R&T UPDATE
Concrete Pavement Research & Technology

Rules of Thumb on Pavement Noise

Introduction

Noise pollution is not a new issue. It has been around since the beginning of transportation, and its roots closely parallel that of transportation development itself. In the beginning, animal hooves and people were the primary noise sources, but they were eventually replaced by the clickety clank of iron wheels on cobblestone and block roads. This problem resulted in the first documented noise regulation. In 44 B.C., Julius Caesar declared: "Hence-forward, no wheeled vehicle whatsoever will be allowed within the precincts of the city, from sunrise until the hour before dusk….Those which shall have entered during the night, and are still within the city at dawn, must halt and stand empty until the appointed hour" [1]. It may seem odd at first that Caesar would want it noisy in the city at night when people were trying to sleep, but at that time in history the affluent members of the Roman society lived outside the city, so only the urban dwellers had difficulty sleeping.

In the 1870s, the iron wheel clank led some large urban U.S. cities to replace cobble stone streets with wooden blocks, to minimize the noise impact. With the advent of the automobile and pneumatic tires, the wheel, the primary noise source for almost 6,000 years, was replaced by other vehicle noise sources like the engine and exhaust. The non-tire noise sources were the dominate contributors to overall traffic noise levels for much of the 20th century.

In recent times, there exists a renewed interest in the selection of pavement surface type to control traffic noise. This idea, although relatively new for citizen groups and government entities, has been investigated for over 50 years by researchers. This paper will present the "rules of thumb on pavement noise" derived by research and experience over this time.

The data presented in this paper was developed from passenger car tire data, so the rules of thumb may not be applicable to truck tires and/or commercial vehicles.

Contributions of Noise

Many factors influence the total noise that a vehicle makes. Among these are: vehicle speed, vehicle type, tire type, pavement surface type, tire load and pressure, and temperature. A rough estimate in the range in effect that each variable can have on the total noise is shown in Table 1[1, 2].

Table 1: Possible Range in Effects of Variables Influencing Measured Traffic Noise

Variable	Possible Range in Effect (dB)
Speed	25 (30 -130km/h)
Surface Type	9-13
Vehicle Tire Type	10-15 (including tire pressure)
Temperature	4 (0-40^{o} C)
Road Condition (Wet/dry)	5
Construction Variability	2-7
Transverse Joint Contribution	1-2

As seen in Table 1, the range for most variables is quite large. Speed is the most significant variable, followed closely by surface type and tire type. Although adjustments can be made to speed and temperature to normalize data to a common reference, it is traditionally not done. Tire type becomes important when comparing results from two near-field measurement systems, such as the Close Proximity Method (CPX) and the On-board Sound Intensity (OBSI) method. The temperature at the time of testing can influence both the magnitude and the variability of measurements. As noted in Table 1, variability due to construction for a given pavement could be 2-7 dBA. Such variability can result in measurable differences between similar pavements. These variables exemplify the difficulty in identifying "rules of thumb" from reviewing research from many sources, over many years. Thus, the "rules of thumb" presented herein should be considered indicators until more substantial research can prove if actual cause and effect relationships do or do not exist.

ACPA

In an attempt to isolate different variables, Donovan was the first researcher to remove the effect of transverse joints from measurements[2] (2003). This effect can be as large as 1-2 dBA on a new project, depending on the joint design. So, when evaluating existing roadways, the joint effect contributions to the overall noise should be noted. Pavements with wide joints or older sections with faulted joints may confound the effects of the surface characteristics under evaluation.

The data presented in this paper refers to *exterior* passenger car noise (unless otherwise noted), as measured in decibels [dBa]. Other forms of annoyance measurement, such as interior vehicle noise, can be used but are not considered herein. All data was generated by passenger cars at the tire/pavement interface, under dry conditions. No relationships to friction or other surface characteristics are presented herein, so caution is necessary when applying these rules of thumb. Proper roadway design must consider durability and safety in the analysis along with noise, which is the subject of current research efforts of the American Concrete Pavement Association (ACPA).

Relationship between Pavement Texture and Tire Noise

Rule of Thumb (1): When considering all pavement types, a meaningful relationship between texture and exterior noise does not exist. For a given concrete pavement texture type, increasing the texture depth generally increases the noise produced.

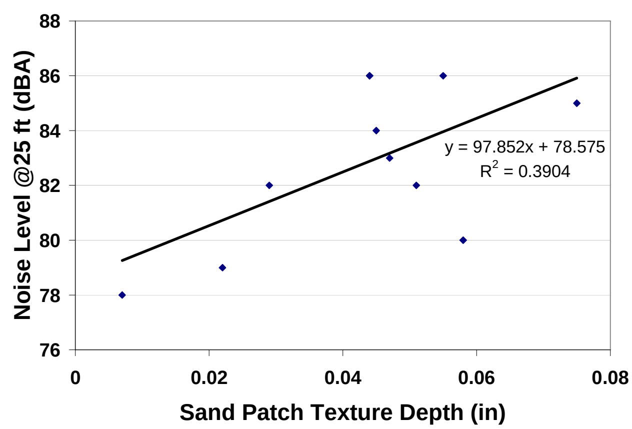
Early noise researchers in the U.S. recognized the need to relate pavement texture to noise measurements. Typically, such research conducted sand patch testing (ASTM E 965) to establish the mean texture depth at the time of noise measurement. Although more accurate measurements can now be made using laser based measurement systems, no comprehensive relationship has yet been established between texture and overall tire/pavement noise. In general, the overall texture level cannot be used to relate pavement noise across different pavement types. However, useful relationships have been demonstrated within selected pavement types.

One of the earliest studies conducted in the U.S. related texture depth to 25 ft (7.6 m) roadside noise levels used a single test car and the pass-by method at three different speeds [3, 4]. This study, conducted by the New York State Department of Transportation (NYSDOT) in the early 1970's, evaluated lightly-textured concrete pavement sections. These textures consisted of mechanical longitudinal burlap drag, hand-operated natural-bristle paving broom, mechanical natural-bristle paving broom, and hand-operated transverse burlap drag. Except for the mechanical longitudinal burlap drag section, all sections were transversely textured.

The longitudinally textured section had the lowest sand patch texture depth and produced the lowest noise. The various transverse texturing methods produced higher noise levels at 60 mph (97 km/h) than the longitudinal section. The hand floated section produced noise levels that were the second quietest.

The results of this study (Figure 1) indicated that pavements exhibiting higher sand patch texture depth measurements resulted in higher noise levels. The linear regressions had correlation coefficients ranging from 0.4 to 0.5 for the three test speeds of 40, 50, and 60 mph (65, 80, and 97 km/h). If polynomial regressions are used, slightly higher correlation coefficients result. Such a fit indicates that noise increases with texture depth at small texture depths and then appears to plateau (e.g. no increase in noise for increase in texture) around 0.05 in. (1.25 mm) of sand patch texture depth.

Figure 1: Comparison of Sand Patch Texture Test and 25-ft Roadside Noise Levels for 60mph Test (NYSDOT), with linear fit



Rule of Thumb (2): Negative Texture is more effective at reducing tire/pavement noise than positive texture.

When considering pavement texture, a distinction between positive and negative texture is necessary. Positive texture is the magnitude of texture that exists above a planar surface (the riding surface). Positive texture almost always produces greater noise with increasing texture depth. Chippings on concrete or exposed aggregate surfaces could be considered the extreme case of positive texture.

Negative texture refers to the magnitude of the texture that exists below a planar surface (again the riding surface). A longitudinally grooved pavement would represent a negative texture. Negative textures do not “interfere” with the tire, resulting in less vibration and noise than a positive texture.

Therefore, the effect of negative texture is different than the effect of positive texture. This is another reason why texture depth alone cannot be used to correlate noise across different pavement types.

Effects of Tine/Groove Shapes, Spacing, Dimensions, and Orientation

Tining vs. Grooving

For the purposes of this paper, grooves produced through the diamond grooving process are considered essentially the same as grooves produced through the tining process. Although construction processes and resulting dimensions are quite different, the effects of the significant variables appear to be similar.

Additionally, the effect of these variables on transverse tines/grooves appears to be different than for longitudinal tines/grooves. These differences will be discussed in subsequent sections.

Transverse Tining

Rule of Thumb (3): Increasing transverse tine/groove spacing generally increases the overall noise produced. The frequency at which the noise is produced will also be affected.

Rule of Thumb (4): Decreasing the transverse tine/groove spacing generally increases the higher frequency spectral content of the resulting noise.

One of the most dramatic effects created by the tining/grooving process is the whine (tonal spike) produced when uniformly spaced transverse tines or grooves are used as texturing. The tire whine is produced at frequencies particularly annoying to the human ear. An example of this tonal spike is evident in Figure 2, in the middle of the frequency spectrum, at about 1.5 kHz. Although the tonal spike is often reported as occurring at 1000 Hz, the frequency at which the spike occurs is a function of both the groove/tine spacing and the speed at which the vehicle tires are passing over them. Figure 3 provides the frequencies of tonal spikes produced by various spacing widths and traffic speeds. As evident, the frequency increases with increasing traffic speed and decreases with increasing tine/groove spacing. When using 0.5 in (1.2 mm) spacing at 55 mph (88 km/h) as the baseline, there is a 36% increase in frequency as a result of a 20 mph (32 km/h) increase in speed. Similarly, there is a 75% reduction in frequency by increasing spacing an additional 1.5 in (38 mm).

Figure 2: Example of Tonal Spike for Uniformly Transverse Tined Texture

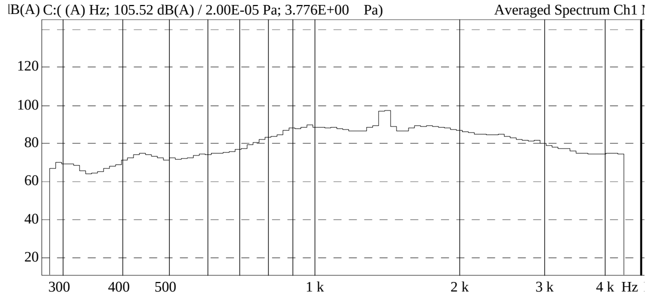
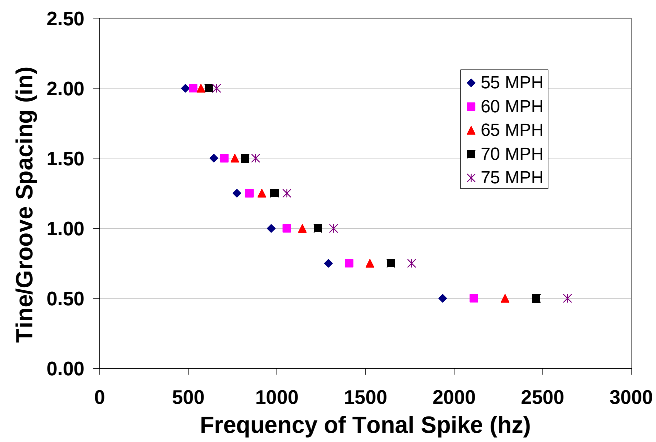


Figure 3: Plot of Tonal Frequency as a Function of Traffic Speed and Tine/Groove Spacing



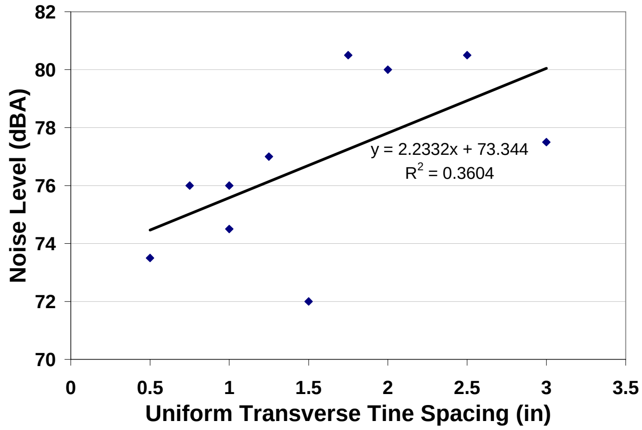
Rule of Thumb (5): Different frequencies have different effects on annoyance.

Even though frequency is an important part of the annoyance factor, this aspect is often overlooked when selecting tining patterns. The need for random transverse tining, to eliminate the tonal spike, was recognized over 30 years ago. However, it was not generally implemented until after the Marquette studies of the late 1990s[5].

Although randomization of transverse tining/grooving can remove the tonal spike by spreading the energy across a larger frequency range, the effect of spacing is still similar. Close spacing contributes to the overall noise at higher frequencies and larger spacing at lower frequencies.

One of the earliest U.S. studies on the effect of tine spacing was conducted by the Minnesota Department of Transportation (Mn/DOT)[6]. The results of this study are shown in Figure 4. For these test sections, an astro-grass (artificial turf) drag was used prior to applying the uniform transverse tining. The noise levels indicated represent wayside measurements taken at a distance of 45 ft (14 m).

Figure 4: Uniform Transverse Tine Spacing vs. Noise Level (Mn/DOT Study)



Since tine spacing, depth and width all affect noise levels, considerable scatter is often obtained when attempting to evaluate the effect of a single variable, as is the case with Figure 4. If the 3 in (75 mm) spacing data point is removed, the correlation coefficient jumps to 0.51. The results of the Mn/DOT study suggests that smaller spacing produces lower overall noise.

The aforementioned Marquette study also found a positive correlation between tine spacing and overall noise generation. As is evident in Figure 5, there is a 3.3 dBA increase between the 0.5-in (13-mm) spacing and the 1-in (25-mm) spacing. The correlation coefficient is also much higher than the Minnesota study. However, if the two lower right points in Figure 4 are "cleansed", the correlation coefficient for the Mn/DOT study becomes 0.85 and there is a 1.9 dBA increase in noise levels from the 0.5-in to the 1-in (12-mm to 25-mm) spacing. The results from these two studies would suggest a 2-3 dBA increase in noise level for each additional 0.5-in (12-mm) increase in tine spacing, for uniformly transverse tined pavements (ongoing research will further define this relationship).

The noise levels in the Marquette study were obtained from wayside measurements using a single vehicle, control pass-by test method. The microphones were located 25 ft (7.6 m) from the travel lane.

Although the data scatter may seem discouraging, it should be remembered that there are many uncontrolled variables in these experiments, such as pavement age, joint effects, texture depth, width, etc.

Figure 5: Uniform Transverse Tine Spacing vs. Noise Level (Marquette Study)

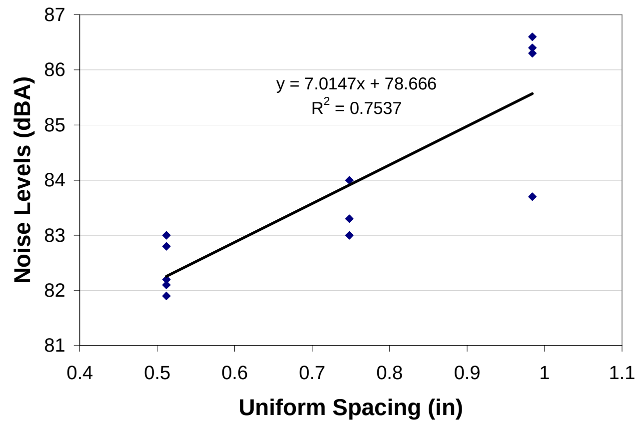
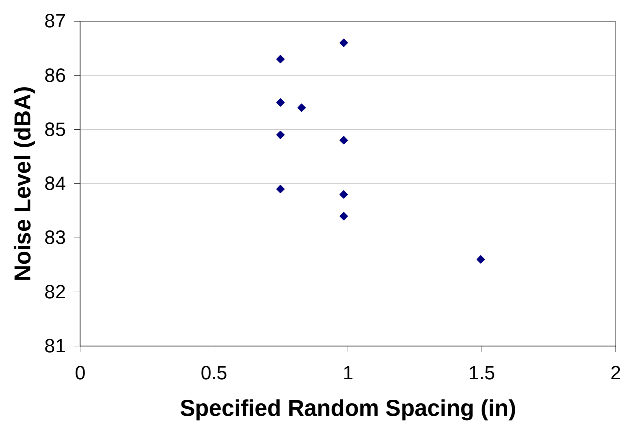


Figure 6 indicates the Marquette results for random transverse tined pavements [5]. There does not appear to be a trend, as exhibited with the uniform spacing. However, this could be an artifact of the means for designating the random transverse spacing, since no measure of "average" spacing is provided.

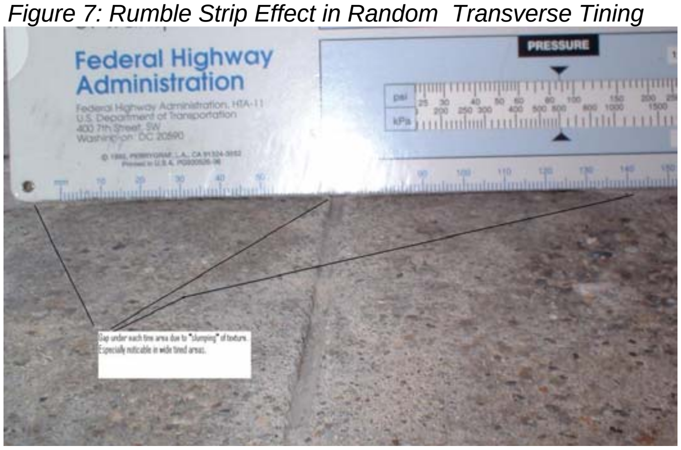
Figure 6: Random Transverse Spacing versus Noise Levels (Marquette 2000 Study)



It is interesting to note that many of the data values for the uniformly transverse tined data shown in Figure 5 were lower than the random transverse data presented in Figure 6. This provides insight into the fact that the random tining only reduces the tonal "spikes," it does not necessarily produce an overall quieter pavement. In fact, as will be shown later, random transverse tined pavements generally produce greater overall noise levels. This is probably due to the increased tine spacing typically used to create the random pattern, but may also be influenced by the concrete mixture and other variables.

The assignment of increased noise to wider spacing is not solely a function of the spacing alone, per se, but a combination of the spacing and tine interaction with the concrete mix in some instances, as indicated in Figure 7. Figure 7 indicates the rumble strip effect imparted by the random transverse texture to the pavement surface. Note that the ruler is not contacting the pavement at the indicated locations. In this instance, the wide spacing caused a surface profile change, adding to the noise level.

Figure 7: Rumble Strip Effect in Random Transverse Tining



Rule of Thumb (6): Increasing transverse tining depth generally increases the noise produced.

In actual construction, tining depth and width are not well controlled and vary highly on any given project and between projects. This makes it very difficult to distinguish the effect of depth from other variables. Normally, deeper grooves are also wider, so the effect of depth is confounded. However, it is generally believed that deeper grooves produce more noise.[5, 7] Deeper grooves provide better drainage characteristics and longer wearing textures so, historically, most texturing was intended to produce deep grooves. However, as the grooves become deeper, more aggregate and mortar is displaced and this results in additional positive texture, increasing noise. The trade off has been to err on the side of durability and safety, which often times results in noisier pavements.

Rule of Thumb (7): Increasing transverse tine width generally increases the noise produced.

As discussed previously, the effect of depth and width are difficult to evaluate using field data. However, a recent study by Purdue evaluated the effect of groove width using the Purdue Tire Pavement Test Apparatus (TPTA)[7]. The TPTA is a laboratory device that can test under very controlled conditions. The findings of that study suggest that wider grooves produce more noise. This is presumably due to the greater penetration of the tire tread into the groove and the resulting vibrations generated in the tire. Data from on-going field research will be used to gain further insight into the effect of tine width.

Longitudinal Tining

Rule of Thumb (8): Variables that affect transverse tining may not be relevant to longitudinal tining noise generation.

Little research has been conducted on the variables affecting the noise generation characteristics of longitudinal tining. This makes it difficult to develop meaningful rules of thumb for this texture type. Most research was undertaken in the late 1960s and early 1970's, when noise was not as important. The typical longitudinal groove spacing of 0.75 in (19 mm) using 0.125 in (3 mm) tines was established early on, in California. This particular configuration had advantages for vehicle control over wider grooves, which were credited with creating the perception that vehicle control was influenced by the roadway. Subsequent California studies suggested that 3/32-in (2.5 mm) grooves reduced the vehicle tracking influence even more [8].

Although no rules of thumbs are provided, it can be said that, in most noise studies conducted over the past 30 years, longitudinal tining was demonstrated to be the quietest tined surface for new construction. Recent trends have been to reduce the groove depth to create less positive texture and potentially produce even quieter surfaces. Minimum groove depths were originally established by California to provide a durable wearing surface and were not predicated upon noise reduction. It is doubtful that groove depth and width are as important for longitudinal texture as they as they are for transverse tining in regards to noise generation, but additional research is needed to determine this.

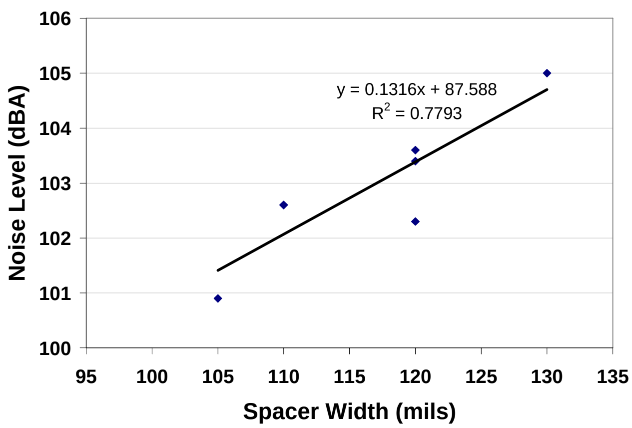
Diamond Grinding

Rule of Thumb (9): Grinding heads that use narrower spacers produce quieter resulting textures

Although diamond grinding is the most effective noise mitigation strategy for existing concrete pavement, the verdict is still out regarding how to optimize for noise. Traditionally, most grinding has been accomplished for ride quality or frictional improvement, and not for noise mitigation. Typical blade widths are 0.125 in (3 mm), and the spacers between the blades typically range from 0.105 to 0.120 in (2.7 – 3.1mm). For very soft aggregate, wider spacers are often used, and for hard aggregate, narrower spacers. The wider spacers provide larger land areas, better resisting wear.

European experience suggests that wider spacers (eg 0.130 in [3.3 mm]) are preferred for noise mitigation. Experience to date in the U.S. does not support this. The results of field evaluations conducted in Arizona, California, and Kansas suggest that narrow spacers may work best, as indicated in Figure 8. The California and Kansas data were obtained using On-Board Sound Intensity measurement equipment. The Arizona data was obtained using Close Proximity sound pressure measurement equipment. The Arizona data was increased 3 dBA to simulate the OBSI data. The Arizona data was obtained 16 months after opening to traffic. The California and Kansas data was obtained prior to opening to traffic. In addition, the joint effects were removed from the California data but not the Arizona or Kansas data. So, the comparison is not completely apples to apples.

Figure 8: Effect of Spacer Width on Noise Levels for AZ, CA, & KS Data



When Arizona data is removed from Figure 8, the correlation coefficient becomes 0.81 and the slope remains almost constant. This U.S. data suggests that narrower spacers produce quieter diamond-ground sections. More data, consistently obtained, is needed to verify this relationship.

Work currently underway at Purdue University suggests that the profile of the fins resulting from the grinding operation, and not the spacer width, is the most important variable. Extensive research on this issue is presently underway and improvements to this rule of thumb should be possible in the near future.

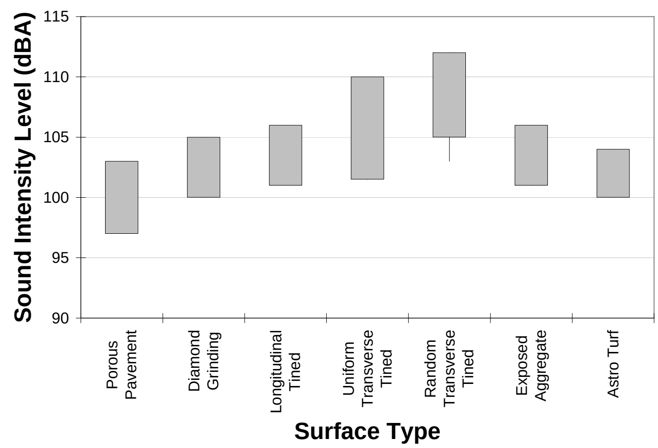
Effect of Texture Type on Resulting Noise Level

Rule of Thumb (10): The most significant roadway feature that controls tire/pavement noise generation is surface texture and not paving material.

Since pavement designers typically do not set highway speeds, they cannot use traffic speed as a noise mitigation measure. Therefore, surface type becomes the most significant factor when attempting to control noise at the source. When selecting surface type, it is important to consider all the elements of a proper design; namely durability, safety, cost effectiveness, and noise. The acoustic performance should be considered over the service life of the roadway and not just in the short term.

The data presented in Figure 9 indicates the approximate ranges of performance for various texture types. While Figure 9 is based on limited data, it is anticipated that as more data is gathered for all the surface types, the ranges of expected values will more than likely increase. The bar that has a line extending down represents the anticipated expansions of that surface type.

Figure 9: Typical Range of OBSI Noise Levels for Selected Pavement Textures



It is interesting to note that the noisiest surface appears to be the random transverse surface, which was ironically developed to solve a noise issue. Be aware that Figure 9 represents the overall noise level at the tire source. Wayside measurements located at 50 ft (15 m) from the source would be approximately 30 dBA lower. Also, Figure 9 does not provide any information related to the frequency or spectral content. As such, the random texture which tests louder overall may be less objectionable than the uniform transverse tined surfaces which exhibit tonal spikes. The higher noise levels associated with the random tining are presumably a result of the wider tine spacing used in this approach. The results shown in Figure 9 do not currently include sections from Wisconsin, where it is believed that random tining has been implemented most successfully.

The results presented in Figure 9 also do not account for the effect of pavement age. It is simply a portrayal of tested pavements of different ages. As more data becomes available, it will be desirable to develop a three dimensional plot that indicates the ranges as a function of time, to increase awareness of the acoustic durability of the various textures. Currently, acoustic durability of the various textures is not well documented.

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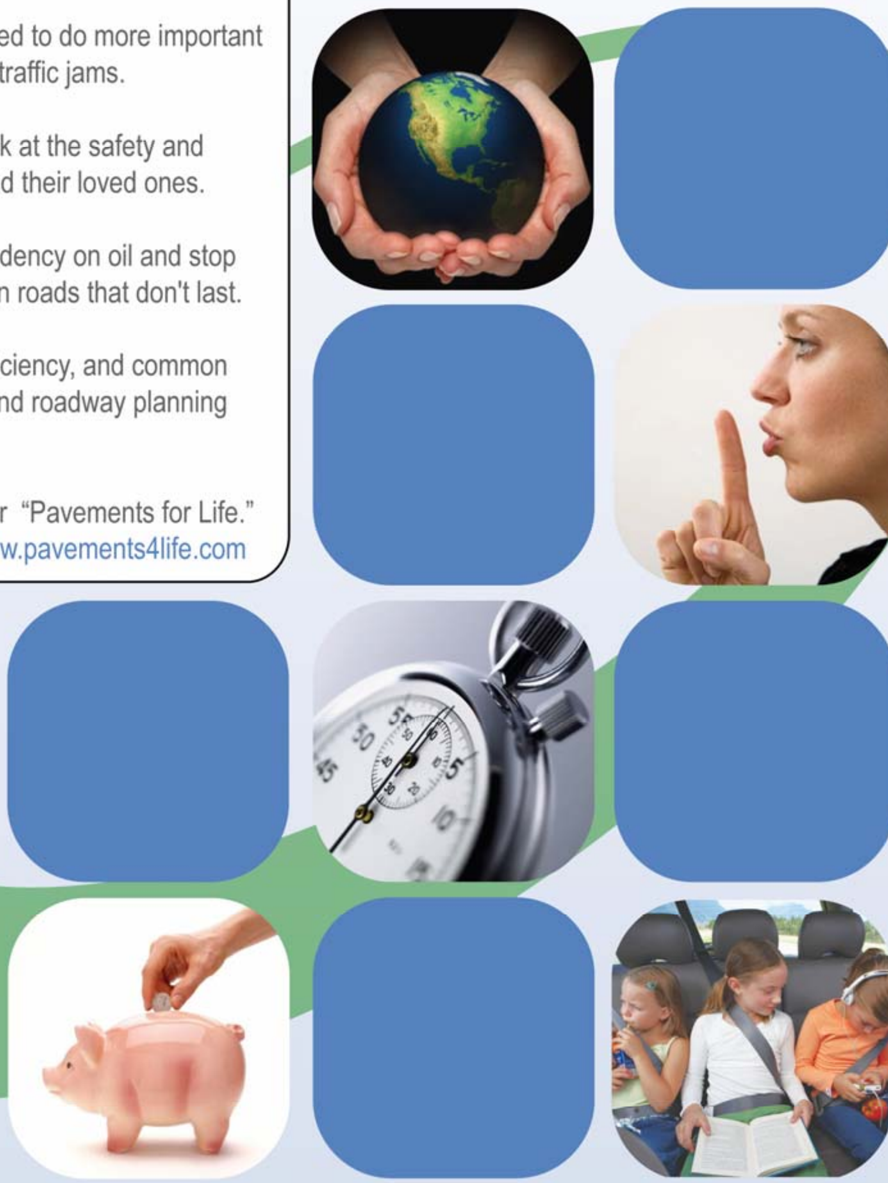

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