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Transportation Noise and Concrete Pavements

Using Quiet Concrete Pavements as the Noise Solution

This summary presents the issues surrounding highway noise design and management and the history and future use of concrete pavements as a quiet pavement noise solution.



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Transportation Noise from a Historical Perspective

Traffic noise has been an integral part of the development of transportation systems since the beginning of civilization. In fact, the first documented noise ordinance was issued by Julius Caesar in 44 BC when he controlled the time at which wagons could enter Rome. This was to prevent the clanking of wagon wheels on cobble stone streets during business hours. A more modern historical example is in the US during the late 1800's when wooden blocks were sometimes used instead of cobble stones in high density urban areas to help reduce the clank of the wagon wheel.

With the introduction of the automobile in the early 1900s, however, transportation noise would forever be changed. The noise source changed from horse's hooves and wagon wheel clanking to engine and exhaust noises. In fact, it wasn't until the 1950s that the auto manufacturers voluntarily agreed to limit exhaust noise. Noise regulation in the US first occurred at the state level with California pioneering the way with legislation in 1967. The first federal attempt at noise regulation occurred in 1972 when Congress passed the Noise Control Act. Many changes in technology and population have occurred in the 37 years since the first federal regulation.

Today, in many urban areas, noise is clearly a quality of life issue for the public and represents one of the many competing factors in urban design and living. In terms of highways; safety, smoothness, capacity, and noise are all competing and important design issues that every owner/agency contends with.

Noise Basics

Highway noise is the result of vehicular travel along a roadway. It is most importantly a function of the *volume and speed of the traffic*. It consists of all the noise produced by each vehicle's drivetrain, exhaust, tires, air turbulence, and other design features such as horns and braking operations. All these noises together combine to form the traffic noise that adjacent properties contend with.

For typical highway applications it should be noted that the noise contribution of cars and large trucks is quite different. Passenger cars for example, generate about 70 to 90% of their total noise through the tire-pavement interaction. This fact implies that modification of the roadway surface and/or the tire type can meaningfully impact the overall tire-pavement noise. The total noise for autos can also be represented by a noise source at or near the roadway surface level.

Large trucks contribute to noise in a much different way than cars, and this should always be considered in the design stage. Although trucks have similar types of noise sources, the magnitude and location of these sources is quite different. The drivetrain noises are positioned much higher and the exhaust stacks, in particular, are approximately 11-12 ft above the roadway surface. These higher locations create the potential for the noise to be heard over longer distances. Truck tires also interact with pavement differently than car tires and generally the surface texture does not have a significant effect on the tire-pavement noise level. This suggests that where truck percentages are higher, little can be gained through pavement surface types.

One important aspect of noise mitigation is breaking the line of sight to the noise source. This is important both from a psychological viewpoint and also for actual noise reduction. Once the line of sight is broken, as shown in Figure 1, the noise level is reduced approximately 5 dBA. Note also, however, how much more difficult it is to break the line of sight for a heavy truck than for a car since the noise sources are much higher off the ground. This requires any noise wall or barrier type solution to be higher when trucks are involved.

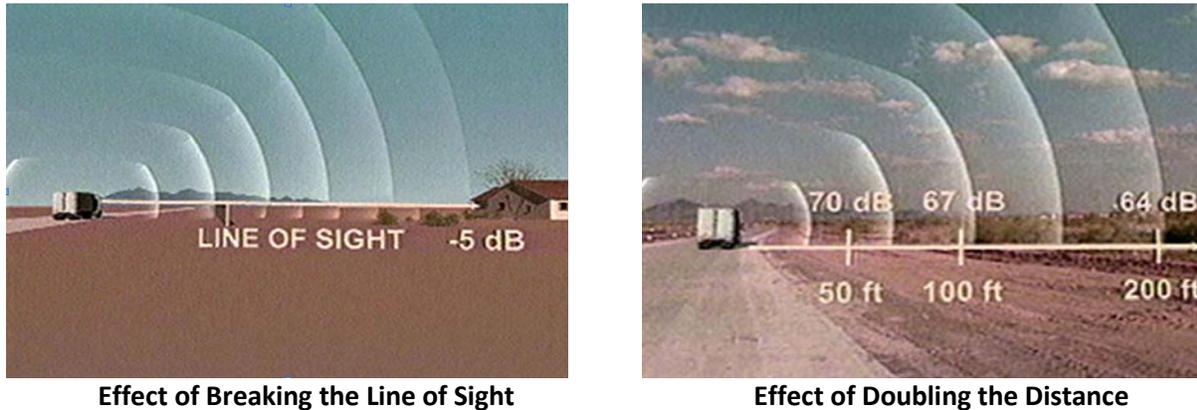
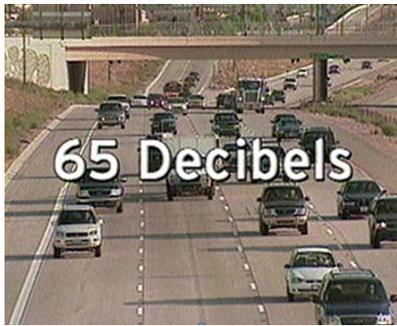


Figure 1 Sound Propagation Rules of Thumb

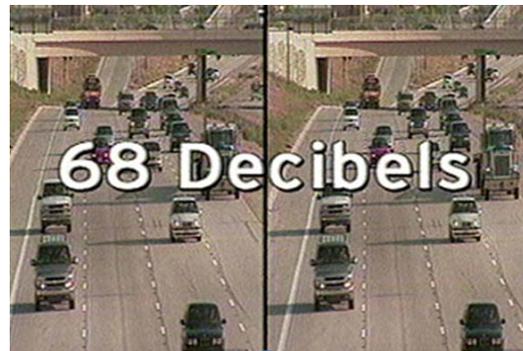
As noise travels away from its source it decreases in overall loudness. Typically, for highway applications noise is reduced by 3 dBA for each doubling of the distance as indicated in Figure 1. So if it were 70 dBA at 50 ft from the roadway, it would be 67 dBA 100 ft away. For typical highway design it is common to prevent the surrounding properties from achieving noise levels of 67 dBA or higher. The 67dBA would be at the property location. At the shoulder of a roadway, noise levels can be in the 70 to 80 dBA range.

Another important noise fact is that if you double the traffic you increase the overall noise level by 3 dBA. If the existing traffic produced a noise level of 64 dBA within the neighborhood, doubling the same traffic would increase it to 67 dBA. Reducing the traffic by half also reduces the total noise level by 3 dBA. Figure 2 indicates this effect.

As mentioned previously, speed also affects total noise level. A good rule of thumb for passenger cars is that the overall level is increased 3 dBA for each 10 mph in speed increase. The converse is also true. This rule of thumb does not apply to trucks which are not dominated by tire noise. As speeds become lower and lower, however, the tire-pavement noise contribution becomes less important for all vehicles and eventually the drivetrain and exhaust noise dominate. The cross over condition (e.g. the condition where tire noise is less important than drivetrain and exhaust noise), although different for cars and trucks, is probably in the range of 25 to 40 mph. Once the cross over threshold has been achieved then noise mitigation by surface type is not practical. Low speed urban areas are examples of this type of situation where the drivetrain noise dominates.



Normal Traffic Noise Level



Traffic Noise Level After Doubling Traffic

Figure 2 the Effect of Doubling Traffic

When evaluating noise levels it should be remembered that a 3 dBA difference is considered a barely perceptible change by the FHWA as indicated in Table 1. A 10 dBA change is a doubling of the noise that is heard by the ear. A 5 dBA change is considered a substantial change. Note that in the previous paragraphs it was indicated that a doubling of the traffic volume results in only a 3 dBA change whereas a 10 dBA difference is necessary to double the noise level that is heard. This peculiarity is a function of how logarithms work and how noise is analyzed.

Table 1 Decibel Changes, Loudness, and Energy Loss		
<u>Sound Level Change</u>	<u>Relative Loudness</u>	<u>Acoustic Energy Loss</u>
0 dBA	Reference	0
-3 dBA	Barely Perceptible Change	50%
-5 dBA	Readily Perceptible Change	67%
-10 dBA	Half as Loud	90%
-20 dBA	1/4 as Loud	99%
-30 dBA	1/8 as Loud	99.9%

Another aspect of noise is how human annoyance, in regards to noise, is evaluated. The current procedures gauge *annoyance based on the overall level* (e.g. volume) after measuring the sound using a filtering technique (e.g. A-weighting) which attempts to simulate how a human ear hears. This technique was developed over 50 years ago and is the basis for all current regulations. Although these procedures have served the industry well, they probably *under emphasize certain tonal attributes* common to textures such as *uniform transverse tined concrete pavements*. A simplistic way of thinking about the level and tonal aspects of noise is to consider an analogy to a radio. The level or volume would be represented by how loud the radio is playing. The tonal properties can be considered what station or frequency the radio is tuned to. If the radio is too loud it can be annoying. If it is tuned improperly (e.g. static) it can also be annoying. When both conditions apply it is even more annoying.

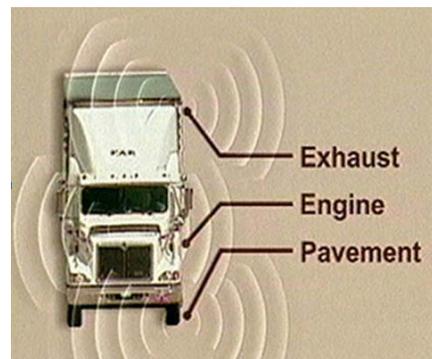
Factors Affecting Transportation Noise

For highways, noise mitigation is concerned with protecting the surrounding properties from excess levels of noise. This can be accomplished by three different methods: (1) distance, (2) installation of berms or walls, or (3) controlling the noise source (e.g. volume, speed, surface type, exhausts, etc.). Since sound is typically reduced 3 dBA for each doubling of distance, if the neighborhoods are far enough removed then noise levels are not an issue. Where insufficient land is available for distance as a solution, it is common to install berms and/or walls to break the “Line of Sight”. The breaking of the line of sight reduces the noise level approximately 5 dBA. Each additional 1-2 ft of wall or berm height reduces it another 1 dBA. Therefore extending the wall height shown in Figure 1 an additional 2ft above that shown, would result in an approximate 6 dBA reduction in noise level.

In recent times, there has been more interest in controlling noise at the source by selection of pavement type. As mentioned previously, this can only be effective when passenger cars comprise the traffic stream and traveling at highway speeds. However, if large trucks are present, it only takes between 4-20% heavy trucks for the trucks to become the dominant noise source and hence the pavement solution would not be effective. Similarly, if speeds are low, then pavement surface is not an effective solution since the drivetrain/exhaust becomes the major noise source and not the tire-pavement interface. All of this is highly dependent upon the traffic composition and the mix of trucks and cars and the types of trucks in the traffic. The dominant noise sources for cars and trucks are indicated in Figure 3.



Auto Noise Sources



Truck Noise Sources

Figure 3 Traffic Noise Sources

Noise regulation is concerned with the amount of noise that impacts surrounding neighborhoods. This is an important concept to remember as the regulation is not concerned with the noise that occurs within an automobile. However, the consumer’s perception of roadway noise is often developed from their driving experience and not from their experience living alongside the highway. For a given urban corridor, the affected neighborhoods could include between hundreds to thousands of consumers whereas the number of drivers traveling along the same corridor represents between several million to many millions of consumers per day. So driver perception, even though not of concern from a regulatory standpoint, is an important reality in consumer satisfaction of highway surfaces.

How Noise is Measured

The two most common forms of noise measurement in the US consist of wayside measurements and On-Board Sound Intensity (e.g. OBSI) measurements. Wayside measurements, shown in Figure 4 consist of placing a microphone alongside a highway and *measuring the total noise* that reaches a given point. Although Figure 4 indicates a wayside measurement point 50 ft from the roadway, a more typical location would be a microphone set up in an adjacent property since that is the noise of concern. The wayside measurement includes all highway related noise such as tire-pavement interaction, drivetrain and exhaust, etc. As such, it is the best indicator of what is happening in the neighborhood. However, since it measures the total noise which is a function of traffic volume, speed, composition, etc. it is difficult to evaluate how the tire-pavement properties change over time as all the other variables could also be changing over time.



Wayside Measurement –Total Traffic Noise

OBSI Measurement -- Tire-Pavement Noise Only

Figure 4 Photos of Sound Measurement Systems

OBSI measurements, on the other hand, *measure only tire-pavement noise* as indicated in Figure 4 and do not include drivetrain, exhaust, and other noise sources. OBSI measurements are useful for determining the effect of pavement surface on noise levels and for evaluating how pavement properties change over time. The basis for this test method is the assumption that the traffic fleet can be represented by a single tire. Since this is a tenuous assertion, this type of measurement is generally used for ranking pavements and determining how the pavement noise characteristics change over time. It should be recognized that the reported value is a function of the tire type and that by changing tires a different value would be reported. AASHTO currently specifies an ASTM Standard Reference Test Tire (e.g. SRTT) to conduct this work.

How Do Agencies Design for Noise

Noise mitigation is typically conducted in the design phase of a project and is intended to limit the maximum noise level in the adjacent neighborhoods. This is often accomplished using a software program developed by the Federal Highway Administration (FHWA) called Traffic Noise Model (e.g. TNM). With the use of this model, it is possible to predict the *total noise level* that would occur at a given location away from the roadway for a specified traffic volume, traffic mix, and design conditions

such as berms or noise walls and the prevailing topography. This provides the designer the ability to ensure that future noise levels will comply with regulations prior to construction.

In the current TNM software pavement type is fixed as an *average pavement* and does not allow pavement type as a user selectable input. This is due to FHWA policy and is based on the concept that berms or walls are permanent structures and have a permanent effect on traffic noise. Pavements however, particularly asphalt pavements, change in acoustic properties over time. Therefore it is difficult to determine what the actual effect of a pavement surface is over time since it continually changes.

Concrete Surface Types

Up until the late 1960s, many of the concrete roadways constructed in the US used a burlap drag type texture. This type of texture provided a quiet pavement and proved useful when speeds and traffic volumes were low. However, as highway speeds and traffic volumes increased, friction became a growing concern and eventually the FHWA (e.g. 1979) required other surface texture types to be used for roadways above 40 mph. This led to the widespread use of uniform transverse tining as the texture of choice on concrete pavements in the United States. This surface texture was adopted by every state except California and persisted as the major texture until the 1990s when communities began experiencing noise issues. The noise issues were the result of the regularly spaced transverse grooves which produce tonal spikes at a frequency in the range of 1000 Hertz. Human hearing is particularly sensitive to frequencies in this range.

This tonal property is referred to as tire whine and is commonly associated with concrete pavement. Tire whine is an artifact of transverse grooving and not the concrete itself. However, it constitutes a particularly annoying component and when coupled with excessive level, it provides considerable dissatisfaction. If an asphalt pavement is transverse grooved the same tire whine would be experienced. The best example of this is the Honda Civic commercial where transverse grooves were spaced and sized to play the William Tell Overture. That commercial was conducted on an ac pavement.

In the 30 years since the 1979 FHWA Technical Advisory, there has been considerable research and awareness concerning the annoyance of transverse tined pavements. In 2005 the FHWA issued a new Technical Advisory and promoted other textures for use on concrete surfaces. This was in part due to the growing awareness of the objectionable properties of transverse tined pavements in high density urban areas.

Since the late 1990s a number of states have migrated away from transverse tining to longitudinal tining since it does not possess the tonal aspects which are so particularly annoying. Longitudinal tining is becoming more and more prevalent as the texture of choice among highway agencies.

Figure 5 indicates several concrete texture types commonly used on highways and their respective OBSI levels. The reader should be reminded that these levels are at the tire-pavement interface and *do not* represent levels alongside highways. In viewing this Figure, the reader should note that there are two aspects to annoyance; one is the level or *volume* of the noise and the other aspect is

the *tonal qualities*. Figure 5 indicates only the levels of noise generated by the tire-pavement interface. The tonal characteristics are not presented. The longitudinal textured surfaces do not possess the tonal spikes which a uniform transverse and sometimes a random transverse tined surface do.

It should be noted that the upper range of the transverse tine level in Figure 5 is 110 dBA while the diamond ground surfaces (e.g. two right most surfaces) both can produce approximately 100 dBA surfaces. This 10 dBA difference indicates the transverse tined surface can be twice as loud. In addition, the transverse tined surface can also have undesirable tonal qualities exacerbating the annoyance even further.

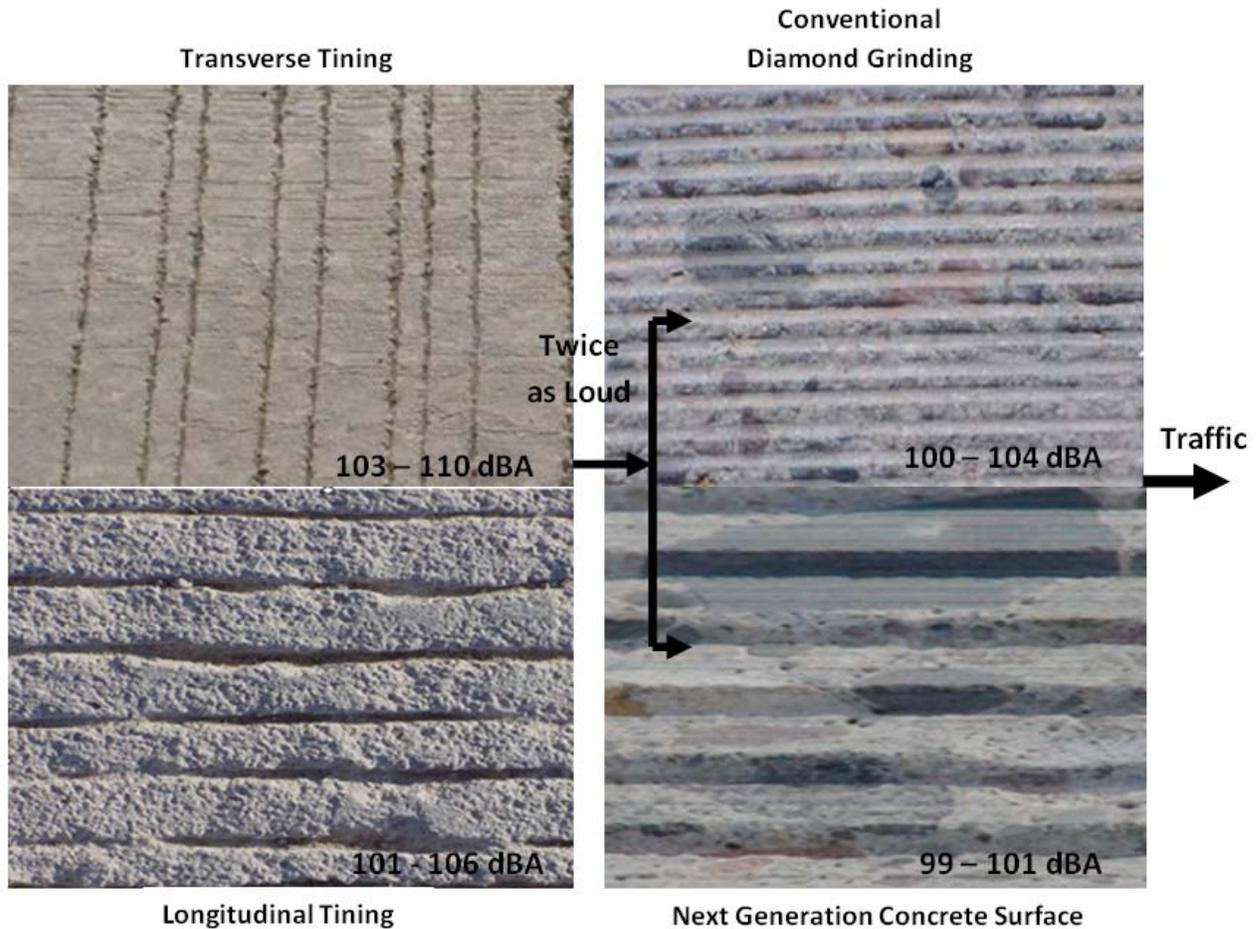


Figure 5 Typical Concrete Surface Textures and their Typical OBSI Noise Levels

For existing highways with noise issues, diamond ground surfaces are the solution of choice for producing quiet concrete pavements. This can be accomplished using conventional diamond grinding techniques (e.g. upper right-hand photo) or the recently developed experimental Next Generation Concrete Surface. Both of these techniques produce quiet surfaces and are a competitive noise solution. The conventional diamond ground surface is the less expensive of the two surfaces. The Next Generation Concrete Surface (e.g. NGCS) was developed at Purdue University under research sponsored by the Portland Cement Association, the American Concrete Pavement Association, and the

International Grooving and Grinding Association. This surface has been placed in test sections in four locations with one job bid in a competitive environment. Several more installations will occur this summer. This surface represents more of a manufactured surface and the product produced during construction is very consistent. It also has produced the quietest non porous concrete pavements measured to date.

For new construction, the noise solution of choice is typically longitudinal tining (e.g. lower left photo). This is the technique used by Caltrans from the 1960s and is increasing in popularity since it does not possess the objectionable tonal spikes associated with uniform transverse tining. The Minnesota DOT is the only state that uses an Astro turf texture on their highway network. This surface is produced by dragging astro-turf behind a paver with the turf-side down. This provides a quiet surface with no adverse tonal characteristics. This surface is typically quieter than longitudinal tining.

Transverse Joint Slap Effect

Most concrete pavement is constructed with transverse joints spaced every 13-20 ft with a 15 ft spacing being very common. These joints can contribute to the overall noise level of the roadway in two ways. First, if inadequate load transfer exists and the joint becomes faulted, the tires will produce a “joint slap” every time they contact a joint. Once faulting exceeds 1/8 inch this can become very annoying, particularly to the interior noise of the vehicle. The best way to avoid this situation is to dowel the pavements and/or provide a design which will not fault under the actual traffic conditions. If a roadway has already faulted, then diamond grinding will remove the fault and restore both the noise and ride qualities. Figure 6 indicates what a faulted joint looks like before and after grinding. The dashed lines indicate the amount of faulting of the existing surface. Once it is diamond ground the faulting is zero.

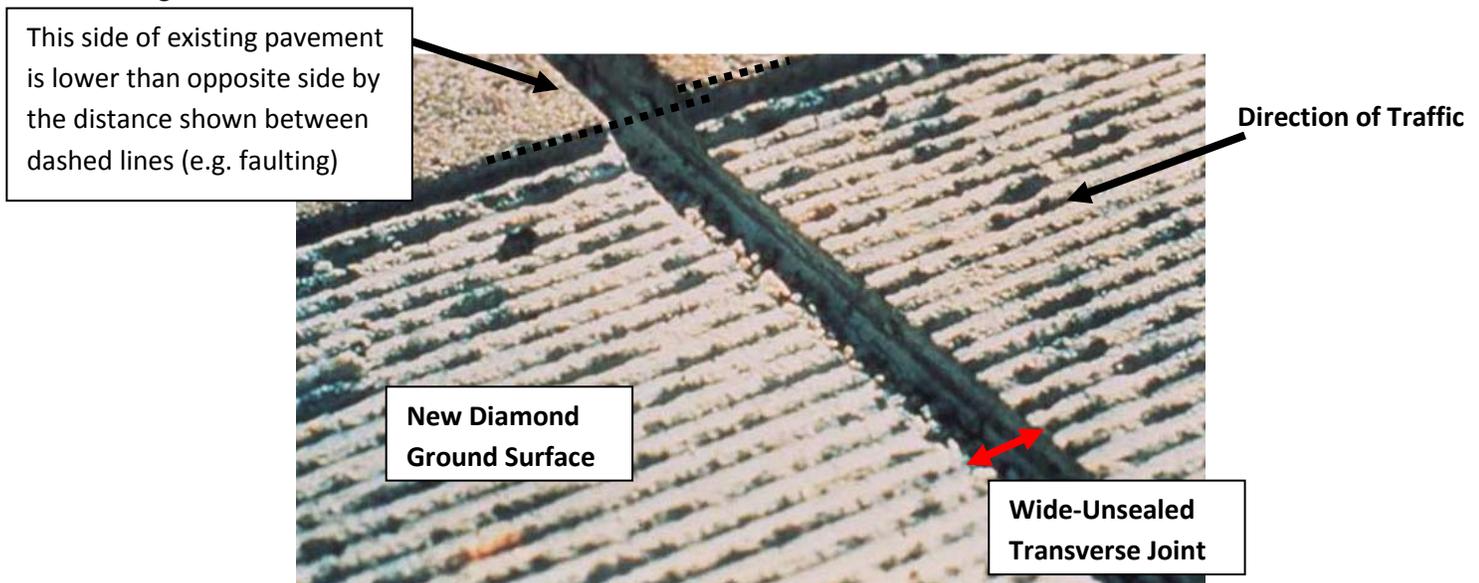


Figure 6 Diamond Ground Faulted Transverse Joint

The second way in which joints can produce additional noise is through the joint opening size. The wider the joint opening, the greater the joint slap produced. Figure 6 indicates a very wide and unsealed joint. To minimize joint slap during the design stage, joints should be narrow and sealed. A

sealed joint will be quieter than an unsealed joint. Joints with widths greater than 1/8 inch can produce joint slap. However, it typically takes widths 3/8 inch or more to produce noticeable joint slap. Well designed concrete pavements should consider the joint design in regards to its contribution to pavement noise. Joints should be narrow and sealed from a noise perspective.

Acoustic Longevity

Perhaps the most misunderstood aspect of pavement noise from the consumer side is acoustic longevity. As mentioned previously, most consumers develop impressions based on their driving experience and if the interior of the car is quiet they perceive the roadway as quiet. When pavements are newly constructed this can almost always be the case if that is desired. However, the acoustic property of a pavement surface changes over time. This change occurs rather gradually so the driver is not necessarily even aware that the change is occurring. Then years later when a new surface is placed, the consumer once again is wowed by the reduced noise levels, not realizing that this pattern will be repeated in the future.

Unfortunately, this consumer reaction to a new surface has allowed the perpetuation of a myth; simply put, that AC pavements are quieter than concrete pavements. At the time of construction the very quietest AC pavements are quieter but many are noisier than properly textured concrete pavements. Comparing asphalt pavements to loud transverse tined pavements is a very misleading comparison since it is the transverse grooves and not the concrete that is creating the issue.

The second issue that confounds the discussion is the long life of concrete pavements. Since concrete pavements last a long time, it is not uncommon for the 1970s and 1980s concrete pavements to continue in service today. Unfortunately, it is also common that these older pavements were textured with transverse tining. As the urban areas build up, these pavements are then perceived as noisy and subsequently covered with asphalt overlays. The perception is often that the asphalt is quieter than the concrete, but the consumer does not realize that they are comparing an old concrete pavement to a new asphalt pavement. This is analogous to evaluating a Ford and Chevy by comparing a 1979 Ford to a 2009 Chevy. If you really want to compare brands then you should compare new to new and old to old. However, this is rarely done or reported. This has led to much misunderstanding in regards to concrete as a quiet pavement solution.

Changes in acoustic properties over time, as mentioned previously, is the reason the FHWA does not allow pavement type as a noise mitigation strategy. The ACPA recently examined this issue by evaluating the Asphalt Rubber Friction Course (ARFC) placed on the Phoenix freeway system between 2003 and 2007 and the conventional diamond ground surfacing used in Kansas as a standard pavement rehabilitation strategy. Note that the Arizona ARFC was placed for the sole purpose of reducing noise while the Kansas diamond ground surfaces were placed as standard rehabilitation efforts and were not intended nor constructed as a noise reduction surface.

Figure 7 indicates the predicted ARFC acoustic longevity as reported by ADOT in 2003 and the actual Kansas diamond grinding OBSI data measured by the ACPA in 2008. The Arizona ARFC is arguably the quietest AC pavement placed in the US and that is why it was selected for comparison. The ARFC

was also evaluated using the ACPA OBSI system in 2008 and the ADOT prediction is fairly close except for about a 5 mile section of freeway which has exceeded 103 dBA after just 8 years.

As indicated in Figure 7, the Arizona ARFC is very quiet when constructed, however after only 4-6 years of service it begins to approach the 100 dBA level which is attainable by concrete pavements placed for the purpose of noise reduction. By the 4th year it is already within the limits of the FHWA barely perceptible difference indicated in Table 1. After only 8-9 years it is approaching the diamond grinding values that exist on the conventional diamond ground pavements used in Kansas for typical rehabilitation projects. Beyond that period the ARFC level begins to exceed the diamond ground texture levels. The only way to get the ARFC lower is to remove and replace the surface which creates a significant expense and disruption to the freeway system.

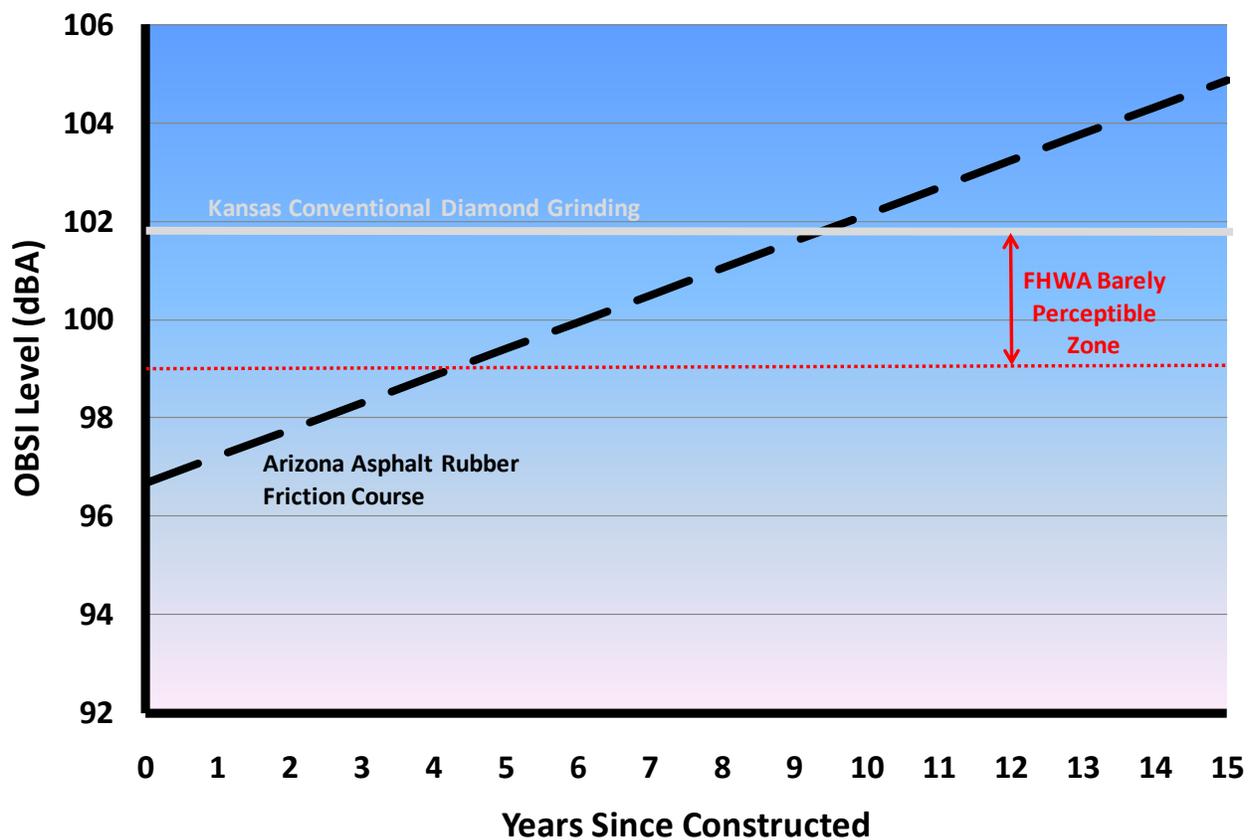


Figure 7 Acoustic Longevity of the Arizona ARFC and the Kansas Diamond Grinding

Economic Comparisons

Acoustic longevity is an important issue because consumers need to be guaranteed of its permanence if pavements are to be used as noise mitigation strategies. For example, after only four years the ARFC is within the barely perceptible zone difference. At a cost of approximately \$70M dollars to construct, its meaningfulness is questionable after just four years unless the consumer is willing to expend \$70M every four years and contend with the associated traffic disruptions and delays. That

amounts to an average expenditure of \$17.5M per year forever, just for pavement noise mitigation. This is far in excess of what traditional noise migration costs.

Even ignoring the FHWA perception zone, the ARFC would need to be replaced at approximately a six year interval to ensure it was quieter than the concrete pavements that can be constructed at a 100 dBA level. This would result in annual expenditures of \$11.7M per year; again, forever.

Perhaps the most difficult issue confronting the ARFC perpetual replacement strategy (e.g. PRS) is the continually escalating costs associated with petroleum based products. That is, the average annual cost of replacement will more than likely increase at a fairly significant rate. This can once again be demonstrated by the Arizona quiet pavement program’s ARFC strategy.

Figure 8 indicates the asphalt rubber unit bid costs and the ADOT bituminous price index from inception of the quiet pavement program in 2003 until five years later. Notice that the bituminous price index increased approximately 325% during this period. This suggests that if ADOT had waited five years to begin the construction of the ARFC overlays, the actual construction costs would have been much more than the \$70M expended; perhaps almost double the original cost. With the future volatility of petroleum based products, perpetual replacement strategies are dangerous strategies.

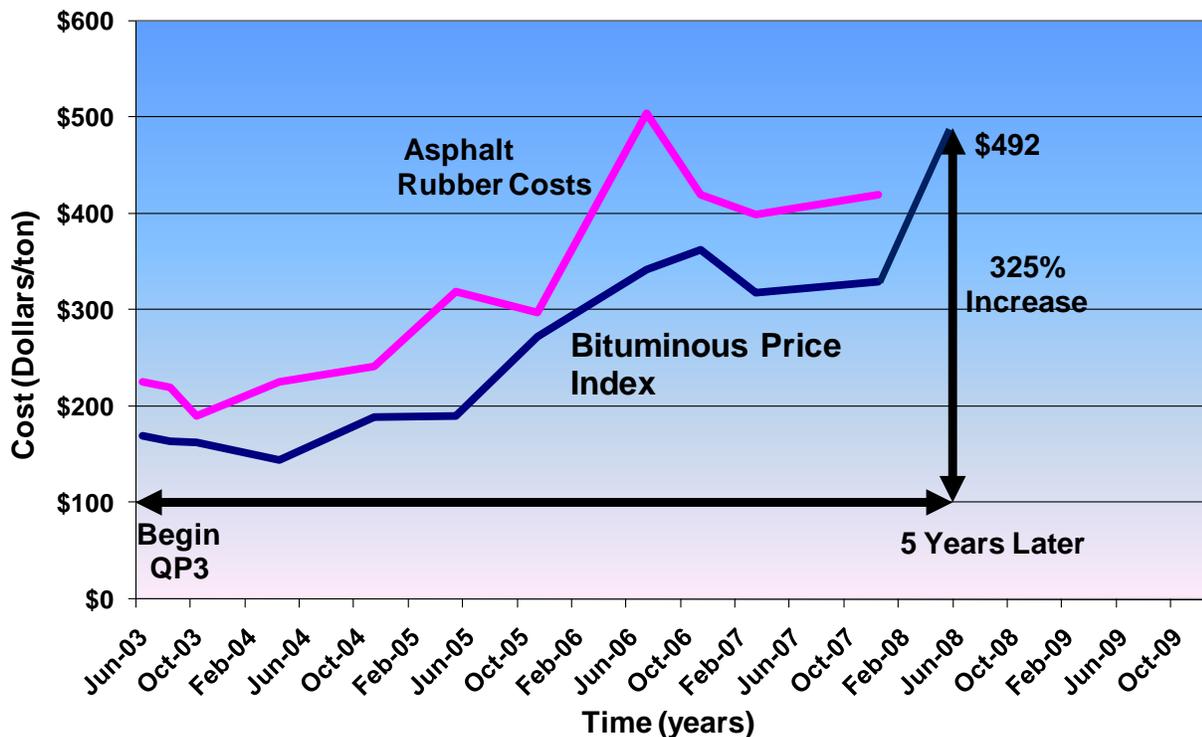


Figure 8 Price Escalations in ADOT Commodities

Conclusions

In recent times there has been interest in controlling noise at the source through the use of quiet pavements. This strategy can be effective when cars are the dominate noise source and traffic volume and speeds are such that they do not produce noise levels that overwhelm surrounding

neighborhoods. In situations where large trucks represent at least 5 to 10 percent of the traffic composition, this strategy may not be effective.

Pavements that produce OBSI levels below 104 dBA without any tonal issues can generally be used successfully as a quiet pavement surface. The very quietest concrete pavements produce levels in the range of 99 to 101.

Using pavement surface for noise mitigation has not been allowed by the FHWA due to its changing properties over time. That is, before embarking on a quiet pavement strategy it is necessary to develop the acoustic longevity of the selected surface. By establishing this, it becomes possible to develop the economic consequences of the perpetual replacement strategy. For concrete pavements the replacement strategy may be quite large where as for the asphalt pavements this cycle may only be on the order of 5 to 10 years.