THE TRANSTEC GROUP

# THE LITTLE BOOK OF QUIETER PAVEMENTS

THE TRANSTEC GROUP

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16. Abstract

The idea of designing and building quieter pavements is not new, but in recent years there has been a groundswell of interest in making this a higher priority. Various State Highway Agencies and the Federal Highway Administration have responded accordingly with both research and implementation activities that both educate on the state-of-the-practice, and advance the state-of-the-art. The Little Book of Quieter Pavements was developed with this purpose in mind... to help educate the transportation industry, and in some cases the general public, about the numerous principles behind quieter pavements, and how they connect together.

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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|--------|---------------|-------------|---------|--------|
| **LENGTH** | | | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| **AREA** | | | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| **VOLUME** | | | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | | | |
| **MASS** | | | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| **TEMPERATURE (exact degrees)** | | | | |
| °F | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | °C |
| **ILLUMINATION** | | | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| **FORCE and PRESSURE or STRESS** | | | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|--------|---------------|-------------|---------|--------|
| **LENGTH** | | | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| **AREA** | | | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| **VOLUME** | | | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| **MASS** | | | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| **TEMPERATURE (exact degrees)** | | | | |
| °C | Celsius | 1.8C+32 | Fahrenheit | °F |
| **ILLUMINATION** | | | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| **FORCE and PRESSURE or STRESS** | | | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

*SI is the symbol for the International System of Units.  Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

# The Little Book of Quieter Pavements

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# What's Inside?

# Thanks to...

# Introduction

## Why was this book written?

The idea of designing and building quieter pavements is not new, but in recent years there has been a groundswell of interest in making this a higher priority. Various State Highway Agencies and the Federal Highway Administration have responded accordingly with both research and implementation activities that both educate on the state-of-the-practice, and advance the state-of-the-art. The Little Book of Quieter Pavements was developed with this purpose in mind... to help educate the transportation industry, and in some cases the general public, about the numerous principles behind quieter pavements, and how they connect together.

## Who is this book written for?

This book is not a synthesis. It is not a textbook. And it is not a policy guide. Instead, it is intended to briefly touch on the numerous aspects of tire-pavement noise and quieter pavements that may be of interest to anyone. In other words, this book is intended to appeal to a wide audience. So while some of the content of this book is technical in nature, the depth of these discussions is minimal. Instead, resources are identified herein for further study.

## How can I listen along?

In addition to the Little Book of Quieter Pavements, a listening experience has been developed, built off of the Soundscape Design™ concept pioneered by Mr. Nicholas P. Miller, Senior Vice President of Harris Miller Miller & Hanson Inc. This listening experience is in the form of a collection of MP3 files. To experience it properly, this collection should be loaded onto an MP3 player and played in a setting free from other noise sources or distractions.

Throughout the Little Book, notations of corresponding track numbers are given as a small blue speaker with a track number. While the listening experience can be useful as a stand-alone tool, the tracks played at the appropriate times will allow the reader to enjoy a more fulfilling educational experience. A reference to each of the tracks can also be found at the end of the Little Book.

# The Big Picture

## Why is noise so important?

Traffic noise pollution has become a growing problem, particularly in urban areas where the population density near major thoroughfares is much higher and there is a greater volume of commuter and commercial traffic. To mitigate the noise – at least for those living and working near these roads – engineers are currently resorting to noise barriers at a cost of two million dollars or more per mile. But while effective in many instances, noise barriers aren't always the best solution for noise pollution. For one thing, they must break the line of sight to be effective. Barriers are also of questionable effectiveness in rolling terrain or on arterial streets where gaps are required for side streets and driveways, as sound tends to "bend" over the top and around the ends of walls.

In recent years, alternative solutions to noise barriers have been advanced – ones that can mitigate noise for both the drivers and for those living and working alongside the highway. Motivated in large part by public outcry leading to policy, engineers worldwide have developed alternative pavement types and surfaces that reduce the noise generated at the tire-pavement interface. While the noise produced from tire-pavement interaction is just one of several sources, for almost all roads and for most vehicles, it becomes the primary source of traffic noise for vehicular speeds over about 30 mph.

## Where did all this talk of noise begin?

Until recently, the demand for quieter pavement surfaces has not existed in the United States, therefore little expertise, much less experience, can be found here. However, this demand is significant throughout Europe, Japan, and elsewhere in the world. In some cases, dedicated research programs have been underway for many years on this topic. Noise has likely taken a more pronounced role in other countries due to the proximity of their residents with respect to major transportation corridors including rail and highways. With the exception of the older areas of the United States, development along transportation corridors here has been reasonably managed through large right of ways and zoning restrictions.

Over the years, numerous researchers, particularly in Europe, have advanced innovative tire-pavement noise solutions. Novel solutions for quieter pavements can be found in both asphalt and concrete. In the early 1990s, the FHWA and AASHTO began to take note of these paving technologies, and conducted international scanning trips to investigate the details of these techniques first-hand. However, with some exceptions, little was subsequently implemented in the US. While some obstacles were technological and economic, the resistance to adopt the techniques was likely due to political and institutional reasons.

Today, this climate has changed. A renewed demand for quieter pavements now exists, and the solutions to fill this demand are more readily available and proven. In this book, some of these solutions are described, along with a rationale behind their selection in light of the numerous other decision-making criteria.

# The Basics of Sound and Noise

## What is sound and what is noise?

*Sound* is all around us.  It comes from the baby crying next to you on the plane, the radio playing your favorite song, the lawn mower that startles you out of your slumber on Saturday morning, and from waves crashing on the beach.  Sound is all of these things and more.  From a technical perspective, sound is small but fast changes in air pressure that cycle higher and then lower than the air pressure that is all around us.  It includes everything we can hear, and even some things we can't.

*Noise* is sound.  However, not all sounds are noise.  The difference is that noise is sound that we find objectionable.  As such, what is noise to one person may not be to another.  What is your favorite song?  Would everyone you know enjoy it as much as you do?  To everyone, that song will be sound.  However, to someone who doesn't enjoy it, the song is noise.

In terms of quieter pavements, we often interchange the terms Sound and Noise, but we must be careful to understand the difference.

## How do we hear?

As we learned, sound is simply small air pressure changes.  The human hearing system is a marvel in converting these air pressure changes into a human response.  It begins with a vibration of the eardrum as a result of the pressure changes.  If you hold a piece of paper flat in front of a speaker, you will feel vibrations in the same way that your eardrum vibrates.  These vibrations then move some small bones that transfer the vibration to the inner ear.  Full of fluid, the inner ear transfers the vibrations to the basilar membrane which has small, sensitive nerve endings that convert this information to what your brain interprets as sound.

## What is a Decibel?

Our hearing system is capable of sensing a very wide range of pressure changes.  Pressure is often given in either units of Pascals (Pa) or pounds per square inch (psi).  We know that most people can sense sounds as little as 0.00002 Pa.  Furthermore, at some point in our lives, we may experience something that is 100 Pa or more.

Our hearing is what is called *non-linear*.  Hearing something change from 0.1 to 1 Pa (an increase of 0.9 Pa) sounds about the same as a change from 1 Pa to 10 Pa (an increase of 9 Pa).  In addition, something heard at 2 Pa does not sound twice as loud as 1 Pa.  As a result of this, we often convert measures of sound to *sound level*.  More specifically, we convert pressure changes in Pa to something that crudely relates to the human experience – units of *decibels (dB)*.  Mathematically, this conversion is made as follows:

$$Sound\ Level\ [dB] = 20 \times log_{10}\left(\frac{Pressure\ [Pa]}{0.00002\ [Pa]}\right)$$

3

Figure 1 also shows this conversion, along with pictures that help to identify what kinds of sounds produce the various levels.
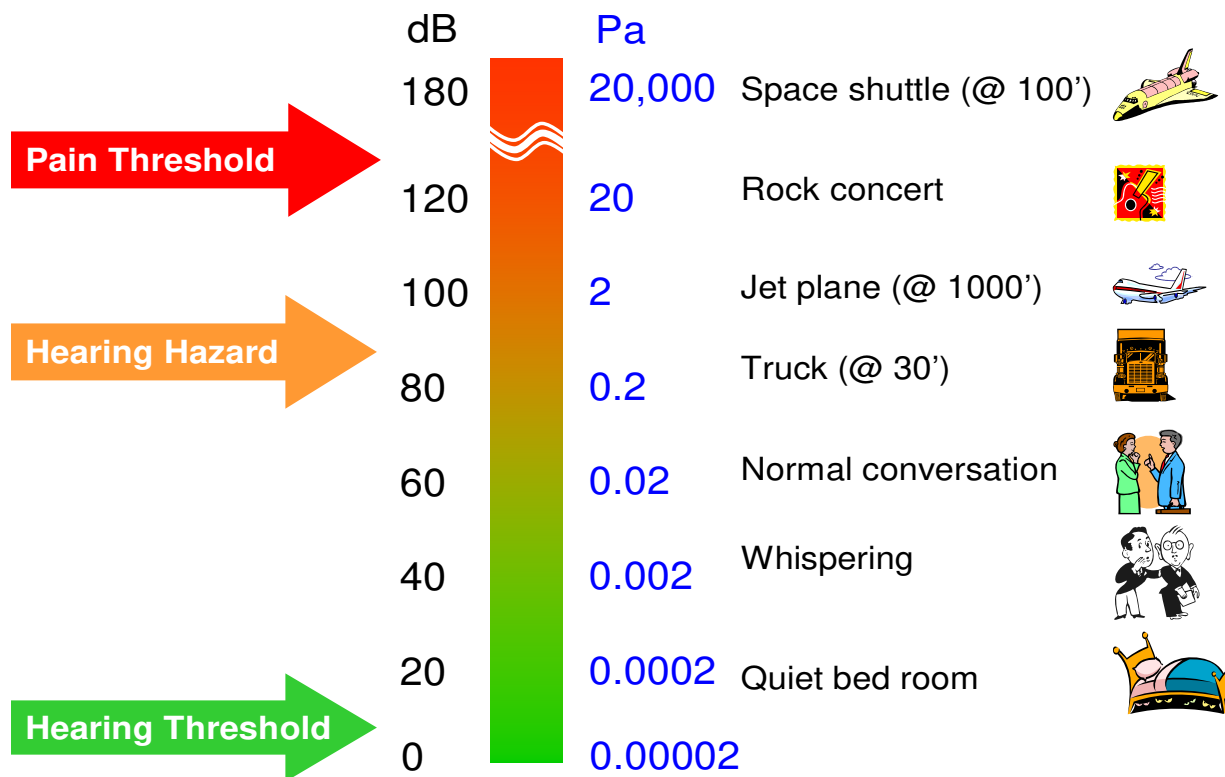
| dB | | Pa | |
|----|----|----|----|
| 180 | | 20,000 | Space shuttle (@ 100') |
| 120 | | 20 | Rock concert |
| 100 | | 2 | Jet plane (@ 1000') |
| 80 | | 0.2 | Truck (@ 30') |
| 60 | | 0.02 | Normal conversation |
| 40 | | 0.002 | Whispering |
| 20 | | 0.0002 | Quiet bed room |
| 0 | | 0.00002 | |

**Pain Threshold**

**Hearing Hazard**

**Hearing Threshold**

Figure 1. Comparison of sound pressure, sound levels, and common examples.

Rules of thumb regarding sound level are sometimes helpful. To begin, most would consider a 1 to 3 dB change as "just noticeable", and it takes a 5 dB change to be considered definite. This is especially true if there is any gap in time between listening to the sounds being compared. Most also consider 10 dB change a "doubling" (or "halving") of sound. There is one very important thing to note about these rules of thumb... they are only true for the <u>same sound</u>. If the type of sound changes, these changes in perception may no longer be valid.

## What is the difference between $L_{max}$ and $L_{eq}$ and $L_{10}$ and...?

In most situations, the sound levels around us will not stay the same from moment to moment. As someone talks, for example, we will experience higher levels as they speak, and lower levels when they stop.

There are a number of ways to convert these types of *non-uniform* sounds into a single measurement (number). To illustrate how this can be done, Figure 2 shows what a *sound level meter* might produce if placed next to a road. It shows the rise and fall of the sound level over time. The sound from individual vehicles can be noted as they pass by the meter alongside the road. The levels of each vehicle vary depending on the type (e.g., car vs. a truck) and the distance between passing vehicles.
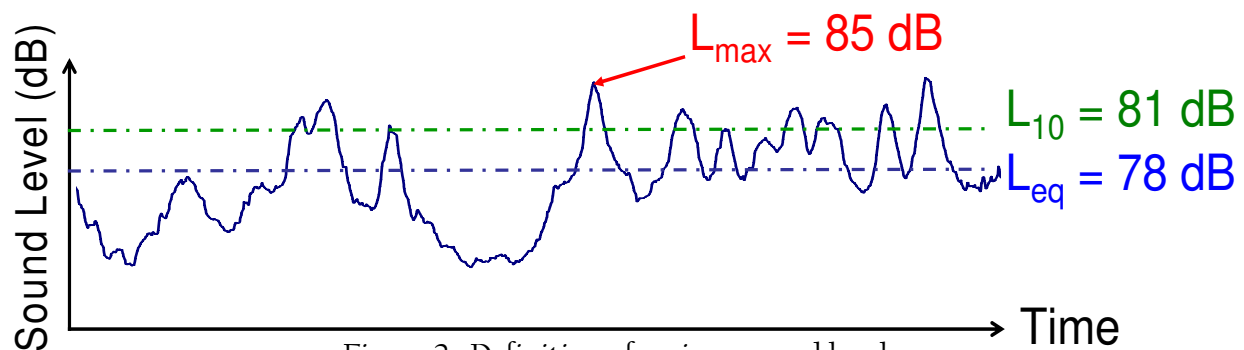
Figure 2. Definition of various sound levels.

The first thing to note when reporting this type of information is the length of time that such a measurement is made. In the case of traffic noise measurements, this is typically on the order of 5 to 90 minutes, and sometimes up to 24 hours. Next is the selection of the single level that represents the data. This will depend on what is important to you. The following are the most common options used in traffic noise:

- $L_{max}$ – This level is the maximum sound level during the measurement period. In Figure 2, this is 85 dB. It may be this single event that is most significant to you (e.g., a loud motorcycle going by at 3AM).

- $L_{XX}$ – The "XX" is instead actually a number (e.g., 10). It represents the sound level that is exceeded only XX% of the time. Like $L_{max}$, this type of measurement is relevant in those instances where isolated and infrequent sounds may be dominating the perception of the road. In reporting aircraft noise, this type of measurement is often used. In Figure 2, this is 81 dB.

- $L_{eq}$ – This level is the equivalent sound level during the measurement time. In Figure 2, this is 78 dB. It is calculated by adding up all the sound energy during the measurement period, and then dividing it by the measurement time. $L_{eq}$ is probably the most common way of reporting traffic noise, as not only is it required to interpret FHWA policy, but it also is representative of the actual traffic noise that is present, and thus a function of both the vehicle type and speed, as well as the pavement.

There are numerous other ways to report sound levels. $L_{dn}$, for example, is a type of weighted average of the sound level to account for what time of day it is heard – (d)ay or (n)ight. Sound heard at night is effectively "penalized" since it is more likely to affect sleep. Another metric, *Sound Exposure Level ($L_E$)*, is also used sometimes to describe a single event – giving what the level would be if all of the sound energy occurred in 1 second.

## What is a Hertz?

The *frequency* or *pitch* of a sound describes how fast the small air pressure changes are occurring. This is often reported in cycles per second or *Hertz (Hz)*. Like sound levels, the perception of

frequency is also non-linear. A change from 1000 Hz to 2000 Hz (an increase of 1000 Hz) is perceived in a similar way as a change from 2000 Hz to 4000 Hz (an increase of 2000 Hz). These doubling of frequencies are called *octaves*, and will be discussed in more detail later.

## What frequencies matter?

In addition to hearing over a wide range of sound levels, humans can also hear over a wide range of frequencies. Assuming you have no hearing loss, you may be able to hear sounds from 20 cycles per second (Hz) to 20,000 Hz. Human hearing is less sensitive near these extremes, and is often most sensitive in the range from 1000 to 4000 Hz. As we get older, or if our hearing has been damaged, we tend to lose our sensitivity to some frequencies, particularly those on the higher end of this range.

## How do we view and understand frequencies?
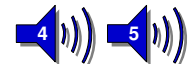
In order to interpret highway noise, we must understand how *frequency content* is often reported. To begin, Figure 3 illustrates two simple sounds – a tone of 1000 Hz and one at 4000 Hz. When shown as pressure vs. time, both tones have very simple *sinusoidal* patterns. When converting from the *time domain* to the *frequency domain*, each signal is shown as a single bar at its characteristic frequency. The length of the bar is representative of the size ("height") of the waves. Figure 3 shows the addition of these two simple sounds into more complex-looking sounds. The frequency domain of this sound is still very simple, however.
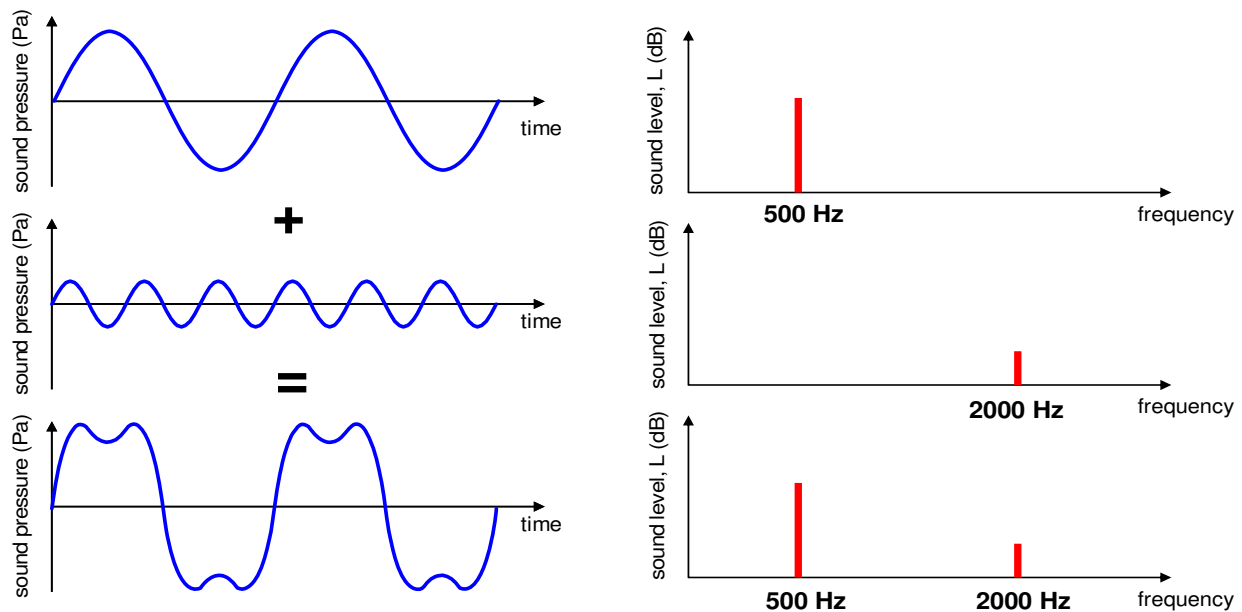


Figure 3. Time and frequency domains of simple sounds (source: Brüel & Kjær).

More complex sounds are given in Figure 4. The first is the sounds of gears meshing. On a time domain plot, this is very complex looking, and it is difficult to understand from this plot alone

what kind of sound this is. On the frequency domain plot, however, characteristic *tonal* peaks can be seen at various frequencies (likely corresponding to the number of teeth and speed of the gears). These peaks are sometimes an indication that a sound might be unpleasant. The second example looks similar to the first in the time domain, but very different in the frequency domain. As rain on the umbrella, this sound is more *random* (or *broadband*), and thus often more pleasant. The third sound is that of an anvil being hit. While very similar to the umbrella example in the frequency domain, it is much different in the time domain. This type of sound is *transient*, meaning that it changes significantly with time. This underscores the importance of looking at both the time and frequency domains when interpreting sounds.
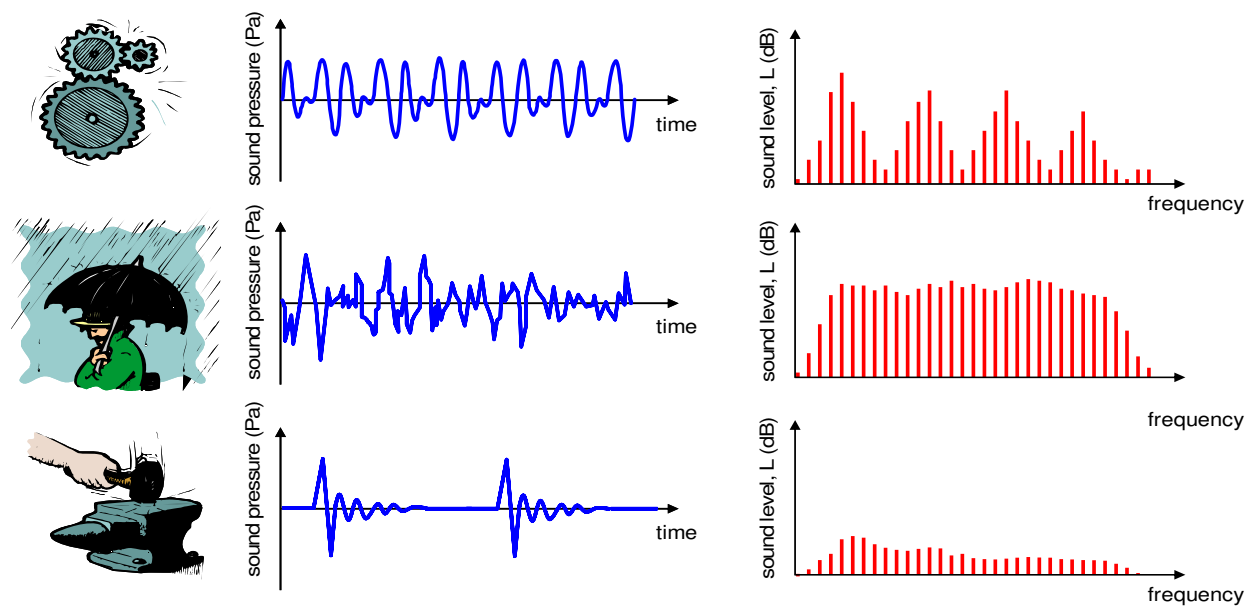


Figure 4. Time and frequency domains of real sounds (source: Brüel & Kjær).

Figure 5 shows various ways that frequencies can be plotted for a sound. The first is called a *narrow-band* plot, and while very complicated looking, allows for subtle components of a sound to be identified. The second is a *one-third-octave band* plot that adds up the sound energy into various standardized bands. These bands simplify the reporting, but compromise some of the ability to interpret the sound. *Octave bands* can also be reported which sum the energy in groups of three consecutive third-octave bands. Each octave represents a doubling of frequency. Finally, a *total level* can be reported by summing all of sound energy in the octave bands together.

## How does sound travel?

Sounds can often be analyzed by breaking them down into a *source*, *propagation path*, and *receiver*. If the position and *intensity* of a source is known, along with the path, a good prediction can often be made of the sound level at the receiver. This calculation becomes increasingly complex, however, as things that may block or reflect sound are introduced. Furthermore, the way that

sound travels through the air is dependent on climatic variables including temperature, humidity, and barometric pressure. While predictions at shorter distances (less than 100 m) can often ignore these, longer distances may require more sophisticated models.
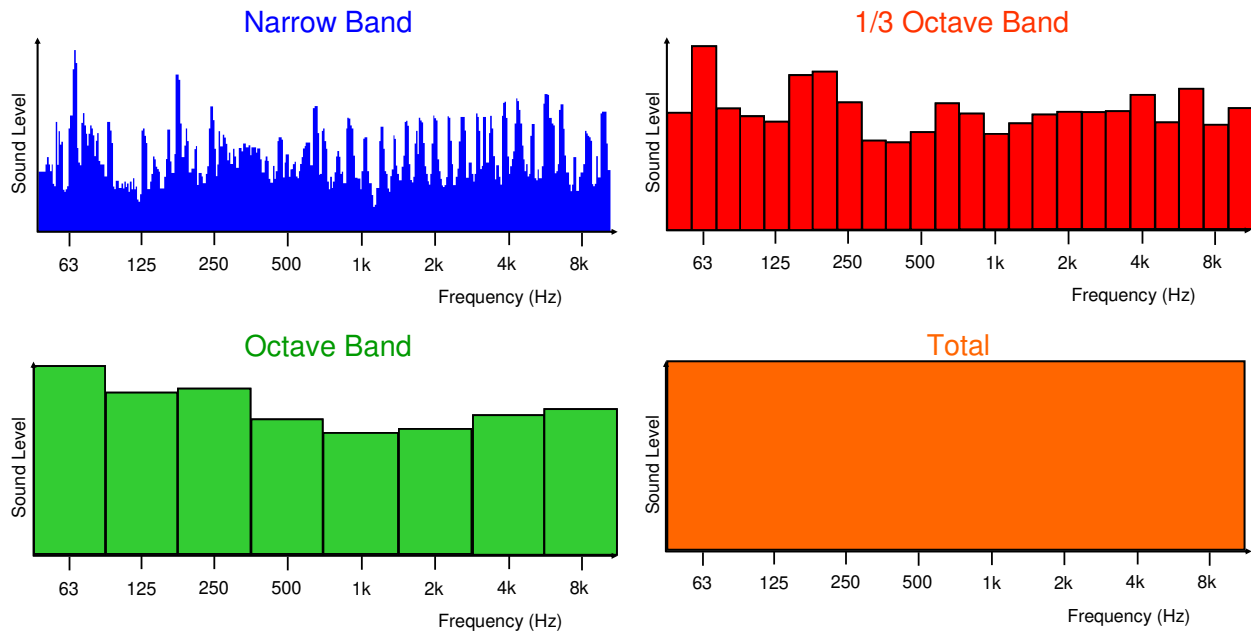


Figure 5. Frequency spectra forms of the same sound.

## How is sound perceived?

Ideally, the way that a person will respond to a sound is the way the measurement should be reported. However, there are numerous reasons why this is easier said than done. Human response will vary as a function of the transient and frequency characteristics of a sound, not to mention the individual's definition of noise. To simplify this, measurements are often    reported after being *filtered* using a *weighting scheme.*

Weighting means that the levels at the various frequencies are modified according to how a person might hear them. As Figure 6 illustrates, there are four commonly used weighting schemes to do this, with the *A-weighting* scheme the most commonly used in traffic noise measurements. In this case, the most importance is placed on frequencies between 1000 and 4000 Hz, as people are most sensitive in this range. Levels outside of this range are *attenuated* (reduced).

When reporting sound levels, it is important to include the designation of the weighting scheme. One way is to add the letter (e.g., "A") to the index. For example, $L_{Aeq}$ should be used instead of just Leq. The units of the calculated sound levels could also include the weighting scheme that was applied. For example, *dB(A)* or *dBA* should be used instead of just dB when the A-weighting scheme is used. Ideally, the term "A-weighted decibels" should be used to minimize any chance of confusion. Furthermore, if no weighting is used, it is better to use *linear weighting* (or *LIN*) instead of simply leaving the designation off.
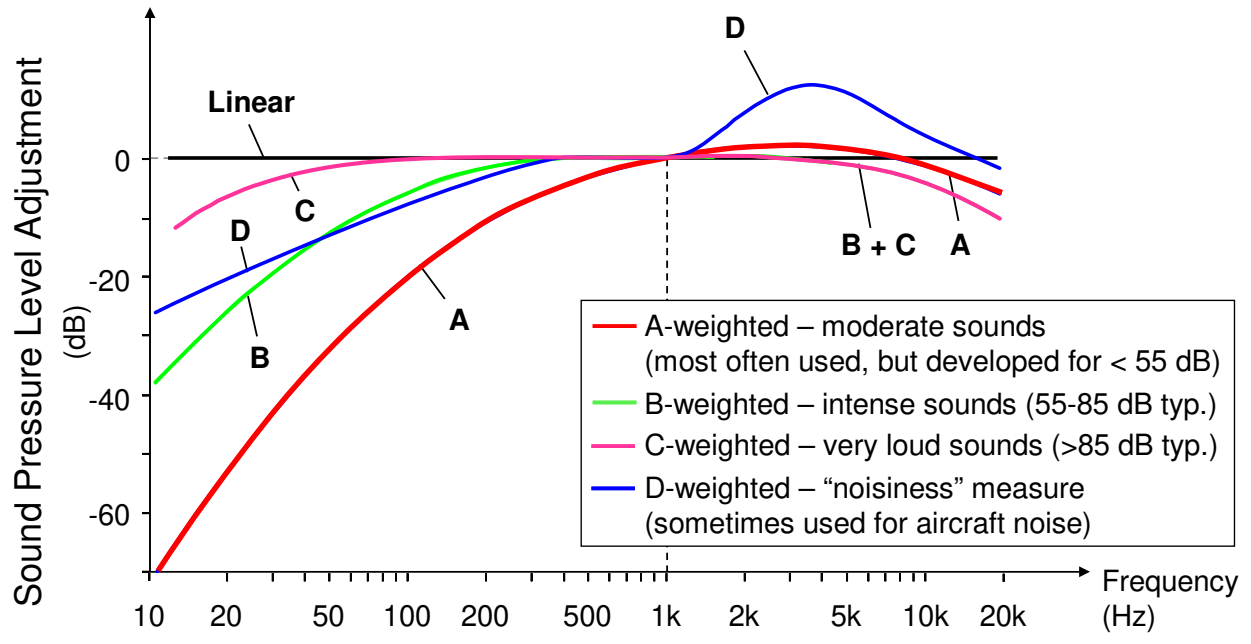
Figure 6.  Weighting schemes for sound level calculation.

# Traffic Noise

## What is traffic noise?

While a clear distinction between sound and noise was given previously, the sound generated by traffic is usually termed *traffic noise*. It is all of the sound that is heard as a result of vehicles traveling down a road, and includes the combination of all possible sources of noise on a vehicle. These sources are commonly divided into *propulsion*, *tire-pavement*, and *aerodynamic* noise. Propulsion noise includes sounds generated by the engine, exhaust, intake, and other powertrain components. The tire-pavement noise is that which is generated as the tire rolls along the pavement. Aerodynamic noise is caused by turbulence around a vehicle as it passes through the air.

## What effect does vehicle type and speed have?

Figure 7 illustrates the relative importance of the three primary sources of traffic noise – propulsion, tire-pavement, and aerodynamic. Propulsion noise will dominate the total noise at very low speeds. As speed increases, a *crossover speed* is reached at which the tire-pavement noise becomes the dominant source. Only at very high speeds will aerodynamic sources begin to dominate.

The crossover speed is an important concept. One way to view it is as a practical threshold, above which quieter pavements will be most helpful. It is a function of vehicle type and operating condition. As car engines become quieter, the crossover speed becomes lower, and quieter pavements become more practical.

Vehicle type is an important variable in the noise that is generated. Heavy trucks with their large propulsion systems and numerous tires are among the noisiest vehicles on the road. A "typical" heavy truck is on the order of 10 dBA louder than a "typical" passenger car at highway speeds. This means that one truck generates the same sound energy as ten cars, and thus if trucks make up more than 10% of the traffic stream, they will likely dominate the overall sound level.

As Figure 7 illustrates, speed is also a variable in traffic noise. On many highways, an increase in speed of 10 mph will result in an increase in sound level of approximately 2 to 3 dBA.

## What other things affect traffic noise?

The amount of traffic on a highway will also affect the sound level, but not as significantly as some would think. Assuming speeds and traffic mix stay the same, doubling the traffic volume will result in only a 3 dBA increase.

Vehicle operating characteristics including braking (especially engine braking), accelerating, climbing, and cornering will all increase noise to varying degrees.
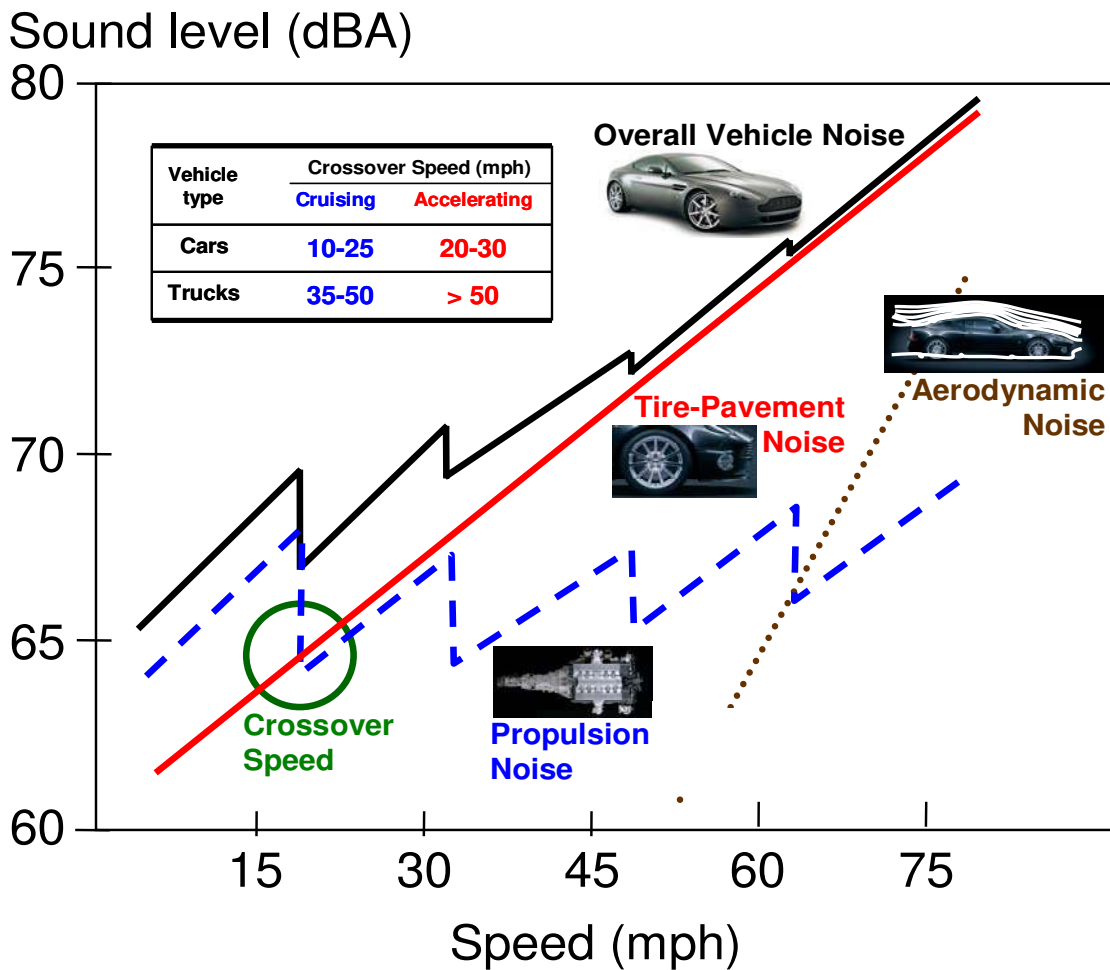
Figure 7. Speed effects on vehicle noise sources and crossover speed.

## How can we control traffic noise?

Within the FHWA policy found in 23 CFR 772, there are six possible methods to reduce traffic noise. If noise mitigation is found to be feasible and reasonable, noise *barriers* of some type are the most commonly used option. These often take the form of *sound walls* and/or earthen *berms*. The height of the barrier is a factor since if the line of sight between the source and the receiver is not broken, the barrier will not reduce the noise. Fortunately, most of the sound is generated close to the ground, which is the reason why most barriers can be effective to some degree.

The effectiveness of a barrier is a function of how far away you are. For example, if you are directly behind a barrier, you may experience a decrease in sound level of typically 5 to 10 dBA. Once you are 100 to 150 m from the barrier, however, its effectiveness is different. A "shadow effect" will often occur, meaning that some of the traffic noise will "bend" around the top of the barrier. At this distance, however, background noise in the neighborhood may begin to dominate as *spreading* of the sound generated by the highway will decrease its level. It should be similarly noted that the effectiveness of a barrier can also be partially lost if there are any breaks in it – driveway access, for example.

Spreading is a natural decrease in sound level, and varies depending on the type of traffic. As Figure 8 illustrates, sparse traffic can be viewed as individual *point sources*, and the sound level will decrease by approximately 6 dB per doubling of distance. Heavy traffic can viewed as a *line source*, which often has only a 3 dB decrease in sound level per doubling of distance.
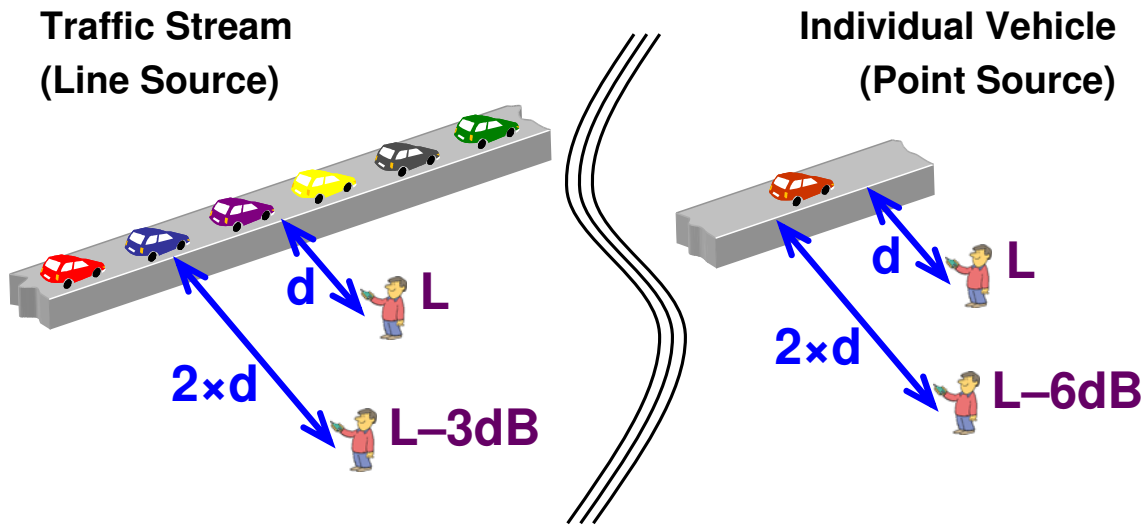


Figure 8. Spreading of traffic noise from various source types.

## When is a noise barrier used?

For projects in the US that qualify for federal cost sharing, federal policy governs when funding for noise mitigation will be provided. Within the policy, a systematic method of data collection and analysis is outlined, along with specific thresholds that must be met before funding will be allowed. The State Highway Agencies, in turn, weave these guidelines into their policies and practices in order to conduct noise studies.

While the specifics of this can be sought from the FHWA Noise webpage and elsewhere, some highlights are as follows:

1. Federal cost share for noise abatement is only considered on some types of projects. This includes the addition of lanes or significant changes to vertical or horizontal alignment; a renewal of the pavement surface is not a candidate project.

2. Highway traffic noise impacts are determined by analyzing exterior (outdoor) areas with frequent human use. If there are no usable exterior areas, then an interior analysis may be done. In addition, the area must already be developed, or have building development approved or underway.

3. As part of the data collection and subsequent modeling, it must be determined that the potentially impacted parties meet specific *Noise Abatement Criteria (NAC)*. The NAC is an absolute A-weighted sound level that must be approached before the party is considered impacted. The definition of "approach" is set by the State; however, most select an approach level that is 1 dBA lower than the NAC.

4. The NAC is not intended to be a level that will be achieved after noise abatement is in place. Furthermore, the NAC varies depending on the land use, and includes different criteria for different categories. Residential land falls under Category B, for example. In this case, an impact occurs when approaching 67 dBA. This level is about where conversational speech can be adversely affected. It is also far below a level that can lead to hearing damage, as Figure 1 illustrates.

5. The potential noise mitigation methods are then evaluated for being feasible and reasonable in their ability to control noise. Only if these tests are passed can mitigation be approved for federal funding.

# Tire-Pavement Noise

## What things about a tire affect noise?

Tires in use today are the result of a high level of engineering. Heavy competition and overcapacity of production also make them a commodity item. As a result, cost is a principal consideration, but many other aspects of a tire still govern its design and construction. Safety, for example, is paramount and cannot be compromised. Durability and handling are also important, as buyers will often include these in their decision-making process. Noise is an additional consideration, although the emphasis is on noise inside the vehicle, and not alongside the road.

Tires are often engineered for a specific application; from summer tires that are optimized for handling and noise, to mud and snow tires that move water and improve friction. The tire *tread pattern* and rubber compounds are what typically affect most of the properties of interest to the tire companies as well as tire-pavement noise. The more *aggressive* a tire tread pattern is (with clearly defined blocks and gaps), the louder it will typically be. Harder tires (rubber compounds) will also typically be louder compared to softer compounds.

As illustrated in Figure 9, there are other more subtle but important tire and tread characteristics. One important characteristic for noise is the degree of randomness of the tread block size, which will minimize tonal frequencies that most would find objectionable. Skewed (angled) blocks are also used since they allow for a more gradual roll in and out of each block. This prevents sudden impacts that can lead to a noisier tire.
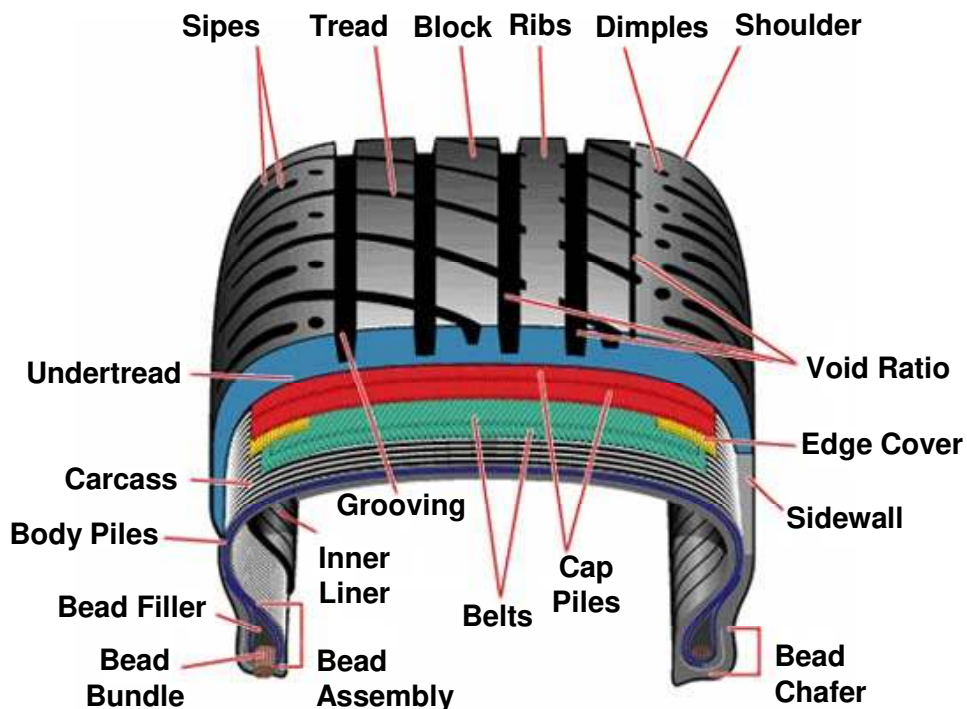
Figure 9. Typical features of a tire (source: Yokohama Tires).

Air gaps in the tread pattern (including grooves and sipes) help to minimize some sounds from being generated, but also amplify other sounds. More on this later.

## What things about a pavement affect noise?

The influence of a pavement on tire-pavement noise is as equally important as the tire. Quieter pavements are typically smooth, but still provide adequate "ventilation". To a lesser degree, pavements that are "softer" will also typically be quieter. Pavements, like tires, must not be built just for noise, however. Of paramount concern is safety, with additional considerations for cost and durability. Fortunately, we know that quieter pavements do not have to compromise these other characteristics of interest.

## What makes tire-pavement noise?

When the tire and pavement get together, they sure get noisy! And they do so in a very complex way. The sound often begins with various types of *generation mechanisms*. Making it complex is the fact that numerous mechanisms happen simultaneously, and to varying degrees, depending on the specific tire-pavement combination. Generation mechanisms are those that make sound. In the next section, we will discuss things that can amplify these sounds.

To better understand the complexity of the various tire-pavement noise generation mechanisms, they are often described using physical analogies. The more prominent of these mechanisms are described as follows:

  **Tread impact (a.k.a. "The Hammer")** – As the tire rolls along the pavement, the tread on the tire and the texture on the pavement will come together as individual impacts. The resulting interaction can be seen as hundreds or even thousands of small hammer strokes occurring each second, each generating sound. See Figure 10.
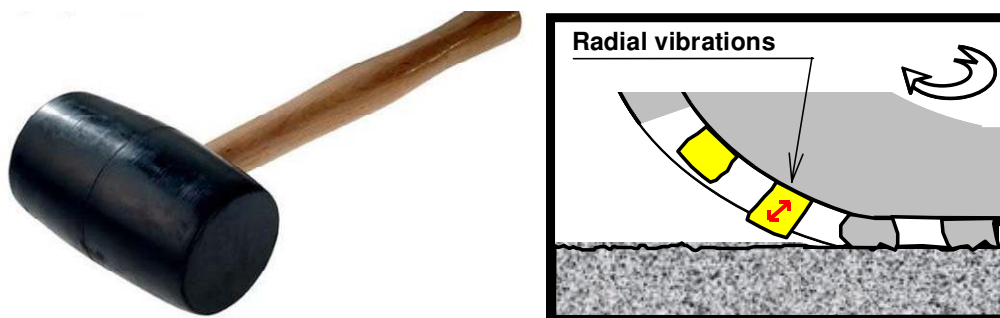


Figure 10. "The Hammer" generation mechanism.

**Air pumping (a.k.a. "The Clapper")** – In between the tread on a tire and the texture on a pavement are gaps filled with air. As the tire and the pavement roll together, some of that air is squeezed out, and some is trapped and compressed. Moments later, as the tire loses contact with the pavement, what air was trapped is now forced out. And in some cases, air is sucked back in. All of this happens hundreds or thousands of times a second. This process is similar to clapping your hands, where much of the sound that is heard is air being pushed away quickly. Whistling is another example, where air is forced out of a small opening, generating sound as a result. See Figure 11.
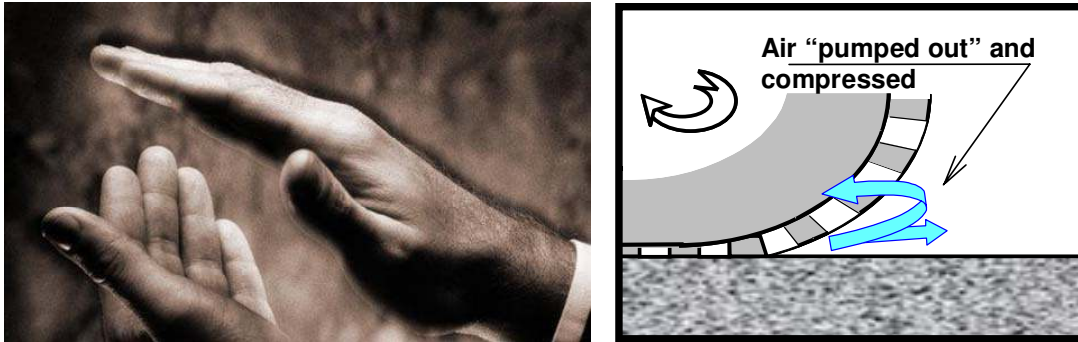


Figure 11. "The Clapper" generation mechanism.

**Stick-slip (a.k.a. "The Sneaker")** – As one watches a basketball game, the distinctive sound of sneakers squeaking on the court can be heard. This same type of sound is produced as a tire rolls along the pavement. As the rubber is continually deformed and distorted underneath the tire, it will mostly *stick*, but also periodically *slip* once a critical limit is reached. These "corrections" under each tread block happen thousands of times a second, thus generating high frequency sound. See Figure 12.
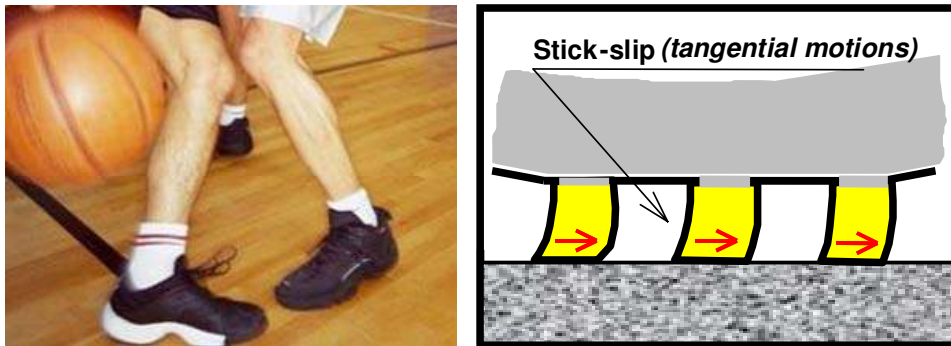


Figure 12. "The Sneaker" generation mechanism.

**Stick-snap (a.k.a. "The Suction Cup")** – A suction cup can stick to a smooth surface because of both adhesion and a vacuum that is created when the air in the cup is pushed out. As tread blocks interact with some pavements, a similar effect can occur, generating sound. See Figure 13.
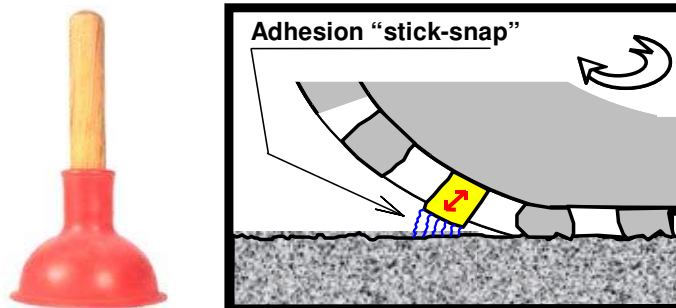


Figure 13. "The Suction Cup" generation mechanism.

## What makes tire-pavement noise even louder?

The sound that is created by the various generation mechanisms is simply not enough to explain all of the noise that is heard. It is well accepted that a number of *amplification mechanisms* are also at play which increase the sound level.

Amplification of tire-pavement noise is also complex. Like many musical instruments, the sound at some frequencies will be amplified more than others. As a result, if one seeks to reduce overall noise, they should target those frequencies that are amplified the most.

To better understand specific amplification mechanisms that affect tire-pavement noise, physical analogies are again used. These include:

**Acoustical Horn (a.k.a. "The Horn")** – The geometry of a tire and a pavement in contact includes a wedge-shaped segment of open air. Within this wedge, multiple reflections of sound generated near the throat can occur, much like the reflections that occur within a musical horn or megaphone. In the case of tire-pavement though, the horn is poor as it is open on two sides. The result is a significant amplification in the forward and aft directions, along with a distortion of some frequencies. See Figure 14.
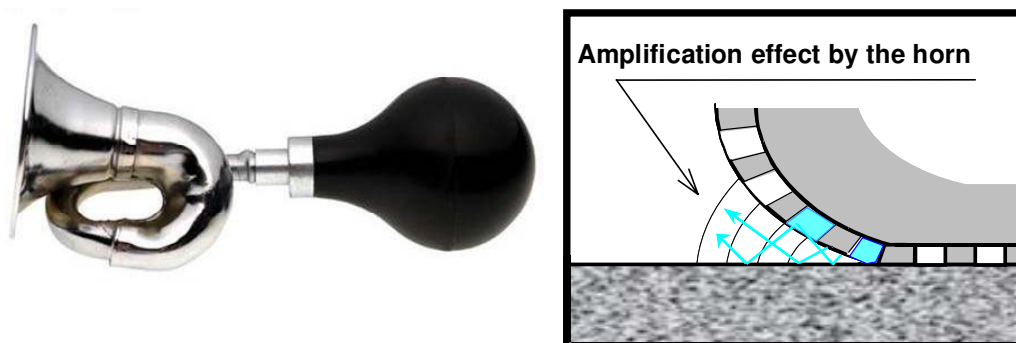


Figure 14. "The Horn" amplification mechanism.

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**Helmholtz Resonance (a.k.a. "The Pop Bottle")** – When you blow across the top of a pop bottle, a distinct tone can be heard. This occurs as the air in the neck of the bottle (acting as a mass) vibrates up and down on the pillow of air inside the bottle (acting as a spring). By itself, blowing creates very little sound. However, blowing across the bottle significantly amplifies the frequency that is distinct to that bottle. A similar geometry can be found close into the wedge where the tire and pavement meet. In this case, the mass and spring are side-by-side. The result is an amplification of some frequencies unique to the geometry of the tire and the pavement. See Figure 15.
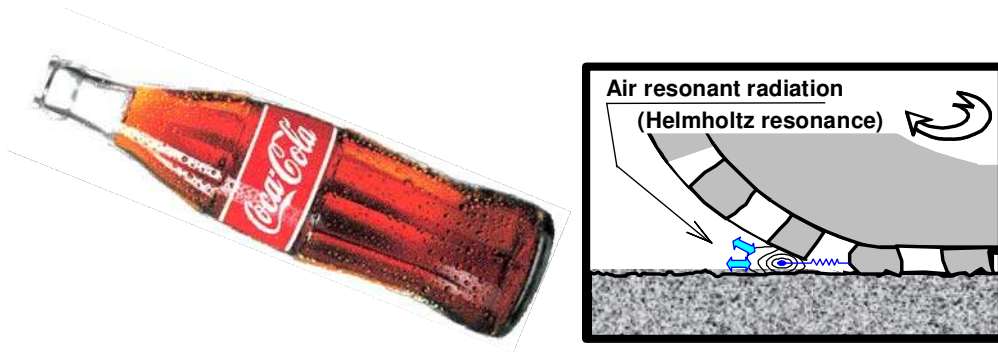


Figure 15. "The Pop Bottle" amplification mechanism.

**Pipe Resonance (a.k.a. "The Organ Pipe")** – When air is blown across an organ pipe, a sound will be amplified that is unique to the length of the pipe and how many openings are in the pipe. On a tire, similar "pipe" geometries can be found as the various grooves and sipes on a tire are pinched off and opened up at various places underneath the contact patch. Sound that is generated elsewhere can be amplified within these pipes. See Figure 16.
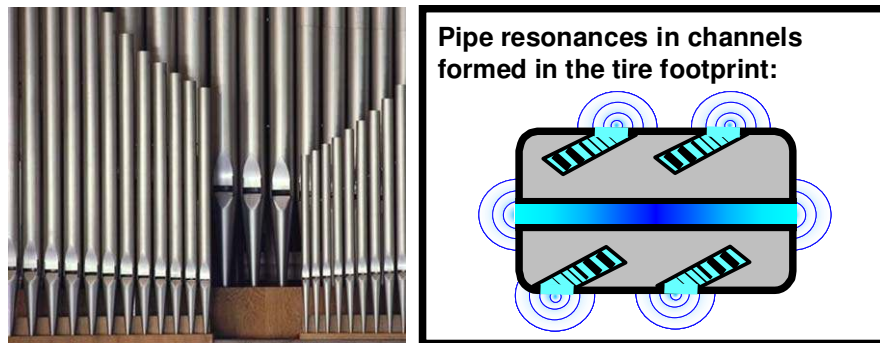


Figure 16. "The Organ Pipe" amplification mechanism.

**Sidewall Vibrations (a.k.a. "The Pie Plate")** – An electric shaver or vibrating cell phone do not make much sound by themselves. However, if one is placed on top of an upside-down pie plate, the small vibrations are amplified significantly. Many of the small vibrations described as generating mechanisms will be similarly amplified as vibrations of the tire sidewall. See Figure 17.
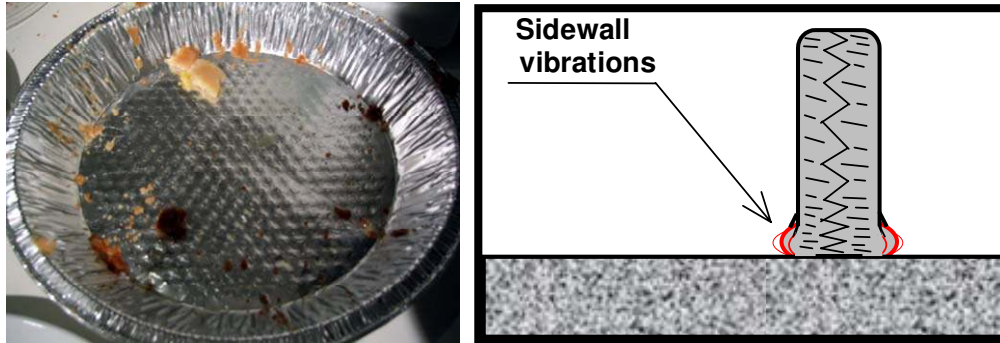


Figure 17. "The Pie Plate" amplification mechanism.

**Cavity Resonance (a.k.a. "The Balloon")** – When a balloon is thumped, a distinctive ringing sound can be heard. The same is true as a tire is kicked. This sound can actually be better heard inside the vehicle. In fact, this mechanism is less important for noise heard outside the vehicle as it is inside the vehicle, as the vehicle itself tends to further amplify this frequency. See Figure 18.
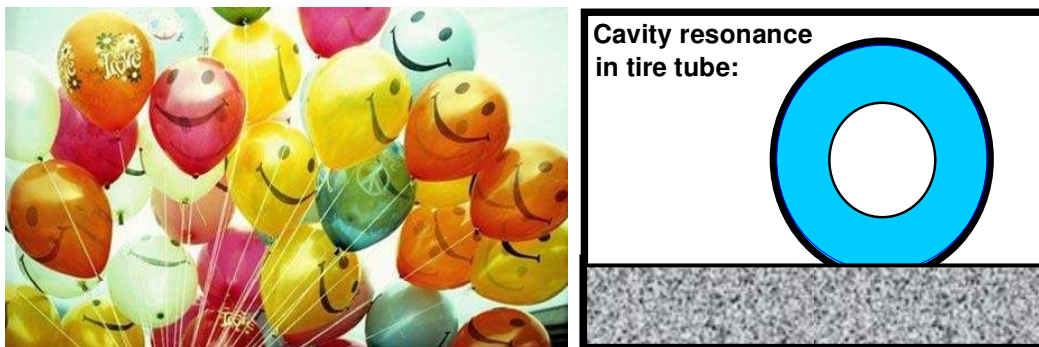


Figure 18. "The Balloon" amplification mechanism.

# Measurements

## What are wayside noise measurements?

The most common way of measuring noise is "at the side of the road". Technically, these are termed *wayside* measurements, and can be done either at a fixed distance from the road (commonly 7.5 or 15 m), or else at the location of receivers such as a residential backyard or playground. Ideally, wayside measurements include the measurement of sound levels using microphones, as well as traffic speeds and classifications. This is illustrated in Figure 19.
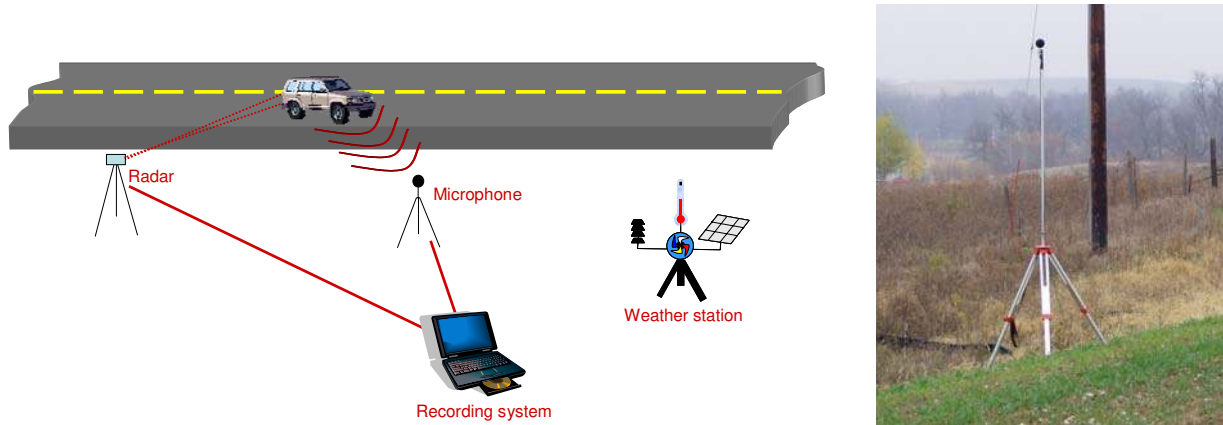


Figure 19. Components of a wayside measurement.

There are three common types of wayside testing. In instances where there is little traffic, *statistical pass-by (SPB)* testing can be done. In this case, a microphone at a fixed position is used to measure the maximum sound levels ($L_{max}$) of hundreds of individual vehicles. From these, a calculation is made of the sound level from an "average" car, medium truck, and heavy truck traveling at a standardized speed. A similar test is sometimes done with one or more known test vehicle/tire combinations. In this case, it is called a *controlled pass-by (CPB)* test.

Using SPB and CPB, pavements at different locations can be compared to one another. Some caution must be exercised, however, as there can always be differences in the "average" vehicle from site to site (for SPB) or unique interactions between a specific tire and pavement combination (for CPB).

A third type of wayside testing that is commonly conducted is termed *time-averaged*. This is sometimes referred to as *continuous flow traffic time-integrated model (CTIM)*. In this case, the microphone is set to record all of the traffic noise over a fixed time (commonly 5 to 30 minutes) and traffic levels and speeds are simultaneously recorded. An average equivalent sound level ($L_{eq}$) over this period is calculated, and is often reported as an average of repeat measurements.

All wayside testing is subject to some degree of human interpretation. For example, consideration must be given to the presence of objects that might reflect or block sound. Weather conditions must also be monitored, especially the wind which can affect the sound level. Finally, "contaminating sources" must also be identified including aircraft and roadside noise (lawn mowers, trains, etc.). If significant enough, measurements must be discarded.

## What are source noise measurements?

A measure of tire-pavement noise as opposed to traffic noise is of increasing interest, particularly for those that wish to design and build quieter pavements. *Source measurements* measure sound "near the tire".

There are currently two principal techniques for measuring tire-pavement noise: *close-proximity (CPX)* and *on-board sound intensity (OBSI)*. CPX is currently documented as a draft international (ISO) standard 11819-2. OBSI was initially developed by General Motors for use in tire evaluation at their test facilities. The technology was developed further by Dr. Paul Donavan of Illingworth & Rodkin as part of quiet pavement research for the Departments of Transportation in both California and Arizona. The OBSI measurement technique is now in the process of being standardized.

As Figure 20 illustrates, both techniques are similar in that they include microphones positioned close to the tire-pavement contact patch. Both collect measurements as the vehicle is in motion. However, there are also some important differences:

- The CPX method uses single microphones that measure sound pressure. OBSI uses dual-microphone probes that measure sound intensity. The latter is directive, meaning that the measurements from each of the two microphones can be used to sort out the direction of the various sources.

- Currently, the CPX and OBSI methods specify different positions for the microphone including the height (from the ground), spacing between the front and rear positions, and distance from the tire sidewall. These differences mean that the generation and amplifying mechanisms will play different roles in the sound measured by the two tests.

- While not required, CPX testing is often run in an enclosed trailer that is intended to isolate the microphones from other sources of sound. Because of the ability of OBSI to identify the direction of a sound source, this is not required.

- There is more experience with the OBSI method in the US, while the CPX technique has been the preferred method elsewhere in the world.

The measurements from any source measurement will be highly dependent on the tire that is used during testing. Specifications for both CPX and OBSI remain under development, with the identification of suitable test tires being a significant issue. Until recently, the vast majority of OBSI testing has been conducted using a Goodyear Aquatred III tire (P205/70R15). Recently, a newer *Standard Reference Test Tire (SRTT)* (P225/60R16) has been introduced and adopted for noise testing (ASTM F 2493). CPX testing in the US has also used the Aquatred, as well as a Uniroyal Tiger Paw AWP which differs only slightly from the new SRTT. According to the draft ISO CPX standard from 2000, the two most commonly used tires to date are an Avon/Cooper ZV1 (P185/65R15) and a Dunlop SP Arctic (P185/R14).

Figure 20.  CPX and OBSI test equipment.

## What other kind of noise measurements are there?

In addition to measuring noise wayside or at the source, there are measurements that can be conducted *in-vehicle*, using microphones placed inside the passenger compartment.  Data is collected as the vehicle is in motion, but without other potential sources such as the air conditioning or radio.  In-vehicle noise is commonly much lower frequency than noise outside.  Not only does the vehicle attenuate (decrease) the high frequency sound, but it also amplifies it at low frequencies.  Any measurements collected and reported as in-vehicle should be interpreted with caution, as the effect of the vehicle type and condition is significant.

## What kind of pavement properties relate to noise?

Three pavement properties that affect tire-pavement noise (in decreasing order of importance) are texture, porosity, and stiffness.

*Texture* can be thought of as the "bumps and dips" on the pavement surface.  There are long bumps and dips that might give your car a rough ride.  There are also very short bumps and dips that cannot be seen by the naked eye – things that result from the type and amount of sand in the pavement, for example.

Noise heard outside the vehicle is affected most by texture that repeats itself every 10 to 150 mm.  All else being equal, this type of texture should be minimized ("flattened").  Smaller texture – that less than 10 mm in size – may actually prove beneficial, as it provides "escape paths" for air that lessen the effect of some of the mechanisms previously described.  There is also evidence that so-called *negative texture* is a benefit.  Negative texture means that the pavement surface is largely flat on top, but does have occasional dips that can create escape paths.  Being flat on top also means that there are not as many bumps that would otherwise punch into the tire, generating noise.

Texture can be measured using a volumetric technique such as the "*sand patch*" test (ASTM E 965), or using laser-based height sensors such as that on various pavement profilers (ISO 13473).  Specialized laser-based techniques for measuring texture include the Circular Texture Meter and RoboTex (see Figure 21).

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The *porosity* of a material is the ratio of the volume of air to the total volume. Materials used in most pavement surfaces have a porosity less than 5%. However, when the porosity increases to 20% or more and/or when air can flow through the material, the result can be a benefit in noise reduction. Porosity increases *acoustical absorption*, which is the ability of a material to absorb sound, and thus prevent it from reflecting back into the air.

Porous materials also have less contact area between the tire and the pavement, and thus provide additional escape paths for air that can reduce noise. This effect may also be possible when *inclusions* are used in the pavement surface layer. Inclusions can be materials such as rubber, polymers, or fibers that partially replace air voids.
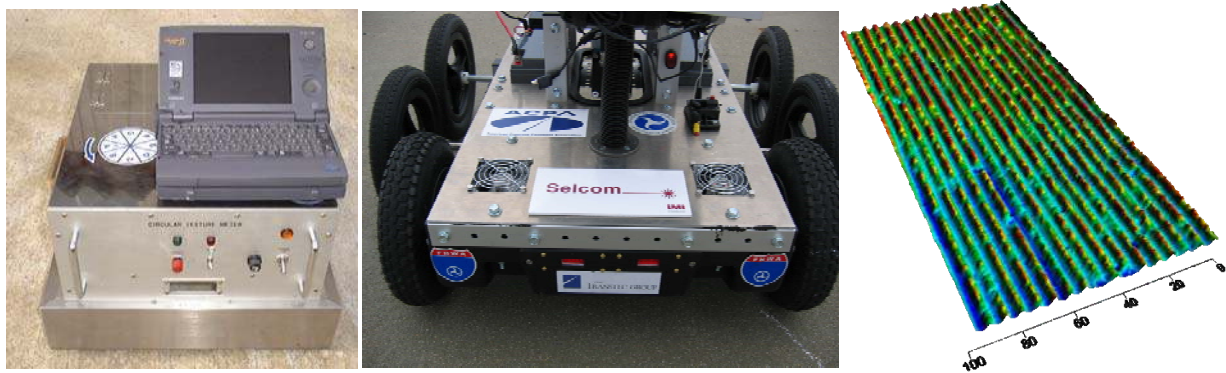


Figure 21. CTM and RoboTex test equipment (source: CP Tech Center).

Porosity can be calculated from a simple evaluation of the weight and volume of a pavement specimen and its components. Acoustic absorption can also be evaluated directly using a number of techniques; both in the laboratory and in-place (see Figure 22). The most well known uses a core sample inserted into an *impedance tube* (ASTM C 384/E 1050). Another technique that has been used with both lab samples and in-place involves *impulse response measurements* using the *extended surface method* (ISO 13472-1). A third technique uses *effective flow resistivity* (ANSI S1.18). This is believed to be a more relevant measure of absorption since it is measured at a shallow angle rather than perpendicular to the pavement surface.



Figure 22. Acoustical absorption test equipment (source: NCAT, Zircon, Caltrans).

The *stiffness* of the pavement surface also contributes to tire-pavement noise, but to a lesser degree. To minimize the influence of many of the mechanisms previously described, a pavement stiffness that approaches that of the tire is ideal. In fact, significant noise reductions have been noted on experimental pavements containing epoxy-bound shredded rubber termed *poroelastic*. These pavements are similar to the surface of a running track on many sports arenas. It will absorb impacts from tires much in the same way that the sports tracks absorb impacts from running shoes. While not as extreme, inclusions of rubber and other materials are sometimes used in pavement surfaces. Depending on what material is used and to what extent, the stiffness of the pavement surface can be affected.

Stiffness is not a simple parameter to measure as it is often significantly affected by temperature, and the type, rate, and amount of force that is applied to the material being tested. Most techniques used to date (that are relevant to noise) involve small impact loads such as those used by the *impact echo* technique (ASTM C 1383).

## Can noise be measured in the laboratory?

If quieter pavements become a goal, it is imperative that fast, accurate, and relevant test procedures be developed for measuring tire-pavement noise in the laboratory. One technique that is in use today is the *laboratory drum*. While several drums are in use around the world, the only known device of its kind in the US is operated at the Institute for Safe, Quiet, and Durable Highways at Purdue University. Shown in Figure 23, the *Tire-Pavement Test Apparatus (TPTA)* consists of a rotating arm with a tire assembly which is in contact with individual test panels that allow real pavement materials to be tested for tire-pavement noise at up to 30 mph. Microphones and probes can be positioned to collect CPX or OBSI style measurements. While large in size and used primarily for screening potential quieter pavement types in a research environment, the TPTA serves as a model for potential lab tests of the future to measure tire-pavement noise more directly prior to full-scale implementation.



Figure 23. TPTA test equipment and sample surface (source: Purdue SQDH).

# Quieter Pavements

## What things make a quieter pavement?

A quieter pavement can be designed and built in virtually any location subject to any environment and any amount and type of traffic. Furthermore, quieter pavements of both asphalt and concrete can achieve the same level of cost effectiveness, durability, and safety expected of our highways today.

While much is still to be learned about quieter pavements, there is guidance that can be provided today to help us achieve this goal. To begin, we should recognize that quieter pavements are generally quieter for three reasons, in decreasing order of importance:

1 **Texture** – Goal: Keep it Small and Negative – Texture that will stab and poke at a tire will lead to undesired noise. As such, an objective common to all quieter pavements is to reduce the dimensions of any texture that is 10 mm or larger ("peak to peak"). However, some texture must remain to allow for "escape paths" for air. This remaining texture should be small (less than 5 mm) and negative (see Figure 24).
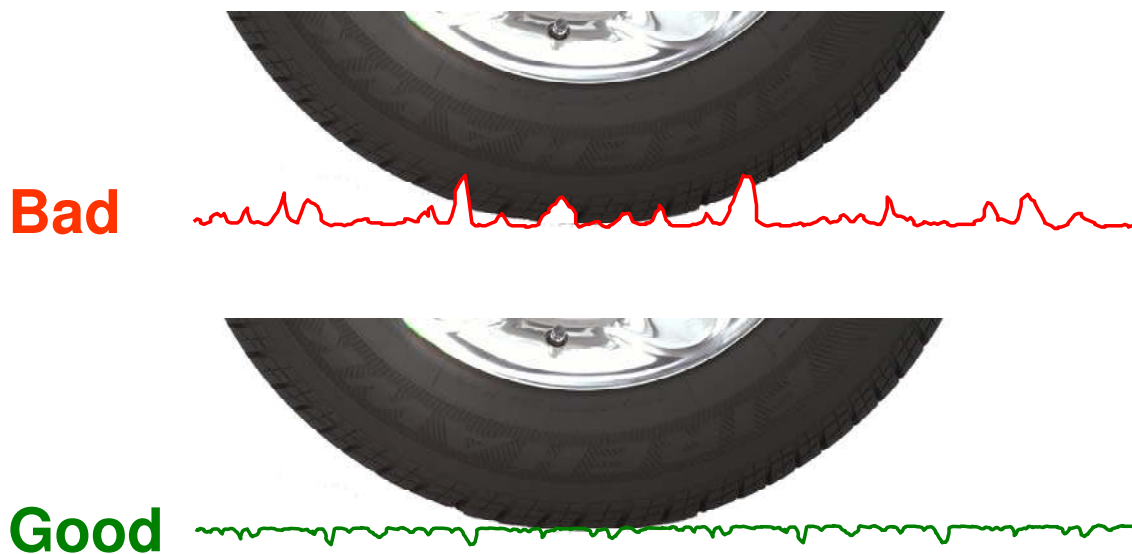


Figure 24. Conceptual schematics of "bad" and "good" texture.

2 **Porosity** – Goal: Make it High – Porosity can help absorb noise and reduce contact area, especially when in excess of 20%. However, since additional air voids can affect durability of any paving material, this tradeoff must be balanced. Inclusions (e.g., rubber, polymers, and fibers) in lieu of air voids continue to be looked at as a viable alternative.

3 **Stiffness** – Goal: Keep it Low – While the most difficult to control for practical purposes, it is known that pavements that have stiffness characteristics approaching that of a tire can be quieter than those that are more typical of asphalt and concrete in

use today.  The target of a very low stiffness will be the most difficult one to meet, as durability of such soft pavements will likely be highly compromised.

When optimizing a pavement material and/or surface for noise, however, one should recognize that focusing on controlling just one noise mechanism may lead to disappointing results.  Quite often, there is more than one mechanism that contributes significantly to the overall sound level.  As a result, reducing just one will lead to an overall reduction in noise that is less than expected.  For example, one might think that a very smooth pavement would be the quietest.  However, this is not the case, due in part to the air pumping, stick-slip, and possibly stick-snap mechanisms that will remain as significant noise generating mechanisms.

## What asphalt alternatives for quieter pavement are there?

Under sponsorship of the FHWA, the National Center for Asphalt Technology (NCAT), located at Auburn University, has been evaluating a number of US and European materials and techniques for quiet asphalt pavements.  Utilizing a 2-mile test track, dozens of asphalt mixtures have been placed and evaluated at various stages of accelerated truck loading.

Quiet asphalt pavements can be constructed of virtually any nominal mix type: dense-graded, gap-graded (SMA), and open-graded (porous).  Mixtures containing rubber or other polymer modifiers have also been demonstrated to be quiet.

In following the principles of quieter pavements described previously, one of the common elements to a quiet asphalt pavement is small texture.  This can be engineered using a small maximum aggregate size ("top size").  Pavements in Europe that are among the quietest include double-layer porous asphalt, where the surface course consists of a top size of 6 to 8 mm.  This compares to mixtures in the US that typically range from 9.5 to 12.5 mm.  To achieve a smaller top size while maintaining reasonable durability demands, both porous asphalt and gap-graded stone-matrix asphalt (SMA) mixtures are commonly used.

Figure 25 illustrates *porous asphalt* pavements, where the size and combination of aggregates is selected to result in a high porosity (15 to 25%).  The aggregates are open-graded, and sometimes almost uniformly graded, giving the pavement surface the appearance of a "puffed rice cereal square".  Because the mixture contains so many voids, "drain down" of the binder during placement can be a concern.  Polymers and/or fibers are therefore used in the mixture to minimize this.  Furthermore, while the additional porosity is beneficial in producing a quieter pavement, it is also the source of potential durability issues due to freeze-thaw effects, rapid oxidation, raveling, and/or fatigue cracking.

*Stone matrix asphalt (SMA)* is a *gap-graded* mixture that "leaves out" intermediate sized material (see Figure 26).  The mixture therefore consists of the larger aggregates and mastic (a blend of the binder and the smallest aggregate fraction).  During construction, the larger stones are aligned so that they are in contact with one another, forming a "skeleton".  By doing so, SMA mixtures can be constructed with smaller aggregates without significantly affecting durability.

*Dense-graded asphalt* mixtures (Figure 27) can also be built quiet, but more work is needed to identify specific mixtures and/or construction techniques that result in consistently quieter

pavements. The work at NCAT on these and other mixtures will result in more guidance in the near future.
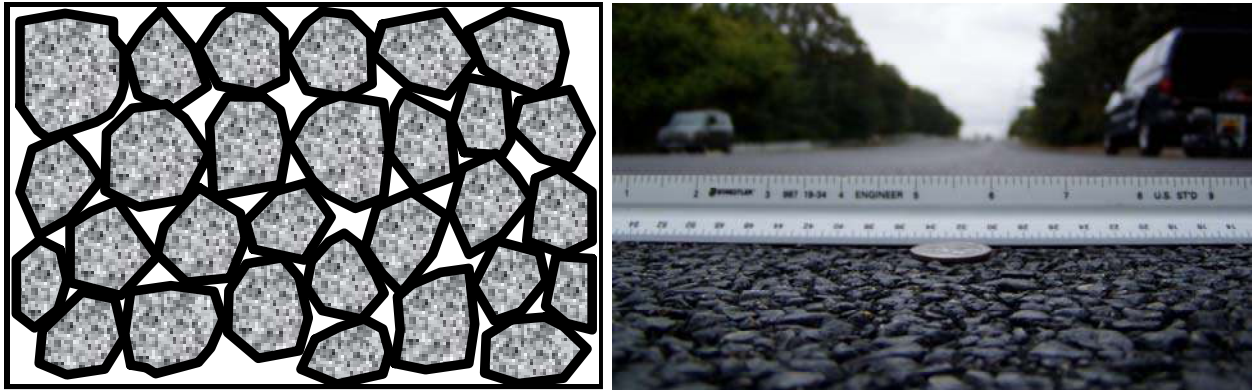


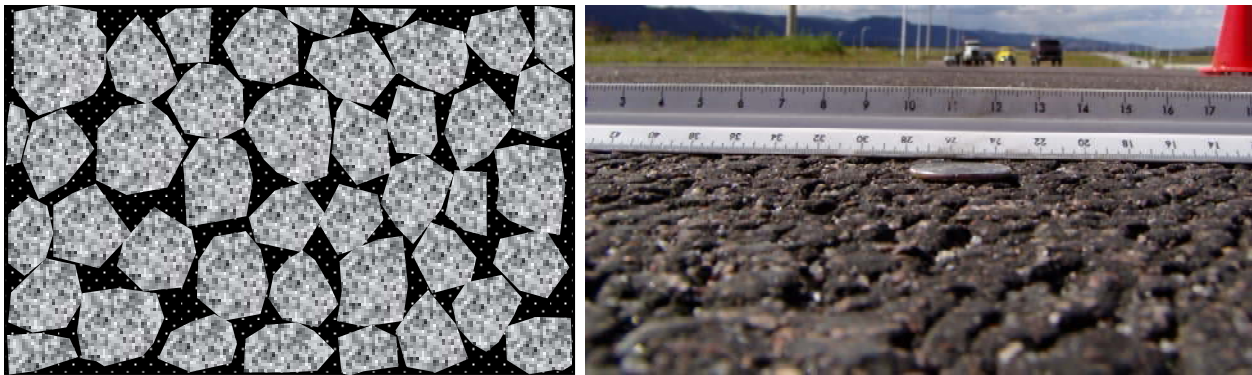Figure 25. Porous asphalt schematic and photo.



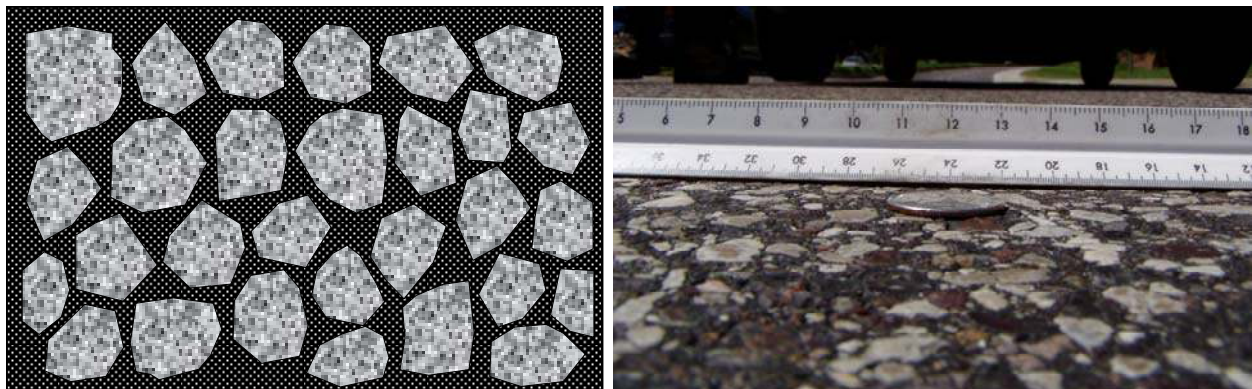Figure 26. Gap-graded SMA schematic and photo.



Figure 27. Dense-graded asphalt schematic and photo.

The asphalt rubber friction course (ARFC) used in Arizona has received a lot of attention due to the large overlay initiative in the Phoenix metropolitan area. It is an open-graded material, but contains additional binder due to the addition of the rubber. Helping make ARFC a quieter

surface is the smaller aggregate (9.5 mm), along with a possible change in stiffness that makes it a closer match to the tire.

## What concrete alternatives for quieter pavement are there?

The National Concrete Pavement Technology Center (CP Tech Center), located at Iowa State University, currently has a joint research effort underway in cooperation with the FHWA, American Concrete Pavement Association (ACPA), and a consortium of State Highway Agencies. The primary objective of the Concrete Pavement Surface Characteristics Program is to identify the quieter concrete pavement options that do not compromise safety. As part of this effort, over one thousand pavement test sections throughout the US and Canada have been tested for noise, texture, friction, and smoothness. The resulting database has allowed for the characteristics of quieter vs. louder concrete pavements to be identified. The project is now seeking to connect tire-pavement noise characteristics back to specific design and construction elements.

Among the concrete pavement textures in use today, both *drag* surfaces (burlap and artificial turf) and *diamond ground* surfaces are among the quietest. These can be seen in Figure 28. If an appropriate concrete mix design is used (containing hard, durable aggregates), both of these textures can be used to produce a quiet, safe concrete pavement.



Figure 28. Drag and diamond ground concrete pavements (source: CP Tech Center).

*Longitudinal tining* (Figure 29, left) can also be used to produce quieter pavements. However, some longitudinal tining has also been found to be loud. To ensure a quieter surface, a higher degree of quality control is required, especially when texturing. There must also be a compatibility between the mix, speed of placement/texturing, and the texturing technique, which must be identified in advance. While specifics of this process are under development as part of the ongoing study at the CP Tech Center, simple guidance includes techniques to minimize periodic deposits of concrete displaced by the tining process. Minimizing vibrations of the paver and texture cart may also help.

*Transverse tining* (Figure 29, right) is responsible for many objectionable concrete pavements. Not only are they among the loudest, but when tined with a uniform spacing, they can contain a

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"whine" that increases the annoyance even further. Quieter transverse tined pavements are possible, but are often found to have a short spacing between the tines – nominally 12 mm or less. Furthermore, randomizing this short spacing can minimize the potential for "whine". Even with this nominal spacing, however, the potential remains for constructing an objectionable pavement in terms of noise. Both material compatibility and quality control issues must be addressed to help overcome this.
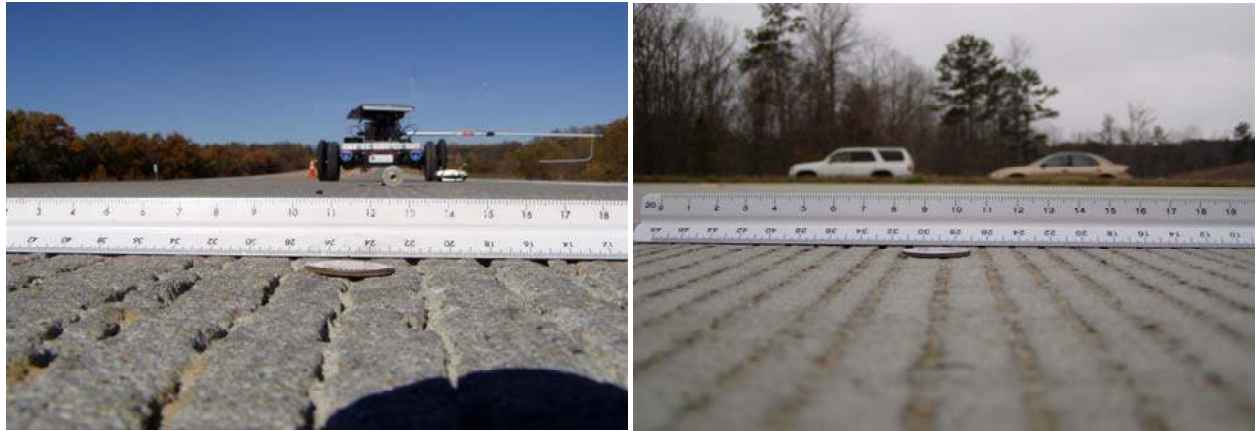


Figure 29. Longitudinal and transverse tined concrete pavements (source: CP Tech Center).

In Europe, a technique for concrete pavement surfacing termed *exposed aggregate* (Figure 30, left) is sometimes touted as a quiet concrete pavement. Measurements on similar surfaces placed in North America have not been favorable. Furthermore, noise measurements found in the literature show these pavements to be at a similar level to those constructed with more conventional concrete pavement textures that are typical in the US.



Figure 30. Exposed aggregate and porous concrete.

Finally, *porous concrete* pavements (Figure 30, right) have been built in trial sections. While many have measured quieter than any dense concrete, their durability remains an unresolved issue.

## How do I choose a quieter pavement?

Before any quieter pavement is selected, it is in the best interest of all stakeholders to evaluate a number of other criteria. These include the durability of the pavement; not only in resisting the effects of both traffic loads and climate, but also the ability of the pavement to remain quiet over time (*acoustical durability*). The cost of the pavement – both initially and over the life cycle – should also be evaluated and considered. Finally, safety must never be compromised. Any quieter pavement that is constructed should face the same scrutiny as any pavement for its ability to provide a safe stopping distance as well as other issues including vehicle handling and splash and spray.

Tools for decision-making based on such different criteria are readily available. Some are based on the conversion of many of these factors to equivalent dollars, with further consideration to the time phasing of these costs by way of *life-cycle costs*. Other tools include *multi-criteria analysis* methods, which have historically been used in other industries where complex decisions must be made.

# For More Information

## Where can I read to learn more?

- *Tyre/Road Noise Reference Book* by Ulf Sandberg and Jerzy Ejsmont
  - www.informex.info
- Traffic Noise Model Technical Manual (FHWA-PD-96-010)
- *An Introduction to Tire/Pavement Noise* by Robert Bernhard, et al. (SQDH 2005-1)
- Advanced References
  - *Fundamentals of Acoustics* by Lawrence E. Kinsler
  - *Signal, Sound, and Sensation* by William M. Hartmann
  - *Noise and Vibration Control Engineering* by Leo Beranek and István Vér

## What are some good web sites?

- Federal Highway Administration
  - Noise -
    - www.fhwa.dot.gov/environment/noise
  - Pavements -
    - www.fhwa.dot.gov/pavement
  - International Technology Scan on Quiet Pavement Systems in Europe -
    - international.fhwa.dot.gov/quiet_pav
- State Department of Transportation
  - Arizona -
    - www.quietroads.com
  - California
    - www.dot.ca.gov/hq/env/noise
  - Washington -
    - www.wsdot.wa.gov/Projects/QuieterPavement
- Transportation Research Board Committees
  - Noise and Vibration (ADC40) -
    - www.adc40.org
  - Surface Properties – Vehicle Interaction (AFD90) -
    - www.trb.org/directory/comm_detail.asp?c=AFD90
- Paving Industry Research
  - Asphalt (NCAT) -
    - www.ncat.us
  - Concrete (National CP Tech Center) -
    - www.cptechcenter.org
- Institutes of Noise Control Engineering
  - International -
    - www.i-ince.org
  - USA -
    - www.inceusa.org
- European Union Noise Policy -
  - ec.europa.eu/environment/noise
- Institute for Safe, Quiet, and Durable Highways (SQDH) -
  - tools.ecn.purdue.edu/~sqdh
- Center for Pavement Surface Characteristics -
  - www.tcpsc.com

# Who are we?

### Robert Otto Rasmussen, Ph.D., P.E. (TX)

Robert Otto Rasmussen is an internationally recognized expert in pavement engineering and construction, including the analysis and modeling of pavement smoothness, texture, and noise. He holds a B.S. in Civil Engineering from the University of Arizona, and a M.S.E. and Ph.D. from the University of Texas at Austin. He currently serves as Vice President and Chief Engineer of The Transtec Group, Inc., a pavement and materials engineering firm headquartered in Austin, Texas and is a registered professional engineer in the State of Texas. Dr. Rasmussen has authored dozens of peer-reviewed papers, and is an active member on numerous editorial boards, expert task groups, and industry groups including TRB, AAPT, ASCE, ACPA, RILEM, INCE, and ASA.

### Robert J. Bernhard, Ph.D., P.E. (IN)

Robert J. Bernhard received a B.S. in Mechanical Engineering from Iowa State University in 1973, an M.S. in Mechanical Engineering from the University of Maryland at College Park in 1976, and his Ph.D. in Engineering Mechanics from Iowa State University in 1982. He joined Purdue University in 1982. He was the Director of the Ray W. Herrick Laboratories from 1994 through 2004, and has been the Director of the Institute for Safe, Quiet, and Durable Highways since 1998. He became the Associate Vice President for Research at Purdue University in December 2004. In 2007, Dr. Bernhard became Vice President for Research of Notre Dame University.

### Ulf Sandberg, Sc.D.

Ulf Sandberg is a Senior Research Scientist at the Swedish National Road and Transport Research Institute in Linköping. He is also an Adjunct Professor at Chalmers University of Technology in Göteborg. He is known worldwide as one of the leading experts in tire-pavement noise, and is maybe most well known in the US as a co-author of the "Tyre/Road Noise Reference Book". Dr. Sandberg's accomplishments in this field are vast, and include service as chairperson and member on numerous ISO, TRB, and CEN committees related to highway noise.

### Eric P. Mun

Eric P. Mun received his B.S. in Mechanical Engineering from The University of Texas at Austin in 2002. He joined The Transtec Group, Inc. in 2005 and is currently a Project Manager specializing in pavement surface characteristics. He has extensive experience in designing and building equipment systems for evaluating pavement surface characteristics and has collected and analyzed pavement noise, texture, and friction data on hundreds of pavement surfaces throughout North America.

### Nicholas P. Miller, M.S.M.E. (Developer of accompanying Listening Experience)

Nicholas P. Miller is Senior Vice President of Harris Miller Miller & Hanson Inc. He started his work in environmental acoustics in 1970 at the University of North Dakota. In 1973, he began working at Bolt Beranek and Newman in highway noise and regulatory acoustics. He then helped to found Harris Miller Miller & Hanson in 1981. His recent innovations include revisions to sleep disturbance analysis and development of Virtual Soundscapes™ - a technique that permits listeners to hear how a place will sound.

# What can I find in the listening experience?

🔊 Introduction

🔊 Is it Sound or Noise?

🔊 Decibels

🔊 Frequencies

🔊 Complex Sounds

🔊 The Perception of Sound

🔊 Introduction to Traffic Noise

🔊 Controlling Traffic Noise

🔊 Controlled Pass-By Testing

🔊 Comparing Noise Measurement Types

🔊 Comparing Pavements at Wayside

🔊 Comparing Pavements at the Source

🔊 Pavement Variability

🔊 Who are We?