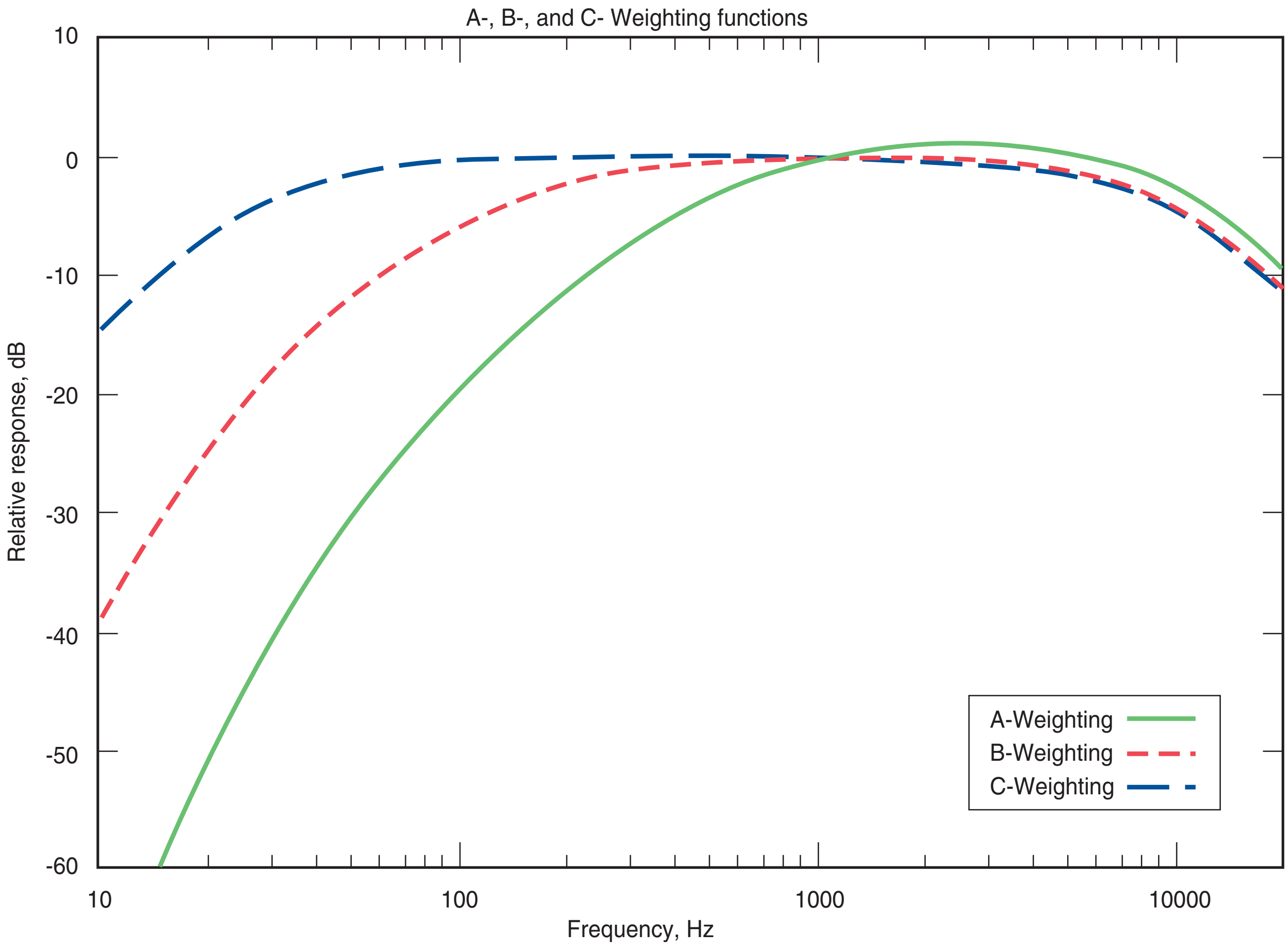


Figure 3.5. Different standardized frequency weighting curves used for sound measurements.[27]

Frequency Sensitivity and Other "Psycho-acoustic" Parameters

Sound levels are often presented in terms of A-weighted decibels or *dBA*. A-weighted sound is the sound intensity level that results when different sound frequencies are weighted (using the filter shown in Figure 3.5) to mimic human response to sound.[12] The use of dBA does not capture *all* of the subtle annoyances that some sounds can produce, but it is a better measure of typical human perceptions of sound than pure decibel measures. Factors such as the *sharpness, roughness,* and *tonality* of sound are not necessarily captured by A-weighted decibels; these and other measures of sound are available to address broader ranges of psychoacoustic (human response to sound) parameters.[29]

Of these additional factors, tonality (the frequency component of sound) is probably the most important in highway noise studies. A sound that has only one frequency is called a "pure tone." Outside of music, this is rarely encountered. Most highway and industrial noise consists of a broad band of frequencies, but may have particularly intense levels of sound at particular frequencies.

An example of tonality is shown in Figure 3.6, which presents a typical frequency distribution for sound recorded near a highway pavement. This figure shows a broad and relatively uniform distribution of frequencies produced on the subject pavement except in the region near 1000 Hz, where there is a very pronounced increase in sound pressure level (a peak in sound intensity). This peak will tend to

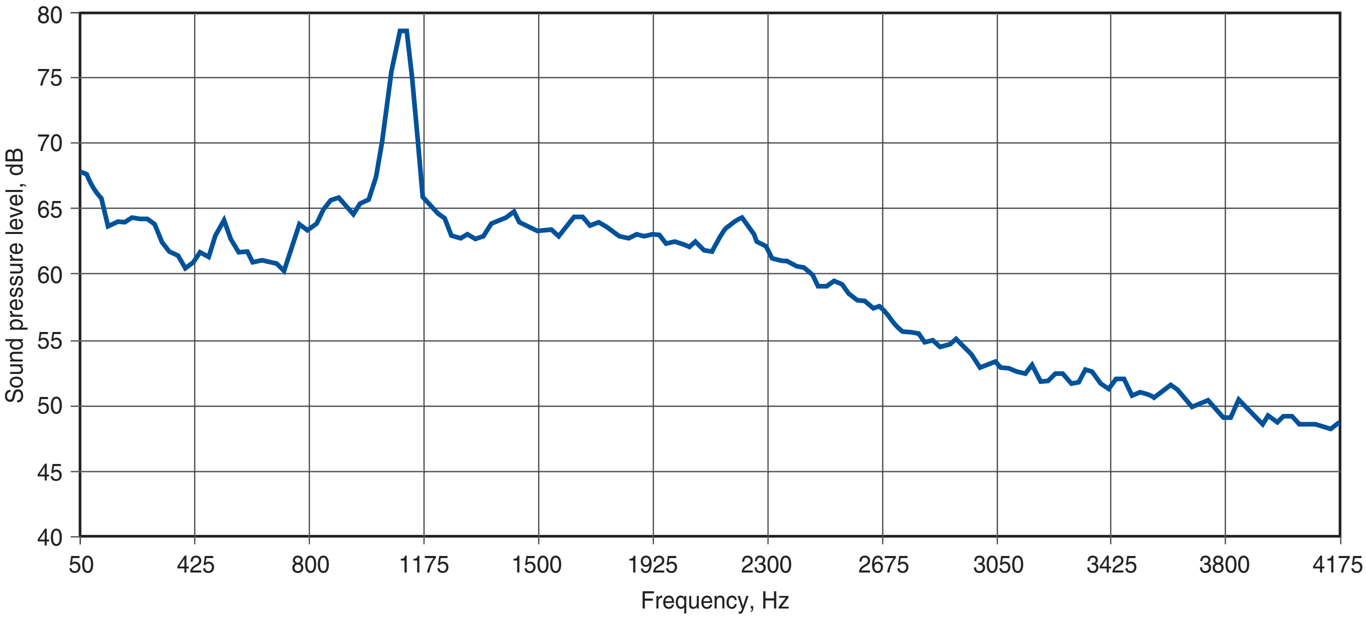


Figure 3.6. Frequency distribution for sound recorded near a typical transversely tined concrete pavement in Wisconsin (after Ref. 30).

dominate the rest of the sound spectrum, and listeners will be more aware of (and perhaps irritated by) this particular tone.

In this particular case, much of the sound at the 1000 Hz frequency is probably caused by the interaction of vehicle tires with a particular transverse texture pattern of the pavement surface. However, recent research suggests that many additional factors contribute to peaks near 1000 Hz, including the geometry of the road surface texture, several tire design parameters, and the fact that the A-weighting scale fully weights sounds near this frequency while de-emphasizing sounds significantly above or below this frequency.[27]

It can also be shown that some loud sounds (such as cheering at a nearby sporting event) might not be considered noise by some listeners, even though they are actually louder than other sounds that are considered to be irritating (such as roadway noises). These examples help to illustrate some of the many "psychoacoustic" factors that influence the ways that different people perceive different types of sounds.

For more information on the fundamental concepts and definitions used in the field of acoustics, References 32 and 33 are highly recommended. References 34 and 35 contain definitions of internationally agreed-upon terminology in the fields of acoustics and noise.[1]

WHAT CAUSES ROADWAY NOISE?

Noise emitted from vehicles and their interaction with pavements can be attributed to several source categories, including tire-pavement, engine, intake system, exhaust system, powertrain and other sources (including air turbulence). Figure 3.7 provides a graphical representation of typical levels of sound produced by each of these source categories in a standard drive-by test. Note that the noise contribution of each of these 6 categories ranges from about 64 to 70 dB(A), but that the combined effect of all sources is no more than 74 dB(A). The relative contributions of each of these categories to overall noise (as a percentage of total sound level) *for this example* are shown in Figure 3.8 (studies using other vehicles and mixed traffic produce different distributions).

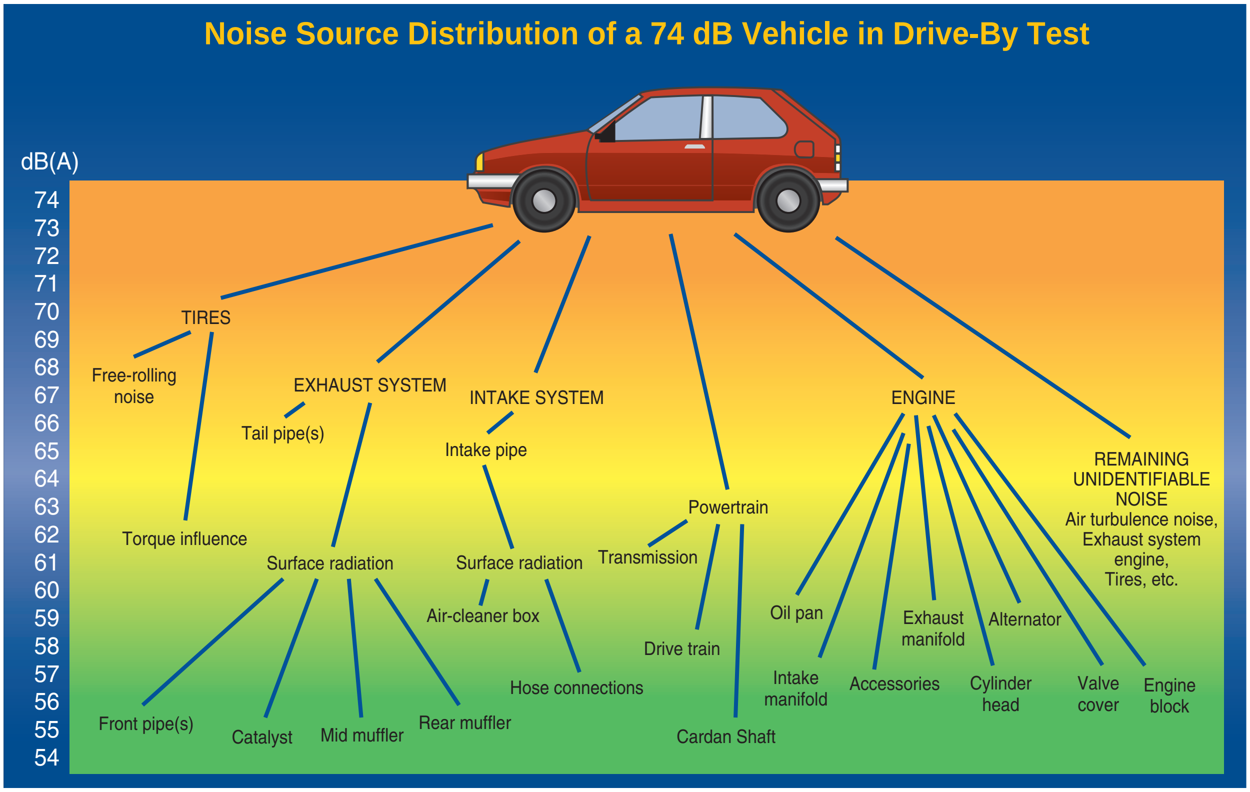


Figure 3.7. Typical noise source distribution for a passenger car meeting European 74 dB(A) limitations during an ISO 362 drive-by test (from Sandberg and Ejsmont, 2002 (Refs. 1 and 36); used with permission).

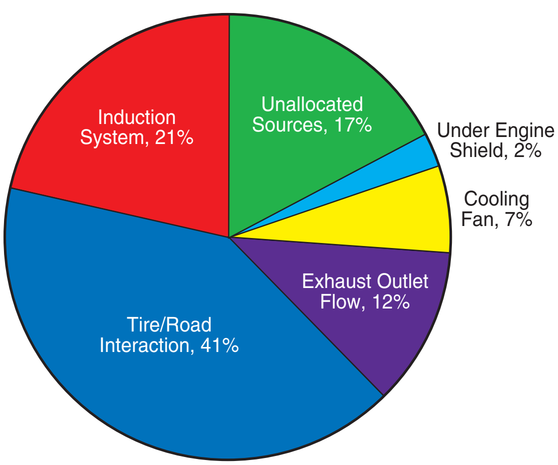


Figure 3.8. Typical source contributions to overall noise levels for American cars meeting European noise requirements in 1996 and tested using ISO 362 (from Sandberg and Ejsmont, 2002 (Ref. 1); used with permission).

Tire-road noise is a major contributor to overall sound levels (although it is a significantly smaller contributor than the combined contribution of other sources) in this particular test. Motor and exhaust noise generally control total noise levels for vehicles at speeds below about 55 km/hr (35 mph) while tire-pavement interaction becomes the principal source of pavement noise at greater speeds.[11] Thus, the relative contributions of each sound source varies with vehicle speed (among other factors), as shown in Figure 3.9.

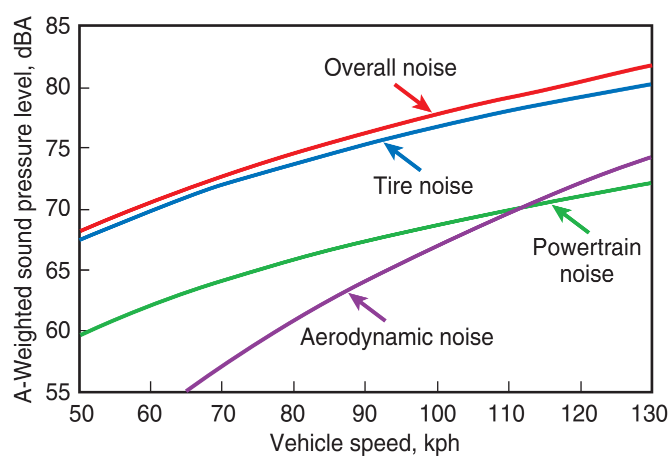


Figure 3.9. Contributions of various sources to overall traffic noise levels as a function of vehicle speed.[2]

Pure Vehicle Sources

Engine and Exhaust Noise

Figure 3.7 shows that engine and exhaust noise are generally second only to tire-pavement interaction in contributing to sound levels outside of the vehicle at higher operating speeds, and they are sometimes the primary sources of sound at lower operating speeds (particularly for heavy vehicles). Furthermore, engine/exhaust braking systems on heavy vehicles can produce sound levels that overwhelm all other contributing sources.

Transmission (Axle) Noise

Sound levels obtained from pass-by measurements are generally assumed to represent mainly tire-road noise (and possibly aerodynamic noise at higher vehicle speeds). However, various parts of the transmission rotate and produce sound even when the clutch is disengaged, and these sounds can be significant (especially for busses and heavier vehicles). Therefore, when measuring tire-road noise, part of the measured sound is sometimes from the transmission. Axle noise emissions come from mechanical action, as well as from structural resonance, and are significantly higher under engine loading conditions. Measurement techniques that do not involve cruise or acceleration conditions may fail to reflect the effects of axle noise and may underestimate overall levels of vehicle-pavement noise.

An extensive bibliography on transmission noise is available in Reference 38.

Other Pure Vehicle Sources

Other vehicular sources of sound, as described in Figures 3.7 and 3.8, are typically relatively minor (although sometimes significant) when compared with engine, exhaust, powertrain sounds and the interaction sources described in the next section.

Vehicle Interaction Sources

Aerodynamic Effects

While the aerodynamics of highway vehicles has improved dramatically over the last few decades, so-called “wind noise” can still be significant for vehicles running at high speeds. There are many potential locations for air turbulence and separation/reattachment in most vehicles, and open windows, sun roofs and joints between doors and body panels can generate resonances. Other features, such as external antennae, hood ornaments and side mirrors, can support vortex shedding, causing whistles and other pure tones. The problem of aerodynamic effects is further complicated by the fact that it is often difficult to distinguish wind noise from tire-road noise in pass-by measurements.

Sandberg and Ejsmont suggest that aerodynamic noise effects should be considered a potential contributor to measures of tire-road noise when passenger car speeds exceed 70 mph and heavy vehicle speeds exceed 45 – 60 mph (depending upon the specific vehicle).[1]

Tire-Pavement Interaction

Many factors influence the generation of tire-pavement noise. A brief summary of the major factors and their relative influences is presented in Table 3.1.[1]

This table gives a general idea of the major influences that affect tire-pavement noise, but there are many parameters that affect each of these major factors. For example, the combined effects of many different tire characteristics (e.g., tread pattern, tire geometry, rubber hardness, etc.) are included in the larger factor of “car tire type/design.” Similarly, several pavement surface characteristics (e.g., texture depth, orientation and acoustic absorption) are included in the broader category of “road surface type.” Each of these major and contributing factors are discussed in detail in Chapters 8 through 10 of Reference 1 and are summarized briefly in the following sections.

Table 3.1. Major Factors Influencing Tire-Pavement Noise Generation (after Ref. 1)

Factor	Relative influence range (dBA)
Vehicle/tire speed	25 dB (20-80 mph [30-130 km/hr])
Road surface type (conventional)	9 dB
Road surface type (including "extreme" surfaces)	17 dB
Car tire type/design (conventional)	8 dB (same width tires)
Car tire type/design (conventional)	10 dB (including width effects)
Studs in car tire (compared to no studs)	8 dB (for new studs)
Truck tire type/design (conventional)	10 dB (for same size tires)
Tire load and inflation pressure	5 dB (± 25%)
Road condition (wet vs. dry)	5 dB (heavy rain)
Temperature	4dB (32 – 104°F [0 – 40°C])
Torque/acceleration on wheel	3 dB (0 – 10 ft/s^2 [0 – 3 m/s^2])

Sound Generation Mechanisms

There are several mechanisms in the interaction of tires and pavements that generate sound. The four most-commonly mentioned sound generators are shown in Figure 3.10 and are described below:[39]

- Impact of the tire tread block against the pavement texture, which induces radial vibrations of the tread block and tire carcass. These vibrations can produce sound over a wide range of frequencies.
- Adhesion (and release) between the tread block and the pavement surface (sometimes referred to as "stick-snap"), which also causes tire tread block and carcass vibration. The magnitude of this source depends largely on the amount of adhesive force between the tread block and the pavement surface, which is, in turn, largely dependent upon the properties of the rubber compounds used in the tire tread.
- Tangential slippage of the tread blocks (a mechanism similar to that of a squeaky sneaker on a tennis court and sometimes referred to as "slip-stick"), which can cause high-frequency squeaks and squeals.
- Pumping of air through the tire treads and pavement texture, which can produce high-frequency sounds. This mechanism depends upon the tire tread pattern and the pavement texture and porosity.

There are also several mechanisms through which the tire-pavement sounds generated above are amplified and directed, including:[39]

- "The horn:" The tire and pavement can be envisioned as a horn or megaphone shape that directs sounds outward from the tire-pavement contact patch (see Figure 3.11). This is a fairly significant effect, particularly for high-frequency sounds, and is dependent on the width of the tire and the acoustical properties of the pavement. The "horn" mechanism is particularly sen-

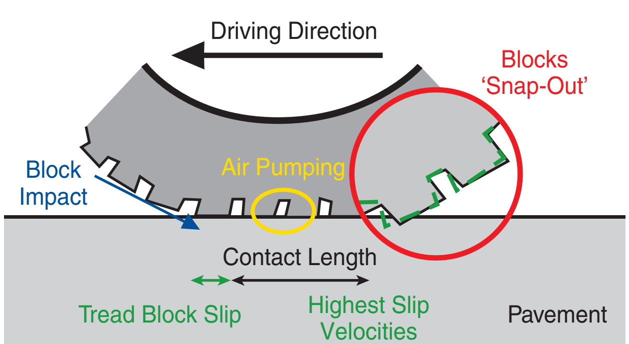


Figure 3.10. Overview of tire-pavement noise generation mechanisms.[39]

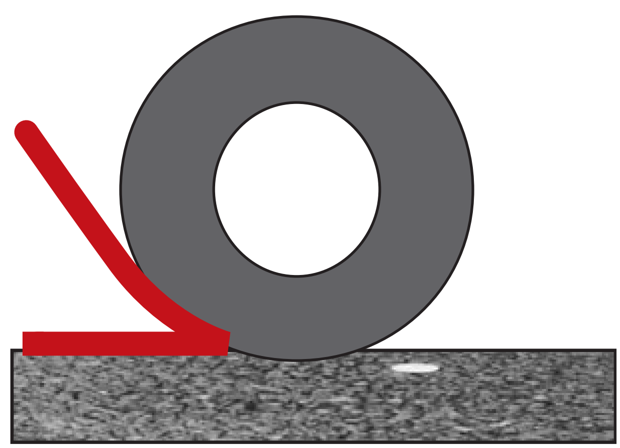


Figure 3.11. Illustration of tire-pavement "horn" amplification effect.[163]

sitive to pavement surface type, as roughened or porous surfaces tend to disperse or absorb the sound being projected from the interface.[1]

- "The pop bottle:" This is the amplification of sound near the front and back of the contact patch due to air resonance in the tread passages as they open and close. This mechanism of amplification has been compared to blowing air across the top of a pop bottle; it is most significant for high frequency sounds.
- "The pipe organ:" Channels in the tire footprint can act like organ pipes, amplifying the sound and causing it to radiate out from the channel. This effect mostly amplifies mid-range frequencies.
- "The speaker:" Vibrations of the tire sidewalls can amplify tire carcass sounds in the same way that a speaker cone does and radiates that sound towards the sides of the road. The magnitude of this effect varies with tire construction and sizes.
- "The balloon:" Amplification can take place through cavity resonance in the tire, which amplifies sounds similar to the way that a balloon does when it is struck or thumped. The result is a very lightly damped resonance at low frequencies and can be very noticeable both inside and outside the vehicle.

The pitch and magnitude of sound produced by tire-pavement interaction depends strongly on factors such as the pavement surface characteristics, the tire design (geometrics, structure and tread design), tire load and internal pressure, and vehicle speed and acceleration.

Pavement Surface Characteristics

As illustrated in Figure 2.1, pavement texture is commonly classified by its dimensions, and includes megatexture, macrotexture and microtexture.[14,40] Objectionable tire-pavement noise is caused mainly by the higher wavelengths of macrotexture and by megatexture.[8] Smoothness (sometimes described as roughness or evenness) is technically its own classification of texture, with long wavelengths of 20 in. (500 mm) or more.

Megatexture is defined by wavelength values ranging from 2 to 20 in. (50 to 500 mm). Texture depth (amplitude) in this range is typically between 0.004 and 2 in. (0.1 and 50 mm).[14,41] Variations in texture at this level usually result from poor construction practice, surface deterioration, or local settlements.

Macrotexture is an important category of texture with wavelength values falling between 0.02 and 2.0 in. (0.5 and 50 mm) and texture depths typically ranging between 0.004 and 0.8 in. (0.1 and 20 mm).[14,41] Most aggregates used in concrete pavements also fall within this size range. Macrotexture can be produced by grooving, indenting, or otherwise forming small surface channels in the pavement surface. Macrotexture is important because it is a primary contributor to pavement noise and it is also a key to many other pavement surface characteristics, including friction and splash/spray. Average depths of macrotexture are currently measured most commonly through the use of high-resolution lasers (ISO 13473, ASTM E-1845) or by using the sand patch method (ISO 10844, ASTM E-965), as described previously.[13,18,42,43] Since macrotexture influences both tire-pavement noise and safety issues, pavement design engineers must consider both factors in the final selection of a surface texture.

The importance of macrotexture on tire-pavement noise is demonstrated by the recent development of equations that accurately predict the level of noise on pavement surfaces as a function of pavement type, aggregate type and macrotexture characteristics. These equations are accurate to ± 2 dB(A) 90 percent of the time and ± 1 dB(A) 60 percent of the time.[44]

Microtexture consists of the irregularities not readily visible to the naked eye. This includes texture from fine sands and the surface roughness of the aggregate particles themselves. Wavelengths in this category are less than 0.02 in. (0.5 mm), and depths are typically less than 0.008 in. (0.2 mm).[14,41] Texture at this level does not directly contribute to tire-pavement noise, but can have a significant influence on other surface characteristics, such as pavement friction.

While various properties of the pavement surface layer (e.g., stiffness and porosity) have been found to be important in the generation and propagation of tire-pavement noise, the distribution of the various texture wavelengths often dominates, and aggregate particle size distribution is often very important in establishing macrotexture and microtexture wavelengths.

It has been found for some pavement types that tire-pavement noise increases as the texture depth increases for macrotexture wavelengths between 0.4 and 20 in. (10 and 500 mm).[1,45,46] Conversely, noise levels can decrease when texture depth increases for wavelengths less than 0.4 in. (10 mm).

- *Changes in Pavement Surface Characteristics with Time*

Pavement texture does not remain constant over time, as factors such as traffic, weather, and winter maintenance activities eventually wear on the pavement surface, reducing friction levels and affecting the tire-pavement noise level.[47]

For concrete pavements, initial tire-pavement noise levels are typically governed by the as-built surface texture. After a few years, the composition of the concrete becomes increasingly important as mortar wear and surface polishing begin. It is known that aggregate top size can influence the effectiveness of quiet pavements as smaller aggregate sizes tend to produce lower noise levels, all else being equal.[1,47] However, pavement durability is also strongly affected by the mix design, and mix design modifications that sacrifice durability for relatively small decreases in pavement noise are not cost-effective in most environments.[10]

Asphalt-based pavement surface characteristics typically change more rapidly and more severely than those of concrete pavements. Rates of serviceability loss over time are well-documented by most state highway agencies, but sound generation and absorption characteristics are also adversely affected with time. Asphalt binders harden and surface porosity generally decreases due to infilling and some consolidation under traffic. These factors, along with the accumulation of cracks and other forms of pavement distress, have been found to lead to significant increases in sound generation over time for asphalt pavements.[48,49]

In general, sideline or passby noise levels associated with porous pavement surfaces have been reported to increase by about 3 dB(A) over a 7-year period as they fill with grit and dirt. Cleaning and flushing these surfaces can help to restore their noise reducing capabilities.[48]

It should be noted that changes in pavement surface texture over time (e.g., loss of microtexture and macrotexture) and the development of rutting (which can be considered a form of megatexture or roughness that is unique to asphalt pavements) can also greatly reduce pavement *safety* characteristics, especially in wet weather conditions.

Effects of Pavement Joints

Many concrete pavements have transverse contraction joints at intervals of 15 to 40 ft (or more), as well as occasional construction and expansion joints. These joints are typically relatively narrow when they are first placed – often ½ in. (12.7 mm) wide or less, but they may widen over time with wear and rehabilitation activities.

When tires pass over these joints, they often produce an impulsive slap or clapping sound that is typically about 5 dB higher than baseline noise levels and can be a source of annoyance.[1] In addition, relatively wide expansion joints (often provided at bridges and other structures for isolation) can produce less frequent but even higher impulsive sound levels.

Transverse joints can also develop faulting or "step-off" if they have inadequate load transfer capacity and are subjected to repeated heavy loads. Faulting can also result in impact and structure-borne noise as the tires drop from the approach slab to the leave slab upon crossing a joint.

Approaches to reducing the annoyance of joint width-related tire-pavement sounds include skewing the joints, keeping the joint widths as narrow as possible and eliminating the use of most transverse joints by constructing continuously reinforced concrete pavements (CRCP).[1] The development of faulting can be minimized with properly designed doweled joints or the use of CRCP. Each of these approaches to reducing joint-related tire-pavement noise has associated performance, design and/or cost considerations.

Acoustic Absorption

The sound emission characteristics of pavement surfaces are also a function of acoustic absorption, which is a measure of the amount of sound energy that is absorbed (rather than reflected) by a material.

Acoustic absorption is closely linked to surface porosity, which reduces both the *generation* of noise at the tire-pavement interface as well as the *reflection* of noise off the pavement. All else being equal, the more porous and permeable a material is, the higher the acoustical absorption. Acoustic absorption is also linked to material stiffness, with less stiff materials often being somewhat more acoustically absorptive. Materials with lower stiffness may also reduce the level of sound generated at the tire-pavement contact area.[10] Absorption is a function of many other factors as well, including the frequency of the sound and the angle at which sound waves approach the surface.

Effects of Tire Design

Many tire design and geometry parameters influence tire-pavement noise, as discussed previously. The mechanisms associated with noise generation within the tire itself (as a result of it's interaction with the pavement surface) are shown in Figure 3.12.

Today's tire designs feature a variety of combinations of the design parameters (and sound generation mechanisms) described above as manufacturers strive to achieve different performance characteristics (e.g., high speed capability versus

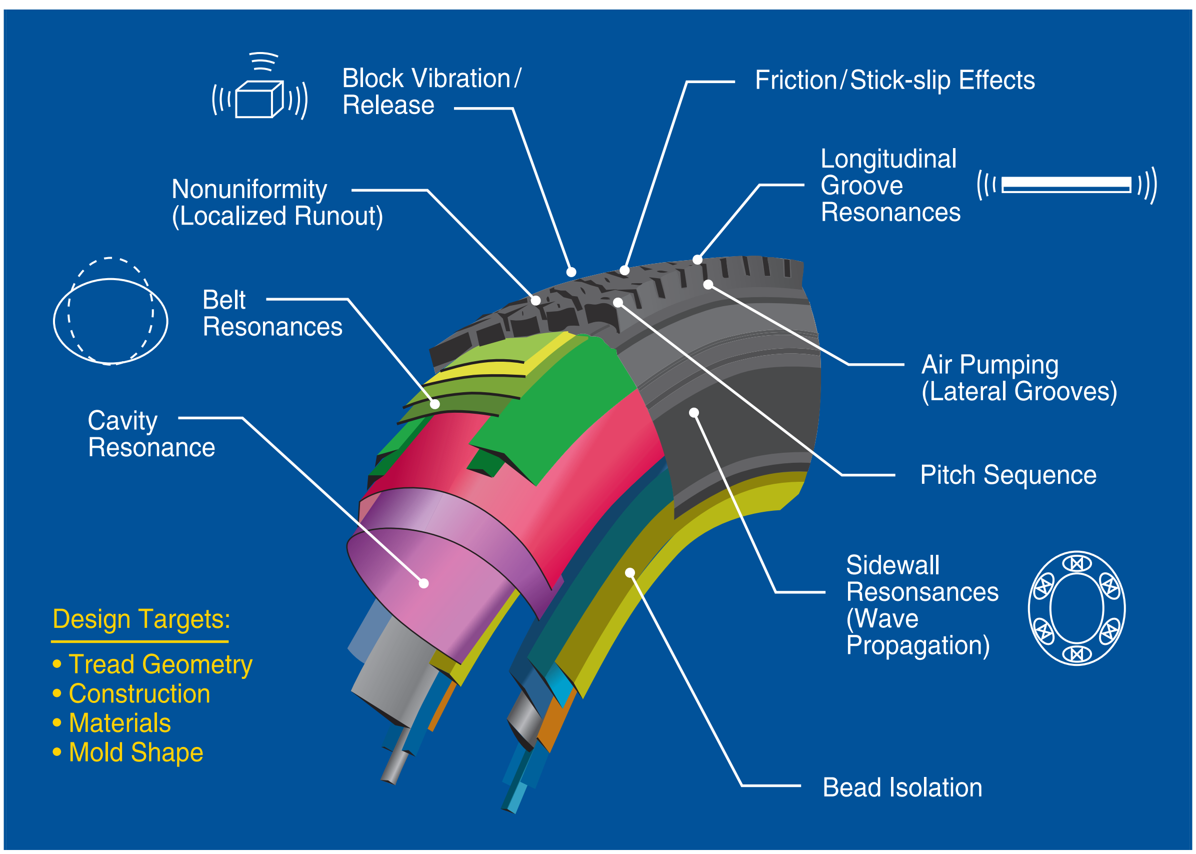


Figure 3.12. Illustration of tire design parameters that influence the generation of tire-pavement sound (provided courtesy of Goodyear Tire).

good "mud and snow" capability). It is not surprising, then, that there is a wide range of sound generation associated with available tires of a specific size and geometry.

This is illustrated in Figure 3.13, which presents a compilation of sound pressure level data obtained from three independent labs for various automobile tires on standard ISO surfaces (50 mph [80 km/hr] coast-by).[1] It shows *a range of 9 dB* overall (and 8 dB within certain tire sizes) *for different tires under identical test conditions on the same reference pavement surface.* These data were collected in the first half of the 1990s. Data compiled in Europe in 2003-2005 show that the sound levels produced by modern tires has been reduced, especially for wider tires, to the point where there is now little difference in sound levels for tire widths of 6.7 – 9.8 in. (17 – 25 cm) (source: personal communication with Ulf Sandberg, 2005).

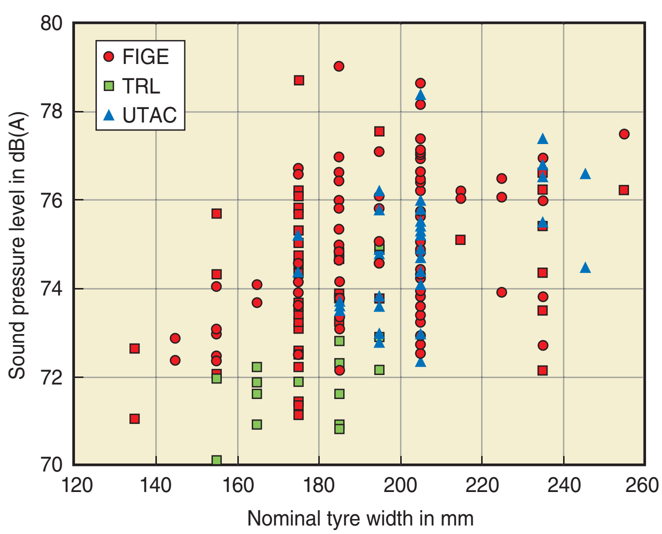


Figure 3.13. Measures of sound pressure level for various tire designs and varying tire width, from three different studies (from Sandberg and Ejsmont, 2002 (Ref.1); used with permission).

Effects of Tire Tread Pattern, Depth and Wear

Much of the variation in sound pressure shown in Figure 3.13 can be attributed to differences in tread patterns and depth. Tire tread pattern and depth influence almost all sound generating mechanisms (especially for travel on smooth surfaces).[1]

One early study that illustrated the effects of tread pattern and depth on tire-pavement noise compared sound levels generated by 9 different truck tires and measured 50 ft (15 m) from the vehicle track. The test surfaces consisted of smooth concrete and "textured" asphalt. Table 3.2 shows the results of these measurements.

It is apparent that tire designs A,B,C and G (longitudinally ribbed tires) were generally quietest, while designs D and I (which featured potential air pockets) produced the most sound. The researchers concluded that the quietest tread patterns were those that allowed the air between the tread grooves to escape as the tread contacts the pavement surface. They also noted that noise generally increases as

Table 3.2. Summary of Data from Study of Sound Levels Due to Tread Design *after 50*

Tread type	Road surface	New tread	Half-worn	Fully worn
A	Concrete	73		
	Asphalt	75	81	
B	Concrete	77	79	
	Asphalt	77		87
C	Concrete	76	91	85
	Asphalt	77	86	
D	Concrete	84		
	Asphalt	83	88	
E	Concrete	84	86	86
	Asphalt	82		
F	Concrete	81	86	
	Asphalt	81	94	
G	Concrete	73	90	
	Asphalt	75		
H	Concrete	81		
	Asphalt	82		
I	Concrete	96		
	Asphalt	88		

tires wear and the tread depth decreases because air cannot escape as easily.[51]

Table 3.2 also shows that pavement texture and material interact with the tread pattern in the generation and projection of sound. Tread patterns A, C, G and H produced lower sound levels on concrete than on asphalt, while patterns D, E, F and I generated less sound on asphalt pavements. Since all 9 tires were tested over the same two pavement surfaces, this is further proof that many factors are involved in the generation of tire-pavement sounds and *no one paving material is inherently superior to another with respect to tire-pavement noise.*

Additional studies of the effects of tire wear and aging on noise have been conducted, sometime producing apparently contradictory results because of their respective scopes and limitations. Many of these studies are described in detail in the Tyre/Road Noise Reference Book.[1] When considering these studies in total, it appears that tire wear and aging generally (but not always) increase tire-pavement noise (compared to levels measured with new tires), although noise levels may initially increase with wear and then decrease somewhat with additional wear.

It is clear that the effects of tire wear on noise are complicated and vary with different tire designs. It is also apparent that tire wear may be as important as (and may even be more important than) any other tire-related variable in impacting tire-pavement noise. The importance of tire wear in comparing the acoustical performances of various tires suggests that, as with various pavement surface types and textures, performance measures must represent the lifetime of the product and not just the performance when new.

Chapter 10 of the Tyre/Road Noise Reference Book provides an excellent and detailed discussion of these and other tire tread design parameters and their impact on tire-road noise.[1]

Effects of Tire Geometry

There is no simple way to determine the influence of tire dimensions on tire-pavement noise. The relationships between tire geometry and factors such as load, inflation pressure, tread pattern and internal structure are often very complex, which helps to explain the differences in results that different researchers have obtained.[1] Extensive discussion of this topic is presented in Chapter 10 of Reference 1.

Effects of Inner Tire Structure

It has been shown that increased tread bending stiffness reduces shoulder tread vibration and associated sound levels. It also appears that increased belt stiffness (e.g., layers of steel cord vs. rayon) reduces tire-pavement noise. Studies of truck tires show that increased carcass stiffness produces reductions in sound pressure level of up to 5 dB(A).[1]

Effects of Rubber Hardness

The results of many studies suggests that, in general, the use of softer rubber compounds in tire treads can reduce generated sound levels by 2 to 3 dB(A).[1] The use of softer rubber often has negative implications for tire wear and aging, however.

The rubber used on truck tires is often much harder than that used in automobile tires (to improve wear characteristics). The harder rubber often results in reduced friction resistance at the tire-pavement interface, which can increase the risk of accidents in mixed traffic

Effects of Tire Load and Inflation Pressure

Tire load and inflation pressure can significantly impact exterior tire-road noise. Several noise generation mechanisms are involved and each is influenced differently (and sometimes in opposing directions) by tire load and inflation pressure, resulting in complex relationships. Citations, summaries and discussions of many studies in this area can be found in Chapter 9 of Reference 1.

FACTORS AFFECTING PERCEPTION OF NOISE

Receptor Location

Roadway noise is generally discussed in terms of two different perspectives: sounds heard by people inside of vehicles (i.e., interior noise) and sounds heard by people outside the vehicle (i.e., exterior noise). In either case, the listeners are often referred to as *receptors*. The factors that influence the perception of sounds in these two locations are quite different and a given vehicle traveling a particular road can produce very different responses in the receptors inside and outside of the vehicle, as shown in Table 3.3.

Table 3.3. Comparison of Interior and Exterior Pavement Noise Levels, L_{eq}, dB(A)[52]

	Vehicle speed	
	60 mph (96 km/hr)	70 mph (113 km/hr)
Exterior receptor	78.9 – 87.3	79.9 – 89.4
Interior receptor	65.0 – 72.0	67.8 – 74.2

Inside the Vehicle

Recent research has found that *objectionable* interior noise is associated more with tonal quality (specific frequencies) than with total noise level.[30] Objectionable tonal quality (often described by users as a *tire whine*) is primarily the result of spikes in sound pressures at particular frequencies, such as those shown in Figure 3.14, which presents sound spectra for two concrete pavement surfaces in the Wisconsin study.[30,53]

Different texturing techniques produce different tonal qualities, and pavements that produce identical levels of sound pressure (decibels) under traffic can be perceived as producing very different levels of noise. The key to reducing "tire whine" and perceived noise is to eliminate the peaks in the noise spectra (such as those shown in Figure 3.14).[53]

The highest sound levels inside of most vehicles do not necessarily occur on pavement surfaces that produce the greatest exterior sound levels because many other factors affect the perception of interior noise, including vehicle structural, suspension and

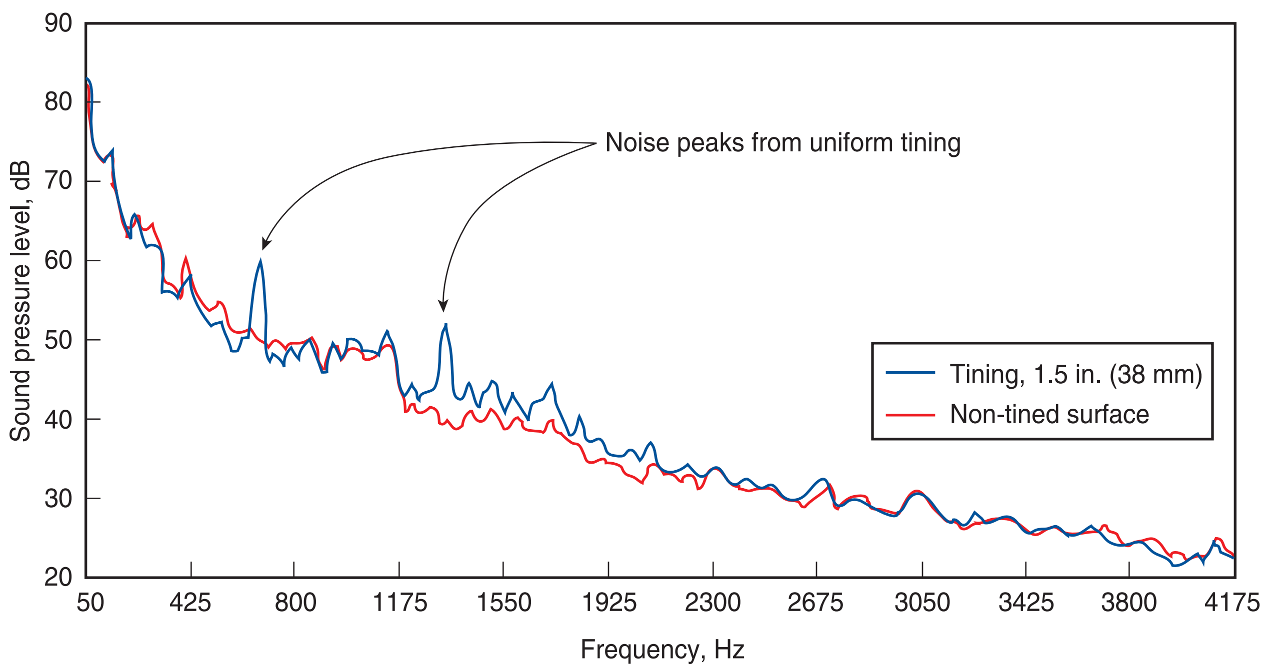


Figure 3.14. Graph from Wisconsin noise study showing the prominent peaks that produce objectionable tire whine.[30,53]

insulation characteristics. In addition, sound levels inside the vehicle are generally not affected by amplifying mechanisms (i.e., the "horn" mechanism and others) that affect the sounds measured at passby locations.[53]

Outside the Vehicle

Exterior noise is primarily a concern in urban areas and it generally increases with increases in macrotexture.[8] There are many other factors that influence the level of sound that reaches receptors outside of the vehicle, including distance between the receptor and the sound source, presence of barriers to the sound, and environmental effects such as wind, temperature and humidity.

Distance to Source

In a perfect acoustical environment (i.e., no wind, sound reflections, temperature gradients, etc.), the propagation of sound can be accurately modeled using a relatively simple model that is sometimes called "the distance law."[1] This model predicts that doubling or halving the distance from the receptor to a *point* source decreases or increases (respectively) the sound pressure level by 6 dB(A). Similarly, doubling or halving the distance from the receptor to a *line* source (e.g., bumper-to-bumper traffic) decreases or increases (respectively) the sound pressure level by 3 dB(A).

The highway environment is actually far from acoustically perfect; the effects of wind, sound reflections and temperature on sound propagation and perception are presented in other sections of this report. In addition, typical traffic flow (consisting of multiple vehicles separated by some distance) probably falls somewhere between the "point source" and "line source" models described above, so an appropriate distance law value for doubling or halving the distance from the highway to the receptor is usually more than 3 dB(A) and less than 6 dB(A). Nevertheless, the distance law is still widely used to provide reasonable estimates of changes in sound level with distance.

Because noise level decreases rapidly as the distance from the pavement increases, much larger changes in sound level can be achieved by changing this distance than by changing pavement surface characteristics.[53]

Barriers to Sound

Noise barriers are solid obstructions built between highways and homes or businesses along the highway. Barriers can be formed from a variety of materials ranging from earth mounds or "berms" to high, vertical walls made of wood, stucco, concrete, masonry, metal, or other materials. They are typically very effective in reducing noise for receptors located within 200 ft (16 m) of the pavement, and can reduce noise levels in this zone by 10 to 15 decibels, cutting the loudness of traffic noise.[54]

The effectiveness of noise barriers is often limited by geometric and/or economic constraints. For a noise barrier to work, it must be high enough and long enough to block the view of the noise source from the point of reception. A noise barrier can achieve a 5 dB(A) noise level reduction when it is tall enough to break the line-of-sight from the noise source to the receiver; an additional noise level reduction of about 1 dB(A) can be achieved with every 2 ft (0.6 m) of additional barrier height above the height required to break the line-of-sight, with a maximum theoretical total reduction of 20 dB(A).[54] Note that if truck exhaust stacks (or other elevated sources) are significant sources of noise, a significantly taller wall may be necessary to mitigate that sound than is required for tire-pavement noise.

Since sound will diffract around the ends of a barrier, it is generally accepted that barriers should extend 4 times as far in each direction as the distance from the receiver to the barrier. Openings in noise walls for driveway connections or intersecting streets degrade the effectiveness of barriers.[54]

Surface Color

Surface color can be said to have an indirect effect on pavement noise in that darker surfaces absorb sunlight more readily, increasing their temperature and reducing their stiffness when compared to more lightly colored pavements. The reduced stiffness can result in small reductions in tire-pavement sound emissions.[1]

There also appears to be a psychological effect, in which the public tends to perceive darker colored surfaces as being smoother and quieter than lightly colored surfaces. This phenomenon was documented by Krarup, who describes a Danish concrete highway that was essentially painted black with an asphalt emulsion to give the traveling public the impression that the surface was asphalt.[55] As a result, no complaints of noise were received. This changing of the surface color to affect people's perception of noise without actually affecting the sound generated has been called a "placebo effect."[1]

Environmental Factors

Wind

Wind speed and direction directly influence both the generation of sound due to aerodynamic turbulence produced by moving vehicles (especially at high vehicle speeds). Vehicles traveling into the wind generate more sound than those traveling with the wind. This type of sound is difficult to distinguish from tire-road noise in pass-by sound measurements.

Wind can also affect the measurement of sound by producing background noise through direct interaction with microphones and the surrounding environment (e.g., rustling of tree leaves, turbulence as it passes around and through nearby structures, etc.). These wind-induced background noises can result in inflated measures of roadway noise. Wind is not normally a factor in standardized sound measurement tests, such as the pass-by test, which must be performed in conditions where the wind speed is below some critical threshold (e.g., 10 mph). The discussion above justifies such test limitations and describes another source of sound level variability under normal operating conditions.

Humidity

Humidity is not considered to be an important factor in traffic sound measurements at typical sound measurement distances (e.g., 50 ft [15 m] or less from the source).

Temperature Effects on Sound Generation

It was recently recognized that tire-road sound emissions are influenced by temperature. Current models suggest that the noise coming from automobile tires varies inversely with temperature at a rate of about 1 dB per 18°F (10°C). Thus, a sound level test performed at 32°F (0°C) using a particular tire and pavement would be expected to produce sound levels about 3 dB(A) higher than the same tire-pavement combination at 86°F (30°C). The magnitude of this effect is comparable to that of very different tire tread patterns.[1]

The actual rate of sound level variance with temperature is strongly dependent upon pavement type (the sensitivity of asphalt-based surfaces is 2 – 4 times higher than that of concrete surfaces), vehicle speed and pavement texture. Chapter 12 of Reference 1 presents a much more complete discussion of this topic.

Temperature Effects on Sound Propagation

There are two primary effects of air temperature on sound propagation: 1) change in the speed of sound due to changes in air density, and 2) refraction and reflection of sound due to vertical temperature gradients. The latter poses more interesting and significant effects in roadway noise studies.

Sound refraction occurs when the air temperature over the ground varies significantly, such as may occur when the sun shines on a dark asphalt surface. The variation in temperature from the surface upward corresponds with a gradient in air density, so that the speed of sound also varies with height. This causes sound wave diffraction – an effect that can be important for sources close to the pavement surface (i.e., tire-pavement sounds). The effect of this diffraction is generally considered to be substantial at distances of 75 feet or more from the source; it is much smaller in the range where sounds are typically measured.[1]

Sound reflection takes place whenever sound waves hit a surface of any kind – including a layer of dense air aloft caused by a temperature inversion. Part of the sound is reflected from the surface, part is absorbed and part is transmitted through. The portion that is reflected may be returned to an observer who is also receiving sound directly from the source. The direct and reflected sound waves will interact and interfere with each other at the point of reception, producing amplifying and canceling effects, depending upon their relative phases as determined by the distances between the receiver and the real and reflected sources.

MEASUREMENT OF ROADWAY SOUND

Far-field Measurement vs Near-field Measurement

The two general approaches for measuring sounds generated in the highway environment are far-field and near-field measurement techniques. These two approaches are described and discussed herein.

Far-field Measurements

Highway noise comes from many sources (e.g., tire-pavement interaction, engine noise, etc.) and the sound generated along any given corridor varies with the traffic volume and composition, operating speeds and conditions, environmental conditions, and many other factors. The variability of these factors and others often makes it difficult (if not impossible) to accurately model the exposure of abutting properties to highway noise. For these reasons, many highway agencies believe that the best way to obtain measures of highway noise that are representative of typical receptor locations is to position a microphone at some standard position relative to the roadway (typically [in the U.S.] 5 ft [1.5 m] above and 50 ft [15 m] from the center of the travel lane) and measure *all* of the sounds produced by the traffic stream. This type of measurement is referred to as “wayside”, “roadside”, “pass-by” or “far-field” measurement.

Far-field measurements are considered to have a number of drawbacks:

- They are often time-consuming and expensive.
- They cannot be performed properly when sound reflectors (e.g., sound walls, safety barriers, guard rails, etc.) are located nearby.
- It is often difficult to find suitable test sites in dense urban areas (where noise issues are often a concern).
- Measurements can be greatly affected by prevailing traffic operations and environmental effects (such as wind direction and speed).
- They represent noise levels at the measurement site and cannot necessarily be used to indicate levels at other locations along the same facility.

Near-field Measurements

Near-field measurement systems are typically vehicle-mounted systems that place microphones within inches of the tire-pavement interface with the intent of *measuring only the noise generated by the tire on the pavement* at typical travel speeds. The sound levels measured are typically much higher than those obtained from far-field measurements.

One key advantage of near-field measurement systems is their ability to isolate tire-pavement interaction sounds from other sounds in the highway environment. Another advantage is that hundreds of measures of sound pressure can be obtained along a pavement corridor in the same amount of time typically required for a single far-field measurement, making near-field measurement techniques useful for identifying variations in tire-pavement noise levels along the length of a project, as well as for monitoring changes in pavement noise properties over time.

One limitation of near-field sound measurements is that test results can vary significantly with the type of tire that is used on the test vehicle. Another is that it can be difficult to use individual near-field measures to estimate overall sound levels due to mixed traffic and sound reflection for abutting residents and businesses. The effects of vehicular interactions of these types are most accurately assessed through far-field measurements.

Techniques for Measuring Exterior Roadway Sound

The Statistical Pass-By Method (SPB)

The Statistical Pass-By Method (SPB) involves using a roadside microphone (as shown in Figure 3.15) to measure maximum A-weighted sound levels from normal vehicles that have been selected from the traffic stream and are operating under approximately constant speed conditions and without sound interference from other vehicles. Only vehicles from the following three classifications are used in determining the SPB index: passenger cars, dual-axle heavy vehicles (i.e., 2-axle buses, coaches and commercial trucks with more than 4 wheels), and multiple-axle heavy vehicles (i.e., trucks with 3 or more axles, including trailers).

When acceptable sound and speed measurements have been obtained from at least 100 passenger cars and 80 heavy vehicles (including a minimum of 30 dual-axle and 30 multi-axle heavy vehicles), the measured sound levels are plotted against the measured speeds and regression analyses are performed to identify best-fit curves for each of the three vehicle classifications.

Figure 3.15. Photos of (clockwise from upper left) SPB set-up, CPX trailer, SI equipment and NAH antenna array (courtesy of McDaniel and Bernhard,[163] Ulf Sandberg, Caltrans and Paul Donavan/Caltrans,[162] respectively).

One of the following three "road speed categories" is selected: low (posted speed limits of 25 – 38 mph [40 – 61 km/hr]), medium (posted speed limits of 44 – 56 mph [71 – 90 km/hr]) or high (posted speed limits of 61 – 81 mph [98 – 130 km/hr]). Each vehicle classification is assigned a specific reference speed within each of these three categories and the regression curves are used to determine the sound level for each vehicle class at its specified reference speed.

The three vehicle class sound levels are then converted to linear values related to sound power, are weighted using standardized factors that represent the proportions of each vehicle classification expected to be on a road of the given speed category, are added, and are then converted back to an average sound level for the assumed mix of vehicles. This final composite value is called the Statistical Pass-By Index (SPBI).

The main advantages of the SPB method are that it provides results that are representative of actual traffic noise emissions and accurately represents source and propagation effects. It also provides a good assessment of road surface influence on noise emissions for all vehicle types (including heavy vehicles). The principal drawback of the SPB method is that it typically measures the impact of "normal," nonstandard traffic sources (i.e., in-service vehicles), which vary with measurement location and time and may be biased by the activity (or inactivity) of nearby industries. The SPB method is also time-consuming, must be conducted within strict conditions regarding traffic interference, driver behavior, and reflective objects near the microphone, and it provides a measure of road surface sound emission properties only at a single location.

A more complete description of the SPB test method can be found in ISO 11819-1.[56]

The Close-Proximity Method (CPX)

The Close-Proximity (CPX) method consists of rolling a test tire on the driving surface with one or more microphones mounted close to the tire (within 3 – 18 in. [8 – 46 cm]) and pavement surface (4 in. [10 cm] above) at each end of the contact patch. The test tire(s) can be either a normal part of the driven vehicle, an extra tire mounted on the vehicle, or a tire mounted on a specially designed trailer (the most common approach).

Most trailers used for this test are constructed with an acoustically lined enclosure around the microphone and test tire(s) to provide screening from wind and extraneous traffic noise, as shown in Figure 3.15. ISO 11819-2 provides guidance on trailer acoustics and construction to assure that external noises are excluded from measurements.[3]

The microphones are used to determine the average A-weighted sound pressure levels emitted by either two or four specified reference tires operating at a specified speed over a specified road distance. The four standard reference tires include two specific "summer" tread patterns, one "winter" tread pattern and one "aggressive block" pattern that resembles those used on many truck tires. Specifics concerning these reference tires are available in the ISO specification. It should be noted that none of the reference tires are designed for use with heavy vehicles, and it is known that heavy vehicle tires have different sound emission characteristics than light vehicle tires. Therefore, the results of this test are considered to best describe field conditions where light vehicles comprise the major part (> 90 percent) of the traffic stream.

The primary advantages of the CPX method are that measurements can be obtained relatively quickly and inexpensively, and they can be obtained without having to close the roadway to normal traffic (assuming that an enclosure is used to shield the microphones from wind and traffic noise). In addition, the test accuracy and repeatability have been proven to be good, and the correlation between CPX and controlled pass-by measurements of surface noise characteristics (e.g., SPB) can be very good. The primary disadvantages of the CPX method include the expense of purchasing and maintaining the test equipment, its inability to account completely for the directionality of tire-road noise and the impact of that directionality in the far field, potentially large variations in measuring results between test vehicles, influences of the test vehicle on sound measurements and other background noise problems.

An international standard for conducting the Close Proximity Test can be found in ISO 11819-2.[57]

Sound Intensity (SI)

Introduction

Sound fields include both acoustic pressure (commonly measured using microphones) *and* particle velocity, and sound intensity (SI) is the product of these two characteristics.[58] Particle velocity is most commonly measured by comparing the differences in signals between a pair of phase-matched microphones locked at a fixed distance apart. An SI analyzer can compute both the sound pressure and particle velocity at the mid-point between the two microphones, and can multiply the two together to compute the SI.[58]

Because sound intensity is based on both acoustic pressure and velocity, it has direction. This directionality makes it possible to locate specific sound sources and construct “intensity maps” that show regions of high and low sound radiation and indicate the direction of their emissions. This cannot be done using CPX or SPB equipment.[58]

Description

The SI method was originally developed by General Motors in late 1970s and early 1980s.[59,60] Like the CPX method, this approach also uses two microphones mounted near a test tire, but the microphones are phase-matched so that they can be used without the need for a trailer or other acoustical enclosure; signal processing is used to essentially eliminate all sounds except those produced at the tire-pavement interface. The result is a measure of sound intensity being radiated in a particular direction from a *specific* source (i.e., the tire-pavement interface). This is very different and much more useful than the overall measure of ambient sound pressure obtained by CPX equipment. Overall SI values are calculated by summing the dB(A) values from these third-octave bands (the “area under the curve”) between 500 and 5000 Hz.

Like the CPX method, SI measurements can be conducted at highway speeds. Figure 3.15 shows a sound intensity probe that is mounted to the lug nuts of a test vehicle.

Function

The main advantage of sound intensity techniques over other close-proximity sound measurement techniques is their ability to essentially isolate tire-pavement noise sources. SI techniques also correlate well with far-field (pass-by) test values. While both SI and CPX tests measure sound from positions that are very close to the tire-pavement contact patch, their resulting test values are generally different (with the SI readings typically being 2 – 3 dBA higher) due to differences in the distances between the microphones and the tire as well to inherent differences in the nature of sound intensity and sound pressure values.

Additional information concerning the SI test and equipment can be found in References 59 and 60.

Near-field Acoustic Holography (a.k.a. Noise Mapping or Beam Forming Techniques)

Near-field Acoustic Holography (NAH), sometimes refined with Spatial Transformation of Sound Fields (STSF), is now being used to measure roadway noise radiation characteristics from all sources, including tire-pavement interaction and all of the various vehicle sources. This technique uses many microphones (up to 100) arranged in arrays, matrices or spirals to form an acoustic antenna, as shown in Figure 3.15. This technology is currently being used in research studies to produce colorized snapshot maps that show the location and magnitude of the various noise sources on truck tractor-trailer combinations. It offers great promise for improving our current understanding of the relative contributions of various sources to overall noise levels produced by moving vehicles, especially heavy trucks.

Measuring Sound Absorption

ISO/FDIS 13472-1 ("Measurement of Sound Absorption Properties of Road Surfaces In Situ – Part 1: Extended Surface Method")[61] features the use of a sound source (driven by a signal generator) that is positioned above the road surface, and a microphone that is located between the source and the surface. The microphone picks up sound directly from the source and reflected sound from the pavement surface (which must travel a longer distance before reaching the microphone). These two responses are separated using time domain processing. Fourier transforms and other mathematical processes are then used to determine a sound power reflection factor, from which a sound absorption coefficient can be computed (taking into account geometric spreading of sound power over the distance between the microphone and pavement surface). All sound energy that is not reflected directly back towards the microphone and source is considered to be absorbed, which may result in a slight overestimation of actual absorption. Sound absorption coefficients range from 0 (hard, acoustically nonabsorptive surface) to 1 (perfect acoustically absorptive surface that reflects no sound).

Time Weighting and Equivalent Sound Levels

Sounds generated by a stream of vehicles vary in strength over time and are affected by factors such as distance between the vehicle stream and the listener, number of vehicles and their speeds, weather conditions and the pavement surface texture. The variations in sound level with time are often so large that momentary values are meaningless. Therefore, it is often necessary to convert fluctuating sound levels to some sort of "average" value that takes these fluctuations into account and provides a meaningful measure for characterizing the level of sound. Descriptions of some common time-weighted sound level measures follow.

The *maximum sound level* (L_{Amax} or L_{max}) is the common and traditional measure of the sound generated by a passing vehicle. It is determined as the maximum sound level measured by a microphone as the vehicle passes.

The *equivalent sound level* (L_{Aeq} or L_{eq}) is a calculated value of sound level that would provide the same sound energy as the actual sound history over a given period of time. This measurement approach is typically employed where traffic volumes are very high and no separation of vehicles is possible. The period of time over which the sound signal was averaged is often listed with the symbol L_{Aeq} (e.g., L_{Aeq24h} indicates that the referenced equivalent sound level is averaged over a 24-hour period). Sometimes the 24-hour day is subdivided into 2 or more segments, such as day and night or day, evening and night, and the equivalent levels obtained for each period are "weighted" to account for the more severe impact of sound exposure during nights and evenings (e.g., equivalent night levels might be increased by 10 dB and evening levels by 5dB). The adjusted values are then combined to produce the overall equivalent day-night or day-evening-night sound level, designated as L_{dn} or L_{den}, respectively.

Another way of characterizing a sound event is to measure its' A-weighted sound exposure level (L_{AE}). This is an equivalent level like L_{Aeq}, except measured over a sufficiently long time interval to convert the complete sound event and then normalized to a certain time (usually 1 second).

Section 15.1.1 of Reference 1 provides detailed descriptions of techniques for weighting measured sound signals with respect to time.

Measuring In-Vehicle Sound

Current techniques for measuring in-vehicle sound levels use one or more microphones (often mounted near the driver's seat at ear level) and a suitable acoustic analyzer. SAE J1477 ("Recommended Practice for Measurement of Interior Sound Levels of Light Vehicles") provides details concerning this technique.[62]

Many studies have identified interior sound pressure level peaks of as much as 10 dB(A) above general sound levels at frequencies around 1,000 Hz.[1,4,14,30] These peak frequencies are perceived by humans as irritating pure tones (i.e., either a higher frequency tire-pavement whine or a lower pitched rumble). These tones are present on most concrete pavements with uniformly spaced transverse tining, and traditional third-octave band analysis does not detect these frequency peaks because total sound averaging masks them.

Kuemmel, et al found that a fast-fourier transform (FFT) analysis was more effective than third-octave band analysis at identifying the narrow band frequencies associated with objectionable tire whine.[4,30] They developed an in-vehicle noise measuring system and FFT-based analysis method (based on the SAE J1477 practice) that can be used to identify pavement textures that generate objectionable tonal qualities.[30] This equipment makes it possible to identify surface textures with objectionable tonal characteristics and avoid their use on future construction and restoration projects.[14,30]

Chapter 4. Fundamentals of Roadway Friction and Pavement Texture

THE LINKS BETWEEN PAVEMENT SURFACE TEXTURE, FRICTION AND SAFETY

While highway users and abutters are concerned with roadway noise issues, they also deserve roadways that have good surface friction and are capable of providing safe travel. Highway crashes in the U.S. currently result in almost 43,000 fatalities and 3 million injuries annually; poor pavement conditions (including poor surface texture and friction characteristics) contribute to about 13,000 deaths annually.[44] It is essential that pavement surface friction be considered directly in roadway design to reduce the currently unacceptable level of highway crashes, fatalities and injuries. *Highway safety must not be sacrificed in favor of reductions in roadway noise.*

Pavement surface friction (or "skid resistance") is the force developed at the tire-pavement interface to resist tire slippage. Adequate surface friction often exists on dry pavements, but even thin films of water reduce direct contact between the pavement and the tire and cause a loss of friction. If the water film becomes deep enough and if vehicle speeds are sufficiently high, tires can completely lose contact with the pavement surface (hydroplaning).[63] Studies suggest that 15 to 35 percent of wet weather crashes involve skidding.[4]

Water on the pavement also contributes to splash and spray when it is picked up by vehicle tires. Such airborne water can reduce visibility for drivers traveling next to or closely behind the vehicle creating the splash and spray. It has been reported that 10 percent of wet weather accidents are caused by reduced visibility due to splash and spray (especially at night).[4]

A 1980 National Transportation Safety Board (NTSB) report estimated that 16 to 18 percent of fatal accidents in the United States occur on wet pavements.[64] Similarly, a 1990 survey reported that about 19 percent of the nearly 25 million reported accidents occurred on wet pavement.[65]

Research suggests that up to 70 percent of wet weather crashes can be prevented with improved pavement texture/friction.[44] If wet weather crashes account for about 19 percent of all fatal crashes, *improved pavement texture/friction could reduce overall highway crash, fatality and injury rates by 13 percent (i.e., 5600 fewer deaths, 390,000 fewer injuries and 3.25 million fewer accidents each year).*

While the reduction of wet weather accident potential should be a high priority in the pavement design process, it must be recognized that more than 80 percent of all fatal crashes occur on *dry* roadways. Even though most dry pavements have sufficient friction for normal driving conditions, improved texture and friction would significantly reduce dry pavement accident rates and severity by reducing stopping distances.

Figure 4.1 shows the effect of skid resistance and mean texture depth on observed accident rates in the U.K. This graph shows that increasing the texture depth from 0.3 mm to 1.5 mm (0.012 in. to 0.60 in) while holding pavement friction constant reduces the accident rate by about 50 percent; conversely, increasing the skid resistance from 0.35 to 0.6 while holding the texture depth constant reduces the accident rate by about 65 percent. Improving texture depth and surface friction together provides the greatest reductions in accident rates. These data clearly show the expected benefits that increasing texture and friction can have on reducing the number of fatal and serious injury accidents.[66]

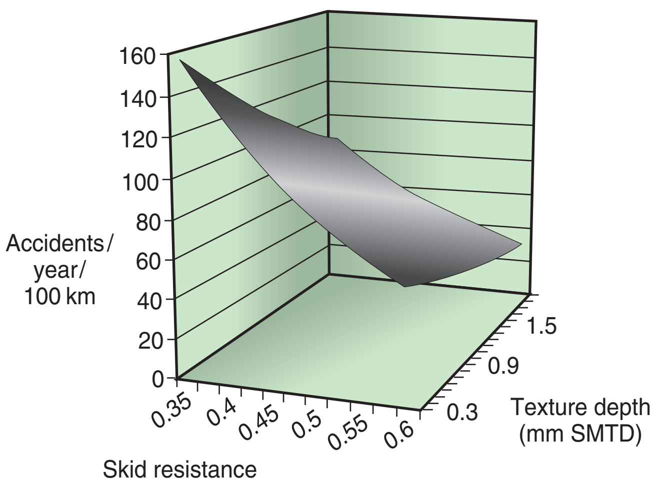


Figure 4.1. Accident model for skid resistance and texture depth on U.K. single carriageways.[67]

It is essential that pavement design processes specifically include the selection and design of surface textures that reduce hydroplaning potential and provide improved long-lasting surface friction for both wet and dry pavements, especially for higher speed urban roadways.

FACTORS THAT AFFECT PAVEMENT FRICTION AND SAFETY

Tire Design and Condition Parameters

The friction force between the tire and the road surface consists of four primary components: adhesive, deformation, viscous and tearing forces.[68] Each of these components may be influenced differently by factors such as contact stress, sliding speed, temperatures of the tire and roadway surface, the nature of the rubber compound used in the tire, texture of the road surface, contamination of the surface, tire tread pattern and tread wear, and presence of a water film.[1]

Given the complexity of the relationships between all of these factors and the primary components of tire-pavement friction, it is clear that tires must be designed differently to provide good friction in different conditions. For example, tires that are designed for dry friction tend to have fewer, narrower grooves and may use very different rubber compounds than tires designed for wet conditions.

It has been suggested that tires that are designed to provide good frictional performance under various conditions (e.g., wet weather or hard cornering) must, by necessity produce higher amounts of tire-pavement noise. Numerous studies in recent years have shown that, while different types of tires provide very different frictional characteristics due to changes in their tread patterns and rubber compounds, there are no significant differences in the noise they generate in service (except for studded tires, of course).[1,69,70]

Microtexture and Macrotexture

The relative difference in speed between the tire tread and the pavement surface is called the "slip speed". Slip speed is zero for a free rolling tire and equals the vehicle speed when the wheels are locked (full skid). Peak levels of friction are usually observed when the slip speed is about 15 percent of the vehicle speed.

Pavement microtexture (texture depth of 0.0004 to 0.02 in. [10 – 308 µm]) has a strong influence on skid resistance at low slip speeds, while macrotexture (texture depth of 0.02 to 2 in. [508 µm – 50 mm]) has a stronger influence at higher slip speeds. If both microtexture and macrotexture are maintained at high levels, there will be good resistance to skidding on wet pavements.

A 1998 study performed in the U.K. reports that increased macrotexture reduces accident rates under both wet *and* dry conditions, and even reduces accident rates at lower speeds.[71]

In a 2004 Australian study, macrotexture levels were strongly correlated with crash rates for most of the pavement locations and categories that were studied, particularly at intersections. The lower limits of satisfactory surface texture were determined to be 0.015 – 0.02 in. (0.4 and 0.5 mm) (measured using laser-based devices), respectively, for two different highways. Crash risks were determined to be 1.8 and 1.9 times higher, respectively, when average macrotexture dropped below these critical values.[72] The authors estimated that 13 to 17 percent of all crashes on the two study highways could be prevented by improving all low macrotexture sites.[72,73]

Effect of Macrotexture on Splash and Spray

Increasing macrotexture generally reduces the potential for splash and spray and increases skid resistance, as discussed in Chapter 2 and shown in Figure 2.1.

Effect of Pavement Surface Texture on Hydroplaning

Hydroplaning is different from skidding on wet pavement. When hydroplaning occurs, the entire tire footprint is separated from the pavement by a layer of water and the pavement surface texture no longer plays a role in the friction process.

When a rolling tire encounters a film of water on the roadway, the water is channeled through the tire tread pattern and through the surface texture of the pavement. Hydroplaning occurs when the drainage capacity of the tire tread pattern and pavement surface is exceeded and the water begins to build up in front of the tire. This build-up creates a water wedge that can lift the tire off the pavement surface – a condition referred to as "full dynamic hydroplaning." Since water offers little shear resistance, the tire loses its tractive ability and the driver may lose control of the vehicle.

Potential for hydroplaning increases with increasing water depth and vehicle speed and decreases with increasing tire pressure and tread depth. Hydroplaning potential is also influenced by roadway geometric factors and pavement surface condition.

Pavement surface texture does not directly influence the potential for hydroplaning, although pavement texture and transverse profile *do* influence the amount of water available to cause hydroplaning (i.e., rutted pavements can collect and hold significant depths of water, and the very smooth surfaces can have greater effective water film thicknesses than surfaces with significant macrotexture).

Hydroplaning potential can be reduced in many ways. For example, the highway geometry can be designed to reduce the length of the drainage paths lengths (e.g., use increased cross-slope) to remove water more quickly from the pavement surface. Another technique is to increase the depth of pavement surface texture depth to increase the water channeling/drainage capacity at the tire-pavement interface. The use of open-graded and porous pavement surfaces has also been shown to greatly reduce the hydroplaning potential of the roadway surface by allowing water to be forced through the pavement under the tire, reducing hydrodynamic pressures.

Environmental Conditions

Pavement friction usually decreases with pavement age due to two mechanisms: 1) aggregate polishing under traffic reduces microtexture, and 2) aggregate wear under traffic reduces macrotexture. However, there are other seasonal changes (especially in colder climates) that may produce either decreases *or* increases in pavement friction.

For example, winter conditions and winter maintenance operations tend to increase aggregate microtexture, sometimes leading to higher friction measurements in the spring and early summer than in the late summer or fall. Periodic rainfalls can also influence friction test results in almost any climate. In addition, dust and oil that accumulate on pavements during dry periods sometimes mix with test water to reduce measured friction values until the contaminants are washed away by rainfall.

Some agencies apply seasonal corrections to their friction test values to account for the mechanisms described above. In Virginia, for example, skid numbers measured in January are reduced by 3.7 while July and August values are not adjusted. Additional examples of friction adjustment values are tabulated in Reference 8.

MEASUREMENT OF PAVEMENT FRICTION

Measures of Surface Friction

Friction Number (FN)

Most agencies in the United States currently measure pavement friction using an ASTM locked-wheel trailer using either a standard ribbed or smooth (blank) tire (in accordance with ASTM E 274 or ASTM E 524, respectively).[8,74] Locked wheel testing devices simulate emergency braking conditions for vehicles without anti-lock brakes. In this procedure, water is applied to dry pavement in front of the locked-wheel trailer. The friction between the locked tire and pavement surface is generally measured at a speed of 40 mph (64 km/hr) and the friction number (or *skid number*) is computed as 100 times the force required to slide the locked test tire over the pavement surface divided by the effective wheel load.

Friction numbers are reported as the designation "FN" followed by the test speed in mph and the letter "R" if a ribbed tire was used or the letter "S" if a smooth (blank) tire was used. If the test speed is expressed in km/hr, the test speed is enclosed in parentheses. For example, if a ribbed tire was used in a locked-wheel trailer test at a test speed of 40 mph (64 km/hr), the friction number would be reported as FN40R or FN(64)R (English and metric units, respectively).

International Friction Index (IFI)

The International Friction Index (IFI) was proposed in 1992 by PIARC as a method of incorporating simultaneous measurements of friction and macrotexture into a single index that represents overall pavement friction characteristics. It is now an approved ASTM standard test (E-1960).[75]

The IFI is dependent on two parameters that describe the skid resistance of a pavement: a speed constant (S_p) derived from the macrotexture measurement (typically the Mean Profile Depth) that indicates the speed dependence of the friction, and a friction number (F60) that is a harmonized level of friction for a speed of 60 km/hr (36 mph).[8,75] Equations for determining the IFI and its component parameters can be found in Reference 8.

One advantage of the IFI is that valid tests can be conducted at any speed because the F60 value for a pavement is independent of the slip speed used during testing.[8] This allows the test vehicle to operate safely at higher speeds on high-speed highways and lower speeds in urban situations.

Common Surface Friction Measuring Devices

Four basic types of full-scale devices are most commonly used to obtain direct measurements of pavement surface friction: locked wheel, side force, fixed slip, and variable slip testers. All of these devices can be equipped with tires featuring either a "ribbed" tread (one with longitudinal grooves on the tread surface) or a "blank" (smooth) tread.

Ribbed treads have been used widely in the U.S. because they are relatively insensitive to water film thickness, which makes them a good choice for tests that would ideally be insensitive to all operational factors (such as water film thickness). However, measurements obtained using ribbed tires are somewhat insensitive to macrotexture and are mainly influenced by microtexture.[77] This helps to explain why the use of ribbed tires is partially responsible for the sometimes poor correlation between friction test values and highway accident rates.[92,93] Many studies indicate that standard smooth tires produce friction test results that correlate much better with wet weather accident rates.[5,78,79] FHWA Technical Advisory T5040.36 also recommends the use of ASTM E-574 smooth tires in highway pavement friction tests.[5]

Using smooth test tires generally produces lower friction numbers, which may be one reason many agencies are reluctant to use them. Either tire can be used to report the IFI, which requires the measurement of macrotexture to adjust the ribbed tire data in determining the friction number, F60.

Locked Wheel Devices

Locked wheel trailers simulate emergency braking conditions for vehicles without anti-lock brakes by dragging a locked wheel on a pavement wetted with a specified amount of water. The brake is applied and the force is measured and averaged for 1 second after the test wheel is fully locked. Locked wheel testers are usually fitted with a self-watering system for wet testing, and a nominal water film thickness of 0.02 in. (0.5 mm) is commonly used.[8]

Side Force Devices

Side force testers are designed to simulate a vehicle traveling though a curve. They function by maintaining a test wheel in a plane at an angle to the direction of motion (the yaw angle), while the wheel is allowed to roll freely.[8] Side force is measured perpendicularly to the plane of rotation.

The main advantage to this method is that these devices can measure friction continuously through the test section (rather than over 1-second intervals, like the locked wheel devices). It should be noted that the relative velocity is proportional to the sine of the yaw angle, which is usually small. Therefore, these systems produce a low-speed measurement even though they can be operated at high speeds. Thus, they tend to be sensitive to pavement microtexture.

Examples of specific side force testing equipment include the MuMeter and the Sideways-Force Coefficient Routine Investigation Machine (SCRIM), both of which originated in the United Kingdom (see Figure 4.2). Some SCRIMs are now fitted with laser macrotexture measurement systems to provide a more complete indication of pavement surface friction. The MuMeter was developed mainly for airport use and has seen only limited use on highways in the United States.

Figure 4.2. Photos of MuMeter[21] and SCRIM.[80]

Fixed and Variable Slip Devices

The fixed and variable slip methods attempt to detect or operate around the peak friction level to simulate a vehicle's ability to brake while using antilock brakes. Fixed slip devices operate at a constant slip (usually between 10 and 20 percent slip) by driving the test wheel at a lower angular velocity than its free rolling velocity) while the variable slip devices sweep through a predetermined set of slip ratios (in accordance with ASTM Standard E 1859).[8,81] Examples of fixed slip devices include the Griptester and SAAB Friction Tester. A specific example of a variable slip device is the Norsemeter Road Analyzer and Recorder (ROAR).

Fixed and variable slip testing devices have not been widely used on highway pavements in the United States and there is no current ASTM standard for fixed slip testing.

British Pendulum Tester

Another method of measuring pavement friction (microtexture, indirectly) is the British (Portable) Pendulum Tester (BPT), which is described completely in ASTM E303.[82] Developed for use as a laboratory test for cores or lab-prepared samples, it can also be used on pavements in the field. The slip speed of the BPN is very slow (typically about 6 mph [10 km/hr]), so the BPN is generally believed to correlate most strongly with pavement microtexture.[8] This is useful, because direct measurement of microtexture is difficult. However, recent studies suggest that the BPN is also influenced by macrotexture in some situations.[83]

Dynamic Friction Tester

The dynamic friction tester (DFT) consists of a disk that spins with its plane parallel to the test surface. Three rubber sliders are mounted on the lower surface of the spinning disk and can reach tangential speeds of up to 56 mph (90 km/hr). Water is placed on the test surface in front of the sliders and the test is performed by lowering the spinning disk to the surface of the pavement and then monitoring the torque as the speed of the disk is slowed to a stop by the friction between the pavement texture and the rubber sliders. The use of this apparatus is described completely in ASTM E-1911.[84]

It should be noted that the rotational nature of the DFT test prevents it from distinguishing directional effects of pavement texture (e.g., it will produce the same values for tining performed in the transverse and longitudinal directions).

Current Surface Friction Criteria and Measurement Practices in the U.S.

FHWA

In 1979, the FHWA provided guidance to state and local highway agencies in establishing textures for concrete pavement through Technical Advisory TA 5040.10 "Texturing and Skid Resistance of Concrete Pavements and Bridge Decks."[85] This document was superceded in June 2005 by TA 5040.36 "Surface Texture for Asphalt and Concrete Pavements."[5] Neither document provides specific recommended values for minimum or desirable pavement friction test results.

AASHTO

The 1976 AASHTO Guide for the Design of Skid Resistant Surfaces is currently being updated under NCHRP Project 1-43.[86] It is expected that the updated guide will provide more specific guidance on considering texture and friction during the pavement design process. New Guidelines for PCC Surfacing Texturing are being developed under NCHRP Project 10-67 and will address the need for adequate friction and for low noise PCC surfaces.[87]

State Highway Agencies

A 1999 survey of U.S. highway agencies revealed that only 11 of 42 responding agencies had published minimum acceptable levels for skid resistance.[8] It appears that many highway agencies are reluctant to assign minimum acceptable friction levels for highway pavements because of liability concerns. In practice, FN40R values of 30 to 40 have generally been considered acceptable for interstate highways and other roads with design speeds greater than 40 mph (64 km/hr)-. Lower friction numbers have generally been accepted for pavements with low traffic volumes (e.g., average daily traffic of less than 3,000 vehicles) and traffic speeds less than 40 mph (64 km/hr).

Table 4.1. FAA Pavement Friction Requirements for Various Test Devices and Speeds[88]

	40 mph (64 km/hr)			60 mph (97 km/hr)		
	Minimum	Maintenance planning	New design/ construction	Minimum	Maintenance planning	New design/ construction
Mu Meter	0.42	0.52	0.72	0.26	0.38	0.66
Dynatest Consulting, Inc. Runway Friction Tester	0.50	0.60	0.82	0.41	0.54	0.72
Airport Equipment Co. Skiddometer	0.50	0.60	0.82	0.34	0.47	0.74
Airport Surface Friction Tester	0.50	0.60	0.82	0.34	0.47	0.74
Airport Technology USA Safegate Friction Tester	0.50	0.60	0.82	0.34	0.47	0.74
Findlay, Irvine, Ltd. Griptester Friction Meter	0.43	0.53	0.74	0.24	0.36	0.64
Tatra Friction Tester	0.48	0.57	0.76	0.42	0.52	0.67
Norsemeter RUNAR (operated at fixed 16% slip)	0.45	0.52	0.69	0.32	0.42	0.63

Federal Aviation Administration (FAA)

FAA Advisory Circular 5320-12C identifies desirable friction and texture values for airfield pavements and provides specifications for implementation.[88] Table 4.1 summarizes current FAA pavement friction threshold values for new construction, maintenance planning and minimum allowable conditions for various testing devices.

The FAA also provides guidance on texture depth, suggesting that the average texture depth (ATD) be 0.045 in. (1.15 mm) or more for new construction and that texture deficiencies should be corrected within 1 year when the ATD in a runway zone falls to between 0.016 in. and 0.030 in. (0.41 mm and 0.76 mm). Corrections should be made within 2 months when the ATD falls below 0.010 in. (0.25 mm).

The FAA guidelines for skid-resistant airport pavement surfaces are considered to be an example of "best practices" that could be modified to address various highway pavement classes.[66]

Current Surface Friction Criteria and Measurement Practices by Non-U.S. Agencies

United Kingdom (U.K.)

The U.K. recently published a revised Skid Resistance Policy that established desirable, investigatory and minimum friction levels for paved highway surfaces based on 15 years of experience.[67] Table 4.2 shows the guidelines that were developed based (in part) on the relationships shown in Figure 4.1. The lightly shaded boxes represent levels that are considered appropriate for lower traffic volume facilities, while the darker boxes generally represent a range of values considered appropriate for higher traffic volume facilities. This approach is considered to be a good example of current "best practice" in pavement friction management.[66]

Table 4.2. U.K. Site Categories and Investigatory Levels for Pavement Friction[after 67]

Site category and definition		Investigatory level at 31 mph (50 km/hr)							
		0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
A	Motorway class	□	■						
B	Dual carriageway, non-event	□	■	■					
C	Single carriageway, non-event		□	■	■				
Q	Approaches to and across minor and major junctions, approaches to roundabouts				■	■	■		
K	Approaches to pedestrian crossings and other high-risk situations					■	■		
R	Roundabout				■	■			
G1	Gradient 5 to 10%, longer than 164 ft (50 m)				■	■			
G2	Gradient > 10%, longer than 164 ft (50 m)				□	■	■		
S1	Bend radius < 1640 ft (500 m) – dual carriageway				■	■			
S2	Bend radius < 1640 ft (500 m) – single carriageway				□	■	■		

■ Dark cells for normal risk. □ Light cells for lower risk (light traffic).

Australia

The Australian National Road Safety Action Plan 2005 and 2006 has a targeted 40 percent reduction in the national per capita highway fatality rate by 2010, with nearly one-half of the fatality rate reduction to come from the use of safer roads.[89] Recommended road safety improvements include better engineering of the roadway, reduced levels of surface distresses, and improved texture and friction. A guide on the management of roadway skid resistance has been published and a second publication provides guidance on establishing texture depth requirements for both new pavements and "investigatory levels" for various site conditions.[89,90]

New Zealand

Transit New Zealand's implementation of a skid resistance strategy on the state highway network (where all roads on the network are tested annually) has reduced crash rates in wet conditions by 30 percent. Crash savings totaling NZ $395 million are anticipated over the first 10 years of the strategy's implementation.[89]

Germany

Skid resistance in Germany is measured using the SCRIM and limiting values, based on 328-ft (100-m) average values, are specified in their new concrete pavement guidelines. These limiting values include a value of 0.46 for acceptance at 50 mph (80 km/hr), with 0.43 triggering warranty corrections. A "warning" value of 0.39 and "threshold" (minimum allowable) value of 0.32 are specified for interstate highways.[41]

Other Countries

Table 4.3 summarizes surface friction intervention levels used in other countries.

Table 4.3. Surface Friction Intervention Levels Outside the U.S. [after 8]

Agency	Highway Classification			
	Interstate/Motorway	Primary	Secondary	Local
Denmark	Speed < 50 mph (80 km/hr), μ = 0.4 Speed > 50 mph (80 km/hr), μ = 0.5 at 37 mph (60 km/hr)			
Hungary	SCRIM > 0.50	SCRIM > 0.40	SCRIM > 0.33	
Japan	Friction > 0.25			
Netherlands	DWW > 38	DWW > 38		
New South Wales	Varies (see guidelines): SCRIM > 0.30 – 0.55			
New Zealand	SCRIM > 0.55 on event sites, 0.35 for non-event sites			
Quebec	SCRIM > 0.7	SCRIM > 0.7	SCRIM > 0.55	SCRIM > 0.40
South Australia	BPN > 45	BPN > 45	BPN > 45	BPN > 40
Switzerland	Same as for construction and rehabilitation (see Table 6, Reference 12)			
United Kingdom	Investigatory levels (described previously)			
Victoria	Depends on conditions: SCRIM > 0.35 – 0.55			

Notes: SCRIM = Sideways–Force Coefficient Routine Investigation Machine; DWW = Dienst weg- en Waterbouwkunde Friction Tester; BPN = British Pendulum Number.

Chapter 5.
Controlling Sound from the Highway Environment

HOW MUCH SOUND IS TOO MUCH?

Excessive amounts of noise contribute to a variety of problems, including hearing loss, sleep disturbance, interference with communication, and some physical health problems typically associated with stress, such as cardio-vascular problems.[1,91,92] The levels of sound required to produce these problems depend on many factors, including the frequency spectrum associated with the sound, the sources and context of the sound, and individual tolerance to various types of noise and different noise levels. A 1995 report by Berglund and Lindvall[93] (currently available online through the World Health Organization website at www.who.int) provides extensive information concerning the effects of noise and provides very conservative recommendations for limiting overall noise levels in various contexts.

CURRENT FHWA PAVEMENT AND ENVIRONMENTAL POLICIES

For each federally funded highway project being considered, current federal law requires that highway agencies determine and analyze expected traffic noise impacts and alternative noise abatement measures to mitigate these impacts, giving weight to the benefits and costs of abatement, and to the overall social, economic and environmental effects. Details concerning FHWA policy in this area are presented in References 94 and 95.

It should be noted that federal law *does not require that noise levels be abated to any particular levels.* It stipulates that the views of impacted residents be *considered* in selecting noise abatement procedures, but it does not require that those views control the design process. Federal pavement policies also state that the plans and specifications for each federally funded highway project must be developed to "adequately serve the existing and planned future traffic of the highway in a manner that is conducive to safety, durability, and economy of maintenance.[95] *Therefore, the selection of pavement surfaces that reduce tire-pavement noise at the cost of significant reductions in pavement safety and durability are unacceptable.*

CONTROLLING SOUND FROM THE HIGHWAY ENVIRONMENT

For highway purposes it is useful to think of the generation and perception of noise in terms of three components: a source, a path and a receiver. Trucks and passenger cars are typical sources. Nearby businesses and private property owners are typical receivers. The path is the route that the sound must take to travel from the source to the receiver – generally a straight line in cases where no sound reducing measures or features are present. Sound from highways can be controlled at any (or all) of these three components.

Control at the Receiver

The primary technique for controlling the perception of sound at the receiver is providing acoustic insulation, which is useful only for receptors that are inside of buildings or vehicles. This technique is generally *very* expensive. For example, the insulation of Minneapolis area homes to mitigate aircraft noise cost an average of $40,400 per house in 1999; actual costs varied with the size and type of home and the insulation methods being used.[96] Acoustic insulation is completely effective only if all doors and windows in the building or vehicle remain closed.

Control Along the Path

Noise control along the sound path is often attempted in two ways: through increased distance or by inserting an obstruction (e.g., walls, berms, vegetation, etc.) between the source and receivers. Both methods can effectively reduce noise levels.

Mitigation Through Distance

Increasing the distance between the source and receiver is a very effective means of noise control. If a traffic stream is considered to approximate a line source, the rate of sound pressure reduction with distance is about 3 dBA for each doubling of distance between the source and receiver. For example, if the noise level from a stream of vehicles (a line source) at 50 ft (15 m) was 70 dBA, it would be about 67 dBA at 100 ft (30.5 m) and about 64 dBA at 200 ft (61 m). *With enough distance, any highway noise can be reduced to acceptable levels.* In fact, much larger changes in sound level can be achieved by changing this distance than by changing pavement surface characteristics.[30]

Changing the Sound Path: Barriers, Berms, Bushes and More

Barriers

The second form of noise control consists of the use of walls, berms and other devices to intercept or absorb the sound. Noise barriers are solid obstructions built between highways and homes or businesses along the highway and are the most common approach for reducing the impact of highway noise on adjacent properties. They are typically effective in reducing noise for receptors located within 200 ft (61 m) of the pavement. A noise barrier can achieve a 5 dB(A) noise level reduction when it is tall enough to break the line-of-sight from the highway to the receiver; an additional noise reduction of about 1 dB(A) can achieved with every 2 ft (0.6 m) of additional barrier height above the height required to break the line-of-sight. Since sound diffracts around the ends of barriers, it is a generally accepted that noise walls should extend 4 times as far in each direction as the distance from the receiver to the barrier. Openings in noise walls for driveways and intersecting streets degrade the effectiveness of barriers, making them impractical in many urban settings.[54]

Noise walls are generally very expensive, with reported costs of $1 – 5 million/mi ($0.62 – 3.1 million/km), depending upon the wall material, height, location and architectural details.[26] The FHWA reports that state highway agencies spent *more than $1.4B* on noise walls prior to 1998; that number has certainly increased greatly since then.[26] In addition, noise walls do not reduce noise at the source, so they do not mitigate in-vehicle noise.

The bottom line is that *noise walls are generally not considered to be the most cost-effective solution to highway noise problems, but they are typically highly desired by residents along highways.*[2]

Berms and Vegetation

"Berms" are mounds of earth that are constructed along the side of a roadway to provide a natural barrier to the sights and sounds of the highway environment. Berms typically provide slightly greater noise reductions than do sound walls of the same height (due to the acoustically absorptive characteristics of soils). Unfortunately, berms occupy a great deal of space (a 10-ft [3.05-m] tall berm typically extends 35 ft [11 m] on each side of the peak) and the cost of land and construction fill can make them economically unfeasible.

Trees, bushes and other vegetation may be aesthetically pleasing, but generally provide only minor acoustical benefits.

Other Sound Path Changes

Other strategies for noise mitigation along the sound path include the use of acoustically absorptive materials in the shoulder paving, and alteration of the horizontal and/or vertical alignment of the highway. These approaches and others are generally of limited usefulness.

Control at the Source

Factors that highway engineers can modify for controlling sound at the source include traffic composition, vehicle speed and pavement surface characteristics.

Traffic Control (Truck Restrictions, Vehicle Speed Restrictions)

Traffic noise generally increases with both vehicle speed and as the number of trucks in the mix increases, so reductions in highway traffic noise can be achieved by restricting either or both of these factors. This has been done successfully in some urban areas, such as a portion of Interstate 35E in St, Paul, Minnesota, where trucks over 9000 lbs are not permitted and the posted speed limit is 45 mph (72 km/hr).

The magnitudes of noise reduction that can be accomplished depend upon the magnitude of speed reduction and the number and nature of trucks that can be eliminated from the traffic stream. Table 5.1 illustrates typical sound reduction values for a small series of combinations of these variables for a specific project.

The elimination of heavy vehicle traffic is a useful option only where acceptable alternate travel routes exist for those vehicles. Reductions in speed limits are effective only where they are supported and can be reasonably enforced (e.g., in some urban areas).

Table 5.1. One-Hour Equivalent Sound Levels at 150 ft (45 m) from Roadway[97]

Vehicles per hour				
Autos	Medium trucks	Heavy trucks	Speed, mph (km/hr)	L_{eq}(h), dB(A)
1500	100	200	65 (105)	67
1500	100	200	50 (80)	64
1500	100	0	65 (105)	63
1500	0	0	65 (105)	62

Management of Pavement Surface Texture

Managing pavement surfaces allows some control of noise at a primary source – the tire-pavement interface. By reducing noise at the source, propagation and environmental effects become less important. This approach to noise management generally has a relatively low initial cost (especially in new construction) because it typically involves only minimal material and labor and has little (if any) impact on structural design. The degradation of acoustic properties for certain surfaces is a drawback of this approach. Maintenance and user impact may be high for thin asphalt overlays, as an example.

Pavement Texture vs. Pavement Type

Highway engineers today are subject to ever-increasing pressure to significantly reduce traffic noise levels. This has driven interest in the development and use of "quiet pavements" that achieve significant noise reductions through designed surface characteristics, such as macrotexture and porosity. These properties are independent of pavement type and, like pavement friction and smoothness, can be managed over time using traditional pavement management tools.

Managing pavement surface texture does not imply selection of surface type. The FHWA has never allowed pavement *type* (i.e., asphalt vs. concrete) to be used as a noise mitigation strategy because it is recognized that many significant components of highway noise (e.g., heavy vehicle engine, exhaust, etc.) are independent of pavement type. However, pavement type and structure can impact the rate of change and durability of surface characteristics and *can* strongly influence the true cost and long-term effectiveness of noise mitigation. This is described more fully in Chapter 6 and should be considered in the overall pavement design process when noise mitigation is important.

Managing Pavement Surface Characteristics for Noise Control

Three approaches to pavement surface characteristic management are most effective in reducing tire-pavement interaction noise when other factors are held constant:

- reduce pavement surface megatexture in the 2 – 4 in. (50 – 100 mm) wavelength range,
- reduce air displacement by controlling macrotexture in the 0.2 – 2.0 in. (10 – 50 mm) wavelength range, and
- increase impedance to sound through increased pavement surface porosity.

Of these three approaches, it is generally believed that altering pavement macrotexture is the key to controlling noise generated by tire-pavement interaction (although significant noise reductions can also be achieved with porous pavements as well).

There are several approaches to designing and constructing new concrete pavements with safe, quiet surfaces. These include modern versions of several traditional concrete pavement texturing techniques, such as transverse and longitudinal tining, and broomed, brushed and turf drag textures. Also included are newer paving techniques and materials, such as exposed aggregate and porous concrete. There are also several approaches to modifying existing concrete pavements to produce the improved texture and porosity characteristics described previously, including the use of overlays (both asphalt and concrete) and the use of surface removal techniques (e.g., diamond grinding, grooving, shotblasting, etc.). Chapter 6 provides information concerning the relative effectiveness of each of these techniques in controlling tire-pavement noise while providing good surface friction characteristics.

Caveat for Selecting Surface Textures to Reduce Tire-Pavement Noise

The surface characteristics and quality of any surface texture selected to reduce tire-pavement interaction noise emissions also strongly influence the pavement's wet-weather safety (surface friction and splash and spray). Current FHWA guidelines and the 1993 *AASHTO Guide on the Evaluation and Abatement of Traffic Noise* recommend that the designer should never jeopardize safety to obtain a reduction in noise. A deliberate effort must be made to select surface textures that provide safety and comfort to the traveling public, are sufficiently durable to remain effective for a long period of time while, and are life-cycle cost-effective.

Chapter 6. Concrete Pavement Surfaces – Construction and Characteristics

New concrete pavement surfaces can be constructed with many different types of textures, including various forms of dragged and tined surfaces, exposed aggregate finishes, and several newer techniques and materials. In addition, hardened concrete pavement surfaces can be modified through diamond grinding and grooving, overlays and other approaches. Studies have shown that significant noise-reduction can be achieved with only modest variations of typical current practices of these techniques.

This section describes the development of concrete pavement texturing in the U.S. and discusses common texturing techniques in more detail, including their effects on tire-pavement noise and safety.

A BRIEF HISTORY OF CONCRETE PAVEMENT TEXTURING IN THE U.S.

Early methods of texturing new concrete pavement surfaces in the U.S. consisted mainly of "shallow" texturing techniques, such as broom finishing, burlap dragging and belting (the longitudinal dragging of narrow canvas or rubber belts along the surface with periodic small transverse movements), applied to concrete surfaces still in the plastic state.[14] As of 1969, 46 states were using burlap dragging as their primary texturing technique for new concrete pavements.[12]

While shallow texturing techniques were adequate in times when vehicle volumes and speeds were relatively low, such textures (as they were constructed in the 1950s and early 1960s) were unable to provide adequate friction as vehicle speeds increased, especially in wet weather. Awareness of the need for improved friction can be traced back to 1959, when the first Skid Conference was held in Charlottesville, Virginia.[98] It has been reported that videotape of "highly disturbing skidding incidents on Interstate segments in the Washington, D.C. area" was used in a 1971 congressional subcommittee hearing that resulted in the FHWA being charged with giving states the leadership in preventing skidding accidents.[99]

State highway agencies recognized the need for pavement surfaces with better friction characteristics, and many began to experiment with different machines and finishing tools in an effort to produce "deep" macrotexture on fresh (plastic) concrete.[12,100] These techniques included the use of brooms, tining rakes or "combs", roller imprints, and the use of coarse polyethylene artificial turf drags that were inverted and drawn over the plastic concrete surface.[100] Independent highway agency studies performed during the 1970s demonstrated that transverse tining improved concrete pavement surface friction characteristics.[101,102,103,104] Texturing guidelines published by the American Concrete Pavement Association (ACPA) in 1975 and by the American Association of State Highway and Transportation Officials (AASHTO) in 1976 reflected these research results and recommended transverse tining or grooving over the traditional practices of burlap dragging or brooming, especially for high-speed pavements.[105,106] By the end of the 1970s, more than 33 states were using, or planning to use, transverse tining as their primary texturing technique on plastic concrete pavement surfaces.[102]

Transverse tining continues to be the most commonly used technique for texturing highway pavements today. However, tining patterns have evolved and some agencies have moved towards the use of longitudinal tining and deep turf-drag textures. These changes have greatly reduced tire-pavement noise while continuing to provide superior wet-weather friction on concrete pavements.[14]

TRADITIONAL TEXTURING OF PLASTIC CONCRETE

There are several approaches to texturing new and existing concrete pavements, as shown in Table 6.1. Each of the approaches listed can be designed and constructed to provide durable, safe, high-friction surfaces with relatively low potential for tire-pavement noise. The following sections describe the design and construction of several of the most common concrete pavement texturing techniques and discuss the durability, friction and tire-pavement noise emission characteristics of each.

Table 6.1. Typical PCC Pavement Texturing Techniques[53]

Texture for fresh concrete	Description
Burlap dragging	Produced by dragging moistened coarse burlap from a device that allows control of the time and rate of texturing – usually a construction bridge that spans the pavement. Produces 1⁄16- to 1⁄8-in. (1.5- to 3-mm) deep striations.
Artificial turf dragging	Produced by dragging an inverted section of artificial turf from a device that allows control of the time and rate of texturing – usually a construction bridge that spans the pavement. Produces 1⁄16- to 1⁄8-in.(1.5- to 3-mm) deep striations when using turf with 7,200 blades/ft^2 (77,500 blades/m^2).
Transverse brooming	Obtained using either a hand broom or mechanical broom device that lightly drags the stiff bristles across the surface. Produces 1⁄16- to 1⁄8-in.(1.5- to 3-mm) deep striations.
Longitudinal brooming	Achieved in similar manner as transverse broom, except that broom is pulled in a line parallel to the pavement centerline.
Transverse tining (perpendicular or skewed)	Achieved by a mechanical device equipped with a tining head (metal rake) that moves across the width of the paving surface transversely or on a skew. A hand tool may be used on small areas.
Longitudinal tining	Achieved in similar manner as transverse tining, except the tines are pulled in a line parallel to the pavement centerline.
Exposed aggregate	Occasional European practice of applying a set retarder to the new concrete pavement, and then washing or brushing away mortar to expose durable aggregates.
Texture for hardened concrete	**Description**
Diamond grinding	Longitudinal, corduroy-like texture made by equipment using diamond saw blades gang-mounted on a cutting head. The cutting head produces 50 to 60 grooves/foot (164 to 197 grooves/meter) and can remove 1⁄8 to 3⁄4 in. (3 to 20 mm) from the pavement surface.
Diamond grooving	Grooves sawed (typically longitudinally) into the pavement surface using ganged saw blades spaced appropriately on a rotating head. The resulting grooves are typically 1⁄4 in. (6 mm) deep, 1⁄8 in. (3 mm) wide, and spaced 3⁄4 in. (19 mm) apart.
Abrading (shotblasting)	Etched surface produced by equipment that hurls abrasive media at the surface from within an enclosed housing. The abrasive media impacts the surface and removes a thin layer of mortar and aggregate. The depth of removal is shallow but controllable.

Drag Textures

Until the mid-1960s, new concrete pavement texturing was achieved primarily through shallow texturing techniques, such as a burlap drag, belting, or brooming. A 1969 report stated that 60 percent of the highway departments used burlap drag, and 12 percent specified either a burlap drag or a broom finish.[107] More recently developed drag-type textures include longitudinal brushing and artificial turf drag. Each is described below.

Burlap Dragging

Burlap drag (also known as hessian drag) texturing is created by dragging moistened, coarse burlap across the surface of the pavement to create a very shallow longitudinal texture (typically 0.008 inches [0.2 mm]), with texture depth varying with burlap coarseness, concrete mix design and finishing conditions. Figure 6.1 illustrates a typical burlap drag surface texture.

Figure 6.1. Photograph of a typical concrete surface created using burlap drag.

This texture is constructed easily and inexpensively and is relatively quiet, but may not provide adequate wet weather friction at high speeds unless combined with other features. Many German concrete highway pavements are finished with a burlap drag texture in lieu of tining because of concerns about pavement noise. These pavements typically have 2 percent cross-slope, which is more than has been used in the U.S. until recently (the current U.S. standard for Interstate highways is 2 percent) and may account for some of their improved wet weather performance through improved surface drainage. However, the frictional characteristics of these pavements often decrease over time and under traffic.[10,108]

Broomed Surfaces – Transverse and Longitudinal

Broomed surface textures are created by dragging a hand broom or mechanical broom along the surface of the pavement, creating shallow surface ridges with texture depth ranging from 0.008 to 0.012 in. (0.2 to 0.3 mm).[30,51] Broomed textures may be constructed either longitudinally or transversely. Figure 6.2 is a photograph of a broomed concrete pavement surface.

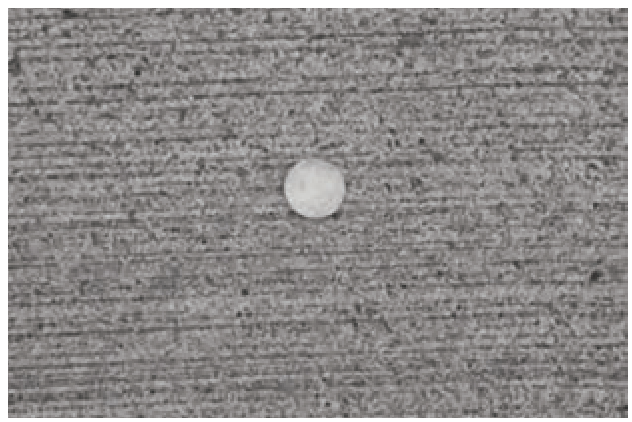


Figure 6.2. Photograph of a typical concrete surface created using transverse brooming.[109]

Like burlap drag textures, broomed surface textures are constructed easily and inexpensively and are relatively quiet, but may not provide adequate wet weather friction at high speeds unless combined with other features. However, if measures are taken to ensure adequate friction and wear resistance, these techniques should be acceptable for many lower speed facilities.[10]

Longitudinal Plastic Brushing

This process consists of a longitudinal burlap drag followed by longitudinal dragging of a plastic-bristled brush. The resulting texture is deeper than those described previously (mean texture depth of 0.03 to 0.04 in. [0.7 to 1.0 mm]). A minimum of 30 percent siliceous sand is typically specified for the concrete mixture to provide satisfactory microtexture.[14]

It has been reported that surfaces constructed with this texture have friction characteristics similar to those of porous asphalt pavements, and successful installations in Spain have shown this technique to be effective at providing good friction characteristics while minimizing tire-pavement noise.[4] However, data are not available to compare wet weather accident rates between this type of texture and others.

Artificial Turf Dragging

Artificial turf drag surfaces are created by dragging an inverted section of artificial turf along the plastic surface of the concrete pavement. Early versions of this process produced textures that were similar to those produced by burlap dragging and longitudinal brooming, with typical texture depths of 0.03 to 0.04 in. (0.7 to 1.0 mm). Like those other shallow texturing techniques, early turf drag textures commonly resulted in quiet pavements, but there were still concerns regarding wet weather skid resistance, particularly for high-speed facilities.[10]

In the late 1990s, the Minnesota Department of Transportation (MnDOT) re-evaluated concrete pavement surface texturing practices and, in 1999, developed and adopted a modified turf drag texturing process and specification to produce a much deeper and more durable texture than previous turf drag textures. Because the resulting surface texture offers good wet weather friction and is as quiet as typical asphalt surfaces (as described in later sections), artificial turf drag is now the sole texturing technique on all new concrete pavements in Minnesota, and other agencies are reconsidering its use.

The Minnesota turf drag texture is constructed using a large strip of artificial turf containing a minimum of 7200 blades of artificial grass per square foot (77,500 blades per m^2). The turf section is inverted (grassy side down) and is typically attached to the construction bridge or other equipment that controls the time and rate of texturing. The turf is weighted (typically using aggregate or other construction materials) to ensure deep penetration of the turf into the plastic concrete, as shown in Figures 6.3 and 6.4.

Figure 6.3. Photos of aggregate weighting on Astroturf drag (photos provided courtesy of Mr. Doug Schwartz, Minnesota DOT).

Figure 6.4. Photo of Minnesota concrete pavement textured by Astroturf drag prior to joint sawing and pavement sweeping (photo provided courtesy of Mr. Doug Schwartz, Minnesota DOT).

Minnesota's current artificial turf drag specification requires production of a mean texture depth of 0.04 in. (1.0 mm) or more (based on an average of 4 sand patch tests per day) and has a goal of creating an FN40S of about 32 and an FN40R of about 45. Collected friction and noise data indicate that the MnDOT artificial turf drag texture provides surface friction and noise qualities that are comparable to (and more durable than) those provided by asphalt pavements.[26,47]

It is important to note that the depth and durability of MnDOT's turf drag textures are made possible, at least in part, by MnDOT's concrete mix design specification, which limits the water-cement ratio to 0.40 and provides the contractor with financial incentives for providing even lower ratios (down to 0.35). A stiff mix is essential to producing the required texture.

Tined Textures

The recognition of the need for improved pavement friction in the early 1970s led to rapid changes in pavement texturing. By the mid-1970s, the most common concrete pavement texturing practices often featured a shallow texturing technique (such as burlap dragging) in combination with deeper transverse grooves produced by drawing a "tining head" (typically a rake-like structure with long, thin metal teeth) across or along a plastic concrete surface to produce a pattern of relatively shallow grooves, as shown in Figure 6.5.[12]

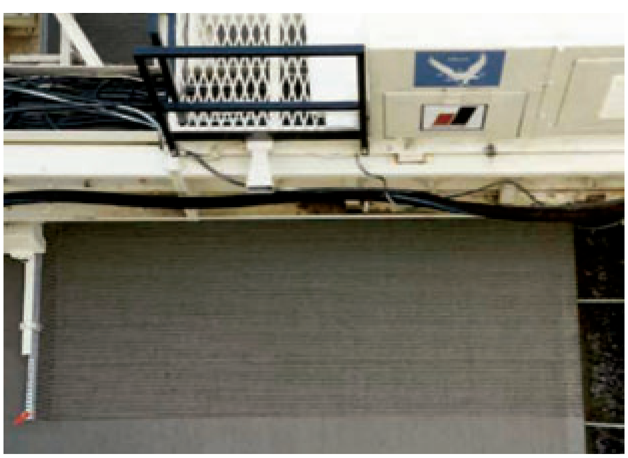


Figure 6.5. Transverse tining (uniform spacing) of a plastic concrete pavement surface.[110]

Tined textures can be produced using hand tools or automated equipment within a paving train. The resulting surface grooves or tining marks provide channels (similar to tread grooves on a tire) through which water can escape the tire-pavement contact patch, thereby allowing better contact between the tire and pavement surfaces and reducing hydroplaning potential.

Transverse Tining

Transverse tining (often preceded by longitudinal drag texturing) is produced by drawing the tining head across the pavement surface, perpendicular to the flow of traffic. This is currently the texturing method most commonly used on higher-speed (50 mph [80 km/hr] or greater) concrete pavements in the U.S. It has proven to be an economical approach for consistently providing durable, high-friction surfaces on new PCC pavements. Figure 6.6 shows examples of transverse tine marks on concrete pavement.

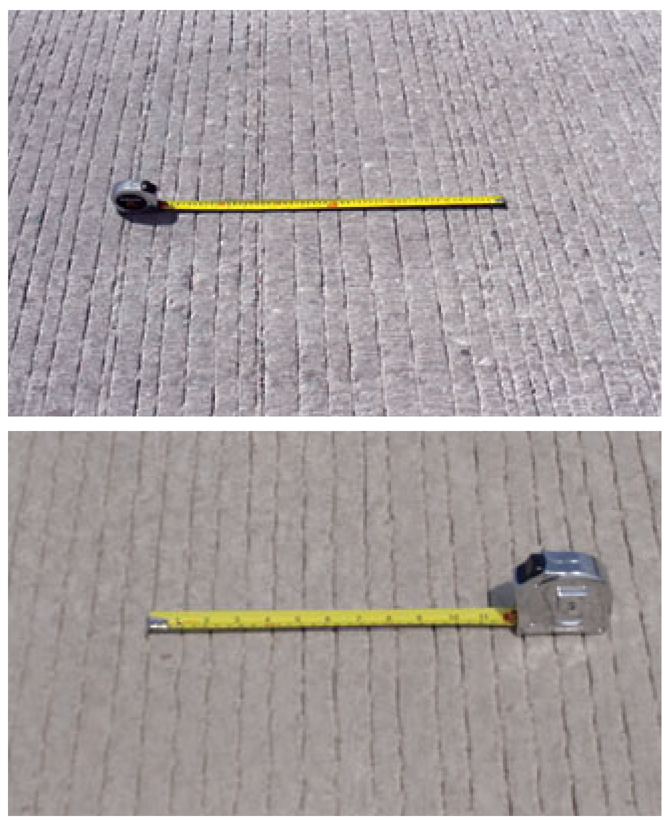


Figure 6.6. Photos of randomly spaced tining, transverse (top) and skewed (bottom).

The durability of transversely tined surfaces is related mainly to the quality of the concrete (including the quality of the coarse and fine aggregates) and the spacing and depth of the tine marks. Tine marks that are spaced too closely have a higher potential for spalling under traffic and snow removal operations, which can lead to pavement roughness and reduced surface friction. For example, it has been noted that concrete pavements with tine marks spaced uniformly at 0.5 in. (13 mm) center-to-center have been less durable than pavements with wider tine mark spacings.[4] Experience suggests that transverse tining can provide adequate surface friction characteristics for 30 years or longer when good construction practices and high-quality materials are used (and when there is minimal exposure to studded tires and tire chains).[4,14] While these deeper transverse texture patterns have greatly improved the wet weather friction characteristics of concrete pavements, they have also been associated with tire-pavement interaction sounds with objectionable tonal qualities – i.e., a "whine."

The sounds produced by the interaction of tires and transversely tined pavements are strongly correlated with the width, depth and spacing of the tine marks. Typical pavement texturing heads have tines that are about 0.12 in. (3 mm) wide, and they are set up to produce texture depths of 0.12 to 0.24 in. (3 to 6 mm).[111] Recent research has led to the development of nonuniform (often called "random") transverse tine spacing patterns that attempt to eliminate this "whine." The influence of transverse tine spacing on tire-pavement noise is discussed in the following sections.

Uniform Spacing Patterns

The individual tines on a tining head can be spaced either uniformly or in a random pattern. Uniform transverse tine spacings (such as the one shown in Figure 6.5) typically range from 0.5 to 1.0 in. (13 to 25 mm) and generally interact with vehicle tires to produce sounds with specific frequency spikes or "tones" (whining) that correspond to the tine spacing and vehicle speed. The frequency of the tone can be computed as the number of tine marks or grooves that the tire crosses in one second. For example, at 60 mph (100 km/hr), the tonal frequencies for various tine spacings are shown below:

- 1.50-in.(38-mm) spacing = 704 Hz
- 1.00-in.(25-mm) spacing = 1056 Hz
- 0.75-in.(18-mm) spacing = 1408 Hz
- 0.50-in.(13-mm) spacing = 2112 Hz

Because people tend to be particularly sensitive to tones in the 700 – 1200 Hz frequency range, it is clear that the 1.0-in. and 1.5-in. (25-mm and 38-mm) uniform tine spacings should be avoided for 60-mph (100-km/hr])pavements. Even wider spacings should be avoided at higher travel speeds (such as on Interstate highways).

It should be emphasized that the total sound level (in dBA) associated with a particular transversely tined surface may *not* necessarily be higher than the sound levels associated with other texturing methods; however, human sensitivity to certain tones or frequencies of sound may make the sound from the transversely tined pavement seem louder or more objectionable.

"Random" Spacing Patterns

Nonuniform (or so-called "random") tine spacings (such as the one shown in Figure 6.6) can be used to produce tire-pavement interaction sounds that lack objectionable tonal peaks. Random tine patterns typically contain highly variable spacings that range from 0.4 to 3 in. (10 to 76 mm), with a limitation on the content of spacings greater than 1 in. (25 mm).[10,111] The typical targeted average texture depth is 0.03 in. (0.8 mm) (with a minimum of 0.02 in. [0.5 mm] for individual tests), as measured by the sand patch test (ASTM E 965).[14]

Using this full range of spacings in a randomly generated repeated pattern can be effective if tining is being performed by a machine that can adequately control the tining spacing, contact pressure and timing of texturing (where pressure and timing control tining depth). The following tine spacing pattern was developed in Wisconsin and has been widely adopted for use with a 10-ft (3-m) rake equipped with 0.12-in. (3-mm) tines:

Tine Spacing (Center-to-Center, mm)[30]

58 74 31 62 53 32 21 26 33 28 59 64 73
70 29 70 54 49 20 22 67 78 77 23 15 15
41 60 25 32 39 75 28 50 55 51 72 25 69
21 47 15 59 47 64 34 55 35 24 22 42 14
45 73 76 41 41 22 15 16 71 41 62 21 31
17 70 58 29 Total Length: 3000 mm

When less optimal finishing conditions are present (e.g., for manual finishing where there is less control over the tining process or in hot and windy conditions), a random, repeated pattern containing spacings that vary between 0.4 and 2 in. (10 and 50 mm) is recommended to improve the likelihood of achieving targeted texture depths.[14] The Pennsylvania DOT recommends the pattern described in Figure 6.7 for this spacing range.

Studies of the safety, noise and other characteristics of several pavement surfaces (including transversely tined, diamond ground and other surfaces) have concluded that randomly spaced tining can adequately prevent audible "wheel whine."[10,110] However, it should be noted that Wisconsin, the state that originally developed the random tining pattern described previously, is now moving away from all forms of transverse tining in favor of longitudinal tining, which more consistently results in lower tire-pavement noise because it is not as sensitive to tining depth, as is described later in this section.

Effects of Transverse Tining Depth and Width on Noise and Friction

A study conducted by the Wisconsin Department of Transportation found that deeper, wider tine marks generally produce higher levels of tire-pavement interaction sound than shallow, narrow tine marks.[30] The effects of depth and width could not be separated because deeper tine marks tended to also be wider. It is believed that objectionable sound can be minimized by using tine widths of 0.125 ± 0.02 in. (3 ± 0.5 mm) with tine mark depths of between 0.125 and 0.25 in. (3 and 6 mm), taking care to avoid dislodging embedded aggregate particles in the tining process.[14] Some agencies have adopted even shallower depth requirements, and tining depths of 1/16 – 1/8 in. (1.5 – 3 mm) are considered by some to be quietest while still providing good friction.

TABLE A (Metric) Center-to-Center Tine Spacing

34	36	47	54	48	43	32	31	27	36	29	46	21	43	23
42	52	24	18	28	40	34	27	26	25	27	20	37	38	52
51	45	37	43	53	14	27	37	42	41	29	43	14	45	44
30	37	33	40	28	31	50	34	45	15	20	45	50	16	53
51	29	25	18	16	53	18	38	51	40	17	15	49	50	39
51	36	36	38	46	29	38	50	24	33	mm				

TABLE B (English) Center-to-Center Tine Spacing

1⅜	1⅜	1⅞	2⅛	1⅞	1¾	1¼	1¼	1⅛	1⅜	1⅛	1¾	⅞	1¾	⅞
1⅝	2	1	¾	1⅛	1⅝	1⅜	1⅛	1	1	1⅛	¾	1½	1½	2
2	1¾	1½	1¾	2⅛	½	1⅛	1½	1⅝	1⅝	1⅛	1¾	½	1¾	1¾
1⅛	1½	1¼	1⅝	1⅛	1¼	2	1⅜	1¾	⅝	¾	1¾	2	⅝	2⅛
2	1⅛	1	¾	⅝	2⅛	¾	1½	2	1⅝	⅝	⅝	1⅞	2	1½
2	1⅜	1⅜	1½	1¾	1⅛	1½	2	1	1¼	(m)				

Figure 6.7. Pennsylvania DOT specification for transverse tine spacing (0 – 2 in. [0 – 50 m] range).[112]

Effects of Skewed Tine Marks on Noise and Friction

The skewing of transverse tine marks (to produce a pattern that is not exactly perpendicular to the direction of traffic, as shown in Figure 6.6) has been found to provide the friction associated with transversely tined pavements while also reducing tire-pavement interaction noise. A longitudinal-to-transverse offset ratio of 1:6 has been recommended, with the direction of tine mark skewing opposite that of any joint skewing (i.e., tining skewed left side ahead when joints are skewed right side ahead). A Wisconsin study found that *this type of surface produced the lowest levels of interior sound of any pavement type tested, including asphalt pavements.*[30] It should be noted, however, that the noise characteristics of this type of texture, as with other variants of transverse tining, are highly dependent on texture depth, which has not been well-controlled on typical construction projects.

Table 6.2 summarizes current recommendations concerning the design and construction of transverse tining for concrete pavements.

Longitudinal Tining

Longitudinally tined textures are constructed similarly to transverse tining, except that the tining head is moved longitudinally along the direction of paving. An example of a pavement with longitudinal tine marks is shown in Figure 6.8. Although historically not as popular as transverse tining, longitudinal tining has been used in California, Virginia, Iowa, Michigan, Minnesota, and Colorado, as well as in Sweden and other countries; it is now seeing in-

Figure 6.8. Concrete pavement surface textured with longitudinal tining.

Table 6.2. Current Recommendations Concerning Transverse Tining Design and Construction *after 14*

Transverse Tining Recommendations	
Tine spacing	Uniform spacing of 0.5 in. (13 mm) – OR – Repeated random spacing of 0.4 to 3 in. (10 to 76 mm) *(Recommended when texturing conditions [i.e., timing, tine length, spacing and pressure] can be controlled well.)* – OR – Repeated random spacing of 0.4 to 2 in. (10 to 51 mm) *(Recommended when there is less control over tining [i.e., manual operations] or in hot or windy conditions.)*
Pattern Depth	0.063 to 0.25 in. (1.5 to 6 mm) (0.063 to 0.125 in. [1.5 to 3 mm] preferred for optimal noise benefits)
Width of Tine Marks	0.125 in. (3 mm)
Orientation of Tining	1:6 skew, with skew direction opposite that of any transverse joint skewing
Additional Texture	Turf or burlap drag prior to transverse tining to provide additional macrotexture

creased use in other states (including Wisconsin) and countries as well.[2,4]

Longitudinal tining is generally reported to result in lower overall noise levels and much less tonality than transversely tined surfaces.[10,14,111,113,114] However, studies have also shown that longitudinally tined surfaces may have slightly lower (but still generally satisfactory) friction numbers than transversely tined pavements when all other factors are held constant.[14] These lower friction numbers (in comparison to transversely tined surfaces) are sometimes attributed to the belief that, for equal cross-slope conditions, water doesn't drain as quickly from longitudinally tined surfaces as it does from transversely tined or grooved surfaces.[10] In addition, some longitudinally tined concrete pavements have proven to be more susceptible to splash and spray problems than their transversely tined counterparts.[4] All of these problems are more likely to be observed on flat grades or sag areas in wet climates; they can be mitigated by increasing the pavement cross slope to 2 – 2.5 percent to provide better surface drainage.[10]

It has also been reported that longitudinal tining may increase the probability of icy pavement conditions due to entrapment of water in the longitudinal channels, particularly at sag vertical curves and superelevation transitions in areas that experience freezing temperatures.[4] However, this phenomenon has not been widely reported or documented.

In addition to reduced noise levels, longitudinal tining also offers a clear advantage over transverse tining on horizontal curve sections, where the longitudinal texture provides better resistance to lateral slip and skid, allowing vehicles to track the curve more accurately.[115]

Spacing Pattern and Depth Considerations

One longitudinal tining pattern that is recommended to produce acceptable wet weather friction with low levels of tire-pavement sound features a uniform tine spacing of 0.75 in. (19 mm) produced using tines that are 0.12 ± 0.2 in. (3 ± 0.5 mm) in width. Tine mark depth should be in the 0.12 to 0.24 in. (3 to 6 mm) range to produce a mean texture depth of 0.02 to 0.03 in. (0.5 to 0.8 mm) for individual results measured using the ASTM E 965 sand patch test.[4] Wider tine spacings should be avoided because motorcyclists and drivers of vehicles with smaller tires often report feeling a slight loss of steering control (sometimes called "squirming") on such pavement textures.[102] Deeper tining marks may produce higher levels of tire-pavement interaction sound and should be avoided.[30]

Design and Construction Considerations

Concrete mixtures intended for use in pavements that will be longitudinally tined should contain *at least* 25 percent siliceous sand to improve the microtexture of the pavement surface.[11] Caltrans, for example, specifies a minimum siliceous sand content of 30 percent and a minimum friction coefficient of 0.30 using its standard test procedure.[4] It is also commonly recommended that the surface be dragged with burlap or artificial turf prior to the longitudinal tining to provide additional macrotexture.[14] These practices ensure good surface friction characteristics in most areas that aren't subject to high studded tire usage.[1,14,116]

Table 6.3 presents a summary of current recommendations concerning longitudinal tining design and construction.

Table 6.3. Current Recommendations Concerning Longitudinal Tining Design and Construction[after 14]

Transverse Tining Recommendations	
Tine spacing	Uniform spacing of 0.75 in. (19 mm)
Pattern Depth	0.125 to 0.25 in. (3 to 6 mm)
Width of Tine Marks	0.125 in. (3 mm)
Mix Design	Minimum of 25 percent siliceous sand and highly durable coarse aggregate are recommended to assure both good friction properties and low-noise characteristics
Additional Texture	Turf or burlap drag prior to transverse tining to provide additional macrotexture

The Need for a "Systems Approach" to Surface Texture Design

The effectiveness of each of the concrete pavement surface textures described previously depends upon many factors, including material properties, finishing techniques, timing, and pavement geometrics. For example:

- Minnesota's success with turf drag textures can be attributed, in part, to the requirement of a low water-to-cement ratio (0.40 maximum, with contractor pay incentives down to 0.35), which helps to ensure that the paste is stiff enough to remain standing after the turf drag passes.
- Minnesota's lower water-to-cement values also help to produce mixes that are sufficiently strong and durable to resist abrasion and wear over time.
- Mix stiffness and proportions can also influence texture depth and uniformity, along with the surface width of tine marks, which is believed to influence tire-pavement noise for transversely tined pavements.
- Mix stiffness and timing of the texturing operation must also be considered in selecting the pressure used to create the surface texture.
- Pavement cross-slope and location of the pavement crown influence pavement surface drainage length, water film thickness and drainage time.

It is clear that a "systems approach" must be used to design and construct pavements that successfully provide quiet and safe travel for many years. The mix design must be selected to provide adequate texture durability, the construction techniques must be selected in consideration of the mix design and must be performed at the proper time to ensure the proper texture depth and uniformity, and the pavement surface geometry (cross-slope and drainage length) must ensure that drainage times and water film thicknesses do not exceed critical levels. *It is rarely sufficient to blindly specify a particular type of pavement texture (e.g., transverse tining) without considering the design and construction of the rest of the pavement surface system parameters.*

NEWER CONCRETE MATERIALS AND SURFACES FOR SOUND REDUCTION

A number of newer texturing techniques and paving materials have been implemented to varying degrees in Europe, Australia and the United States. This section briefly describes the use and effectiveness of texturing techniques such as exposed aggregate texturing and chip sprinkling, and the use of innovative mix designs such as porous concrete.

Exposed Aggregate Pavements

General Concept

Exposed aggregate texturing is the process of removing the surface mortar of the concrete to expose hard, polish-resistant aggregates. Aggregate exposure is commonly accomplished by one of two techniques: 1) watering and brushing the fresh concrete surface with a rotary brush comprising steel or nylon bristles; or 2) spraying the pavement surface with a set retarder immediately after placement, followed 24 hours (or more) later by mechanical brushing to remove the mortar that has not set.[117] The latter approach is less sensitive to possible variations in concrete consistency and is more commonly used.[118] Figure 6.9 shows an exposed aggregate concrete pavement surface.

Figure 6.9. Close-up photograph of an exposed aggregate concrete pavement surface.[172]

This technique was first used in Denmark in 1976, but was more broadly developed and implemented in Belgium beginning in the 1980s.[118] It has also been used in France, the Netherlands, Italy and Austria and Germany. Very few projects of this type have been constructed in the U.S., the most well-known being the I-75 project constructed in Detroit in 1993.[10]

When designed and constructed correctly, exposed aggregate pavements have been reported to reduce noise, improve friction, and be as durable as conventional concrete pavements.[1,10,14,119,120]

The construction of an exposed aggregate surface typically adds about 10 percent to the total cost of the pavement, although significantly higher costs have been documented on relatively short demonstration projects.[12,121] One further disadvantage of EACP is that, while it is not particularly difficult to construct this type of surface, there is often a learning curve that increases costs and slows production while contractors gain familiarity with the construction techniques.[14]

Materials, Mix Design and Construction Considerations

Exposed aggregate concrete pavements are commonly constructed using a two-layer "wet on wet" paving process, although one-layer systems have also been used successfully. In the two-layer system, the top layer is typically designed with a thickness of 1.5 to 2.75 in. (38 to 70 mm) and is constructed using high-quality concrete and hard, angular aggregate.[10] Typical specifications call for a maximum water-to-cement ratio of 0.38 and a minimum cement content of 760 lb/yd^3 (450 kg/m^3).[14] A plasticizer and air entrainment agent are often used in the top layer to help achieve workability and durability and to help match the modulus of elasticity and shrinkage of the top layer with those of the bottom layer.[4] The mix should contain fine aggregate comprising about 30 percent siliceous sand sized 0 to 0.04 in. (0 to 1 mm) and 70 percent high-quality aggregate chips sized 0.2 to 0.3 in. (4 to 8 mm).[4] High-quality coarse aggregates with a maximum size of 0.3 to 0.5 in. (8 to 13 mm) are also commonly used.[14]

Several studies have shown that the use of smaller aggregate in the top layer provides better reductions of tire-pavement noise.[1,47,122,123] For example, EACP constructed in the Netherlands using 0.8 in. (20 mm) chippings was found to be quieter than similar pavement constructed in Belgium with a maximum aggregate size of 1.3 in. (32 mm).[1] It has also been found that, when smaller aggregates are used, heavier vehicles produce lower noise levels on EACP than lighter vehicles.[122]

To maximize the acoustic benefit of exposed aggregate concrete pavements, the exposure depth should be as deep as possible, but no deeper than 30 percent of the smallest particle size in the coarse aggregate fraction. If exposure is deeper than 30 percent, the coarse aggregate particles may be easily dislodged from the surface.[124] Recommended exposure depth of at least 25 percent has been recommended by some, while others recommend a target mean surface texture depth of 0.035 in. (0.9 mm), as measured using the sand patch test (ASTM E 965).[4,10,124]

Exposed aggregate concrete with polish resistant aggregates and polished stone values (PSV) greater than 50 have been shown to result in low tire-pavement noise and good durability, especially in areas where studded tires are used.[10,41]

The lower layer, making up the remainder of the overall concrete layer thickness, is typically much thicker than the top layer. It can be comprised of lower quality (but durable) aggregates with a maximum size of up to 1.25 in. (32 mm). Recycled materials (including crushed concrete and asphalt [up to 30%]) have been used successfully in this layer to reduce overall costs.[10,14]

Studies of EACP Effectiveness

Sweden

The Swedish National Road Administration constructed several concrete and asphalt pavement sections and monitored their abrasion resistance, friction and noise under heavy traffic. The concrete pavement test sections included both jointed plain and continuously reinforced concrete pavement and were constructed using exposed aggregate surfaces with top layer aggregate maximum sizes of either 0.3 or 0.6 in. (8 or 16 mm). The HMA sections were constructed using two types of mixtures. Noise measurements were conducted using Close Proximity (CPX) equipment.[47]

Initial tests revealed that the concrete pavements with 0.6-in. (16-mm) and 0.3-in. (8-mm) exposed aggregates produced 1.0 – 1.5 dBA and 3.0 – 3.5 dBA lower noise, respectively, than the HMA pavements. After one year of service, the CPX test results were unchanged for the HMA sections, but the concrete pavements were actually quieter than when first constructed. After three years of heavy traffic, all three pavement types exhibited slightly higher levels of tire-pavement noise. It was noted that the concrete pavements produced noise levels that were about 1 dBA higher than those of the HMA pavements during the winter.[47]

The Netherlands

The Dutch Province of Noord-Brabant conducted a study to determine the surface characteristics of exposed aggregate concrete constructed using various aggregates, texture depths, curing solutions, and concrete finishing techniques. Although several texture depths were evaluated, the standard depth was considered to be one-quarter of the maximum aggregate size. Several different retarding agents were also evaluated and a special finisher called a “super smoother” was used on some sections. Use of the super smoother produced texture depths of up to 0.07 in. (1.8 mm) while other sections typically exhibited texture depths of 0.04 to 0.06 in. (1.1 to 1.6 mm).[122]

Smaller top size aggregates were generally found to result in lower tire-pavement noise levels, and retarding agent selection was found to have no difference on texture depths or tire-pavement noise levels. Pavements constructed using the super smoother exhibited lower tire-pavement noise levels, possibly due to the better uniformity and smoothness that was achieved.

Extensive research in the Netherlands suggests that a noise reduction of 2 dBA can be achieved on high-speed motorways by using exposed aggregate concrete surfacing. They note, however, that a great advantage of using this type of surface is its durability, stating that “these road types hardly need maintenance.”[124]

Detroit, Michigan, USA

One 1-mile (1.6-km) test section of EACP was constructed on I-75 near downtown Detroit, Michigan in 1993. This pavement was constructed as a jointed concrete pavement with a thickness of 10 in. (250 mm) and was constructed in two wet-on-wet lifts. The top layer of the pavement was 2.5 in. (64 mm) thick and contained polish-resistant trap rock aggregate; the bottom layer was 7.5 in. (190 mm) thick.[121] An exposed aggregate surface was created by spraying a set retarder on the surface within 30 minutes of finishing, followed by mechanical brushing of the surface approximately 20 hours later.[125] A conventional Michigan concrete paving section (11-in. [280-mm] JRCP) was constructed nearby with a transversely tined surface (uniform 1.0-in. [25-mm] tine spacing) as a "control section."

The surface friction and tire-pavement noise levels associated with each pavement section have been monitored since construction. After 1 year of traffic, surface friction measurements performed using ASTM E-274 showed average FN40R friction numbers of 42 for the exposed aggregate section and 53 for the tined section.[125] Friction measurements obtained after 5 years showed very little change from the year 1 numbers.

A traffic noise study conducted after 1 year found that the exposed aggregate surface did not produce the expected reduction in noise levels.[125] Researchers believe that this was because there was excessive macrotexture due to the use of large sand particles, which resulted in large spacings between exposed aggregate particles. As a result, it was recommended to avoid using sand particles larger than 0.04 in. (1 mm) in the top layer of exposed aggregate concrete pavements.[14]

Porous Concrete

General Concept

Porous concrete is a material that is intentionally designed to have a large void content (e.g., 15 percent or more by volume of concrete). The void structure is typically created by using a gap-graded concrete mix with a sand-to-total aggregate ratio of only 5 to 10 percent (vs. about 40 percent in typical concrete paving mixes).[12] The resulting permeability allows water and air to flow easily through the material, as shown in Figure 6.10.

In addition to providing improved surface drainage, porous pavements are also effective at reducing both the generation and propagation of tire-pavement sound through several mechanisms. First, the porous surface results in a decrease in tire-pavement contact area, which reduces the generation of sound through the slip-stick and slap mechanisms. Sounds that *are* generated are partially absorbed and are not reflected cleanly by the porous surface, which also reduces the "horn effect" by which tire-pavement sounds are amplified and directed.

Figure 6.10. Photo of water running through porous concrete.[126]

Porous concrete has typically been used mainly to address surface drainage issues in and around low-volume facilities, such as parking lots, as shown in Figure 6.11. However, this material can also be used to construct quiet pavements through both single layer and overlay constructions (by applying a wearing course of porous concrete over a layer of traditional dense concrete). In either application, porous concrete provides both low tire-pavement noise characteristics and good surface drainage with accompanying excellent wet weather friction characteristics.[1,127,128] Noise reduction in these systems is realized through the acoustical absorption characteristics of the porous material, while strength and durability are improved by the presence of the underlying dense concrete layer or through the increased thickness of the single layer system.[1,10]

Porous concrete pavements and overlays are becoming increasingly popular. For example, current policy in Japan is to replace all existing pavements with porous systems to provide improved highway safety and ride quality.[128] The preferred option for converting existing concrete pavements to porous pavements is through the use of thin bonded porous concrete overlays.[10]

Figure 6.11. Photo of porous concrete parking area during rainy weather (courtesy of Rick Reed, Lehigh Southwest Cement).

Mix Properties and Structural Design

Porous concrete pavements typically have void contents of 15 to 20 percent.[1,128,129,130] One Belgian study reported a 5 dB sound reduction in a porous concrete pavement that contained 19 percent porosity. However, better noise reduction characteristics can be achieved with void contents of 25 percent or more.[1]

Purdue University's Institute of Safe, Quiet, and Durable Pavements reports that decreasing aggregate size improves the sound absorption characteristics of porous concrete. Mixtures containing a blend of aggregates retained on the #4 and #8 (4.75 mm and 2.36 mm) sieves had better sound absorption characteristics than those using straight gap grading. It was noted, however, that it may be difficult to control the gradation of these sand-sized aggregates.[131]

Increased porous concrete layer thicknesses result in greater noise reductions (up to some limit), so the minimum required thickness of the porous concrete layer can be determined in part by the requirements for noise reduction. One study suggested that a minimum layer thickness of 1.6 in. (40 mm) is required for rural highway applications and 2.75 in. (70 mm) for urban settings.[127]

Effectiveness in Tire-Pavement Noise Reduction

Several studies have been conducted to evaluate the durability and noise emission characteristics of porous concrete.[127,128,129] For example, a study of two 8-in. (200-mm) thick experimental porous concrete pavements in Japan found that these pavements exhibited noise reductions (relative to dense asphalt pavements) of 6 to 8 dBA for dry surfaces and 4 to 8 dBA for wet surfaces in the presence of cars traveling at speeds varying from 25 to 45 mph (40 to 75 km/hr). For heavy trucks, noise reduction values were 4 – 8 dBA and 2 – 3 dBA for dry and wet surfaces, respectively.[132]

Even higher noise reduction values have been achieved by diamond grinding porous concrete pavements. The combination of these two techniques provides excellent wet weather friction and noise characteristics, and is described in detail in later sections of this synthesis.

Maintenance

Porous concrete pavements possess surface texture characteristics similar to those initially provided by porous hot-mixed asphalt (HMA) pavements.[4] However, as with porous HMA surfaces, the low noise and improved surface drainage characteristics will decrease if the pores are allowed to clog over time due to "depositions in the voids of dirt and dust from the road surroundings, from wear products from the pavement itself, and from tires."[1]

The propensity for clogging of pores in porous asphalt is slightly higher than porous concrete due to the sticky nature of the binder.

"Self-cleaning" of the void structure can occur during heavy rainfalls and/or when vehicles travel at high speeds. Water and air are pressurized at the leading edge of the tire-pavement interface, and deposits of dirt and dust are removed by suction at the trailing edge. When "self-cleaning" does not take place, active cleaning may be required to help preserve and restore the pavement's good frictional and acoustic characteristics.[128] Typical active cleaning procedures include water jet blasting and/or dirt water suction.[1]

Double-layer porous concrete, where a porous top lift comprising smaller aggregates is placed over a porous layer with larger aggregate particles, has also been demonstrated as a possible solution to pore clogging problems by reducing the infiltration of debris (Figure 6.12).[10]

Figure 6.12. Cross-sectional view of a double layer porous concrete pavement.[10]

Durability and Bond Problems

Some durability and bond problems were documented with early porous concrete pavements, but modifications to the concrete mixtures and pavement structures appear to have addressed these problems. For example, a 1999 United States Environmental Protection Agency (EPA) publication reported a 75 percent rate of structural failure for porous concrete. Factors that contributed to the failure of these pavements included "poor design, inadequate construction techniques, soils with low permeability, heavy vehicular traffic, and resurfacing with nonporous pavement materials."[133] Many failures have "resulted from inadequate porosity."[10] However, porous concrete pavements that have been constructed with void contents of 25 to 30% have been reported to be structurally sound.[1]

The first porous concrete pavements constructed in Belgium exhibited poor durability in freezing weather.[41] However, subsequent installations that included the use of polymer additives and higher cement contents produced significant improvements in service life.[4,10,134,135]

In two-layer pavement systems where porous concrete is placed over conventional (dense) concrete pavement, pavement durability is often controlled by the quality of the interface between the two concrete layers. Since there are differences in the structural properties of porous and dense concrete, stress concentrations can develop at the interface between these layers, sometimes resulting in failure of the bond between the two layers. For this reason, it is essential to achieve a strong bond at the interface. Wet-on-wet placements generally result in good adhesion between the layers, while wet-on-dry placements may require the use of a polymer-cement slurry to enhance the bond between the layers.[10,127] A minimum of 10 to 12% polymer-cement has been used successfully to ensure proper interface bond strength and freeze-thaw durability.[127]

Laboratory simulation tests have demonstrated that porous concrete pavements resist rutting and have a higher resistance to tire chain wear than does porous asphalt.[10]

Cost Issues

Reported costs of constructing two-layer porous concrete pavements are generally consistent. The Belgian Road Research Centre, for example, reported in 2000 that the costs of constructing a pavement comprising 1.6-in.(40-mm) porous concrete laid over 7 in. (180 mm) of conventional concrete was roughly 40 percent more than the costs of constructing an 8.7-in. (220-mm) conventional concrete pavement.[132] The cost of constructing quiet porous concrete pavements in New Zealand has been reported at US $111 per sq yd (NZ $200 per m^2), which amounts to an additional 40 percent.[136,137] Furthermore, "no significant cost difference with an equivalent structure including porous asphalt" was found.[132]

A Dutch Federal Highway report considered the results of abrasion tests and concluded that "porous concrete has a life-cycle of approximately 30 years," which may provide an appropriate analysis period for the justification of construction costs through life-cycle cost analyses.[10]

EPA Caveat Regarding Porous Pavement

The EPA states that some pollutants contained in water runoff are filtered through porous pavement. Studies conducted in Maryland and Virginia have shown "removal efficiencies of between 82 and 95 percent for sediment, 65 percent for total phosphorus, and between 80 and 85 percent of total nitrogen."[133] However, the construction of any porous pavement runs a risk of groundwater contamination by pollutants (such as fuel leaks from vehicles or chemicals from the binder material) that are not contained by the pavement. It is therefore recommended that construction of these pavements be avoided in areas close to groundwater drinking supplies.[10,133]

Chip Sprinkling

Chip sprinkling is the practice of strewing polish-resistant stones of a specified size evenly onto the surface of the consolidated, screeded fresh concrete and setting them in such a way that they protrude slightly from the pavement surface to provide macrotexture.[138] This process produces satisfactory surface friction and ride if high quality aggregate chips are properly distributed and seated.[12] Aggregate chips used for this process are typically in the size range 0.4 to 0.6 in. or 0.6 to 0.8 in. (10 to 14 mm or 14 to 20 mm), and are spread at a rate of 11 to 13 lbs/yd^2 (6 to 7 kg/m^2).[117]

Chip sprinkling originated in Belgium in the early 1970s, but didn't develop beyond experimental stages because of difficulties in uniformly embedding the aggregate particles. These difficulties were over come in the early 1980s in France, where the technique has been applied on several sections of roadway, notably the A26 between Reims and Calais. Since 1984, this technique has been used in combination with a chemical exposed aggregate finish, which achieves a more uniform texture.[140]

REDUCING SOUND FROM EXISTING CONCRETE PAVEMENTS

Texturing techniques to improve concrete pavement surface friction and reduce tire-pavement noise have not just been limited to plastic (fresh) concrete. The following sections describe techniques that have been used successfully to reduce the generation and/or propagation of sound from hardened concrete pavements, including diamond grinding, grooving, shotblasting and overlays.

Diamond Grinding

During the early 1950s, a California road engineer introduced a machine that improved concrete pavement ride by grinding away localized high spots or "bumps."[164] This machine, called the "Bump Cutter," accomplished this task with a large number of diamond saw blades mounted closely together on a single rotating shaft.[14]

The Bump Cutter was first used on a *new* Arizona military base runway in 1956, and was first used on an existing concrete highway on the San Bernardino Freeway east of Los Angeles, California in 1965.[164] The success of the 1965 California project led to the widespread acceptance of diamond grinding as a concrete surface restoration technique during the 1970s.[14] Today, diamond grinding is recognized as a highly effective texturing technique that improves pavement profile and ride quality, and also restores surface friction and reduces tire-pavement noise from existing concrete pavements.

Diamond grinding removes a thin layer of the hardened concrete pavement surface (usually 0.1 to 0.8 in. [3 to 20 mm] in depth) using closely spaced diamond saw blades mounted side-by-side on a rotating shaft, as shown in Figure 6.13. A typical cutting head will produce 50 to 60 saw grooves/ft width of pavement (164 to 197 grooves/m), as shown in Figure 6.14.[11] Diamond grinding should not be confused with "milling," which employs carbide teeth that "rip" into a pavement surface, leaving a very aggressive (rough) and irregular texture.

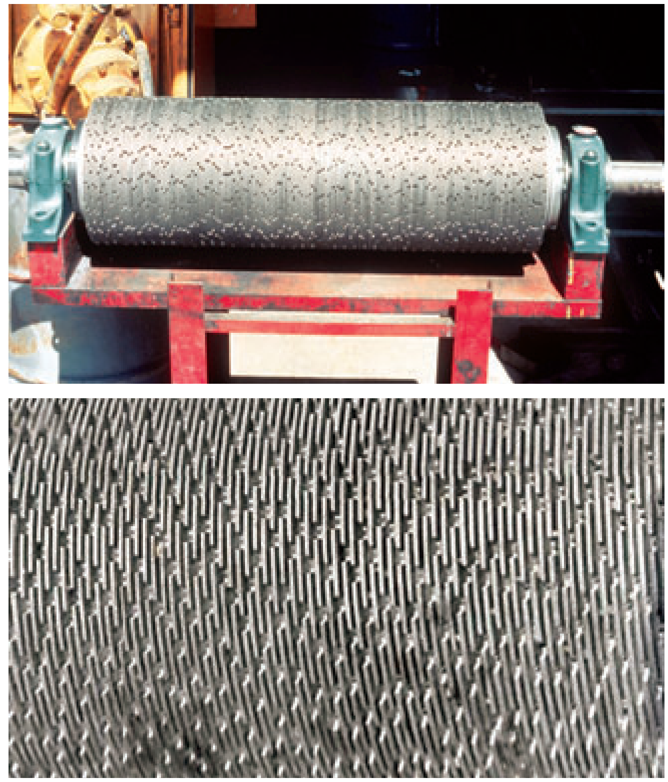


Figure 6.13. Photos of typical diamond grinding head.[114]

Diamond grinding's ability to provide excellent pavement friction with minimal tire-pavement noise also makes it a viable option for texturing newly placed concrete pavement. In new construction applications, the cost of diamond grinding may be partially offset by savings that result when finishing crews are reduced or eliminated and pavement service life is extended.[110]

In the U.S., diamond grinding costs vary with average depth of cut, the hardness of the concrete aggregate and the size of the project, but they typically range between $2 and $5 per square yard ($2.40 and $6.00 per square meter).

Figure 6.14. Close-up photos of diamond ground pavement (bottom photo illustrates use of diamond grinding to remove a noisy transverse tining texture). Photos courtesy of International Grooving and Grinding Association.

Effect on Tire-Pavement Noise

Although diamond grinding has traditionally been used to restore concrete pavement smoothness by removing transverse joint and crack faults and other surface irregularities, it is also a highly effective technique for reducing both interior and exterior tire-pavement noise by producing distinct changes in tire-pavement sound levels and frequencies.[10,14] Grinding effectively reduces the impulses generated at pavement joints, including both the "tire slap" noise that is radiated externally by the tire and the interior noise that is carried through the vehicle structure. It also provides an irregular surface texture that reduces the generation and propagation of other sources of tire-pavement contact noise.

A Wisconsin study found that diamond grinding of recently constructed, transversely tined concrete pavements reduced exterior noise levels by 2 to 3 dB and eliminated discrete frequency spikes (i.e., "whining" characteristics) in both the interior and exterior noise spectra.[14,30]

One recent study compared safety, noise and other pavement characteristics for transversely tined and longitudinally ground pavements and concluded that longitudinally ground pavements were 2 to 5 dBA quieter than the transversely tined pavements when sound was measured at the roadside. When comparing the interaction effects of grinding with different vehicle types, the ground surface was 5 dBA quieter for light trucks and automobiles and 2 dBA quieter for medium and heavy trucks. The lower noise reduction for larger vehicles was attributed to differences in the noise emission sources, with larger vehicles generating a greater percentage of noise from their engine and exhaust systems relative to their tire-pavement noise emissions. When noise measurements were conducted a year later, there were no significant changes in noise levels.[10]

The more random texture created by grinding generally decreases sound levels by as much as 10 to 12 dBA in higher frequencies (1600 to 2000 Hz) for both exterior and (to a lesser extent) interior noise, but can slightly increase sound levels in the 400 to 1000 Hz range, depending on the spacing of the blades in the grinding heads.[109,142,143] Thus, there is potential for "optimizing" diamond grind parameters to maintain the beneficial effects of reducing joint impulses and high frequency tread-related noise while minimizing the effect that increased surface roughness has on the mid-frequency noise.

In one recent study, four test sections were constructed using different diamond grinding setups on a section of Route 202 near Phoenix, Arizona.[114] Prior to diamond grinding, the surface of this new pavement had been tined longitudinally using a 0.75-in. (19-mm) tine spacing. The four test sections were ground using the following blade spacings and grinding setups:

- Section 1: Profile grind with 0.110-in. (2.79-mm) blade spacings
- Section 2: Profile grind with 0.110-in. (2.79-mm) blade spacings, jacks and a floating head

- Section 3: Profile grind with 0.120-in. (3.05-mm) blade spacings
- Section 4: Profile grind with 0.120-in. (3.05-mm) blade spacings, jacks and a floating head

The jacks and floating head served to relieve vertical grinding pressure, thereby producing a more shallow texture (although texture depth was not explicitly measured).

Section 4 produced the best improvement, with noise reductions of 3 to 6 dBA, which led to the conclusion that, in this study, wider blade spacings and shallower texture depths produced the greatest noise reductions. In addition to the benefits of noise reduction, it was noted that pavement roughness was decreased by 58 percent and pavement friction was increased by 27 percent. *It was reported that these test sections produced the smoothest and quietest concrete pavements ever built in Arizona.*[114] The use of jacks and a floating grinding head is sometimes called "whisper grinding" because it produces the quietest diamond ground pavement surfaces.

Effects on Friction

Diamond grinding improves concrete pavement friction by creating macrotexture and exposing new microtexture, thereby immediately improving pavement friction in both wet and dry weather and reducing the potential for hydroplaning and subsequent wet weather accidents. Many different studies have documented this immediate improvement in frictional characteristics.

A 1985 study, for example, showed an increase in average friction number (ASTM E 274 using a locked wheel and smooth tire) from an average of42 before grinding to an average of 80 after grinding at five projects in the United States.[144] A 1998 Wisconsin study found that the overall accident rate for diamond ground surfaces was only 60 percent of the rate for non-ground surfaces.[46] This study also concluded that diamond grinding significantly reduced accident rates for up to 6 years after grinding.

The long-term frictional benefits of diamond grinding depend on the quality of the aggregates in the existing concrete surface. If the concrete aggregates are susceptible to polishing, the dramatic gains in pavement friction may be temporary. In general, however, it has been found that friction values decrease somewhat within the first few years, but that acceptable friction values are maintained for many years.[11]

Diamond Grinding of Porous Concrete

Porous concrete pavement construction was described previously as a highly effective new pavement construction material that provides excellent wet weather friction and pavement-tire noise characteristics. European experience has shown that these characteristics can be further improved by diamond grinding. Figure 6.15 shows examples of porous concrete pavements before and after diamond grinding.

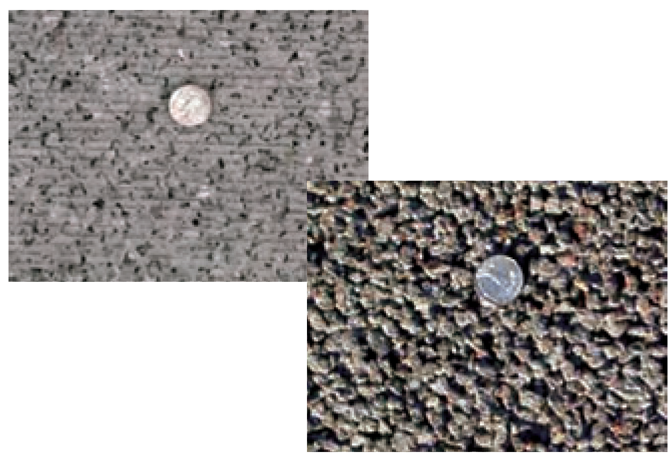


Figure 6.15. Photos of ground and unground porous concrete pavement.[146]

A section of porous concrete (0.16 – 0.31 in. [4 – 8 mm] aggregate size) constructed and diamond ground at a German test track exhibited overall sound levels that were quieter than all other concrete pavements and almost all other asphalt pavements at the same track. For example, the ground porous concrete was 6.5 dBA quieter than the comparable exposed aggregate concrete section, 4 dBA quieter than the transversely broomed concrete section, 3.5 dBA quieter than dense-graded asphalt section, 2 – 4 dBA quieter than the various SMA sections, about 1 dBA quieter than NovaChip® section, and only about 1.5 dBA louder than comparably sized porous asphalt pavement.

It is reasonable to expect that the ground porous concrete pavement will maintain its superior noise characteristics longer than the porous asphalt pavement because the noise reducing mechanisms of the diamond grinding texture provide noise reduction even if the pavement pore structure becomes clogged. The ground porous concrete is also expected to provide more durable friction characteristics than the porous asphalt because of the more rigid nature of ground concrete surface.

Diamond Grooving

Diamond grooving is the process of cutting grooves into a hardened concrete surface using diamond saw blades to produce a pattern that is similar to that produced by longitudinal tining, as shown in Figure 6.16. This technique was developed in California during the late 1950s by the inventor of the Bump Cutter machine and has now become a common technique for improving wet weather friction characteristics at airports, bridges, and in high-accident locations on highways.

Figure 6.16. Photo of longitudinal grooving. Photo courtesy of Dr. Michael Darter, ARA Inc.

The grooves are generally cut longitudinally using a center-to-center blade spacing of 0.75 in. (19 mm) and a cut depth of ⅛ – ¼ in. (3 – 6 mm). Grooving is sometimes cut transversely at pavement intersections, and transverse grooving is a common texturing approach for concrete airport runways.[14] The resulting channels in the pavement surface provide an escape path for surface water in the area of the tire-pavement contact patch, thereby reducing the potential for hydroplaning and wet weather crashes. Longitudinal grooving also provides vehicles with increased resistance to lateral skidding, especially on superelevated curve sections and transitions.[11]

Caltrans has reported wet weather accident reductions of 85 percent after grooving 14 high-accident sites near Los Angeles.[11]

Abrading (Shotblasting)

Abrading or shotblasting uses specialized equipment with an enclosed hood to hurl small abrasive media (typically steel shot) at the pavement surface to remove a 0- to 0.25-in. (0- to 6-mm) layer of mortar and aggregate.[14] The shot and abraded material are typically vacuumed back into the hood, where the shot are reused and the abraded material is disposed of, as shown in the schematic presented in Figure 6.17.

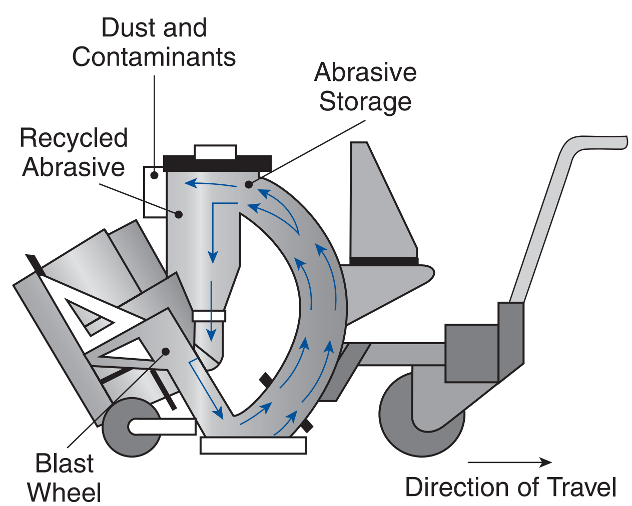


Figure 6.17. Schematic diagram of typical Shotblaster.[148]

Shotblasting has historically been used mainly for preparing PCC surfaces for epoxy-based floor treatments and bonded concrete overlays. However, the abrading process does leave exposed sand-sized particles that provide good microtexture with beneficial friction characteristics, so it may be an appropriate technique for providing a quiet, improved friction surface for lower-speed, lower-volume roadways.[14]

Overlays

Thin asphalt-based overlay products and surface treatments are relatively low-cost options that can be use to reduce tire-pavement noise, enhance skid resistance, or both. These options have proven very successful in providing short-term noise and friction benefits. However, these benefits often diminish rapidly with time, and some overlay treatments have short performance lives or may fail prematurely. For these reasons, asphalt-based overlay products and surface treatments are often not the most cost-effective approaches to noise reduction.

More importantly, many asphalt overlay products are subject to rutting and reduced surface friction under heavy traffic, which can contribute to increased wet weather accident rates. FHWA guidelines and the 1993 *AASHTO Guide on the Evaluation and Abatement of Traffic Noise* recommend that *the designer should never jeopardize safety to obtain a reduction in noise.*[4] The latest FHWA technical advisory states that *"tire/surface noise should be considered* when specifying pavement and bridge surfaces" *but that "safety considerations are paramount."*[5] Clearly, the use of asphalt overlays and surface treatments for purposes of noise reduction must be considered very carefully in terms of durability, cost-effectiveness and safety.

COMPARISONS OF THE NOISE AND SAFETY CHARACTERISTICS OF VARIOUS PAVEMENT SURFACE TEXTURES (SELECTED STUDY SUMMARIES)

Colorado – 1979[51]

A section of I-70 containing the following nine concrete pavement surface textures was tested for both noise and friction:

1. Uniform (1.0-in. [26-mm]) state standard transverse tining
2. Transverse Astroturf drag
3. Variable spacing (0.63-, 0.87-, 0.75-in. [16-, 22-, 19-mm]) transverse tining
4. Uniform (0.5-in. [13-mm]) transverse tining, preceded by longitudinal Astroturf drag
5. Variable spacing (0.63-, 0.87-, 0.75-in. [16-, 22-, 19-mm]) transverse sawing, preceded by longitudinal Astroturf drag
6. Uniform (1.0-in. [26-mm]) transverse tining, preceded by longitudinal Astroturf drag
7. Longitudinal grooving (¾-in. [19-mm] spacing), preceded by longitudinal Astroturf drag
8. Longitudinal Astroturf drag
9. Longitudinal tining (¾-in. [19-mm] spacing), preceded by longitudinal Astroturf drag

All sections were dragged with burlap before the texture treatments above were applied. All tining was intended to be 0.12 in. (3 mm) deep and wide, although as-built measurements were not obtained. Table 6.4 presents the results of these tests.

The variably spaced tining and ½-in. (13-mm) uniform transverse tining provided the most consistently high friction values, but were also among the noisiest pavement textures. The longitudinal textures all provided the lowest noise levels, but the longitudinally tined section also had friction numbers that were comparable to those of the transversely tined sections. The longitudinally tined section might be considered the best overall performer in the Colorado study.

Table 6.4. Results of Colorado I-70 PCC Surface Texture Noise and Friction Tests[51]

	Sound Pressure (dBA) at 65 mph (105 km/hr)						Friction (ASTM E 274, ribbed tire/smooth tire)					
	Inside Vehicle		2.5 ft (7.5 m) from Road		Wheel Well		40 mph (64 km/hr)		50 mph (80 km/hr)		60 mph (96 km/hr)	
	1994	1995	1994	1995	1994	1995	1994	1995	1994	1995	1994	1995
1	68	67	89	87	104	107	56/54	56/43	58/48	50/41	52/45	46/35
2	67	66	87	83	102	104	68/48	52/22	68/40	45/18	52/35	40/14
3	68	68	90	88	103	106	69/67	59/52	68/58	52/50	58/52	51/45
4	68	68	87	86	102	105	68/62	59/55	68/58	56/55	58/55	57/49
5	66	67	88	86	103	106	60/59	52/50	60/52	50/45	49/45	46/41
6	67	67	87	86	102	105	60/55	56/42	59/49	50/39	51/43	49/35
7	66	66	85	82	99	103	54/55	50/48	52/49	48/46	44/41	39/32
8	66	65	84	82	99	101	52/30	49/20	48/21	39/16	39/19	33/11
9	68	67	88	84	101	104	65/57	55/50	61/52	51/44	51/44	42/36

Test vehicle: 1994 Olds Cutlass station wagon.

Wisconsin – 1996[149]

The Wisconsin DOT established a pavement friction inventory program in 1975 using a locked-wheel ribbed-tire skid trailer. Their first pavement surface friction models were derived from four years of data; these models were updated in 1994 to take advantage of the additional available data and to expand the ranges of their predictive capabilities. The 1994 models are:

Asphalt Pavements:

$$FN = 41.4 - 0.00075\ DOLOMITE^2 - 1.45\ \ln(LAVP) + 0.245\ LAWEAR$$

Tined Concrete Pavements:

$$\ln(FN) = 3.99 - 0.0419\ \ln(LAVP) - 0.000129\ DOLOMITE + 0.00474\ HV$$

where:

- FN = Friction Number at 40 mph
- LAVP = Lane Accumulated Vehicle Passes, millions
- LAWEAR = Los Angeles Wear (measure of resistance to abrasion, %)
- HV = Heavy Vehicles in Design Lane as % of Lane ADT
- DOLOMITE = Percent of Dolomite in Mix

These models are used in the pavement design process to predict friction numbers with posted speeds of 40 mph (64 km/hr) or greater. A minimum predicted FN of 35 is desired.

Figure 6.18 compares predictions of pavement friction over time for asphalt and tined concrete pavements for rural and urban settings in Wisconsin. The rural area curves provide upper band values typically associated with pavements with lower traffic and more durable aggregate, while the Milwaukee Area curves present values associated with higher traffic and dolomite contents typical of that region of Wisconsin. These figures show that desirable friction values (FN > 35) are usually present throughout the 35-year performance life (and beyond) of tined concrete pavements in Wisconsin, even in high traffic conditions. They suggest that Wisconsin's asphalt pavements can develop undesirable levels of friction in less than 5 years when traffic is heavy and high dolomite contents are used.

This study also determined typical speed gradients (change in friction value with increased vehicle speed) for several types of pavement as (FN40 – FN50)/10. Lower values mean that there is less loss of friction with increased vehicle speed, and a value of 0.40 is often accepted as the upper limit for pavements with good friction characteristics. Tined con-

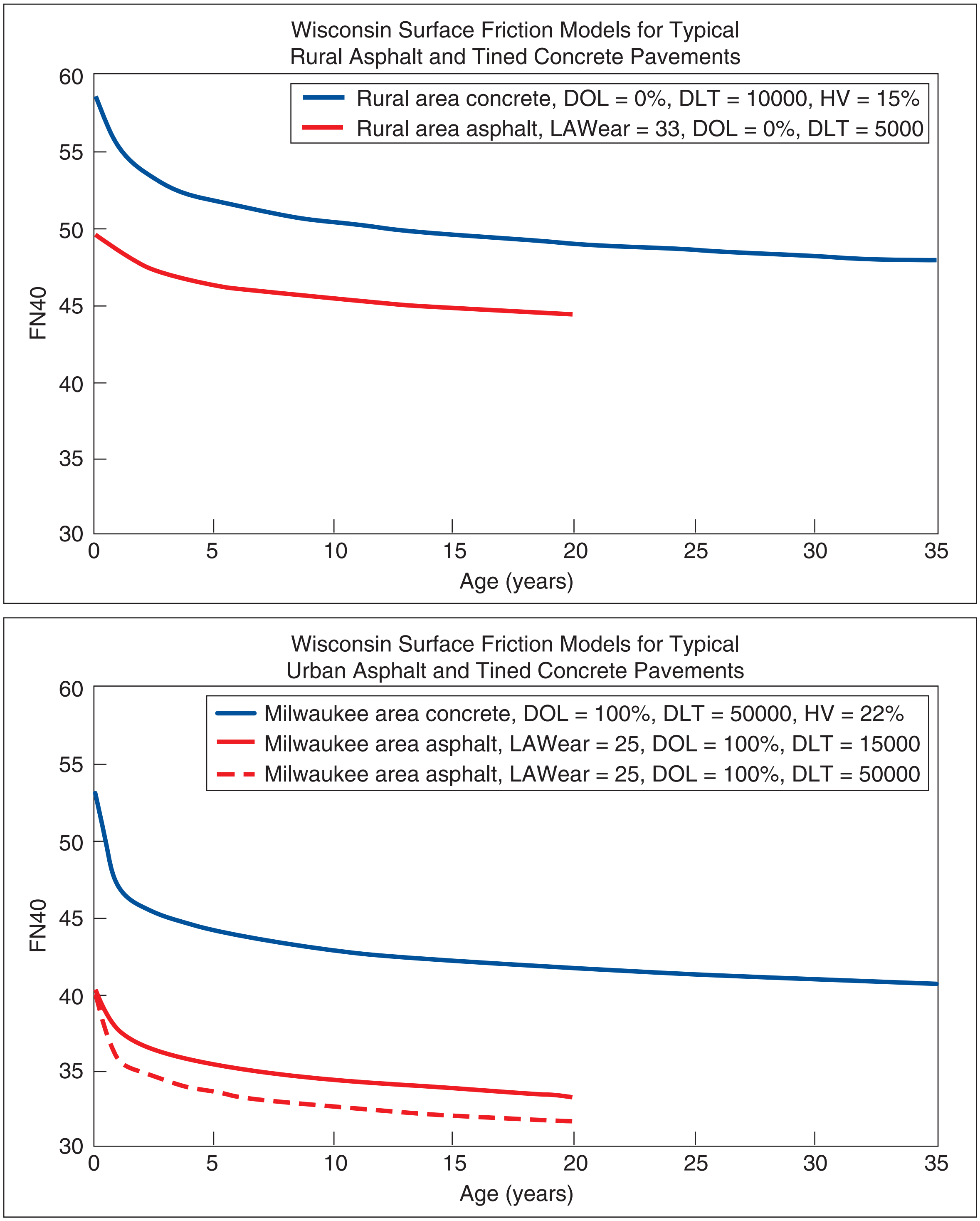


Figure 6.18. Wisconsin pavement friction models for asphalt and concrete pavements in rural and urban areas.[after 149]

crete and SMA pavements were found to have the lowest speed gradient values (0.25). Other types of asphalt pavements had values approaching or exceeding 0.40, and a shallow-textured turf drag concrete pavement had the highest value (0.59).

Wisconsin – 2000[30]

One of the most comprehensive field studies of concrete pavement texture and noise was a project sponsored by the Wisconsin DOT and the FHWA. Pavement noise, texture and friction were measured in 1997 – 1999 at each of 57 test sites in Colorado, Iowa, Michigan, Minnesota, North Dakota and Wisconsin, including 10 new sections built along one Wisconsin construction project in 1997 and featuring several different texture designs.

At the time of testing, all of the test sections were between 3 and 7 years old. Interior and exterior noise levels were measured on all of the study projects, and subjective rankings of interior noise were obtained for 21 selected test sections. Pavement texture was measured using the Road Surface Analyzer (ROSAN) and sand patch tests. Surface friction measures were obtained with a smooth (bald) tire using the procedures described in ASTM E 274.

Table 6.5 summarizes exterior sound level measurements for all 54 projects included in the study, Table 6.6 summarizes interior sound level measurements for all 54 projects included in the study, and Table 6.7 presents a summary of the interior sound level measurements and rankings for the 21 sections that were ranked subjectively. Table 6.8 presents a summary of average sound levels, texture depths, friction measures and ride measures for each of the pavement textures included in the Wisconsin study.

Table 6.5 shows that the range of measured exterior sound levels (L_{max}) ranged from 78.9 dBA for a standard asphalt concrete surface to 87.3 dBA for a transversely tined concrete pavement surface. *Fourteen pavement sections produced exterior sound levels that were essentially indistinguishable (i.e., within 3 dBA) from the lowest sound level measured. These fourteen sections included 10 concrete pavement sections, including three that were within 1 dBA of the quietest pavement and were quieter than all but one asphalt-surfaced section.* Eight of the ten quietest sections were longitudinally textured (including one diamond ground section) and two were transversely tined (one with variable spacing and one with shallow tine marks and a ½-in. (13-mm) tine spacing).

Table 6.6 shows that the range of measured interior sound levels (L_{eq}) ranged from 65.0 dBA for a standard asphalt concrete surface to 72.0 dBA for a milled concrete pavement surface. The highest level of sound associated with a typical concrete pavement surface was 70.2 dBA for a transversely tined surface. *Seventeen pavement sections (including 13 concrete pavement sections) produced interior sound levels that were essentially indistinguishable (i.e., within 3 dBA) from the lowest sound level measured.* Six of these thirteen concrete pavements were longitudinally textured, six were textured transversely or on a skew (including one diamond ground section) and one featured exposed aggregate. The quietest concrete pavements featured longitudinal turf drag, random transversely tined, or longitudinally tined surfaces.

Mechanical sound measurements often fail to represent tonality, sharpness and other frequency- and intensity-dependent factors that affect user perceptions of sound. To address this concern, the Wisconsin study included subjective user ratings of the interior sounds that were recorded and measured for 21 of the study sections. A standard rating of 100 was assigned to a particular pavement section (PCC with ¾-in. [19-mm] randomized transverse tining) and users were asked to subjectively assign sound ratings to the remaining 20 sections with respect to the “standard” section. Table 6.7 summarizes these subjective ratings and rankings along with the interior and exterior sound level measurements. Only one asphalt pavement section was included in this portion of the study, but it was the one that ranked second lowest overall in the interior noise level measurements.

Table 6.5. Ranking of All Wisconsin Study Sections by Exterior Noise Level, L_{max}.[30]

State	Road	Section	Texture	L_{max}
Wisconsin	I-43	3	Std. ACP	78.9
Iowa	I-163	3	¾ in. (19 mm) uniform, longitudinal, 1⁄16 in. (1.5 mm) deep	79.0
Colorado	I-70	7	¾ in. (19 mm) uniform longitudinal, saw cut	79.6
Iowa	I-163	4	3¾ in. (19 mm) uniform longitudinal, 1⁄16 in. (1.5 mm) deep	79.9
Wisconsin	I-43	2	Std. ACP	79.9
Wisconsin	I-43	6	SMA, ⅜ in. (9 mm) stone	80.5
Colorado	I-70	9	¾ in. (19 mm) uniform longitudinal	80.9
North Dakota	I-94	F	Transverse, var., 1, 2, 3, 4 in. (26, 51, 76, 102 mm)	81.0
Wisconsin	I-43	1	SHRP ACP	81.1
Wisconsin	I-43	5	Ground PCCP	81.2
North Dakota	I-94	H	¾ in. (19 mm) uniform longitudinal	81.5
Wisconsin	STH 29	6	1.0 in. (25 mm) uniform longitudinal	81.5
Wisconsin	I-43	4	SMA, ⅝ in. (16 mm) stone	81.6
Minnesota	US 169	1	¾ in. (19 mm) uniform longitudinal	81.7
Wisconsin	STH 29	9	0.5 in. (13 mm) uniform transverse, 1⁄16 in. (1.5 mm) deep	81.9
Wisconsin	STH 29	9a	0.5 in. (13 mm) uniform transverse	82.1
North Dakota	I-94	G	0.5 in. (13 mm) uniform transverse	82.2
New Wisconsin	STH 29	5	¾ in. (19 mm) random skew 1:6, LHF	82.4
Minnesota	US 55	4	1.5 in. (38 mm) random transverse	82.6
New Wisconsin	STH 29	8	1.0 in. (25 mm) random longitudinal	82.7
North Dakota	I-94	A	1.0 in. (25 mm) uniform skewed 1:6, RHF	82.7
Iowa	I-163	1	0.5 in. (13 mm) uniform transverse, ⅛ in. (3 mm) deep	82.8
Colorado	I-70	4	0.5 in. (13 mm) uniform transverse	83.0
North Dakota	I-94	B	¾ in. (19 mm) uniform transverse	83.0
New Wisconsin	STH 29	7	¾ in. (19 mm) random skew 1:4, LHF	83.1
Iowa	I-163	2A	¾ in. (19 mm) uniform transverse, (IA std.)	83.3
Wisconsin	US 151	R2	1.0 in. (25 mm) random transverse (Zignego)	83.4
New Wisconsin	STH 29	6	1.0 in. (25 mm) random skew 1:4, LHF	83.5
Minnesota	US 169	7	LTD only	83.7
North Dakota	I-94	1	25 mm uniform transverse	83.7
Iowa	I-163	8	Milled PCCP	83.8
New Wisconsin	STH 29	4	1.0 in. (25 mm) random skew 1:6, LHF	83.8
Wisconsin	STH 26	R3	1.0 in. (25 mm) random transverse (Trierweiller)	83.8
Minnesota	US 12	3	¾ in. (19 mm) random transverse	83.9
New Wisconsin	STH 29	10	1.0 in. (25 mm) uniform longitudinal	83.9
Wisconsin	STH 29	11	Manuf. random transverse	83.9
Wisconsin	STH 29	8	1.0 in. (25 mm) uniform skewed 1:6, LHF 1⁄16 in. (1.5 mm) deep	83.9
Wisconsin	STH 29	10	¾ in. (19 mm) uniform transverse	84.0
Colorado	I-70	5	Random transverse saw cuts, ⅝, ⅞, ¾ in. (16, 22, 19 mm)	84.1
Minnesota	US 169	8	¾ in. (19 mm) Uniform longitudinal	84.3
Colorado	I-70	3	Random transverse, ⅝, ⅞, ¾ in. (16, 22, 19 mm)	84.4
Iowa	I-163	9	0.5 in. (13 mm) uniform transverse, sawcut	84.6
Wisconsin	STH 29	16	Skidabrader, PCCP	84.6
Wisconsin	US 51	R1	1.0 in. (25 mm) random transverse (Vinton)	84.8
Minnesota	US 169	2	¾ in. (19 mm) random transverse	84.9
New Wisconsin	STH 29	9	¾ in. (19 mm) random longitudinal	85.3
Wisconsin	STH 29	R0	⅞ in. (21 mm) truly random transverse	85.4
Iowa	I-163	5	¾ in. (19 mm) random transverse, ⅛ – 2⁄10 in. (3 – 5 mm) deep	85.5
New Wisconsin	STH 29	2	¾ in. (19 mm) random transverse	86.3
Wisconsin	STH 29	15	1.0 in. (25 mm) uniform transverse	86.3
Colorado	I-70	1	1.0 in. (25 mm) uniform transverse (CO Std.)	86.4
New Wisconsin	STH 29	1	1.0 in. (25 mm) random transverse	86.6
New Wisconsin	STH 29	3	1.0 in. (25 mm) uniform transverse	86.6
Minnesota	US 169	6	1.5 in. (38 mm) random transverse	87.3

All tined PCC surfaces are ⅛ in. (3 mm) deep unless specified otherwise.

Table 6.6. Ranking of All Wisconsin Test Sections by Interior Noise Level, L_{eq}.[30]

State	Road	Section	Texture	L_{eq}
Wisconsin	I-43	3	Std. ACP	65.0
Wisconsin	I-43	1	SHRP ACP	65.9
Wisconsin	I-43	2	Std. ACP	66.0
Wisconsin	I-43	4	SMA, ⅝ in. (16 mm) stone	66.7
Minnesota	I-494	5	LTD only	66.8
Minnesota	MN 55	4	1.5 in. (38 mm) random transverse	66.9
Iowa	I-163	3	¾ in. (19 mm) uniform longitudinal, 1⁄16 in. (1.5 mm) deep	67.2
Minnesota	US 169	1	¾ in. (19 mm) uniform longitudinal	67.2
New Wisconsin	STH 29	7	¾ in. (19 mm) random skew 1:4, LHF	67.2
Michigan	I-75	1	European texture	67.5
Iowa	I-163	4	¾ in. (19 mm) uniform longitudinal, ⅛ – 2⁄10 in. (3 – 5 mm) deep	67.6
New Wisconsin	STH 29	5	¾ in. (19 mm) random skew 1:6, LHF	67.6
North Dakota	I-94	A	1.0 in. (25 mm) uniform skewed 1:6, RHF	67.6
Wisconsin	I-43	6	SMA, 9 mm stone	67.6
New Wisconsin	STH 29	4	1.0 in. (25 mm) random skew, 1:6	67.7
North Dakota	I-94	F	Random transverse, var., 1, 2, 3, 4 in. (26, 51, 76, 102 mm)	67.7
New Wisconsin	STH 29	8	1.0 in. (25 mm) random longitudinal	67.8
New Wisconsin	STH 29	10	1.0 in. (25 mm) uniform longitudinal	68.0
Colorado	I-70	7	⅜ in. (10 mm) uniform longitudinal, saw cut	68.1
Iowa	I-163	1	0.5 in. (13 mm) uniform transverse, ⅛ – 2⁄10 in. (3 – 5 mm) deep	68.2
Iowa	I-163	2A	¾ in. (19 mm) uniform transverse (IA Std.)	68.2
Minnesota	US 169	7	LTD only	68.3
Colorado	I-70	9	¾ in. (19 mm) uniform longitudinal	68.4
Minnesota	US 12	3	¾ in. (19 mm) random transverse	68.4
Michigan	I-75	2	1.0 in. (25 mm) uniform transverse (MI Std.)	68.5
New Wisconsin	STH 29	6	1.0 in. (25 mm) random skew 1:4, LHF	68.5
North Dakota	I-94	B	¾ in. (19 mm) uniform transverse	68.5
North Dakota	I-94	G	0.5 in. (13 mm) uniform transverse	68.5
North Dakota	I-94	I	1.0 in. (25 mm) uniform transverse	68.5
Colorado	I-70	5	Random transverse saw cuts, ⅝, ⅞, ¾ in. (16, 22, 19 mm)	68.6
Wisconsin	US 151	R2	1.0 in. (25 mm) random transverse (Zignego)	68.6
New Wisconsin	STH 29	2	¾ in. (19 mm) random transverse	68.7
North Dakota	I-94	H	¾ in. (19 mm) uniform longitudinal	68.7
New Wisconsin	STH 29	3	1.0 in. (25 mm) uniform transverse	68.8
Wisconsin	STH 29 (EB)	R0	⅞ in. (21 mm) truly random transverse	68.8
Minnesota	US 169	2	¾ in. (19 mm) random transverse	68.9
New Wisconsin	STH 29	1	1.0 in. (25 mm) random transverse	68.9
Wisconsin	STH 26	R3	1.0 in. (25 mm) random transverse (Trierweiller)	68.9
Wisconsin	STH 29	9	0.5 in. (13 mm) uniform transverse, 1⁄16 in. (1.5 mm) deep	69.0
Wisconsin	STH 29	10	10 uniform transverse	69.1
Iowa	I-163	9	0.5 in. (13 mm) uniform transverse, saw cut	69.2
Wisconsin	I-43	5	Ground PCCP	69.2
Wisconsin	STH 29	6	1.0 in. (25 mm) uniform longitudinal	69.2
Wisconsin	STH 29	9a	0.5 in. (13 mm) uniform transverse	69.3
Colorado	I-70	4	0.5 in. (13 mm) uniform transverse	69.4
Minnesota	US 169	6	1.5 in. (38 mm) random transverse	69.4
Minnesota	US 169	8	¾ in. (19 mm) uniform longitudinal	69.4
Wisconsin	STH 29	8	1.0 in. (25 mm) uniform skewed 1:6 LHF, 1⁄16 in. (1.5 mm) deep	69.4
Wisconsin	US 51	R1	1.0 in. (25 mm) random transverse (Vinton)	69.4
New Wisconsin	STH 29	9	¾ in. (19 mm) random longitudinal	69.5
Wisconsin	STH 29	15	1.0 in. (25 mm) uniform transverse	69.5
Colorado	I-70	1	1.0 in. (25 mm) uniform transverse (CT Std.)	69.7
Colorado	I-70	3	Random transverse, ⅝, ⅞, ¾ in. (16, 22, 19 mm)	69.9
Iowa	I-163	5	¾ in. (19 mm) random transverse, ⅛ – 2⁄10 in. (3 – 5 mm) deep	70.0
Wisconsin	STH 29	11	Manuf. random transverse	70.2
Wisconsin	STH 29	16	Skidabrader, PCCP	70.6
Iowa	I-163	8	Milled PCCP	72.0

All tined PCC surfaces are 3 mm deep unless specified otherwise.

Table 6.7 shows that the subjective interior sound ratings ranged from 82.5 to 150.4 and that *the two interior sounds rated best were associated with concrete pavements featuring skewed, randomized tine patterns.* The best-rated section comprised a random transverse tine pattern skewed left ahead (1:6); it was rated 17.5 points better than the "standard" concrete texture and nearly 11 points better than the asphalt pavement section. This section ranked only 5th in terms of both interior and exterior sound measurements, but was rated the best in terms of overall interior sound quality. The two sections with the highest measured interior noise levels were subjectively rated and ranked near the middle of the group. These examples further demonstrate how *typical sound pressure measurements alone are not sufficient for estimating user perceptions of tire-pavement interaction sounds.*

Table 6.7. Summary of Wisconsin Study Sound Levels and Subjective Ratings. *after 30*

Study Section Number	Study Section Description	Interior Sound Level, L_{eq} (dBA)	Interior Sound Level Ranking (1 = lowest)	Subjective Rating of Interior Sound	Interior Sound Subjective Rating Rank (1 = lowest)	Exterior Sound Level L_{max}, Car at 60 mph (96 km/hr) (dBA)
19	0.75-in. (19-mm) random transverse tine with 1:6 skew (left forward)	67.6	5	82.5	1	82.4
18	0.75-in. (19-mm) random transverse tine with 1:4 skew (left forward)	67.2	3	88.9	2	83.1
20	SHRP Asphalt	65.9	1	93.4	3	81.1
15	Variable (1-, 2-, 3-, 4-in.) (26-, 51-, 76-, 102-mm) transverse tine	67.7	6	93.8	4	81.0
14	1-in. (25-mm) uniform longitudinal tine	68.0	7	96.8	5	83.9
16	Exposed aggregate	67.4	4	97.3	6	NA
17	1.5-in. (38-mm) random transverse tine	66.9	2	98.0	7	82.6
7	0.5-in. (13-mm) uniform transverse grooving	69.2	14	99.4	8	83.3
21	¾-in. (19-mm) random transverse tining	68.7	11	100.0	9	86.3
2	0.75-in.(19-mm) uniform transverse tine with 0.13 – 0.2 in. (3 – 5 mm) variable depth	70.0	20	102.0	10	83.8
1	Milled PCC	72.1	21	104.6	11	84.6
13	0.75-in. (13-mm) uniform transverse tine with 0.13 – 0.12 in. (3 – 5 mm) variable depth	68.2	8	107.6	12	82.8
6	Diamond ground PCC	69.3	15	108.0	13	81.2
8	1-in. (25-mm) random transverse tine	68.8	12	109.8	14	86.6
3	1-in. (25-mm) uniform transverse tine (Colorado Standard)	69.7	19	110.3	15	86.4
12	1-in. (25-mm) random transverse tine (Zignego)	68.6	9	113.5	16	83.4
9	0.75-in. (13-mm) uniform transverse tine	69.3	16	124.2	17	82.1
4	1.5-in. (28-mm) random transverse tine	69.1	17	127.7	18	87.3
10	0.75-in. (19-mm) uniform transverse tine	69.1	13	140.8	19	84.0
11	Variable transverse grooving (⅝-, ⅞-, ¾-in.) (16-, 22-, 19-mm)	68.6	10	144.5	20	84.1
5	1-in. (25-mm) uniform transverse tine	69.6	18	150.4	21	86.3

Table 6.8. Summary of Average Wisconsin Test Section Sound, Texture, Friction and Ride Measurements for Various Pavement Types and Textures. *after 30*

Pavement Type/Texture	L_{max} (dBA)	L_{eq} (dBA)	ROSAN (OWP)		Sand Patch Mil (mm)	FN40(S)	FN50(S)	Friction Gradient
			MPD Mil (mm)	ETD Mil (mm)				
Asphalt (SHRP)	80.0	65.6	9.37 (0.278)	6.81 (0.173)	17.6 (0.447)	23.9	18.8	0.51
Asphalt (SMA)	81.1	67.2	18.9 (0.480)	26.9 (0.682)	41.1 (1.045)	32.2	28.7	0.35
PCC – Uniform Transverse Tining	83.8	68.9	27.1 (0.688)	28.9 (0.733)	22.8 (0.578)	44.8	44.5	0.34
PCC – Random Transverse Tining	84.5	68.9	22.1 (0.561)	33.5 (0.852)	33.9 (0.860)	53.4	47.4	0.59
PCC – Skewed Tining	83.2	68.0	18.4 (0.467)	25.7 (0.654)	30.3 (0.770)	53.7	47.5	0.62
PCC – Longitudinal Tining	81.8	68.3	30.7 (0.780)	51.9 (1.319)	31.9 (0.810)	54.4	47.6	0.68

Table 6.8 summarizes average sound, texture, and friction measurements for the different pavement types and textures included in the Wisconsin study. These data indicate that the longitudinally tined concrete pavements in this study were nearly as quiet as the asphalt and SMA pavements (exterior noise within 0.7 to 1.8 dBA, on average) while offering much greater texture depth (MPD and ETD) and superior friction characteristics (FN40 = 54 vs. 24 or 32, respectively). In fact, the asphalt and SMA pavements had *significantly lower friction values (FN40 and FN50) than any of the concrete pavements.*

Table 6.9 (from Reference 30) presents estimates of expected tire-pavement noise reductions for various pavement types and textures from that of uniformly spaced (1-in. [25-mm]) transversely tined concrete pavements while holding mean texture depth constant at about 0.03 in. (0.7 mm). This table shows that the longitudinally tined and randomly spaced skewed tining produce interior and exterior sound level reductions that are essentially indistinguishable from those of open-textured asphalt concrete. As shown in Table 6.6, *these two particular concrete pavement textures* may even be perceived to be *less annoying that the asphalt texture,* and Table 6.7 shows that the concrete texture provides superior friction. Expected interior sound reductions were approximately one-half of expected exterior reductions.

Table 6.9. Expected Tire-Pavement Noise Reductions for Various Pavement Types and Textures[30]

Pavement Type/Texture	Sound Reduction from Transversely Tined PCC (dBA)	
	Interior (L_{eq})	Exterior (L_{max})
Randomly-spaced transversely tined	<1	1 – 3
Randomly-spaced skewed (1:6, left ahead) tining	1.5 – 2	4
Longitudinally tined	2	4 – 7
Open-textured asphalt concrete	2 – 3	5

The following selected general conclusions were drawn by the study authors from their research:[30]

1. pavements with the widest, deepest transverse tining (as measured using the ROSAN) were often among the noisiest, and increased tine mark depth caused greater mark width in most skewed and transversely tined pavements;
2. in four states with longitudinally textured pavements, increases in texture depth of between 50 and 250 percent occurred between test sections, yet only modest (or no) increases in exterior noise occurred;
3. randomly spaced and skewed (1:6) tined pavements can be constructed relatively easily, exhibit lower interior noise and no discrete fre-

quencies, and have good friction and texture, but produce higher levels of exterior noise than longitudinally tined concrete and asphalt pavements; and

4. diamond grinding of transversely tined pavements can substantially reduce tire-pavement interaction sound levels (one cited study showed a 3 dBA reduction in exterior sound measurements) while eliminating the "whine" associated with the original tining.

The study recommended that, where overall noise considerations are paramount, longitudinal tining be considered. It further notes that a tine spacing of ¾ in. (19 mm) will provide adequate friction and comply with AASHTO and FHWA guidelines. It also stated that diamond grinding (if sufficiently deep to remove most of the transverse texture) can be considered a treatment for concrete pavements with excessive whine, noting that grinding does not compromise safety.

CA/AZ Tire-Pavement Noise SI Data Base

Since 2002, the Sound Intensity (SI) method has been used extensively throughout California to quantify the tire-pavement noise generation performance of various pavements. This has included samples of most types of pavement used by the State, as well as textured concrete surfaces of bridge decks and elevated structures.[150,151,152] The maximum sound intensity levels measured in California approach 105 dBA (excluding bridge decks), providing a range of about 8 dB within the State. Caltrans does not use transversely tined concrete for at-grade highway pavement surfaces.

Sound levels have also been measured for a large number of Arizona pavement surfaces, including aggressively tined (transversely) concrete.[142,153] With the inclusion of the Arizona transversely tined concrete, the maximum measured sound levels range up to 109 dBA, resulting in an overall range in A-weighted sound levels from this time period (excluding bridge decks) of about 13 dB (see Figure 6.19). Aggressively tined bridge decks have been found to produce sound intensity levels approaching 113 dBA.

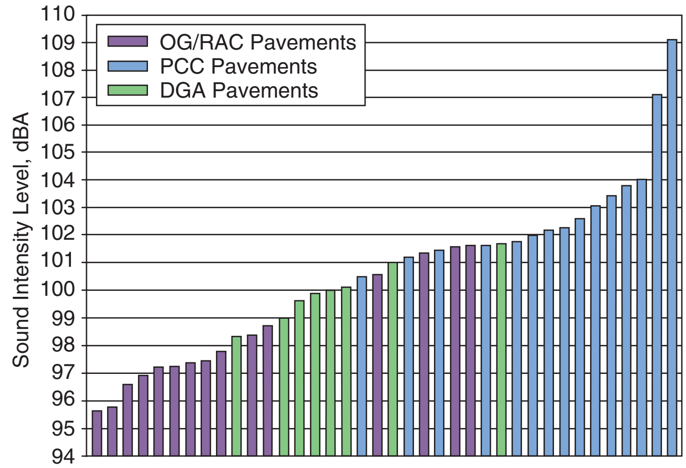


Figure 6.19. Tire-pavement noise (Goodyear Aquatred 3 at 60 mph) for representative, at-grade highway surfaces from the California/Arizona sound intensity data base.[146]

The data of Figure 6.19 can be considered to consist of three main groups: 1) the lower ⅓ of the pavements, comprising either open-graded and rubberized asphalt; 2) the middle ⅓, comprising mostly dense-graded asphalt with some quieter PCC surfaces and some open-graded and rubberized asphalt concrete surfaces; and 3) the upper ⅓, which comprises mainly aggressively textured concrete surfaces and a chip-seal asphalt surface that contained very large aggregate and produced high levels of lower frequency noise.

The California-Arizona database documents the ranges of sound intensity levels currently associated with various pavement types and textures in the U.S. For example, open-graded and rubberized asphalt pavements produce sound intensity levels that range from 95 to 102 dBA, dense-graded asphalt pavements range from 98 – 102 dBA, and various concrete surfaces generally range between 100 and 104 dBA (with two exceptions). Quieter pavements can be identified within each category, and each category overlaps the others.

Noise Intensity Testing in Europe (NITE) Study[146]

Europeans have been experimenting with quiet pavement designs much longer than Americans. However, because of measurement method and test tire differences between researchers in Europe and the U.S., there has been no common scale for comparing the performance of European pavements to those in the U.S. To fill this void, the California Department of Transportation (CALTRANS) and the FHWA funded a project to perform sound intensity measurements in Europe that could be compared directly to those in the California/Arizona study described previously.

The objectives of the NITE study were threefold: 1) measure the sound intensity levels associated with the quietest pavements in Europe; 2) determine the range of sound levels associated with pavements typical of European roadways; and 3) compare and relate the European measurements with those obtained previously using the same equipment in California and Arizona.

Table 6.10 summarizes the countries, roadways/test tracks, locations and pavement surface types included in the NITE study.

Figure 6.20 presents a summary of sound intensity measures for representative highway surfaces from the NITE study. Overall sound intensity levels ranged between 94 and 108 dBA. Double-layered porous asphalt (DLPA) pavements were most consistently quiet, with sound levels ranging from 94 to 97 dBA. Porous asphalt (PA) pavement levels varied between 95 and 105 dBA, concrete pavements ranged from 96 to 108 dBA (depending upon the surface texture and finish), dense-graded asphalt (DGA) pavement levels were between 98 and 107 dBA, and stone mastic asphalt (SMA) surfaces produced sound levels between 98 and 106 dBA.

The quietest concrete pavement was a porous pavement that had been diamond ground (pictured in Figure 6.15) to produce an SI of 96.6 dBA – among the quietest pavements measured and *quieter than most asphalt pavements* other than the double-layer porous asphalt pavements. The second quietest concrete pavement was another porous pavement (not ground) with an SI of 99.8 dBA.

Figure 6.21 summarizes the SI levels measured for various representative concrete pavement surfaces in this study.

Table 6.10. Locations of Roadways and Test Tracks Measured for Tire-Pavement Noise in Europe.[146]

Country	Roadway	Location	Pavement Surface
Netherlands	A15	Gorinchem	Double layer porous asphalt – multiple constructions
	A59	Standdaarbuiten	Double layer porous asphalt – multiple constructions
	A326	Nijmegen	Double layer porous asphalt with fine aggregate
	A270	Eindhoven	Concrete and epoxy overlay on concrete
	A73	Venray	Various asphalt and concrete surfaces
France	Track	Nantes	LCPC test track with seven different test sections
Belgium	N255	Herne	Six different test surfaces
Germany	B56	Duren	Ten different test surfaces
	Track	Dudenhofen	Opel ISO passby test track surface
	Track	Sperenberg	BASt pavement test site with multiple sections

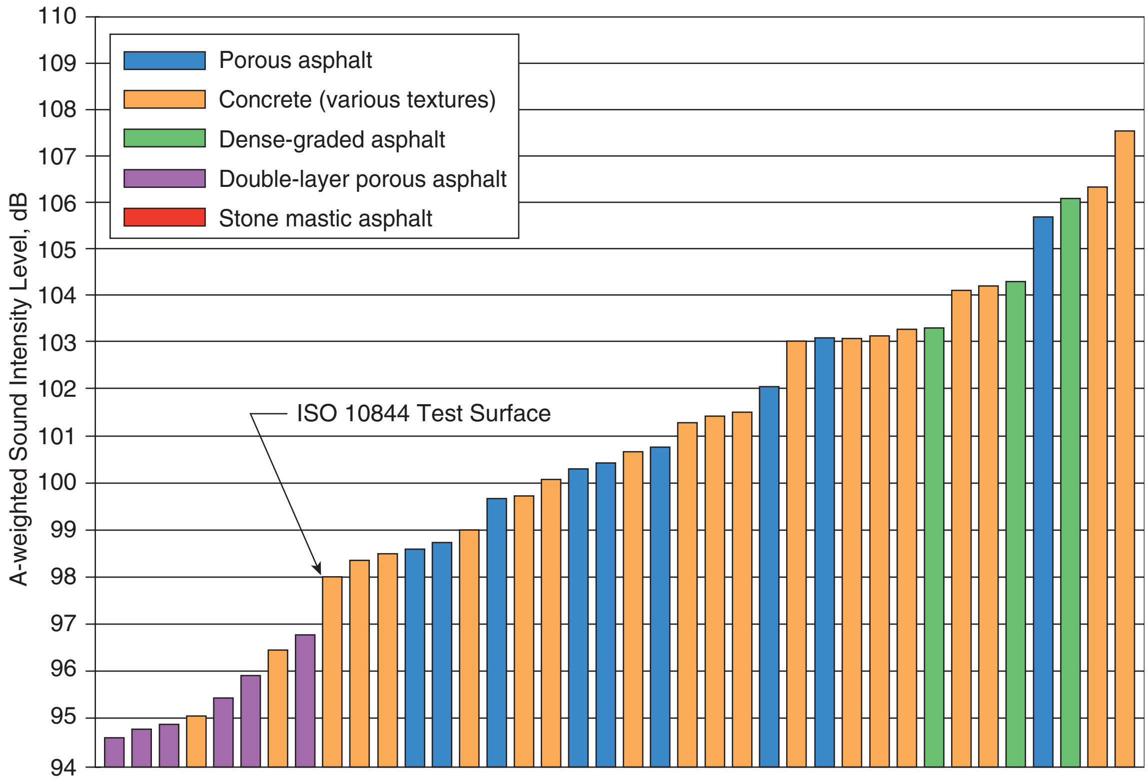


Figure 6.20. Tire-pavement noise for representative, at-grade highway surfaces from the European NITE sound intensity data base – Goodyear Aquatred 3 at 60 mph (100 km/hr).[165]

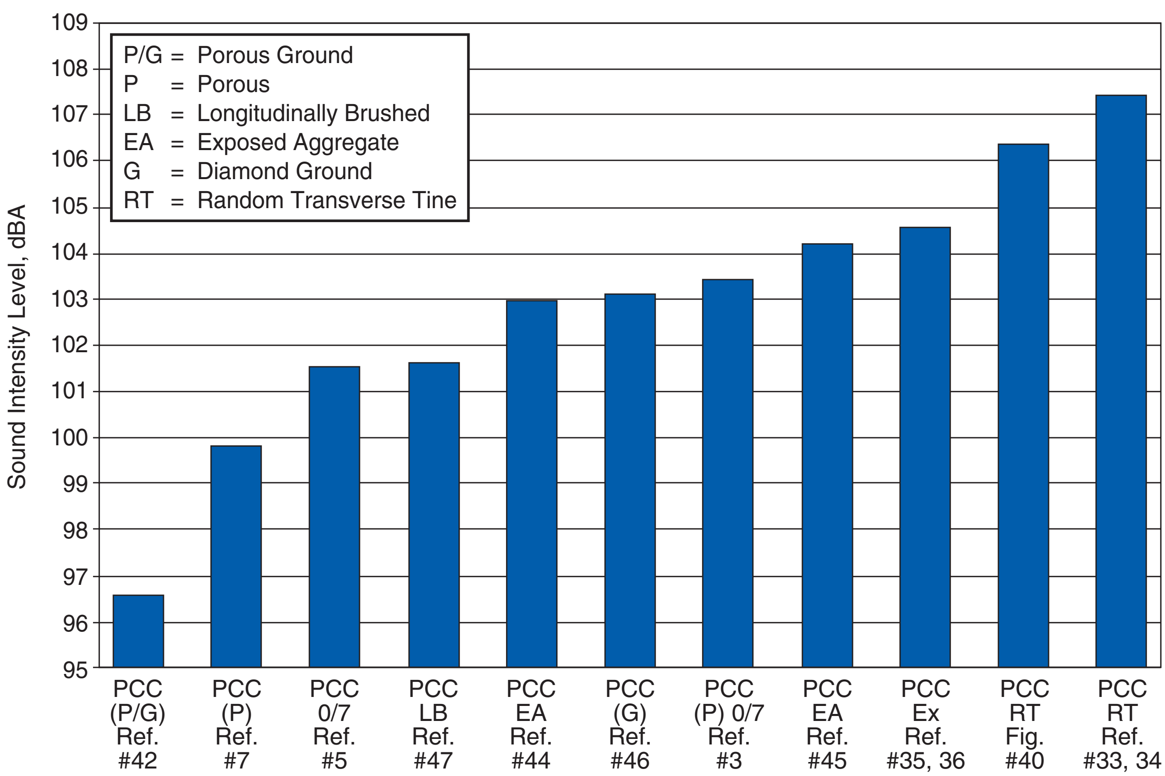


Figure 6.21 Tire-pavement noise for concrete pavements of varying construction and surface characteristics – Goodyear Aquatred 3 at 60 mph (100 km/hr).[146]

The two porous concrete sections described previously were significantly quieter than the others, while the transversely tined pavements produced the highest SI values. All of the other concrete pavement surfaces (exposed aggregate, diamond ground, longitudinally brushed, etc.) produced similar SI values (within a 3 dBA range).

Figure 6.22 presents an analysis of the ⅓-octave band SI values for representative porous concrete and porous asphalt pavements. The frequency content of the sound profile produced by the diamond ground porous concrete surface is very similar to that of the single- and double- porous asphalt pavements and would probably be indistinguishable to most people. The porous (not ground) concrete pavement sound profile contains some added sound intensity in the 500 – 1000 Hz range, but is otherwise also very similar to the other three profiles presented.

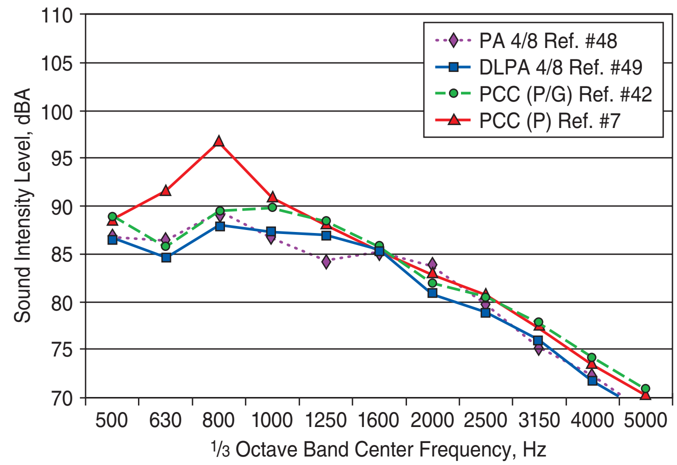


Figure 6.22. One-third octave band sound intensity levels for porous AC and PCC pavements.[146]

Figures 6.23 and 6.24 present similar NITE study SI data for tests conducted at 35 mph (56 km/hr) (rather than 60 mph [96 km/hr]), which is more rep-

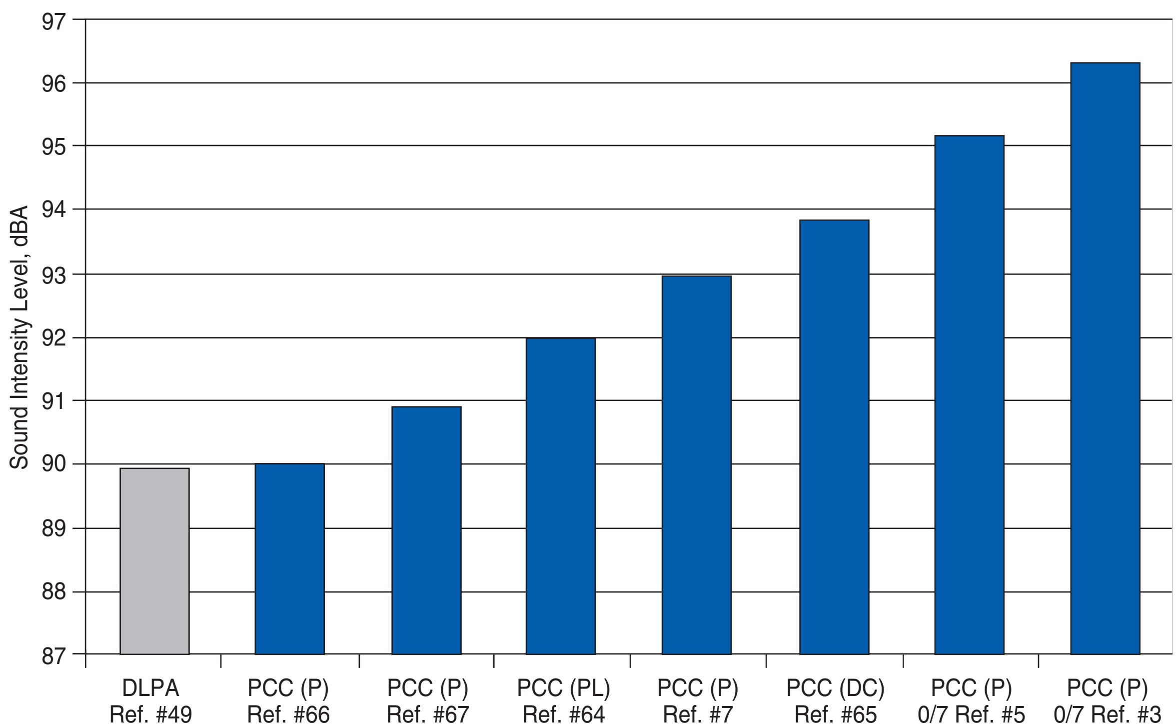


Figure 6.23. Tire-pavement noise for concrete pavements of varying construction and surface characteristics compared to DLPA – Goodyear Aquatred 3 at 35 mph (56 km/hr).[146]

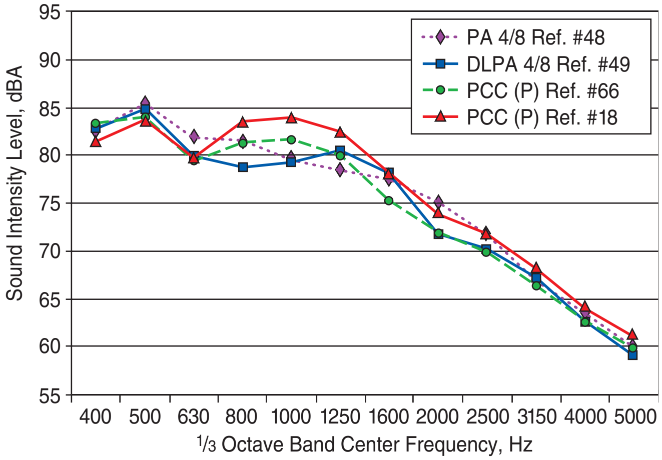


Figure 6.24. One-third octave band sound intensity levels for porous asphalt and concrete pavements – Goodyear Aquatred 3 at 35 mph (56 km/hr).[146]

resentative of many urban travel conditions. It can be seen that the SI levels decreased significantly (5 to 9%, on average) as vehicle speed decreased from 60 mph (100 km/hr) to 35 mph (56 km/hr) for all pavement types. The overall range of SI values at 35 mph (56 km/hr) was 7.9 dBA, compared to 13.1 dBA at 60 mph (100 km/hr). Several concrete pavement sections produced SI levels that were within 3 dBA of the DLPA pavements (and one was practically identical), as shown in Figure 6.23. Figure 6.24 shows that the SI ⅓-octave band profiles for the porous asphalt and concrete pavements are all very similar, suggesting that there would be little difference in the sound generation performance of these pavements in typical urban settings.

Based on these test results, the NITE study authors concluded that porous concrete construction has the potential to provide nearly the same sound intensity performance as "quiet" asphalt surfaces, may be more desirable in some circumstances, and should be investigated further for possible use in the U.S. They also found that fine exposed aggregate concrete surfaces produced SI levels comparable to those of diamond ground surfaces and superior to those of longitudinal tining. It was further recommended that this type of construction be further investigated for application in the U.S.

The pavements included in this study, which had been identified by European researchers and others as some of the quieter pavements in Europe, were found to be only slightly quieter (1 or 2 dB) than the pavements in the California/Arizona data base described previously. The range of tire-pavement noise between the noisiest and quietest pavements was also found to be similar between the NITE and California/Arizona data bases, even though somewhat different design approaches are used in Europe and the U.S.

National Concrete Pavement Technology Center, Iowa State University – 2006[166]

The National Concrete Pavement Technology Center, Iowa State University is currently performing an extensive study of tire-pavement interaction for a wide range of pavement textures. Noise levels are being measured using an on-board sound intensity (OBSI) device similar to the one shown in Figure 3.15. Preliminary (unpublished) data from some of the SI measurements obtained to date are shown in Figure 6.25.

It is apparent that the transversely tined pavements generally produce the highest sound levels, while the diamond ground and turf drag textures generally produce the lowest sound levels, followed by the longitudinally tined pavements. The complete study, which will examine specific concrete pavement texture design parameters and their effects on both noise and surface friction (safety), is expected to be completed in late 2006.

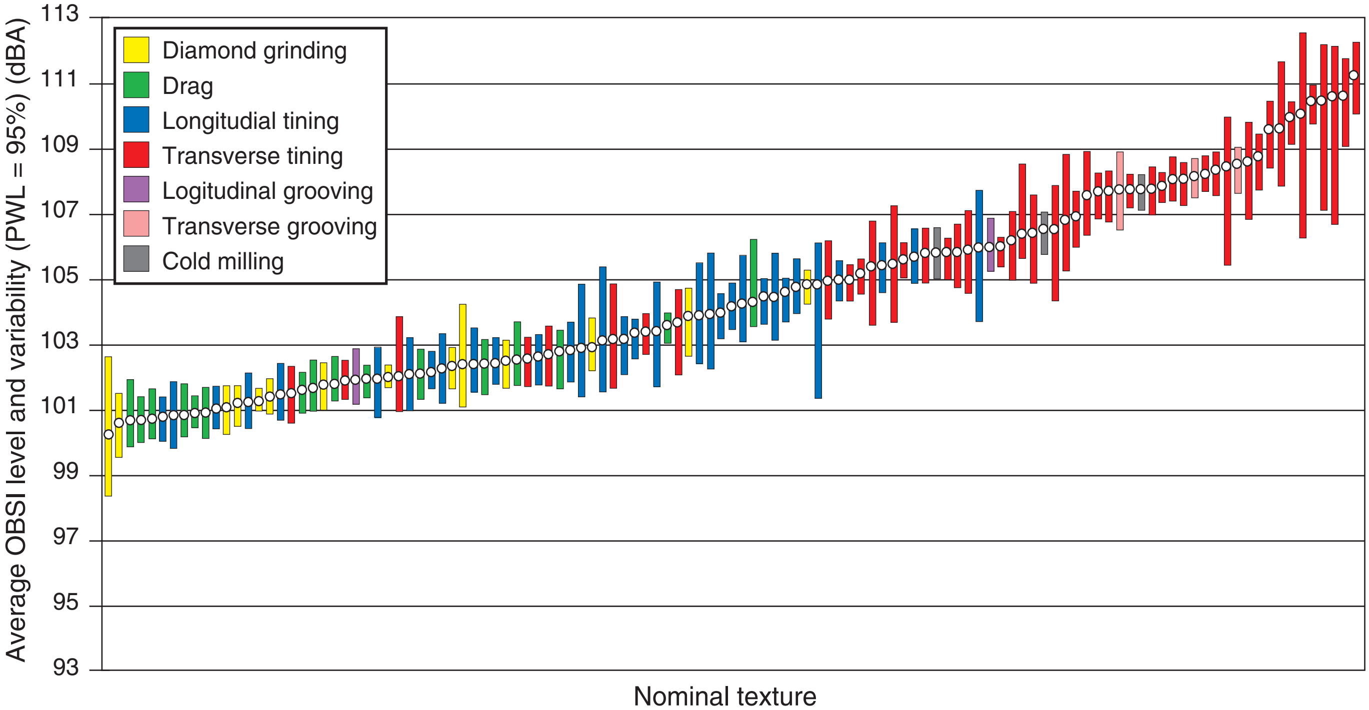


Figure 6.25. A summary of Sound Intensity Data for various U.S. concrete pavements.[166]

QUIET PAVEMENTS IN EUROPE – SCAN TOUR REPORTS

Introduction

The European community has been experimenting with quiet concrete pavements systems much longer than has the U.S. In May 2004, a delegation from the U.S. visited a number of European countries (the AASHTO/FHWA Quiet Pavement Scanning Tour) to discover and document the best European practices for quiet pavement systems.[48]

General

In Europe, it is accepted that tire-pavement noise comprises 75 – 90 percent of the total noise generated by passenger vehicles, as well as a significant (but as yet undetermined) amount of the noise generated by trucks. As in the U.S., sound walls are expensive to build (often costing $1M – $2M per mile [$0.62 m – $1.24 m per kilometer]) and maintain, and they are of limited usefulness in some areas. Additionally, graffiti is a major maintenance issue. As a result, the European quiet pavement effort is focused primarily on three major technologies: thin-surfaced, negatively textured gap-graded asphalt mixes (such as NovaChip, micro-surfacing, and stone mastic asphalt [SMA]); single- and double-layer highly porous asphalt mixes containing more than 18 percent voids; and exposed aggregate concrete (EAC) pavements. Other concrete surfacing technologies, such as the use of porous concrete and diamond grinding, are seeing increased use in some countries.[48]

Country-specific experience with quiet pavement technology is described in the following sections.

Belgium

Belgium now utilizes exposed aggregate concrete (EAC) and SMA pavement designs that have been "optimized" to minimize tire-pavement noise, with exposed aggregate concrete being used for most new high-traffic routes. Porous asphalt surfaces were found to provide slightly better noise benefits than the SMA and EAC, but the government felt that the SMA and EAC provide a better combination of durability and noise reduction. In addition, the recurrent cost of cleaning the porous pavement surfaces (estimated at $0.47/square yard [$0.60/square meter]) is expensive and adds significantly to the cost of ownership of porous asphalt pavements.[48]

The tire-pavement sound characteristics of the exposed aggregate concrete are perceptibly better than those of the SMA. SMA pavements produced higher (presumably more irritating) frequency tones than did the EAC pavements. The Flemish Brabant Roads and Traffic Division reports: "Fine concrete pavement offers positive acoustical results not only in relation to other pavements but also in relation to bituminous pavements. After 3 years, fine concrete pavement still preserves its acoustical characteristics. *This durable cement concrete pavement can certainly be qualified as noiseless pavement and can be compared with noiseless bituminous pavements.* The rolling noise produced on fine concrete pavements remains almost constant. As a result, this kind of pavement continues to score well."[48]

There are no maintenance concerns with the Belgian EAC and it requires about the same amount of winter salt as SMA mixes. The durability of exposed aggregate concrete is demonstrated by the first EAC pavement built in Belgium (on A12 at Miese), which is still in service after more than 35 years. While this pavement is not considered a quiet pavement because of the mix design and construction techniques used at the time, it is considered a good example of the durability and low maintenance of EAC in Belgium.[48]

Diamond grinding, optimized for minimal tire-pavement noise, has been used successfully on sections of E40 from Brussels to Liege. The resulting pavement surface is perceptively smoother and quieter than the adjacent section of EAC.[48]

Denmark

Danish research has shown that 15 percent of the population is exposed to 24-hour equivalent noise levels (LA_{eq24h}) that exceed 55 dBA. National residential noise guidelines (55 dBA outdoors, 30 dBA indoors) have been developed to control noise without necessarily limiting development. Mitigation strategies include turning houses so that their back side faces the street, façade insulation, and living rooms and bedrooms facing the backyard. All new houses constructed in the last 20 years (300,000 or 12 percent of the total homes) have met the national noise guidelines.[48]

Denmark mitigates noise at the tire-pavement interface almost exclusively through the use of various types of porous asphalt (PA) pavements because they believe that these pavements have the greatest potential to reduce noise by more than 3–5 dB. However, they have also experienced performance problems (i.e., clogging, durability, etc.) with these pavements.[48]

The Danes indicate that the PA pavements begin to clog within the first year, although high-speed pavements fare better because of the cleaning action of high-speed vehicles. Studies suggest that the permeability of low-speed PA pavement is significantly reduced by the fourth year, resulting in lower noise reduction benefits. It was found that almost all noise reduction benefits are lost after 7 years of service.[48]

The Danes indicate that porous asphalt pavements must be cleaned frequently and regularly or they may quickly (within 2 years or less) become too clogged to be effectively cleaned. For this reason, Denmark cleans their double-layer porous asphalt (DLPA) pavements three months after construction and semi-annually thereafter using high-pressure (1250 psi [100 bar]) water, followed by a vacuum to remove the fluid/solids. The solids contain heavy metals and must be disposed of in an approved facility. The benefits of this regular cleaning have not, to date, been clearly established.[48]

Denmark's porous pavements also require additional maintenance during the winter because of the potential for icing conditions. This is due in part to the additional surface area, which allows the surface temperature to drop 1.8 – 3.6°F/hr (1 – 2°C/hr) faster than does the DGA surface temperature. It is reported that the porous surfaces increase salt consumption by 50 percent and result in increased call-outs for maintenance. The cost-effectiveness of Denmark's porous asphalt pavements is questioned for these reasons.[48]

The Netherlands

The Dutch currently use mainly porous asphalt pavements to address their quiet pavement needs. Porous pavements have a slightly higher initial cost, but are believed to be about 50% more cost-efficient than using barriers (noise walls) to accomplish the same levels of noise reduction (current barrier costs are estimated at 400-500 Euros per square meter).[48] Problems have arisen, however, concerning the long-term acoustic benefits, safety and performance life of their asphalt pavements.

Loss of Acoustic Benefits With Time

As in Denmark, there are concerns in the Netherlands about loss of acoustic benefits due to clogging of porous asphalt pavements, which begins to be a problem within 6 months. Their experience shows that clogging does not affect noise reduction as much as first thought, resulting in only 1 – 2 dB loss of noise reduction. Porous pavements are cleaned up to twice yearly (depending upon traffic levels, speed and other factors) using high-pressure water blasting (1250 psi [100 bar]) and vacuuming. They note that it is impossible to clean surfaces that become completely clogged. Following cleaning, noise reduction and permeability are generally reduced (due to bringing contaminant material to the pavement surface), but these properties improve shortly thereafter. The effectiveness of pavement cleaning is still being investigated and debated.[48]

Wet Weather Safety and Friction Issues with Porous Asphalt

The Dutch have established that the effect of porous pavements on wet weather safety has been negligible because the lack of splash and spray permits drivers to adapt their behavior with higher speeds and shorter following distances. They note that, in order to avoid adaptive driver behavior, future emphasis must be placed on improving non-perceptible surface characteristics, such as skid resistance.[167]

Poor wet weather skid on porous asphalt pavements (documented using slip-wheel tests) has also been experienced in the Netherlands. The reasons for these problems have not been identified and they are considering a 5-year warranty requirement in an attempt to encourage the use of better aggregates and construction methods. When low friction is detected, speed reductions or post-construction treatments are required (although these treatments may negatively affect the acoustic properties of the porous pavement).[48]

Dry Weather Safety and Friction Issues with Porous Asphalt

Dry weather braking problems on new porous asphalt pavements recently became apparent when accident investigations revealed that unusually long braking distances on such pavements were due to the pavement surface rather than excessive vehicle speed. It was determined that, when braking with locked wheels (i.e., in an emergency stop), the temperature of the bitumen in the contact area became higher than the melting temperature of the bitumen. The molten bitumen would then form a sliding surface (sometimes called "bitu-planing"), which resulted in increased braking distances.[167,168] This problem would dissipate as the bitumen film was worn away by the traffic, and was not as severe a problem for cars with ABS braking systems that prevent wheel lockup during braking.

Table 6.11. Characteristic Values for the Braking Deceleration on Different Surfaces.[168]

	Porous asphalt		Dense asphalt	
	New	Old	New	Old
Without ABS	17.7 ft/s² (5.4 m/s²)	23 ft/s² (7.0 m/s²)	23 ft/s² (7.0 m/s²)	26.2 ft/s² (8.0 m/s²)
With ABS	29.5 – 31 ft/s² (9.0 m/s² – 9.5 m/s²)		31 – 33 ft/s² (9.5 m/s² – 10.0 m/s²)	

Table 6.11 presents typical results of braking tests of porous and dense asphalt surfaces in Holland under new and aged conditions, with and without anti-lock braking systems. It is clear that emergency braking effectiveness is reduced on porous asphalt pavements relative to dense asphalt pavements for all vehicles (especially those without ABS systems) at all pavement ages.

Similar behavior has been observed for double-layer porous asphalt (DLPA) pavements, which often exhibit deceleration values similar to those of normal porous asphalt, but are sometimes below 16 ft/s² (5.0 m/s²).[171] Stone mastic asphalt pavements graded 0 – 0.45 in. (0 – 11 mm) exhibited similar behavior with values of 18.3 – 19.0 ft/s² (5.6 – 5.8 m/s²).

Several techniques have been investigated for addressing the dry weather friction problems associated with these pavements, including surface milling, hydroblasting, sanding, and others, but all were found to be ineffective, too expensive, or counterproductive to noise reduction. The policy that was finally adopted for porous asphalt pavements was to place warning signs at all newly constructed sections with the following text: "New road surface – longer braking distance" and the length of the section (see Figure 6.26). The signs are removed after 4 months or when locked wheel friction values exceed 0.68, whichever occurs later.

The early life dry skid resistance problems of porous asphalt pavements are particularly troubling because they represent a condition that is not expected from new pavement surfaces and drivers cannot observe it directly. Such problems are more acute in urban areas where emergency stops and short following distances are more common.

Figure 6.26 Dutch sign warning of increased braking distances for porous asphalt pavements. (Translation: "New Road Surface – Longer Braking Distance")[168]

Another problem is the large difference in stopping behavior between cars with and without ABS systems on these pavements, which is especially dangerous when a car without ABS is following a car with ABS. Detection of early life dry skid problems and warning of road users will probably not be enough, especially in urban areas.

Performance Life

Porous asphalt mixes do not perform as well as conventional dense asphalt mixes in the Netherlands where there is more braking, acceleration, and turning actions, as might be expected in urban areas. Raveling is the predominant failure mechanism, and when raveling exceeds 25 percent, the surface is replaced. Age hardening of the binder occurs within 6-8 years, although cracking and rutting are not problems. *Current Dutch porous asphalt pavements typically provide 8-10 years of life, whereas previous dense-graded mixes provided 10-12 years.*[48]

Other Dutch researchers have related observed reductions in asphalt pavement life to aggregate top size, void content and noise reduction levels. These relationships have been expressed graphically, as shown in Figure 6.27.

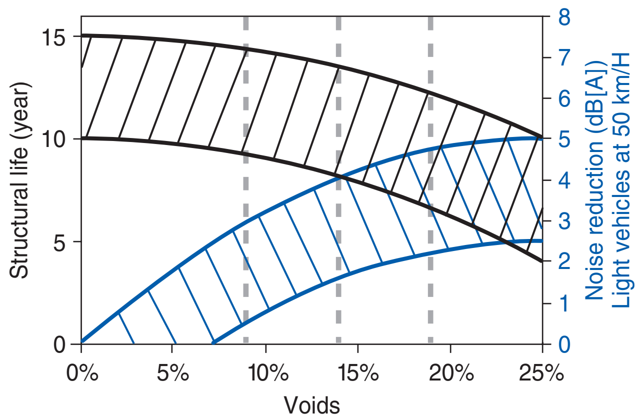


Figure 6.27. Illustration of relationships between void content, noise reduction and structural life for asphalt pavement in the Netherlands.[167]

Winter Maintenance

Similar to other European countries, the Dutch have also noted that porous pavements require approximately 50 percent more salt application for winter deicing operations.[48]

France

The French use mainly porous asphalt pavements for noise reduction. They consider noise reducing mixes to be sacrificial layers and do not give them any structural value in pavement design. They assign these pavements an expected service life of more than 15 years (although older mixes are being recycled after 10-12 years).[48]

The French do not attempt to clean porous asphalt pavements because they have not found pressure wash and vacuum systems to be effective. Instead, they attempt to optimize mix designs to eliminate or reduce clogging. When it is necessary to rehabilitate the porous asphalt surface, milling is employed. If the worn surface is plugged through the full layer thickness, it may be overlaid. Porous asphalt is no longer used in built-up areas because of fast clogging.[48]

France has experienced some winter freezing problems with porous pavements and, to a lesser degree, very thin asphalt concrete, both of which cool to freezing temperatures quickly (30 minutes faster than dense surfaces) and can facilitate the production of black ice.[48]

Italy

Recent Italian research shows that porous concrete pavements can be designed and constructed to provide superior macrotexture and microtexture. Sand patch test results (indicating macrotexture) on specimens of prepared SMA and porous concrete showed texture depths of 39 mil and 55 mil (0.98 mm and 1.4 mm), respectively. British pendulum tests (indicating microtexture) provided average values of 78 for the porous concrete and only 40 for the SMA initially (with an increase to 56 after aging). With 17 percent porosity (suggesting good acoustic properties) and excellent friction characteristics, it is believed that the use of improved porous concrete surfacing will have significant impacts on road safety in Italy.[169]

U.K.

The U.K. has been working to find a good balance between quiet pavement safety (skid) and noise reduction. “Quieter surfaces” are defined as those that produced at least a 2.5-dB reduction in tire-pavement sound when compared with traditional hot-rolled asphalt pavements.[48]

Porous asphalt pavements were introduced experimentally in the 1980s and, although they provided reduced spray and tire noise, they exhibited some problems with durability due to raveling. In the mid-1990s, the U.K. experimented with thin-layer textured asphalt mixes that were relatively inexpensive, quick to construct, and provided acceptable durability. The mid-1990s also saw the early use of “Whisper” or exposed aggregate concrete pavements. These concrete pavements proved effective (as described below). However, current politically-based policy dictates that all concrete must be covered with an approved proprietary quiet pavement mixture.[48]

Noise levels associated with various pavement surfaces have been the focus of several U.K. studies. One study compared statistical passby noise levels for two exposed aggregate concrete (EAC) designs with those of traditional hot-rolled asphalt (HRA) pavement. It was found that, in the first 12 months, EAC comprising ¼ – ⅜ in. (6 – 10 mm) aggregate in the surface produced sound levels that were 1.3 to 1.7 dBA lower than those of the HRA pavement and 3 dBA lower than traditional brushed concrete surfaces. EAC comprising 5⁄16 – 9⁄16 in. (8 – 14 mm) aggregate produced sound levels similar to that of the HRA. Furthermore, the hot-rolled asphalt pavements exhibited greater increases in noise levels with time (up to 82 months) than did the exposed aggregate concrete pavements.[48]

Another study showed that porous asphalt (PA) pavements constructed using ¾-in. (20-mm) aggregate exhibited noise levels that were initially 5 – 6 dBA lower than ¾-in. (20-mm) aggregate HRA noise levels. After eight years, the difference was 3 dBA or less.[48]

The British believe that porous pavements constructed on higher-speed roadways can be considered “self-cleaning,” although it is thought that most of the “cleaning” occurs in the tire tracks and that other locations may clog, which reduces the noise benefits that accrue from the absorption of propagating sound. It is believed that the sound absorption capability of porous pavements is generally reduced by about 50 percent after 5 to 6 years.[48]

OTHER EXPERIENCES WITH QUIET PAVEMENTS

Sweden

In Sweden, concrete pavements are preferred for heavily loaded highways. A maximum aggregate size of ⅝ in. (16 mm) is used, together with either longitudinal tining or exposed aggregate surfacing. Noise levels have been monitored for concrete pavements constructed using these designs in the 1990s using close proximity devices at 55 mph (90 kph). Typical noise measures for new pavements have exceeded 98 dBA, but those levels typically decrease by 1 to 3 dbA after 3 years. Sections that use even smaller coarse aggregate (⅜ in. [8 mm] top size) average 1 to 2 dBA lower sound levels.[2]

Ontario, Canada

The Ontario Ministry of Transportation reports that the frictional performance of asphalt pavement is strongly influenced by the performance potential of the aggregate. Aggregate performance can be predicted by laboratory tests such as Polished Stone Value and Aggregate Abrasion Value, augmented by experience derived from field performance.[170]

Ontario also found that concrete pavement friction is not usually influenced by coarse aggregate type. Satisfactory wet pavement friction is obtained by tining the fresh surface or by grinding of a polished surface. Fine aggregates containing at least 50 percent hard minerals (e.g., quartz) must be used in the concrete mixture.[170]

New Zealand

New Zealand monitors their pavement network friction on an annual basis using a SCRIM. While most of the New Zealand highway network is surfaced using chip seals over unbound aggregate layers, heavy-duty pavements and intersections are often surfaced using hot mix asphalt concrete. The network SCRIM surveys identify almost all of this otherwise compliant material as having macrotexture less than 20 mil (0.5 mm) deep, which is considered unacceptable.[171]

To address this texture deficiency, one local road authority decided to groove the asphalt (¼ in. x ¼ in. grooves spaced 1.5 in. on center [6 mm x 6 mm grooves spaced 38 mm on center]) to improve drainage and aid braking and control by hysteretic friction. The first trial sites were grooved in 1994. Examination of accident data from these sites show that the accident rates have decreased on the sites where hot mix asphalt had been grooved. Since then, many sites throughout New Zealand have been grooved as a safety surfacing treatment with some significant reductions in the accident rates recorded. The grooving appears to be effective for about 10 years, after which time traffic erodes the surface and closes the texture.[171]

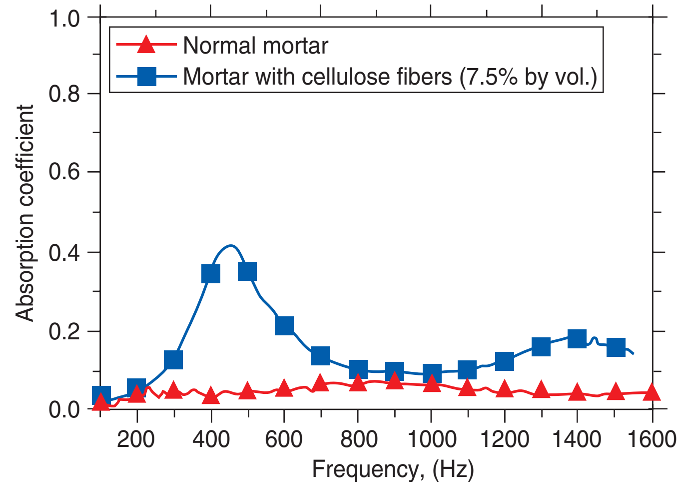


Figure 6.28. Acoustical absorption vs. frequency for normal mortar and mortar containing cellulose fibers.[155]

INNOVATIVE PAVEMENT SURFACES – ROADS FOR THE FUTURE?

Mixtures with Acoustically Absorptive Inclusions

Much research and field experience demonstrates that porous paving surfaces have exceptional promise with respect to sound absorption. However, the tendency of these pores to clog with debris can diminish noise reduction properties with time.[154] The initial and maintenance expense is also a concern. Another approach to increasing pavement porosity involves the use of "aggregates" with a higher-than-typical porosity. It has been suggested that inclusions made from porous, elastic materials will have the ability to combine the conventional mechanisms of sound absorption (i.e., viscous and frictional damping) with structural damping effects.

Researchers at Purdue University investigated the use of several porous alternate aggregate materials, including sintered fly ash, expanded shale, cellular concrete fragments, and cellulose fibers. They found that morphologically altered cellulose fibers were most effective in absorbing sound and damping slab vibrations (see Figure 6.28). They also found that the inclusion of up to 1.5 percent polypropylene fibers in porous concrete mixtures made the resulting material much more acoustically

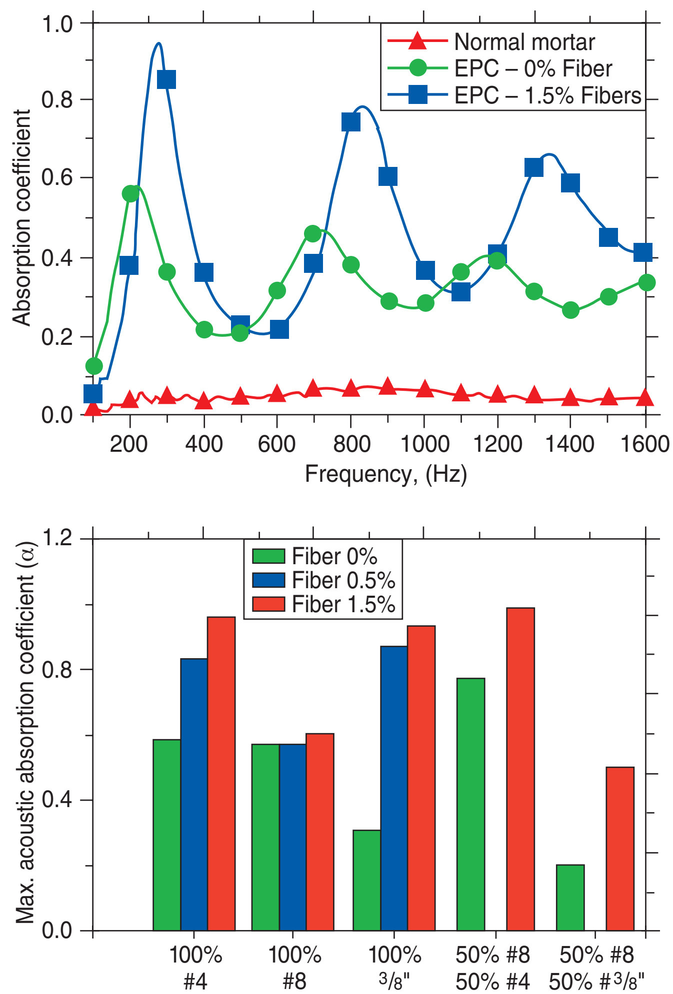


Figure 6.29. Effect of polypropylene fiber content on acoustic absorption properties of porous concrete with various aggregate particle sizes.[155]

absorptive when larger aggregate particles and pore sizes were present, as shown in Figures 6.29. Note that the fibers are particularly effective around 1000 Hz, which is a frequency to which people are generally sensitive.[155]

Poroelastic Road Surfaces (PERS)

Experimental poroelastic road surfaces are prefabricated paving layers of aggregate, bound by a bitumen or polyurethane binder, that are typically produced in panels or rolls. The aggregate particles typically consist of either pure rubber or rubber-related products, such as recycled vehicle tires, but may also include some sand and/or stone material. Aggregate particle shapes vary, ranging from elongated fiber-like particles, which were used for a trial in Sweden, to almost cubic particles (used elsewhere in Scandinavia).[10] Other binders may also produce satisfactory performance and can be used to bind the poroelastic material to the existing pavement surface.

When used as a wearing course, poroelastic surfaces can provide significant tire-pavement noise reductions (5 to 15 dBA when compared to conventional pavement surfaces) due to their high void content, which is often 25 to 40 percent.[1] While PERS noise reduction potential is good, their durability under traffic and snowplow operations has been poor, with failures occurring within one year of installation. Studded tire resistance has been good, however.[1] In general, it appears that PERS can provide good noise reduction, but much development is still needed to make them durable and safe.[1]

Euphonic Pavements

Euphonic pavements, originally developed at the University of Göttingen in Germany, are designed to be quiet pavement structures by incorporating *Helmholtz Resonators* underneath a perforated but plane aluminum structure.[1] Helmholtz resonators absorb low frequencies (typically in the 100 to 250 Hz range). This concept was adopted by Italian researchers in 1992 in their design of a composite pavement consisting of a 1.5 to 2.4-in. (40 to 60-mm) porous asphalt layer placed over a continuously reinforced concrete pavement (CRCP) slab with resonators constructed in the CRCP layer (see Figure 6.30).[10]

Figure 6.30. Double-layer porous asphalt placed over precast concrete containing Helmholtz Resonators.[10]

Various models of euphonic roads have been evaluated in an attempt to improve the design for future implementation as part of an ongoing study by the Silent Road for Urban and Extraurban Use (S.I.R.R.U.S.).[1,132] A similar design was developed in the Netherlands, where precast modular concrete panels (with cast-in-place Helmholtz Resonators) were cast off-site and moved to construction sites during short traffic closure windows. These modular panels were then overlaid with polymer surfaces that were laid down from large rolls (Figure 6.31)

Figure 6.31. Model of “rollable road” surface construction in the Netherlands.

ModieSlab

ModieSlab is a Dutch innovation comprising pile foundations, precast concrete support slabs, and double-layer porous concrete surface construction. It was developed to be a rapid construction method for new roads and road widening projects, especially in areas prone to settlement.[156] Figure 6.32 presents a schematic and constructed example of ModieSlab.

Test sections of ModieSlab constructed on the A50 freeway have resulted in noise reductions of 6 – 7 dBA (extrapolated to 60 mph [100 km/hr]). While the initial cost of this system is high, maintenance costs have been low.[156]

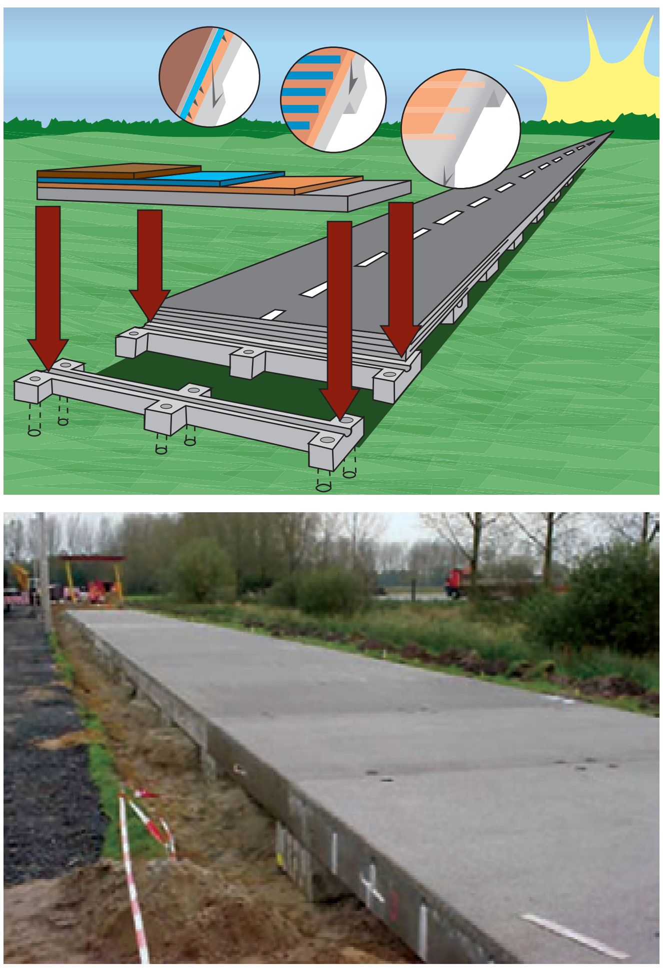


Figure 6.32.Schemadic (top) of ModieSlab construction and photo (bottom) of constructed section.[156]

MAINTENANCE AND DURABILITY CONSIDERATIONS

While tire pavement noise and surface friction (safety issues) are important factors in the selection of pavement surface type and texture, strong consideration must also be given to the durability of the surface (both structural and with respect to noise and friction) along with the periodic costs of maintaining adequate ride quality, structural capacity, and noise and friction characteristics. It is very important to consider not only initial noise reductions and friction measures, but how the pavement surface and sound generation mechanisms change over time due to tire-pavement wear and maintenance activities.

It is generally accepted that concrete pavements last longer and usually require less maintenance than do asphalt pavements.[51] It has been shown that, as concrete pavements wear, tire vibrations generally decrease, reducing the generation of tire-pavement noise until aggregate particles become exposed, at which time sound levels may increase slightly. Even after significant wear has occurred, concrete pavement surface texture can be restored (to low noise and high friction) without the use of overlays through diamond grinding.

SUMMARY

New concrete pavement surfaces can be constructed with many different types of textures, including various forms of dragged and tined surfaces, exposed aggregate finishes, and several newer techniques and materials. Hardened concrete pavement surfaces can be modified through diamond grinding and grooving, overlays and other approaches. Each of these techniques can be designed and constructed to provide durable, safe, high-friction concrete surfaces with relatively low potential for tire-pavement noise. In addition, a number of newer texturing techniques and paving materials have been implemented to varying degrees in Europe, Australia and the United States, including exposed aggregate texturing and porous concrete.

Artificial Turf Drag

Artificial turf drag surfaces are created by dragging an inverted section of artificial turf along the plastic surface of the concrete pavement. In the late 1990s, the Minnesota Department of Transportation (MnDOT) developed and adopted a modified process and specification to produce a much deeper and more durable texture than previous turf drag textures. Because the resulting surface texture offers good wet weather friction and is as quiet as typical asphalt surfaces, artificial turf drag is now the sole texturing technique used on all new concrete pavements in Minnesota.[30] Collected friction and noise data indicate that the MnDOT artificial turf drag texture provides surface friction and noise qualities that are comparable to (and more durable than) those provided by asphalt pavements.[26,47] It is important to note that the depth and durability of MnDOT's turf drag textures are made possible, at least in part, by MnDOT's concrete mix design specification, which limits the water-cement ratio to 0.40. A stiff mix is essential to producing the required texture.

Transverse Tining

Transverse tining is currently the texturing method most commonly used on higher-speed concrete pavements in the U.S. to economically provide durable, high-friction surfaces. Transverse tining can provide good surface friction characteristics for 30 years or longer when good construction practices and high-quality materials are used.[4,14]

Most versions of transverse tining have been associated with tire-pavement interaction sounds with objectionable tonal qualities – i.e., a "whine." Research has led to the development of nonuniform (often called "random") transverse tine spacing patterns that may eliminate this "whine" when properly constructed. Skewing of transverse tine marks appears to be effective in further reducing tire-pavement interaction noise. A longitudinal-to-transverse offset ratio of 1:6 has been recommended.[14]

Wider and deeper tine marks appear to be strongly associated with higher tire-pavement noise levels for all forms of transverse tining.[30] Recent research shows that transverse tining, whether skewed or perpendicular, random or uniform, tends to produce higher tire/road noise levels than other concrete surfaces.[166]

Longitudinal Tining

Longitudinal tining has been used successfully in states and countries with a wide range of environmental conditions, including those that have wet-freeze climates.[14] With a good, durable mix design, carefully selected tine patterns and good construction practices, longitudinally tined PCC pavements can be built to provide a quiet, durable surface with good friction numbers.[4] A 2000 Wisconsin DOT study further concluded that, among all of the concrete pavements evaluated, those with longitudinal tining provided "the lowest exterior noise while still providing adequate texture."[30] Potential splash and spray problems on flat grades or sag areas in wet climates can be mitigated by increasing the pavement cross slope to 2 – 2.5 percent to provide better surface drainage.[10]

Exposed Aggregate Concrete

When properly designed and constructed, exposed aggregate surfaces have performed very well. They can provide tire-pavement noise characteristics similar to porous asphalt, wet weather resistance to hydroplaning equivalent to transversely tined pavements, good surface durability, and low splash and spray. Exposed aggregate texture can be one of the most durable surface textures available for areas of studded tire use.[4] Disadvantages include the additional cost of construction (about 10 percent, based on European experience with large projects).

Porous Concrete

Porous concrete is a material that is intentionally designed to have a large void content by using a gap-graded concrete mix. The resulting permeability allows water and air to flow easily through the material and reduces both the generation and propagation of tire-pavement sound. Reductions of 2 to 8 dBA (relative to dense asphalt surfaces) are typical, depending upon vehicle type, speed and surface conditions, and even higher noise reduction values and excellent wet weather friction have been achieved by diamond grinding porous concrete pavements. As with porous HMA surfaces, the low noise and improved surface drainage characteristics will decrease over time if the pore structure is not kept clean. Porous concrete pavement costs can be as much as 40 percent higher than those of conventional concrete pavements, and one study concluded that they have a life cycle of about 30 years.

Diamond Grinding

Diamond grinding is a highly effective texturing technique that improves pavement profile and ride quality, restores surface friction and reduces tire-pavement noise for existing concrete pavements. A Wisconsin study found that diamond grinding of recently constructed, transversely tined concrete pavements reduced exterior noise levels by 2 to 3 dB and eliminated "whining" characteristics in both the interior and exterior noise spectra.[14,30] Another study concluded that diamond ground pavements were 2 to 5 dBA quieter than the transversely tined pavements when sound was measured at the roadside. New grinding techniques have been found to reduce noise by 3 to 6 dBA.

Diamond grinding creates macrotexture and exposes new microtexture, thereby immediately improving pavement friction in both wet and dry weather. A 1998 Wisconsin study found that the overall accident rate for diamond ground surfaces was only 60 percent of the rate for non-ground surfaces.[46] The long-term frictional benefits depend on the quality of the aggregates in the existing concrete surface. Diamond grinding costs vary with average depth of cut, the hardness of the concrete aggregate and the size of the project, but typically range between $2 and $5 per square yard ($2.40 and $6.00 per square meter).

Grooving

Diamond grooving has become a common technique for improving wet weather friction characteristics at airports, bridges, and in high-accident locations on highways. While it has little impact on tire-pavement noise, it has been noted to reduce wet weather accident rates by up to 85 percent at high-accident rate sites.

Asphalt Overlays

Thin asphalt-based overlay products and surface treatments are used to provide short-term improvements in tire-pavement noise surface friction. However, these benefits often diminish rapidly with time, and some treatments have short performance lives or may fail prematurely. For these reasons, asphalt-based overlay products and surface treatments are often not the most cost-effective approaches to noise reduction. More importantly, many asphalt overlay products are subject to rutting and reduced surface friction under heavy traffic, which can contribute to increased wet weather accident rates. The use of asphalt overlays and surface treatments for purposes of noise reduction must be considered very carefully in terms of durability, cost-effectiveness and safety.

Roads for the Future

Research is underway to develop additional quiet concrete pavements, including the use of concrete containing inclusions made from porous and elastic materials, poroelastic road surfaces that can be bound to existing pavement surfaces, euphonic pavements that incorporate Helmholtz Resonators to absorb low frequencies, and precast concrete support slabs with double-layer porous concrete surface construction supported on piled foundations.

General Considerations for Concrete Pavement Texturing

The effectiveness of each of the concrete pavement surface textures described previously depends upon many factors, including material properties, finishing techniques and timing, and pavement geometrics. A "systems approach" must be used to design and construct pavements that successfully provide quiet and safe travel for many years. *It is rarely sufficient to blindly specify a particular type pavement texture (e.g., transverse tining) without considering the design and construction of the rest of the pavement surface system parameters.*

Results of Pavement Noise and Friction Tests

Many studies of pavement noise and/or friction have been conducted in recent years. Some of the most notable (performed in Colorado, Wisconsin, California/Arizona, Europe and Iowa) are described in this report and the results are generally consistent.

The combined results of the U.S. studies described lead to the conclusion that, *of pavement types and textures commonly used in the U.S., longitudinally tined concrete pavements offer the best combination of consistently low noise, good surface friction (safety), durability and low maintenance.* Asphalt-based pavements are often slightly quieter (at least initially), but do not consistently provide high friction values, are subject to rutting (which can facilitate wet weather accidents) and typically require higher levels of maintenance. Transversely tined concrete pavements (including randomly spaced and skewed tining) generally provide superior friction but are often noisy if the tining pattern parameters are not carefully designed and constructed. At least one state successfully builds longitudinal turf drag textures that are quiet and appear to offer adequate surface friction when properly constructed using stiff, durable concrete mixtures.

Overall sound intensity levels for the European (NITE) study ranged between 94 and 108 dBA. Double-layered porous asphalt (DLPA) pavements were most consistently quiet, with levels ranging from 94 to 97 dBA. Porous asphalt (PA) pavement sound levels varied between 95 and 105 dBA, concrete pavements ranged from 96 to 108 dBA (depending upon the surface texture and finish), dense-graded asphalt (DGA) pavement sound levels were between 98 and 107 dBA, and stone mastic asphalt (SMA) surfaces produced sound levels between 98 and 106 dBA. *The quietest concrete pavement was a porous pavement that had been diamond ground* to produce an SI of 96.6 dBA – among the quietest pavements measured and *quieter than most asphalt pavements* other than the double-layer porous asphalt pavements. The second quietest concrete pavement was another porous pavement (not ground) with an SI of 99.8 dBA.[146]

The NITE study authors concluded that, based on the performance measured in Europe, porous concrete construction has the potential to provide nearly the same sound intensity performance as "quiet" AC surfaces, may be more desirable in some circumstances, and should be investigated further for possible use in the U.S. They also found that fine exposed aggregate concrete surfaces produced SI levels comparable to those of diamond ground surfaces and superior to those of longitudinally tined surfaces. It was recommended that this type of construction be further investigated for application in the U.S.[146]

Maintenance and Durability Considerations

While tire pavement noise and surface friction (safety issues) are important factors in the selection of pavement surface type and texture, strong consideration must also be given to the durability of the surface (both structural and with respect to noise and friction) along with the periodic costs of maintaining adequate ride quality, structural capacity, and noise and friction characteristics. It is very important to consider not only initial noise reductions and friction measures, but how the pavement surface and sound generation mechanisms change over time due to tire-pavement wear (including studded tire wear, where applicable) and maintenance activities.[51]

It is generally accepted that concrete pavements last longer and usually require less maintenance than do asphalt pavements.[51] It has been shown that tire vibrations generally decrease as concrete pavements wear, reducing the generation of tire-pavement noise until aggregate particles become exposed, at which time sound levels may increase slightly.[51] Even after significant wear has occurred, concrete pavement surface texture can be restored (to low noise and high friction) without the use of overlays through diamond grinding.

Chapter 7. "Optimizing" Pavement Texture

INTRODUCTION

Many types of pavement surface texture have been developed to reduce highway noise. The challenge to today's engineers is to specify and design pavement surfaces that balance noise considerations with more traditional requirements of adequate surface friction (i.e., safety), pavement durability (including long-term structural, noise mitigation and safety characteristics), ride quality and economics. There is also a crucial need to better educate road users – the traveling public and commercial carriers – about noise and safety issues and their relationships to one another.

To accomplish these goals, engineers must thoroughly understand the physical and behavioral characteristics of each candidate pavement type and texture under consideration (particularly with regard to safety issues, such as wet and dry pavement friction, which are not as apparent, well-measured and understood as noise, durability, ride quality and economics). It should be recalled that FHWA guidelines and the 1993 *AASHTO Guide on the Evaluation and Abatement of Traffic Noise* recommend that designers should never jeopardize safety to obtain a reduction in noise.[157]

RELATIVE IMPORTANCE OF DESIGN CRITERIA

Most highway agencies around the world recognize that *pavement durability and safety are the most important considerations in selecting a pavement surface.* In a recent (1999) NCHRP survey of highway agencies around the world, respondents were asked to rate the relative importance of various pavement design criteria on a scale of 1 to 3, where 1 means "very important" and 3 means "relatively unimportant." Table 7.1 summarizes the survey results.[8]

Table 7.1. Summary of Design Criteria Ratings.[after 8]

	Average Rating	
Design Criteria	**United States**	**Other Countries**
Durability	1.1	1.3
Skid Resistance	1.2	1.4
Splash and Spray	2.0	1.8
Exterior Noise	2.4	2.2
In-Vehicle Noise	2.4	2.4
Rolling Resistance	2.7	2.7
Tire Wear	2.7	2.9

The ratings (and rank orders) are remarkably consistent between U.S. agencies and their counterparts around the world, which is notable because many of those other countries have been dealing with highway noise issues for a long time. This suggests that, even though highway agencies are under increasing pressure to reduce noise levels surrounding the highway environment, it is recognized that pavement safety and durability are ultimately more important.

While highway users are generally concerned with highway noise issues, it appears that they are less satisfied with issues of pavement durability and safety. In a 2000 FHWA survey of 2030 highway users, respondents were asked about their level of overall satisfaction with quietness of ride, surface appearance, durability and smoothness of ride for U.S. highways. *Only about 23 percent of the users were generally dissatisfied with the quietness* of the ride, while *only about 55 percent were satisfied with pavement durability.*[158]

The same survey found that the biggest source of user dissatisfaction on major U.S. highways is traffic flow, with levels of dissatisfaction increasing rapidly from about 25 percent in 1995 to more than 40 percent in 2000. Additionally, more than 30 percent were dissatisfied with overall pavement conditions and work zones, and nearly 20 percent were dissatisfied with highway safety. *When asked which highway characteristics should receive the most attention and resources for improvement, the top three answers were traffic flow (28 percent), safety (26 percent) and pavement conditions (21 percent).* The improvement that was most frequently cited as a "great help" in overcoming travel delay problems was to use more durable paving materials (67 percent of respondents).[158]

All of these concerns can be addressed by using improved concrete pavement designs that include higher quality materials and higher quality construction and maintenance activities that are determined to be cost-effective.[44]

Work zone safety (reducing deaths, injuries, and traffic delays) is another major concern. In 2002, 1181 highway workers and users were killed in highway work zones. This is a critical area where there are currently few guidelines on desirable texture/friction characteristics, particularly in the work zone transition areas where considerable lane changing and slowing or stopping occurs. *Frictional demands in the vicinity of work zones are significantly higher than for typical divided roadway operations outside of those zones.* Increasing pavement friction would significantly reduce stopping distances in the vicinity of work zones, thereby decreasing accident rates and severities and saving lives.[44]

OTHER CONSIDERATIONS IN SURFACE TYPE/TEXTURE SELECTION

In addition to the design and selection criteria described previously, there are often additional considerations that influence some of those criteria and may limit pavement type/texture options or even dictate specific choices. Some of these considerations include:[2]

- traffic volume, composition and operating speed, which influences both noise generation and safety requirements;
- potential for conflicting vehicle movements (i.e., intersections, work zones), which may require higher surface friction characteristics for vehicle control;
- pavement cross-slope, which affects surface drainage/porosity, which has an impact on splash effects and generation of tire spray;
- geometry of the facility (i.e., curves, superelevation, hills, etc.), which may impact friction and safety requirements;
- climate (i.e., incidence of rainfall, icing conditions), which may create additional emphasis on wet weather conditions or maintenance and deicing costs;
- presence (or absence) of noise-sensitive external receptors (e.g., residential areas, hospitals, schools, etc.);
- availability of materials required for properly constructing specific surface types; and
- ambient temperature requirements that limit the practical application of specific surfaces (e.g., porous rubberized asphalt).

BALANCING TEXTURE DESIGN AND SELECTION CRITERIA

Many studies of pavement surface texture and its relationship to tire-pavement noise have been conducted.[14] One such study summarized subjective ratings of concrete pavement texture, noise and skid resistance for various types of pavement surfaces, as shown in Table 7.2. Such studies and tables can be useful in identifying pavement tex-

Table 7.2. Subjective Ratings of Texture, Friction and Noise Characteristics of Various Concrete Pavement Textures.[41]

Pavement Type	Macro-texture	Micro-texture	Skid Resistance	Noise
Burlap longitudinal	3	2	3	1–
Burlap + comb longitudinal	2	2	2	1–
Turf drag longitudinal	1	2	1–	1–
Broom longitudinal	1	2	1–	2
Broom transverse	1	1	1+	3–
Longitudinal grinding	1	2	2	1–
Exposed aggregate concrete	1	3	2	2
Porous concrete	1+	3	2	1+
Gritted resin coating	1	1	1	1–

Rating key: 1 – very good, 2 – good, 3 – fair or worse.

tures that suitably balance specific project requirements for safety and tire-pavement noise when the textures included are representative of those being considered for construction.

Wisconsin Study of Pavement Noise and Texture Characteristics

The authors of the Wisconsin noise and texture study applied selected criteria (based on their judgment) to determine which of the pavement surfaces considered were "desirable" or generally acceptable.[30] The selected criteria were:

- a maximum exterior noise level (L_{max}) of approximately 83.0 dBA or lower;
- a maximum interior noise level (L_{eq}) of approximately 68.0 dBA or lower;
- a subjective noise rating of 100 (comparable to their ¾-in. [19-mm] random transversely tined concrete pavements) or less;
- no significant frequency spikes (tones or "whining"); and
- a ROSAN ETD of 28 mil (0.7 mm) or above.

Friction requirements were not set because available friction measurements had been obtained by state agency personnel rather than the research team. Friction values (FN40S) were, however, noted for all pavement types. Additional criteria, such as economics, durability and ride quality were not considered directly (although IRI values were measured).

All of the asphalt concrete (AC) pavements included in the study met the criteria for interior and exterior noise. However, the ROSAN ETD was inadequate for the standard dense-graded AC pavements, the SHRP AC pavement, and for SMA pavements with maximum aggregate sizes smaller than ⅝ in. (16 mm). It was also noted that friction values (FN40S) were lower than 34 (and as low as 20) for all of the AC pavements, which were only 6-7 years old at the time of study.

Figure 7.1 compares the tire-pavement noise and texture characteristics of the four study pavements that represent the best of their types with respect to the external noise criterion listed above. The pavement surfaces represented include longitudinal tining, SMA with large aggregate, randomly-spaced skewed tining and randomly spaced transverse tining. The exterior sound profiles of the four pavements are similar, with *the longitudinally tined concrete being the quietest of the four (by nearly 3 dBA).* It should also be noted that the SMA pavement represented in this figure had the deepest tex-

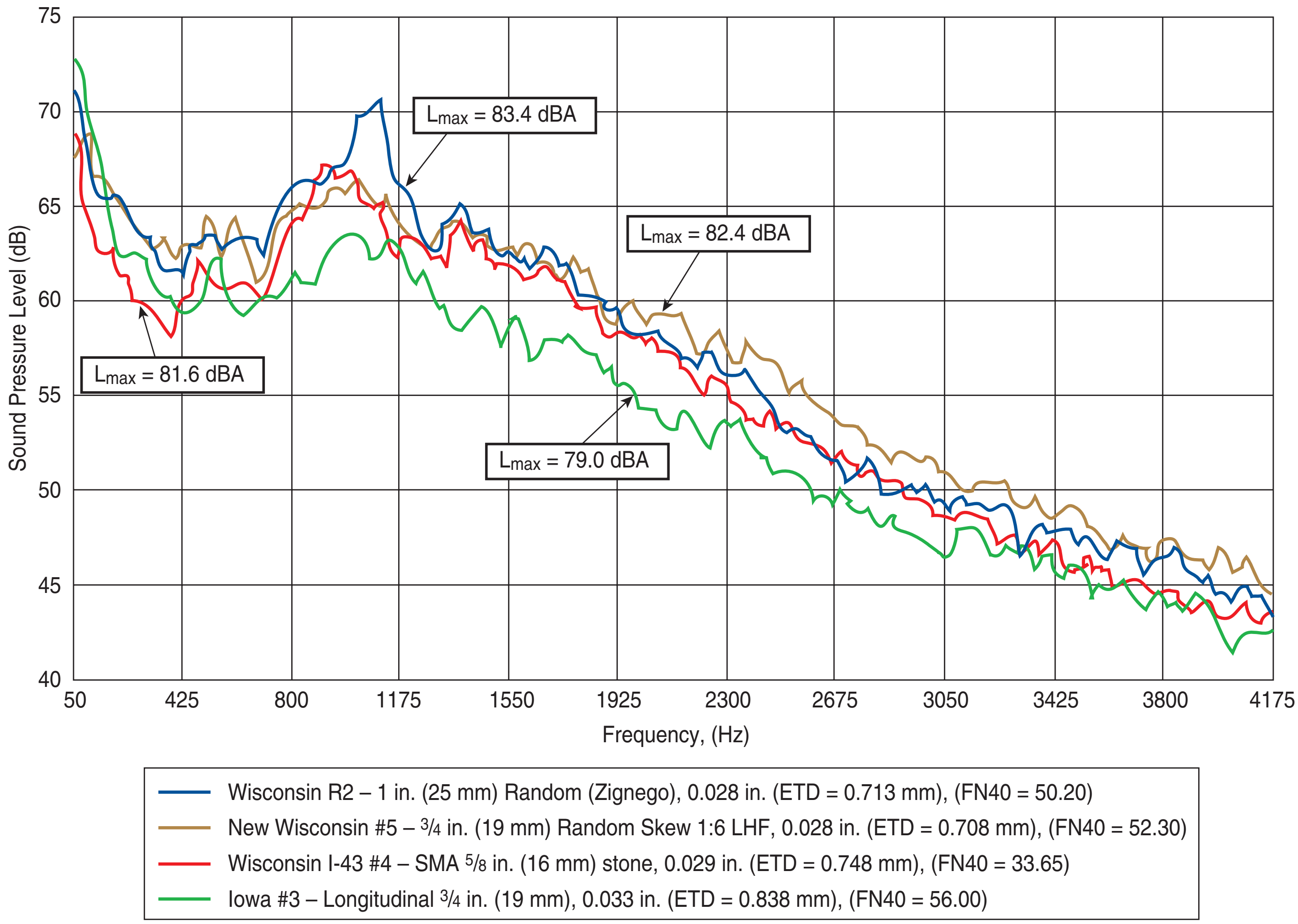


Figure 7.1. Comparison of Wisconsin study "Best of the Best" for exterior noise.[30]

ture and best friction of all of the asphalt pavements included in the study (FN40S = 33.65), but that friction level is far below the range of friction exhibited by the concrete pavements (FN40S = 50 to 56).

It is also interesting to note that the longitudinally tined pavement had the deepest texture of the four (ROSAN ETD of 1.253 vs. 0.7 to 0.8), yet produced the lowest exterior noise of the four. Texture depth of longitudinally tined concrete pavements varied by 50 to 250 percent in the four study states with these pavements, yet little or no increase in exterior noise was observed. Clearly *tire-pavement noise for longitudinally tined concrete pavements is not highly dependent on texture depth, which makes this surface design highly reliable and eases construction consistency concerns.*

Figure 7.2 compares the interior noise frequency profiles for the pavement sections that represent the best of their type with respect to the internal noise criteria described previously, and it includes 3 of the 4 sections profiled in Figure 7.1 (a different longitudinally tined section is used). The closeness of the interior noise profiles is striking, with less than 2 dBA separating the noisiest from the quietest, and only 0.5 dBA separating the SMA profile from the longitudinally tined concrete profile. The longitudinally tined concrete also had one of the best subjective ratings of interior noise.

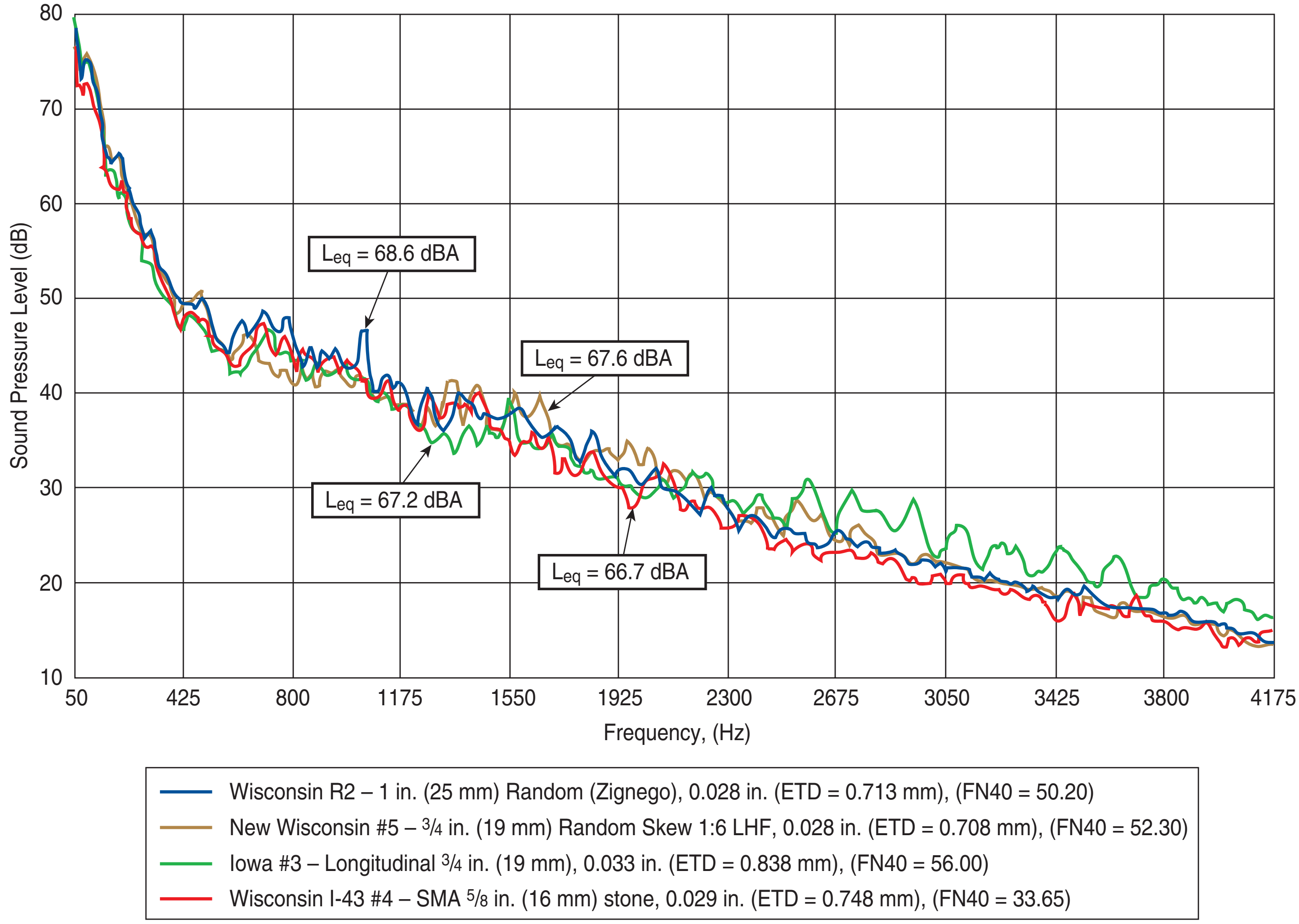


Figure 7.2. Comparison of Wisconsin study “Best of the Best” for interior noise.[30]

Of the 21 study pavements evaluated for subjective interior sound levels, only nine met the third Wisconsin study criterion (subjective interior noise rating lower than 100); several of these (including the asphalt section) exhibited low levels of friction.

The Wisconsin authors concluded that the randomly spaced and skewed tined pavements were among the quietest pavements (both interior and exterior noise) in the study and had the best subjective ratings of the 21 sections considered by users. The test sections produced no prominent discrete frequencies and provided good friction and texture characteristics.[30] However, experience with random transverse tining on projects constructed since this study suggests that it is sometimes difficult to construct randomly spaced transverse or skewed tine patterns that have consistently good noise characteristics.

Based on the Wisconsin study data and criteria, it appears that longitudinal tining might be the best option for new construction of high-volume, high-speed pavement facilities. This texture is easy to construct consistently, exhibits low interior and exterior noise with less sensitivity to tining depth than other tining patterns. Longitudinally-tined pavement has even lower exterior noise than the randomly spaced and skewed tine patterns, and no discrete frequencies, good friction and texture potential, and the superior durability of concrete.

Santa Clara Valley Noise Mitigation Study[159]

Life cycle cost (or economic) analysis is a potentially powerful tool for assisting in making pavement management decisions, including decisions about pavement type and surfacing selection. The Parsons Transportation Group of San Jose, California performed a preliminary study for the Santa Clara Valley Transportation Authority that is a good example of the application of life-cycle cost analysis techniques to pavement noise mitigation.

A portion of Route 85 in Santa Clara County, California was constructed using longitudinally grooved concrete pavement and was opened to traffic in 1994. Traffic volumes and accompanying highway noise levels soon exceeded original estimates, and abutting property owners sought reductions in the noise levels.

Several mitigation options were considered, including:

- speed reductions for vehicles using the highway;
- adding vertical extensions and/or acoustical caps to existing noise barriers;
- adding acoustically absorptive facades to existing noise barriers and retaining walls;
- asphalt overlays (open-graded traditional, open-graded rubberized and "NovaChip"); and
- diamond grinding the existing concrete pavement surface.

It was determined that posted speed reductions (from 65 mph to 55 mph [105 km/hr to 89 km/hr]) would reduce noise levels by 2 dBA, an amount that might be considered imperceptible. This approach would have required relatively little initial expense (sign changes and public awareness programming), but would have required increased enforcement efforts (and associated costs) to be fully effective. Since the highway design operating speed was well over 55 mph (89 km/hr), it was considered unlikely that motorists would be inclined to travel at the reduced speed, so the potential noise reduction would probably not have been realized. Therefore, this option was dropped from further consideration.

The amount of possible noise wall height extension was limited by the design of the existing wall foundations. In addition, much of the highway was depressed below grade. These two factors limited the expected potential effectiveness of wall height extensions and caps to 1-2 dBA – a negligible amount. Furthermore, relatively few abutters (those closest to the walls) would have benefited significantly from this approach. The costs of construction were estimated at $1.17M for the vertical extensions and $1.48M for acoustical caps. The need to modify wall foundations in some areas (to support the additional wall height) would have resulted in construction activities that would have adversely impacted traffic flow. Once constructed, maintenance costs would have been low.

Adding attenuative material to existing retaining walls and noise barriers walls was expected to produce a benefit of less than 2 dBA (again, practically negligible) at a cost of $3.27M. Planting dense shrubs and ivy was expected to produce similar benefits at less cost ($1.85 M). The use of attenuative material and landscaping would have had little impact on traffic flow, and recurrent maintenance costs were assumed to be low. However, it was also expected they would not produce a significant reduction in roadway noise for most abutters.

Several types of asphalt overlay were considered. Table 7.3 summarizes the design thicknesses, expected initial noise benefits, durations of the noise benefits, performance lives and net present costs of constructing and maintaining each overlay type. The costs shown are for 3 travel lanes in each direction and are based on a 35-year analysis period and 5 percent discount rate (details of the economic analysis can be found in the report's appendix).[159]

Table 7.3. Summary of Asphalt Overlay Option Assumptions for Santa Clara Valley *after 159*

Type of Overlay	Open-Graded	Open-Graded Rubberized AC	NovaChip®
Overlay Thickness	¾" to 1" (19 to 25 mm)	1" to 1¼" (25 to 32 mm)	⅝" to ¾" (16 to 19 mm)
Expected Noise Benefit (dBA)	2 to 4	2 to 5	3 to 4
Expected Noise Benefit Life (years)	4 to 5	4 to 6	4
Expected Performance Life (years)	8 to 10	20	10 to 12
Net Present Worth $/mile ($/km)	$1.52M ($0.94M)	$1.83M ($1.14M)	$1.87M ($1.16M)

The construction of any overlay option was considered to have a moderate impact on traffic flow, and the relatively short noise benefits and expected performance lives were believed to result in relatively high recurrent maintenance costs for surface cleaning, repair and/or replacement. However, it was also considered that all abutters would experience (at least initially) a noticeable reduction in highway noise levels.

Diamond grinding was expected to produce an overall reduction in highway noise of 3 to 6 dBA at a distance of 25 ft (7.6 m), and about 3 dBA at a distance of 50 ft (15 m), with the main reduction being observed in the 500 to 2000 Hz frequency range, which contains the frequencies to which humans are most sensitive. Details of the study that was performed to determine the benefits of the diamond grinding were published formally.[159]

Like the asphalt overlay options, the diamond grinding process was assumed to have a moderate impact on traffic flow. However, diamond grinding was expected to have a longer noise benefit life (10 years) and relatively long structural life (30 or more years for the pavement structure, about 12 years for the grinding itself). Like the asphalt overlay options, it was also considered that all abutters would experience (at least initially) a noticeable reduction in highway noise levels. The estimated cost of diamond grinding this project, based on net present worth analyses, was $840,000 per mile ($522,000 per kilometer).

It should be emphasized that the assumptions made concerning the specific costs and performances associated with the asphalt overlay and diamond grinding options are based on the reasonable opinions and analyses of one consultant group for a specific project. Different values might be suggested and used by others for this project or another project, and suitable values might change with time and advances in technology.

Table 7.4 summarizes the consultant's preliminary estimates of the costs, benefits and impacts of the various noise mitigation alternatives considered for this project. The consultant noted that, using these assumptions, *diamond grinding produced a noise benefit similar to that of the AC overlay options at about half of the life-cycle cost* (due to the need to frequently mill and replace the asphalt overlay options to maintain the noise benefit, which would otherwise diminish rapidly with time). *It was also noted that diamond grinding resulted in a surface that would have lower maintenance requirements,* thereby lessening impact to the traveling public and reducing exposure of maintenance workers to traffic. Therefore, diamond grinding was recommended, along with soundwall height increases and/or acoustical capping in selected locations.[159]

The Santa Clara study did not progress beyond the draft final report; it is presented here as a good example of the use of economic analysis, together with consideration of nonmonetary factors, to objectively select the best overall strategy for pavement surface selection. Value engineering techniques can be used to further enhance this process, as described in the next section.

Table 7.4. Summary of Estimated Costs, Benefits and Impacts of Various Noise Mitigation Strategies for Santa Clara Valley, Route 85. [after 159]

Impacts, Benefits and Costs	Modify Pavement				Extend Noise Barrier		Add Absorptive Material	
	AC Overlay Options			PCC Grinding	Increase Wall Height	Acoustical Capping	Metallic Panels	Landscaping
	OGAC	OGAC-Rubberized	NovaChip®					
Construction Impacts	Medium			Medium	High	Low	Low	Low
Maintenance Impacts	High			Medium	Low	Low	Low	Low
Residential Benefit	All			All	Few	Few	None	None
General Noise Benefit (dBA)	2 to 4	4 to 6	3 to 4	3 to 4	1 to 2	1 to 2	< 2	< 2
Net Present Cost $/mile, millions ($1/km, millions)	$1.52 ($0.94)	$1.83 ($1.14)	$1.87 ($1.16)	$0.84 ($0.52)	$0.29 ($0.18)	$0.36 ($0.22)	$0.79 ($0.49)	$0.45 ($0.28)

It is worth noting that, even though the highway agency stopped this study after the draft report, diamond grinding was ultimately chosen and implemented as the primary component of the noise mitigation solution for this project.[160]

APPLYING VALUE ENGINEERING TECHNIQUES

The selection of the preferred pavement surface type and texture for new pavements or noise mitigation on existing pavements involves consideration of many factors that cannot all be quantified on the same scale. In addition, the relative importance of these factors can vary significantly from project to project.

Fortunately, value engineering techniques provide generally accepted tools for identifying the best choices in decision-making situations like these. Some of these tools and guidelines for their use are presented in numerous texts and training courses, including the National Highway Institute's (NHI) Participant's Manual for their Value Engineering course.[161]

One approach described in the NHI Value Engineering course is to identify and weight all of the criteria that should be considered in the decision-making process, to rate each alternative with respect to each criterion (often on a scale of 0 – 100), multiply the ratings by the weighting factors and then add the scores for each alternative. Since the weighting and rating processes depend upon the opinions of the person or team that develops them, the process is necessarily inexact. However, it is often considered useful in identifying alternatives that are clearly superior to others.

The following is a simplified example that illustrates this approach.

Example:
A section of busy urban interstate highway is to be reconstructed. Basic structural designs have been developed for both asphalt and concrete paving alternatives, but pavement surfacing type and texture must be determined. The six options under consideration are: concrete pavement structure (longitudinal tining, randomly spaced skewed tining, diamond ground porous concrete, or rubberized

asphalt overlay of concrete pavement [composite section]) or asphalt pavement structure (porous asphalt surface, SMA surface).

The following criteria are identified as most important to this particular decision-making process (different factors might be identified by other people and for other projects) and relative weighting factors are assigned (values were selected to add to 100 and are shown in parentheses; these values might also vary between projects):

First cost (20)

Structural Durability (15)

Safety, including wet/dry weather friction, hydroplaning potential, black ice, etc. (20)

Interior Noise (10)

Exterior Noise (5)

Durability of Friction and Noise Reduction Characteristics (20)

Future Maintenance Costs and Options (10)

Based on local experience and available noise, friction, cost and durability information, each of the six alternatives is then rated from 0 to 100 with respect to each of the decision criteria, where 100 is the best possible score. Figure 7.3 presents a table that summarizes possible ratings and overall scores for each of the alternatives.

DESIGN ALTERNATIVES / DECISION CRITERIA	First Cost	Structural Durability	Safety	Interior Noise	Exterior Noise	Friction and Noise Durability	Future Maint. Costs and Opts.		TOTALS
WEIGHTING FACTORS, %	20	15	20	10	5	20	10		
Concrete – longitudinally tined	60	100	90	85	90	100	100		88
	12	15	18	8.5	4.5	20	10		
Concrete – random, skewed tining	60	100	95	75	85	100	100		87.75
	12	15	19	7.5	4.25	20	10		
Porous concrete, diamond grind	40	90	100	95	95	80	75		79.25
	8	13.5	20	9.5	4.75	16	705		
Concrete slab with rubberized AC surface	40	75	75	100	100	50	50		64.25
	8	11.25	15	10	5	10	5		
Porous asphalt	80	50	75	90	100	50	40		66.5
	16	7.5	15	9	5	10	4		
HMA base, SMA surface	90	60	80	95	95	70	60		77.25
	18	9	16	9.5	4.75	14	6		

Key:	
	Rating
	Rating x Weight Factor

Figure 7.3. Example summary table for one value engineering approach to selecting pavement surface type and texture.

In this example, two alternatives have scores that are comparable and are probably significantly higher than the others: concrete pavement with longitudinal tining and concrete pavement with randomly spaced, skewed tining. Without additional considerations, one of these alternatives would probably be selected for implementation in this example.

Details concerning this and other value engineering techniques can be found in the NHI training course materials (Reference 161) or one of many other references on the subject.

BEST PRACTICES FOR SURFACE TEXTURE DESIGN AND CONSTRUCTION

"Optimization" of pavement surface texture involves not only the selection of the best pavement type and texture for project-specific conditions (including consideration of pavement geometrics, cross-slope, etc.), but also the specification, design and construction of the selected surface texture to ensure that the properties assumed in the selection process are actually produced in the constructed project. Many of the best practices for the design and construction of various concrete pavement surface textures were described in Chapter 6 of this synthesis.

Chapter 8.
Summary and Recommendations

Many sources of sound contribute to the overall level of sound that is generated in the highway environment, including pure vehicle sources, aerodynamic effects, and tire-pavement interactions. If all other factors are held constant, tire-pavement noise levels vary mainly with pavement surface characteristics such as porosity and texture. Asphalt and concrete pavements constructed with identical surface characteristics and subjected to identical traffic streams will generate nearly identical sounds. Selecting an ideal pavement type and surface texture is a complex problem that requires consideration of several competing factors, including safety, cost, climate, traffic characteristics, proximity and sensitivity to sound of abutting residences or businesses, and durability.

Pavement surface texture influences many different tire-pavement interactions, including wet-weather friction, tire-pavement noise, splash and spray, rolling resistance, and tire wear.[8]

Microtexture (wavelengths of 0.0004 in. to 0.02 in. [1 μm to 0.5 mm]) is usually all that is needed to provide adequate stopping on dry concrete pavements and, in concrete, is typically contributed by the fine aggregate (sand) in the mortar. Macrotexture (wavelengths of 0.02 in. to 2 in. [0.5 mm to 50 mm]) has the strongest impact on tire-pavement noise and splash and spray, and plays a major role in the wet weather friction characteristics of pavement surfaces. In concrete pavements, macrotexture is most commonly produced through small surface channels, grooves, or indentations that are intentionally formed in plastic concrete or cut in hardened concrete.

ROADWAY NOISE AND PAVEMENT TEXTURE

Sound is acoustic energy that results from variations in air pressure and density; it is commonly expressed in decibels (dB), a logarithmic measuring scale which is often adjusted using an “A-weighting filter” to account for human sensitivity to certain frequencies (dBA). An increase of 10 dB is perceived by humans as a doubling of loudness. Under ideal circumstances, 1 dB is the smallest difference in sound pressure level that human hearing can distinguish; 3 dB is the smallest difference that most people can distinguish under less-than-ideal circumstances.

When adding the effects of sound from two or more independent sources (such as multiple tires or vehicles) to determine an overall sound level, the contributing sound levels must be converted to their corresponding measures of sound power, added, and then converted back to the logarithmic measure of sound pressure level. Therefore, the combined effect of two independent sounds of 70 dB each, for example, will result in an overall sound level of 73 dB rather than a simple sum of 140 dB.

Causes of Roadway Noise

Noise emitted from vehicles and their interaction with pavements can be attributed to several source categories, including tire-pavement, engine, intake system, exhaust system, powertrain and other sources (including air turbulence). Tire-pavement interaction is generally the largest individual source at vehicle speeds of more than 10 – 30 mph (15 – 45 km/hr) for cars and 20 – 35 mph (30 – 50 km/hr) for heavy vehicles, depending upon the specific vehicle characteristics, the pavement surface characteristics, whether the vehicle is cruising or accelerating, and other factors.[1] Many factors influence the generation of tire-pavement noise, including vehicle/tire speed, road surface type, tire type/design (including tire width, tread design, rubber hardness, etc.), the use of tire studs, tire load and inflation pressure, road condition, temperature, and torque/acceleration on the wheel.

The sound emission characteristics of pavement surfaces are also a function of acoustic absorption, which is closely linked to surface porosity. Increased surface porosity reduces the *generation* of noise at the tire-pavement interface, as well as the *reflection* of noise off the pavement.

Perception of Roadway Noise

Roadway noise is generally discussed in terms of two different perspectives: sounds heard by people inside of vehicles (i.e., interior noise) and sounds heard by people outside the vehicle (i.e., exterior noise). Recent research has found that *objectionable* interior noise is associated more with tonal quality (often described as *tire whine*) than with total noise level.[30] The key to reducing “tire whine” and perceived noise is to eliminate the peaks in the noise spectra. Exterior noise is primarily a concern in urban areas and has been found to increase with increases in macrotexture.[8] There are many factors that influence the level of sound that reaches receptors outside of the vehicle, including: receptor distance to the sound source, presence of barriers to the sound, and environmental effects such as wind, temperature and humidity.

Measurement of Roadway Sound

Several different methods have been developed and used for comparing tire-road noise from different pavement surfaces, including “far-field” techniques like the statistical pass-by test and “near-field” tests like the close proximity (CPX) and on-board sound intensity (OBSI) methods. The OBSI technique is rapidly becoming the standard test for tire-pavement interaction noise because it isolates tire-pavement noise, measures both sound intensity and directionality, and can be performed relatively inexpensively and quickly. Draft OBSI specifications are currently being developed by an FHWA expert task group (ETG).

Sound levels inside of vehicles are typically measured in accordance with SAE J1477 (“Recommended Practice for Measurement of Interior Sound Levels of Light Vehicles”). Wisconsin researchers recently developed an in-vehicle noise measuring system and analysis method, based on the SAE J1477 practice, which can be used to identify pavement textures that generate objectionable tonal qualities.[30]

ROADWAY FRICTION AND PAVEMENT TEXTURE

Pavement texture affects both roadway noise and friction characteristics. Highway safety must not be sacrificed in favor of reductions in roadway noise. It is essential that the pavement design process specifically include the selection and design of surface textures that reduce hydroplaning potential and provide improved surface friction for both wet and dry pavements, especially for higher speed roadways in urban areas.

Factors that Affect Pavement Friction and Safety

The pavement texture characteristics that affect friction most strongly are microtexture and macrotexture, both of which help to provide resistance to skidding on wet pavements. Increasing macrotexture also reduces the potential for splash and spray and increases skid resistance. Tire design and condition (e.g., rubber compound, tread design, wetness and wear) also strongly influence vehicle safety, especially in wet weather. Hydroplaning potential can be reduced in many ways, including the use of increased cross-slope, increased pavement surface texture depth (including pavement grooving) and the use of open-graded and porous pavement surfaces.

Pavement friction usually decreases with pavement age due to two mechanisms: 1) aggregate polishing under traffic reduces microtexture, and 2) aggregate wear under traffic reduces macrotexture. In addition, seasonal changes, such as winter conditions, winter maintenance operations, periodic rainfalls, etc., may produce either decreases *or* increases in pavement friction.

Measurement of Pavement Friction

Most U.S. highway agencies measure pavement friction with a locked-wheel trailer using either a standard ribbed (longitudinal grooves on the tread surface) or smooth (blank) tire. Water is applied to the dry pavement in front of the trailer, which is towed at a predetermined speed, and the friction between the locked tire and pavement surface is measured. The friction number (or *skid number*) is computed as 100 times the force required to slide the locked test tire over the pavement surface, divided by the effective wheel load.[30]

Ribbed treads are relatively insensitive to macrotexture and are mainly influenced by microtexture, which partly explains the sometimes poor correlation between ribbed tire friction test values and highway accident rates.[78] Research indicates that standard smooth tires produce friction test results that correlate better with wet weather accident rates.[4,78,79]

Surface Friction Criteria

Current and past FHWA documents have provided state and local highway agencies with guidance in establishing skid accident reduction programs, but have not provided specific recommended values for minimum or desirable pavement friction test results. U.S. highway agencies that have published minimum acceptable levels for skid resistance typically consider friction numbers of 30 to 40 (40 mph [64 km/hr] test with ribbed tires) as acceptable for interstate highways and other roads with design speeds greater than 40 mph (64 km/hr). Lower friction numbers have generally been accepted for pavements with low traffic volumes. Outside of the U.S., many highway agencies have established minimum friction levels for intervention and/or investigation, and these levels are often higher than those described above.

CONTROLLING SOUND FROM THE HIGHWAY ENVIRONMENT

Current federal law requires that highway agencies determine and analyze expected traffic noise impacts on federally funded projects. If measured or expected noise levels approach or exceed allowable threshold values, noise abatement procedures must be considered. However, federal law does not *require* that noise levels be abated to any particular levels.

Highway sound can be controlled at the source, at the receiver(s) or along the path between the two. The disadvantages of noise walls (i.e., high cost, visual blight, ineffectiveness where breaks must be provided) and the impracticality of restricting traffic flow in most situations has placed the focus of current highway noise mitigation research on reducing noise at the sources, including at the tire-pavement interface.

Research indicates that effective noise reductions *can* be accomplished by managing pavement *surface characteristics* such as macrotexture and porosity, which are independent of pavement type. The FHWA has not allowed pavement *type* to be used as a noise mitigation strategy because many significant components of highway noise (e.g., heavy vehicle engine, exhaust, etc.) are independent of pavement type. Pavement type and structure *do* impact the rate of change and durability of surface characteristics and can strongly influence the true long-term cost and effectiveness of noise mitigation.

There are several approaches to designing and constructing new concrete pavements with safe, quiet, durable surfaces, as described below.

CONCRETE PAVEMENT SURFACES – CONSTRUCTION AND CHARACTERISTICS

New concrete pavement surfaces can be constructed with many different types of textures, including various forms of dragged and tined surfaces, exposed aggregate finishes, and several newer techniques and materials. Hardened concrete pavement surfaces can be modified through diamond grinding and grooving, overlays and other approaches. Each of these techniques can be designed and constructed to provide durable, safe, high-friction concrete surfaces with relatively low potential for tire-pavement noise. In addition, a number of newer texturing techniques and paving materials have been implemented to varying degrees in Europe, Australia, Japan and the United States, including exposed aggregate texturing and porous concrete.

Artificial Turf Drag

In the late 1990s, the Minnesota Department of Transportation (MnDOT) developed and adopted a modified process and specification to produce a much deeper and more durable texture than previous turf drag textures. The resulting surface texture offers good wet weather friction, is as quiet as typical asphalt surfaces, and is now the sole texturing technique on all new concrete pavements in Minnesota.[30] The depth and durability of MnDOT's turf drag textures are made possible, at least in part, by MnDOT's concrete mix design specification, which limits the water-cement ratio to 0.40 and provides contractor incentives down to 0.35. MnDOT specifications also require periodic verification of texture depth measurement during construction (via the sand patch test) to ensure good results; diamond grinding is required when texture depths are deficient.

Longitudinal Tining

Longitudinal tining has been used successfully in states and countries with a wide range of environmental conditions, including those that have wet-freeze climates.[14] With a good, durable mix design, carefully selected tine patterns and good construction practices, longitudinally tined concrete pavements can be built to provide quiet, durable surfaces with good friction numbers.[5] A 2000 Wisconsin DOT study further concluded that, among all of the concrete pavements evaluated, those with longitudinal tining provided "the lowest exterior noise while still providing adequate texture."[30]

Transverse Tining

Transverse tining is currently the texturing method most commonly used on higher-speed concrete pavements in the U.S. It can provide good surface friction characteristics for 30 years or longer when good construction practices and high-quality materials are used.[4,14] Some transverse tining has been associated with "whining" tire-pavement interaction sounds. Nonuniform (often called "random") transverse tine spacing patterns can (when properly constructed) eliminate this "whine." Skewing of transverse tine marks appears to be effective in further reducing tire-pavement interaction noise. Wider and deeper tine marks are strongly associated with higher tire-pavement noise levels for all forms of transverse tining.[30]

Exposed Aggregate Concrete

When properly designed and constructed, exposed aggregate surfaces have performed very well in Europe. They can provide tire-pavement noise characteristics similar to porous asphalt, wet weather resistance to hydroplaning equivalent to transversely tined pavements, good surface durability, and low splash and spray. Exposed aggregate texture can be one of the most durable surface textures available for areas of studded tire use.[4] Disadvantages include the additional cost of construction (about 10 percent, based on European experience with large projects).

Porous Concrete

Porous concrete is intentionally designed to have a large void content. The resulting permeability allows water and air to flow easily through the material and reduces both the generation and propagation of tire-pavement sound. Reductions of 2 to 8 dBA relative to dense asphalt surfaces are typical, and even greater noise reduction and excellent wet weather friction have been achieved by diamond grinding porous concrete pavements. The low noise characteristics will decrease over time if the pore structure is not kept clean. Porous concrete pavement costs can be as much as 40 percent higher than conventional concrete pavements, and one study concluded that they have a life cycle of about 30 years.

Diamond Grinding

Diamond grinding is a highly effective texturing technique that improves pavement profile and ride quality, restores surface friction and reduces tire-pavement noise for existing concrete pavements. Studies show that it can eliminate "whining" sounds in both the interior and exterior noise spectra and that exterior noise reductions of 2 to 6 dBA are possible. Diamond grinding also immediately improves pavement friction in both wet and dry weather. A 1998 study found that diamond ground surfaces had overall accident rates that were 40 percent lower than those of non-ground surfaces.[46]

Grooving

Diamond grooving has become a common technique for improving wet weather friction characteristics at airports, bridges, and in high-accident locations on highways. While it has little impact on tire-pavement noise, it has been noted to reduce wet weather accident rates by up to 85 percent at high-accident rate sites.

Asphalt Overlays

Thin asphalt-based overlay products and surface treatments are used to provide short-term improvements in tire-pavement noise surface friction. However, these benefits often diminish rapidly with time, and some treatments have short performance lives or may fail prematurely. More importantly, many asphalt overlay products are subject to rutting and reduced surface friction under heavy traffic, which can contribute to increased wet weather accident rates.

General Considerations for Concrete Pavement Texturing

The effectiveness of each of the concrete pavement surface textures described previously depends upon many factors, including material properties, finishing techniques and timing, and pavement geometrics. A "systems approach" must be used to design and construct pavements that successfully provide quiet and safe travel for many years. *It is rarely sufficient to blindly specify a particular type pavement texture (e.g., transverse tining) without considering the design and construction of the rest of the pavement surface system parameters.*

Pavement Noise and Friction Test Results

Many studies of pavement noise and/or friction have been conducted in recent years. The combined results of the U.S. studies described lead to the conclusion that, *of pavement types and textures commonly used in the U.S., longitudinally tined concrete pavements offer the best combination of consistently low noise, good surface friction (safety), durability and low maintenance.* Asphalt-based pavements are often slightly quieter (at least initially), but do not consistently provide high friction values, are subject to rutting (which can facilitate wet weather accidents) and typically require higher levels of maintenance. Transversely tined concrete pavements (including randomly spaced and skewed tining) generally provide superior friction but are often noisy if the tining pattern parameters are not carefully designed and constructed. At least one state (Minnesota) successfully builds longitudinal turf drag textures that are quiet and appear to offer adequate surface friction when properly constructed using stiff, durable concrete mixtures.

European experience suggests that porous concrete construction has the potential to provide nearly the same sound levels as "quiet" AC surfaces, may be more desirable in some circumstances, and should be investigated further for possible use in the U.S. It also indicates that fine exposed aggregate concrete surfaces produce SI levels comparable to those of diamond ground surfaces and superior to those of longitudinally tining; they may also be suitable for application in the U.S.[146]

Maintenance and Durability Considerations

It is very important to consider not only initial noise reductions and friction measures, but how the pavement surface and sound generation mechanisms change over time due to tire-pavement wear (including studded tire wear, where applicable) and maintenance activities.[51] It is generally accepted that concrete pavements last longer and usually require less maintenance than do asphalt pavements.[51] It has been shown that tire vibrations generally decrease as concrete pavements wear, reducing the generation of tire-pavement noise until aggregate particles become exposed, at which time sound levels may increase slightly.[51] Even after significant wear has occurred, concrete pavement surface texture can be restored (to low noise and high friction) without the use of overlays through diamond grinding.

"OPTIMIZING" PAVEMENT TEXTURE

Relative Importance of Design Criteria

In spite of the relatively recent emphasis on highway noise reductions, most highway agencies recognize that *pavement durability and safety are the most important considerations in selecting a pavement surface.* A 2000 FHWA survey suggests that highway users are also more dissatisfied with pavement durability and safety than with noise issues. Work zone safety (reducing deaths, injuries, and traffic delays) is another major concern because *frictional demands in the vicinity of work zones are significantly higher than for typical divided roadway operations outside of those zones.* Increasing pavement friction would significantly reduce stopping distances in the vicinity of work zones, thereby decreasing accident rates and severities and saving lives.[44]

Balancing Texture Design and Selection Criteria

Many considerations may dictate, limit or influence pavement type/texture options including: traffic volume, composition and operating speed; areas that require higher levels of friction (e.g., intersections, work zones); pavement cross-slope, which affects surface drainage and splash/spray; facility geometry (i.e., curves, superelevation, hills, etc.), which may impact friction and safety requirements; climate (i.e., incidence of rainfall, icing conditions), which may create additional emphasis on wet weather conditions or maintenance and deicing costs; presence (or absence) of noise-sensitive external receptors (e.g., residential areas, hospitals, schools, etc.); and availability of materials required for properly constructing specific surface types. These considerations and others must be balanced in the pavement texture selection and design process.

For example, the authors of a Wisconsin noise and texture study evaluated various pavement textures over selected desirable or acceptable values for maximum exterior noise level, maximum interior noise level, subjective interior noise ratings, and ROSAN ETD. A preliminary study in California used life cycle cost analyses, along with considerations of effectiveness, durability and other factors, to determine the most cost-effective pavement noise mitigation techniques for an existing concrete pavement.[159] The study recommended diamond grinding (along with sound barrier modifications in selected areas) over asphalt overlays, vehicle speed reductions, and widespread sound wall modifications.[159]

Value engineering (VE) techniques can also be used to balance decision factors that cannot be easily quantified using a common scale (e.g., first cost, durability, safety, noise, future maintenance options, etc.).

Best Practices for Surface Texture Design and Construction

"Optimization" of pavement surface texture involves not only the selection of the best pavement type and texture for project-specific conditions (including consideration of pavement geometrics, cross-slope, etc.), but also the specification, design and construction of the selected surface texture. This is essential to ensure that the properties assumed in the selection process are actually produced in the constructed project.

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