PAVEMENT MACROTEXTURE MONITORING THROUGH SOUND GENERATED BY THE TIRE-PAVEMENT INTERACTION

A Thesis Presented

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ABSTRACT

Safe roads require pavement surfaces that provide adequate friction to tires, helping to bring vehicles to a complete stop in a timely manner that avoids accidents. The current manual methods of evaluating surface friction of roads and bridges are not only dangerous for the inspectors and motorists on the road but they are also very time-consuming and subject to inspector’s judgment. This thesis confirms the possibility of monitoring friction of pavement through pavement macrotexture from acoustic measurements underneath the body of a moving vehicle. Currently, macrotexture is quantified by a Mean Texture Depth (MTD) index. In the present work, MTD is estimated from the sound generated by the tire-pavement interaction in a moving vehicle. To establish this approach, experiments were performed at the National Center for Asphalt Technology in Auburn, Alabama. Signal processing techniques were used to identify a frequency band that led to an accurate correlation between integrated acoustic pressure and MTD. This frequency band depends on the speed of the vehicle and the pavement macrotexture. The effect of microphone locations and the speed of the vehicle on macrotexture monitoring are studied and conclusions are presented. It is observed that raising the microphones by 13 inches decreased correlation by approximately 13%. Microphones that are close and pointing towards contact patch of rear tire have highest correlation to MTD. Also, it is concluded that correlation increases with vehicle speed. Accurate estimates of MTD were obtained for road surfaces having MTD values in the range of 0.5 – 2.5 mm with vehicle speeds in the range of 32 – 80 km/h (20 – 50 mph).
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1. **INTRODUCTION**

1.1. **Importance of Thesis**

The transportation infrastructure in the United States is extremely large and the task of maintaining this infrastructure is formidable. It is no surprise that the state and federal Departments of Transportation (DOTs) are having a difficult time maintaining roads and bridges. According to the American Society of Civil Engineers (ASCE) Infrastructure Report Card in 2009 U.S. bridges received a grade of “C” and the roads received a grade of “D-“ (ASCE, 2009).

One of the main duties of a highway engineer working for state and federal transportation agencies is to construct roads and bridges in order to facilitate the movement of people, and to maintain these roads and bridges so that people continue to move from one point to another in a safe, fast, and easy manner. A 1985 US study showed that about 34% of serious car crashes had contributing factors related to the roadway or its environment (Lum, et al., 1995). In the U.K., research has shown that investment in a safe road infrastructure program could yield a ⅓ reduction in road deaths, saving as much as £6 billion per year (Hill, 2008). Majority of these car accidents happen due to the lack of friction on the pavement surface. The current methods for monitoring pavement friction through pavement surface texture are expensive, subject to human judgment, and dangerous. A change to our maintenance procedure is needed to keep our infrastructure in a satisfying condition with the financial limits set by our government. Therefore, an automated, inexpensive, and real-time method of monitoring pavement macrotexture through the tire-pavement generated sound is proposed.

Many methods have been devised to monitor macrotexture, which is responsible for the wet pavement friction. Methods like the Circular Texture Meter (ASTM E2157-09, 2009) and the
Sand Patch Method (ASTM E965) are time consuming and require closing down of road lanes, which causes traffic delays and dangerous environment for motorists and inspectors. On the other hand, profilometers perform real-time inspection of road surface but require a minimum of two person crew. Also, profilometers are really expensive. Most of the current macrotexture measuring techniques are compared to the Sand Patch Method which provides a Mean Texture Depth (MTD) value.

Many studies have been performed on the effect that pavement macrotexture has on the sound generated by the tire-pavement interaction. Most of the previous publications studied this research topic in order to see if varying the pavement surface parameters could diminish the noise that is created by the tire-pavement interaction without sacrificing safety. However, instead of trying to get rid of the sound, it is proposed here to use this sound to monitor pavement macrotexture. Perhaps the earliest study that studied the use of sound generated by the tire-pavement interaction in a moving vehicle to monitor skid resistance or macrotexture was “Use of tire noise as a measure of pavement macrotexture” by R. E. Veres et al. in 1975 (Veres, et al., 1975). He confirmed that macrotexture could in fact be measured by the sound generated in tire-pavement interaction if some improvements on the equipment and data processing are made. Afterwards, many have tried to use sound generated by the tire-pavement interaction to monitor MTD and found strong correlation when similar pavement types were studied but poor correlation otherwise.

This thesis confirms the possibility of monitoring pavement macrotexture through the sound generated by the tire-pavement interaction in a moving vehicle by comparing the acoustical signal to MTD value of pavement surface. In addition to that, this thesis discusses which frequency ranges in the spectral density contain observable information about pavement
macrotexture, and the effect of speed and microphone location on monitoring macrotexture. A key issue is the signal-to-noise ratio because noise sources such as wind and vehicle vibration may overwhelm the sound generated at the tire-road interface in certain frequency ranges. Also, equations are proposed for practical monitoring of macrotexture.

1.2. Introduction to VOTERS Concept

This research was part of the Versatile Onboard Traffic Embedded Roaming Sensors (VOTERS) project. An introduction to the project is given to facilitate reader’s understanding of the work in this thesis.

The objective of this project is to develop a novel system based on different instrumental packages that can be installed on a wide variety of private and public vehicles to assess the conditions of bridges and roadways through several different and complimenting methods at regular driving speeds during the course of ordinary use of the vehicles. In other words, to revolutionize the way the departments of transportation evaluate and maintain the condition of their roads and bridges.

VOTERS team aims to provide a continuous stream of accurate, up-to-date information about the state of roadways and bridge decks gathered by sensor systems mounted on vehicles of opportunity, while also eliminating the hazardous, congestion-prone work zones that are often set up to gather this critical data. The VOTERS project is subdivided into Gigahertz Electro-Magnetic Array Roaming Sensors (GEARs), Surface Looking Millimeter-Wave Radar (SLiMER), Surface Optical Profilometry Roadway Analysis (SOPRA), and Tire Excited Acoustic Sensors (TEASe) teams (Saykin, et al., 2011).
Figure 1.2.1: Organizational outline of VOTERS Project

Figure 1.2.2: Proposed microphone arrangement for the TEASe system
1.3. Mathematical Prerequisites

1.3.1. General Mathematical Description

The mathematical equations used for this thesis are mainly of statistical form. In this section mathematical concepts such as air pressure reference value used, Fourier Series, and Regression Analysis are discussed.

When a vehicle drives, the tire-pavement interaction creates acoustical signal. This signal could be described as follows

$$P_{total} = P_{ground} + P_{noise}$$  \hspace{1cm} (1.3-1)

Where
- $P_{total}$ = the total signal received by our microphones
- $P_{ground}$ = the signal that is coming from tire-pavement interaction (correlates to MTD)
- $P_{noise}$ = the signal coming from other sources creating noise (does not correlate to MTD)

For this thesis Matlab, Excel, and STATA software were used to perform many of the mathematical and signal processing aspects. The microphones measured the signal in volts. This had to be converted to Pascal units through calibration experiments. The signal was then converted to dB units using the following equation

$$P_{dB} = 10 \cdot \log_{10} \left( \frac{P_{Pa}}{P_{ref}} \right)^2$$  \hspace{1cm} (1.3-2)

Where
- $P_{ref} = 2 \cdot 10^{-6}$ is the internationally standardized reference sound pressure
- $P_{Pa}$ = pressure in units of Pascal
- $P_{dB}$ = pressure in units of decibels (dB)
The reasons for using the dB units instead of Pascal units are that it is easier to distinguish different signal loudness and they are a standard units used in this field. All of the plots presented in this thesis have pressure converted to the decibel units by the above equation. The Welch Method was then used to take the Fourier Transform of the signal. The reason for choosing the Welch Method was because of its noise reduction \( p_{\text{noise}} \) capability (Welch, 1967).

In order to find a correlation to MTD one needs to know what one will use to correlate to MTD. In other words, one has to find an acoustical variable that has sufficiently strong relationship to the spatial property, MTD. One of the variables that was used to correlate to MTD was what the author calls Energy. This Energy was achieved for each pavement section by picking a frequency range and using the trapezoidal integration function, in Matlab, to perform the integration and get the area under the curve in the power spectrum. The magnitude of the spectrum was in the units of dB. This turned out to be one of the most fruitful methods. It is represented mathematically as follows

\[
\text{Energy} = \int_{f_1}^{f_2} p_{\text{total}} df
\]

(1.3-3)

Where \( \text{Energy} \) = integrated SPL

\( f_1 \) and \( f_2 \) = the minimum and maximum of the frequency range which is to be integrated. It is needful to determine these minimum and maximum values to maximize the correlation between energy and MTD.

Another approach was to use the Fourier Series representation of the signal from each pavement section. From the Fourier Series all of the coefficients were elicited and used in correlation. As with the energy method, the most fruitful Fourier Series coefficient was the \( a_0 \). The form of the Fourier Series that was used is as follows
Where \( n \) = number of coefficients desired (order)
\( x \) = the specific frequency in the frequency range chosen in Hz
\( L \) = the length of the frequency range chosen in Hz

Hence, with the Energy method and the Fourier constant \( a_0 \) method we have a mean representation of the acoustical signal that our microphones are receiving and comparing this to a spatial mean value, MTD; therefore, these two approaches give the best repeatable results.

### 1.3.2. Linear Regression

Looking at the plot of Energy versus MTD (Figure 1.3.1), it was decided to try linear regression analysis to describe the relationship between these two variables. The linear regression model has the following equation

\[
Y = \beta_0 + \beta_1 x + \epsilon
\]

(1.3-5)

Where
- \( Y \) = dependent variable, energy
- \( x \) = independent variable, MTD
- \( \epsilon \) = random deviation, assumed to be normally distributed with \( \text{E}(\epsilon) = 0 \) and \( \text{V}(\epsilon) = \sigma^2 \)
- \( \beta_0 \) = the “y” intercept
- \( \beta_1 \) = the slope, expected change of \( Y \) associated with a 1-unit increase in the value of \( x \)

The linear regression model is developed through the method of least squares or minimization of residuals. In theory, a model that has the summation of residuals equaling zero is the best fit model.
Figure 1.3.1: The linear relationship between MTD and Energy

It is very important to determine how much variation is explained by the proposed model. To determine this, the error sum of squares (SSE) and total error sum of squares (SST) have to be calculated. The SSE and SST are defined by the following formulas

\[
SSE = \sum_{n=1}^{\infty} (y_n - \hat{y}_n)^2 \tag{1.3-6}
\]

\[
SST = \sum_{n=1}^{\infty} (y_n - \bar{y}_n)^2 \tag{1.3-7}
\]

Where \( y = \) observed value of the independent variable
\( \hat{y} = \) estimated value of the independent variable by the linear regression model
\( \bar{y} = \) the mean value of the independent variable

Using the above definitions, the coefficient of determination, denoted by \( r^2 \), which is interpreted as the proportion of the observed variation of the independent variable that can be explained by the proposed linear regression model, is determined as follows
The higher the value of $r^2$, the more successful is the simple linear regression model in explaining variation of independent variable.

A hypothesis-testing procedure is also used in this thesis. Under the null hypothesis ($H_0$), $\beta_1$ has a null value of zero. A zero slope signifies that there is absolutely no linear relationship between the two variables. The test statistics results from having $\beta_1 = 0$ in the standardized variable $T$ equation; hence, standardizing the estimator of $\beta_1$ under the assumption that $H_0$ is true. The test statistic thus has a $t$ distribution with $n – 2$ degrees of freedom when $H_0$ is true, so the type I error probability is controlled at the desired level $\alpha$ by using an appropriate $t$ critical value. For this case, the model utility test has the test statistic value as $t$ ratio given by

$$t = \frac{\hat{\beta}_1}{\sigma_{\hat{\beta}_1}}$$

(1.3-9)

To measure how the two variables under study relate to each other, a correlation coefficient is determined, $\rho$ or $R$, where $\rho$ is the population correlation coefficient and $R$ is the estimator of $\rho$. Correlation indicates a predicative relationship, or suggests possible causal or mechanical relationship. The correlation that is used in this thesis and in this particular field of research is called Parson’s Correlation or Parson’s product-moment coefficient and is represented by

$$R(x, y) = \rho(x, y) = \frac{\text{cov}(x, y)}{\sigma_x \cdot \sigma_y} = \frac{E \left[ (x - \mu_x) \cdot (y - \mu_y) \right]}{\sigma_x \cdot \sigma_y}$$

(1.3-10)

Where $\mu = \text{expected value – weighted average of all possible values that the variable can take on}$

$E = \text{expected value operator}$
x and y = random variables  
$\sigma$ = standard deviation – how much variation or dispersion there is from the average  
$\text{cov}$ = covariance – it is the measure of a linear dependence of two random variables

In particular to this research a correlation coefficient could take values from -1 to 1. A valued of 1 or -1 means a perfect positive and negative correlation and the value of 0 means no linear correlation. Positive correlation would mean that as variable $x$ is increased variable $y$ is also increased. A negative correlation would mean that as variable $x$ is increased variable $y$ is decreased.

Correlation could be looked at as the normalization of the covariance, values going from 0 to 1. The correlation coefficient does not depend on which variable is labeled as dependent and which one as independent. Since correlation is a normalization of the covariance it does not depend on the units used. Thus, correlation measures the normalized linear relationship between the two variables under consideration.

Usually, correlation above 0.8 is considered strong and correlation below 0.5 is considered weak. Therefore, to test the significance of the correlation a different approach than for the slope is used. This approach takes into account that $\rho_0 = 0.5$ and not 0. This test statistic is based on the Fisher transformation and has the following equation

$$Z = \frac{V - \ln[(1 + \rho_0)/(1 - \rho_0)]}{1/\sqrt{n - 3}}$$

(1.3-11)

Where

$$V = \frac{1}{2} \ln \left( \frac{1 + R}{1 - R} \right)$$

(1.3-12)

is a random variable with mean and variance as
\[
\mu_v = \frac{1}{2} \ln \left( \frac{1 + \rho}{1 - \rho} \right)
\]  
(1.3-13)

\[
\sigma_v^2 = \frac{1}{n-3}
\]  
(1.3-14)

A P-value is calculated as in the usual z tests. This test will provide the significance value for concluding that the two variables are linearly related. For example, correlation could be significant for the sample but might be insignificant with certain confidence for the population when number of bivariate data, n, is small.

One of the goals of this thesis is to build a probabilistic model that relates MTD to speed, microphone height, and energy levels which should support hypothesis that macrotexture could be monitored by sound generated by the tire-pavement interaction. This should follow the basic multiple regression analysis formula

\[
MTD = \beta_0 + \beta_1 x_1 + \beta_2 x_2
\]  
(1.3-15)

Where \(x_1 = \text{speed of the vehicle}\)
\[x_2 = \text{energy level from a microphone}\]
2. **BASICS OF PAVEMENT STRUCTURE**

2.1. **Basics of Pavement Structure**

2.1.1. **History of Road Construction**

“First, a few snapped twigs and bruised blades of grass. Soon, a path, a trail. Then, in surprisingly little time, the way becomes a road. Roads are truly exceptional among human works, in both their mutability and their longevity. So many artifacts of ancient times survive only though the deliberate efforts of archaeologists and museums, but thousands, even millions, of people today continue to use roads built many centuries ago. Sometimes, as with Roman roads, even the original surface survives.” (James E Vance Jr.)

In this chapter an overview of road construction is presented with attention on road construction used for the experiments. Before describing current pavement designs and construction it seems reasonable to review some history and some pavement basics. Pavement could be described as a hard surface covering a ground to facilitate movement of vehicles, pedestrians, and sometimes equestrians. As far as we know limestone pavers could have been used as far as the Bronze Age in Britain, which might be the earliest known evidence of a pavement construction. Yet, most of the roads where a surface of compacted soil and sometimes reinforced with stoned or gravel. Yet it was the Romans that made an art out of road construction and left legends for us to admire. The Romans understood that the surface of the road has to facilitate travel and not prevent it; hence, they made their highways with flat stone. This was a great improvement from the current rough stone road construction. Where traffic did not have to travel as fast, the Romans used cobblestones, uncut and often water worn stones. Cobblestones were mainly used in cities. They were usually placed on a bed of sand and then wedged shoulder to shoulder into place; the
longest side usually placed vertically to improve stability. After the Roman Empire, slowly but surely people began to use more and more of carriages. Wheeled urban traffic would favor the use of flat-faced stone blocks, known as setts. In Paris, setts about 125x125x150 mm were introduced in 1415 and by 1720 had increased in size to 230x230x230 mm. Timber blocks were first used for paving in 14\textsuperscript{th} century Russia. Even in the 10\textsuperscript{th} century there are records of timber-plank paving being used in Novgorod, Russia. Wood-block paving improved with creosote against rotting, was used without much competition a century ago. Today, traffic has intensified both in the weight that it carries and the amount of traffic itself. This led to great deterioration of roads, forcing engineers to figure out new ways to monitor and construct pavements.

### 2.1.2. Pavement Construction

To describe pavement construction most of the information has been retrieved from textbook of “Principles of Pavement Design” by Yoder, E. J., Witczak, M. W. with author’s minor changes. Pavements are usually divided in to two broad categories: rigid and flexible pavement (Figure 2.1.1). The difference between these pavements is in their structural behavior, or how they distribute wheel load to the subgrade. A rigid pavement is usually constructed out of Portland Cement Concrete (PCC) and because of high strength of concrete the rigid pavement has the option of having or not having a base course between the pavement and subgrade [15]. Rigid pavement has high modulus of elasticity and high strength; therefore, the rigid pavement tends to distribute the vehicular loading over a wide area of soil. This is the reason that the strength and quality of concrete is the main contribution to structural capacity of the PCC pavement. Minor variations in the subgrade strength have little influence upon the structural capacity of the pavement unless dealing with expansive soils. The flexible pavement, like hot-mixed-asphalt
(HMA) which is extensively used in Massachusetts, consists of relatively thin wearing surface built over a base course and subbase course, and they rest upon the compacted subgrade. In other words, a truly flexible system uses load-distributing characteristics of a layered system to achieve its load-carrying capacity. Flexible pavements consist of a series of layers with the highest-quality materials at or near the surface. Therefore, the strength of a flexible pavement is the result of building up thick layers, through which the pavement structure can distribute the load over the subgrade. The thickness design of the pavement is influenced by the strength of the subgrade.

![Diagram of pavement components](image)

**Figure 2.1.1: Overview of different components of (a) flexible and (b) rigid pavements (Yoder, et al., 1975)**

### 2.2 Pavement Types

To give the reader better understanding about different asphalt mix designs that were used at NCAT, a summary of different pavement construction is presented in this section. The most familiar and widely used type of asphalt pavement is Hot mix asphalt (HMA). HMA is a
generic term that includes many different types of mixtures of aggregate and asphalt cement (binder) produced at elevated temperatures in an asphalt plant. HMA mixtures could be described into three mixture categories: dense-graded; open-graded; and gap-graded as a function of the aggregate gradation used in the mix.

Dense-graded mixes are produced with well or continuously graded aggregate; therefore, gradation curve does not have any abrupt slope change. A dense-graded mix is a well-graded HMA mixture intended for general use. When properly designed and constructed, a dense-graded mix is relatively impermeable. Dense-graded mixes are generally referred to by their nominal maximum aggregate size. They can further be classified as either fine-graded or coarse-graded. Dense-graded pavement use superpave, Hveem, or Marshall Mix procedures. Superpave is the modern mix technique and is summarized below.

2.1.3. Superpave Mix Design

Back in 1987 the Congress of United States of America established a research program called Strategic Highway Research Program (SHRP) with one of its goals being to develop a completely new and better asphalt mix design in order to improve longevity of our asphalt pavements. One of the principal results from the SHRP was the Superpave mix design method. Superpave stands for Superior Performing Asphalt Pavement System. Superpave mix design used previous mix designs like Hveem and Marshall Methods as a basis and solved some of their shortcomings. The Superpave system ties asphalt binder and aggregate selection into the mix design process, and considers traffic and climate as well. The compaction devices from the
Hveem and Marshall procedures have been replaced by a gyratory compactor and the compaction effort in mix design is tied to expected traffic.

The Superpave mix design method consists of 7 basic steps (Muench, 2010):

1. Aggregate selection.
   1. In the Superpave mix design the aggregates are selected in two ways. First, restrictions are placed on aggregate gradation by broad control points. Second, what is called “consensus requirements” is met.
   2. Consensus requirement relates to minimum angularity, flat or elongated particle and clay content requirements based on the anticipated traffic loading and depth below the surface. These requirements are imposed on the final aggregate blend and not the individual aggregate sources.

   1. In Superpave Mix design the binder is selected based on the performance grading (PG) system. This system takes into account the pavement temperature, air temperature, and the geographic area in which the pavement will be constructed. PG asphalt binders are specified in 6 degree Celsius increments.

   1. Similar to the Marshall and Hveem mix designs the Superpave mix design creates several trial aggregate-asphalt binder blends, each with different asphalt binder content. Then, by evaluating each trial blend's performance, optimum asphalt binder content can be selected.

1. The original intent of the Superpave mix design method was to subject the various trial mix designs to a battery of performance tests akin to what the Hveem method does with the stabilometer and cohesiometer, or the Marshall method does with the stability and flow test. Currently, these performance tests, which constitute the mixture analysis portion of Superpave, are still under development and review, and have not yet been implemented. The most likely performance test, called the Simple Performance Test (SPT) is a Confined Dynamic Modulus Test.

5. Density and voids calculations.
   1. All mix design methods use density and voids to determine basic HMA physical characteristics. The densities are then used to calculate the volumetric parameters of the HMA. Two different measures of densities are typically taken:
      1. Bulk specific gravity ($G_{mb}$).
      2. Theoretical maximum specific gravity (TMD, $G_{mm}$).

   1. Moisture susceptibility testing is the only performance testing incorporated in the Superpave mix design procedure as of early 2002. The modified Lottman test is used for this purpose.

2.1.4. Stone Matrix Asphalt

Another pavement type that was used in NCAT was Stone Matrix (Mastic) Asphalt (SMA). SMA is a gap-graded HMA that is designed to maximize deformation resistance, rutting, and durability by using a structural basis of stone-on-stone contact. Therefore, deformation similar to rutting and shoving is almost non-existent in SMA pavements. Even
though SMA is generally more expensive, by about 20 percent, than typical HMA pavements, if constructed properly and in right situations it would prove economical.

Since SMA is gap-graded SMA mixes have high asphalt binder content (on the order of 6 percent); therefore, cellulose or mineral fibers are added to keep the asphalt binder in place. Cellulose fibers are typically shredded newspapers and magazines, while mineral fibers are spun from molten rock. Gap-graded mixes use an aggregate gradation with particles ranging from coarse to fine with some intermediate sizes missing or present in small amounts. A laboratory test is run during mix design to ensure the mix is not subject to excessive draindown, which is a tendency of a binder to drain off the aggregate and down to the bottom. In mix design a test for voids in the coarse aggregate (AASHTO T 19) is used to ensure there is stone-on-stone contact. Also, some of the reported SMA benefits include wet weather friction (due to a coarser surface texture), lower tire noise, less severe reflective cracking, and SMA mixes usually are not permeable.

Figure 2.1.2: Picture of a SMA surface at NCAT W1 section
2.1.5. Open-Graded HMA

Another pavement type that was present at NCAT is the Open-Graded-Friction-Course (OGFC). An open-graded HMA mixture uses only crushed stone (or gravel), a small percentage of manufactured sands, and is designed to be water permeable unlike dense-graded HMA and SMA designs; therefore, this mixture is used as a surface course only. The open-graded mixture reduces tire splash and spray in wet weather and typically results in smoother surfaces than dense-graded HMA. The high air voids trap road noise which could result in tire-road noise reduction by up to 50-percent (10 dBA). Open-graded mixes are produced with relatively uniform-sized aggregate typified by an absence of intermediate-sized particles. The open gradation creates pores in the mix, which are essential to the mix's proper function; therefore, anything that tends to clog these pores, such as low-speed traffic, excessive dirt on the roadway or deicing sand, should be avoided. NCAT Report 99-3 “Design of New-Generation Open Graded Friction Courses” provides a recommended mix design procedure for OGFCs.

Figure 2.1.3: Picture of an OGFC surface at NCAT S4 section
3. **BASICS OF PAVEMENT SURFACE PARAMETERS**

3.1. **Parameters relating to Pavement Surface Texture**

Roadway features that are responsible for sound generation are discussed here. Texture of pavement surface is responsible for sound generation and friction capacity of the pavement; therefore, it is one of the most important features that transportation agencies try to monitor and maintain in pavements. Texture is divided into three parts: microtexture, macrotexture, and megatexture (Figure 3.1.1). Above megatexture the texture is characterized into the unevenness category. The following are the definitions for the different parts of pavement texture according to the International Organization of Standardization:

- **Microtexture** is deviation from the road surface from a true planar surface with the characteristic dimensions along the surface of less than 0.5 mm, corresponding to texture wavelengths with one-third-octave bands with up to 0.5 mm of center wavelengths. (ISO 13473-2, 2002)
  - *Note:* Peak-to-peak amplitudes normally vary in the range of 0.001 mm to 0.5 mm. This type of texture is the texture that makes the surface feel more or less harsh but which is usually too small to be observed by the eye. It is produced by the surface properties (sharpness and harshness) of the individual chippings or other particles of the surface that may be in direct contact with tires. (ISO 13473-2, 2002)

- **Macrotecture** is deviation from the road surface from a true planar surface with the characteristic dimensions along the surface of 0.5 mm to 50 mm, corresponding to texture wavelengths with one-third-octave bands with up to 0.5 mm of center wavelengths.
wavelengths with one-third-octave bands including the range of 0.63 mm to 50 mm of center wavelengths. (ISO 13473-2, 2002)

- Note: Peak-to-peak amplitudes may normally vary in the range of 0.1 mm to 20 mm. This type of texture is the texture that has wavelengths of the same order of size as tire tread elements in the tire-road interface. Surfaces are normally designed with sufficient macrotexture to obtain suitable water drainage in the tire-road interface. The macrotexture is obtained by suitably proportioning the aggregate and mortar of the mix or by surface finishing techniques. (ISO 13473-2, 2002)

- Megatexture is deviation from the road surface from a true planar surface with the characteristic dimensions along the surface of 50 mm to 500 mm, corresponding to texture wavelengths with one-third-octave bands including the range of 63 mm to 500 mm of center wavelengths. (ISO 13473-2, 2002)

- Note: Peak-to-peak amplitudes may normally vary in the range of 0.1 mm to 50 mm. This type of texture is the texture that has wavelengths of the same order of size as the tire-road interface and is often created by potholes or “waviness”. It is usually an unwanted characteristic resulting from defects in the surface. Surface roughness with longer wavelengths than megatexture is referred to as unevenness. (ISO 13473-2, 2002)

Macrotecture of pavement surface is responsible for facilitating the removal of water on a wet pavement when a wheel rolls over it. If macrotecture is worn out hydroplaning could be created. Hydroplaning is when a layer of water on the roadway prevents the tire from forming proper
friction with the pavement surface causing the driver to lose control of his vehicle. Hence, macrotexture is measured to monitor wet skid resistance of a pavement.

Skid resistance is the force developed when a tire that is prevented from rotating slides along the pavement surface. Skid resistance is an important pavement evaluation parameter because: inadequate skid resistance will lead to higher incidences of skid related accidents; most agencies have a duty to provide motorists with a roadway that is safe; and skid resistance measurements can be used to evaluate various types of materials and construction practices. Skid resistance depends on a pavement surface's microtexture and macrotexture and it changes over time. Typically it increases in the first two years following construction as the roadway is worn away by traffic and rough aggregate surfaces become exposed, and then decreases over the remaining pavement life as aggregates become more polished. Skid resistance is also typically higher in the fall and winter and lower in the spring and summer. This seasonal variation is quite significant and can severely skew skid resistance data if not compensated for.

![Figure 3.1.1: Various pavement surface textures (AASHTO, 2008)](image-url)
3.2. Current Methods for Measuring Surface Texture of Pavements

3.2.1. Introduction

Departments of transportation have been measuring the surface texture of pavements for couple of decades; therefore, the technology for direct texture measurement is somewhat in the well-developed stage. The main reason for the DOTs to measure texture of a pavement surface is to evaluate the pavement’s ability in assisting a driver of a vehicle in bringing his vehicle to a stop in a fast enough manner as to prevent accidental collision. This ability of texture is referred to as skid resistance or friction. Also, the texture of a pavement tells an engineer a lot about the condition the pavement. For example, from the pavement texture one could even determine if segregation of aggregate is taking place. Pavement macrotexture or more specifically changes in macrotexture have been used to identify pavement segregation. Segregation refers to separation of the coarse and fine fractions of aggregate in the paving mixture. Coarse areas tend to have lower asphalt content, lower density and higher permeability. These areas tend to fail prematurely. Areas with high levels of segregation are reported to increase the life-cycle cost to the agency by as much as 50 percent. Most of the departments of transportation evaluate the pavement’s overall condition by its mere surface. All of the above are just some of the reasons why pavement texture needs to be evaluated in an inexpensive and real-time manner.

In more recent times measurement of pavement surface texture has become more vital due to traffic noise. This is due to the existence of a probable correlation or relationship between the texture of pavement surface to the noise generation by a tire-pavement interaction. It seems beneficial that a review of different measurement techniques of pavement surface texture be presented in this section. Today majority of the country’s departments of transportation (DOTs) measure the depth of macrotexture or friction directly using the laser-inertial profilometer
methods (ASTM E2157-09, 2009), which is referred to as circular track meter (ASTM E965) which is called volumetric technique or sand patch method. A quick summary of different measuring techniques of the texture of pavement surface is presented below.

### 3.2.2. Profilometers

Profilometer is a measuring instrument used to measure a surface’s profile, in order to quantify its roughness. Profiling devices are quite common for network pavement data collection; however, they are not designed for project level quality control. They measure and record the longitudinal profile in one or both wheel tracks. Inertial profilometers are capable of measuring and recording road surface profiles at speeds between 10 and 70 miles per hour. The profilometer measures and computes the longitudinal profile of the pavement through the creation of an inertial reference by using accelerometers placed on the body of the measuring vehicle. Relative displacement between the accelerometers and the pavement surface is measured with a non-contact light or acoustic measuring system mounted with the accelerometer on the vehicle body (Budras, 2001). Usually two person crew is required to operate the van and profilometer equipment which is mounted in the van. To measure the distance traveled a distance encoder is typically used. The data processing is performed real time as the vehicle is driving. This makes this system very useful. Pavement profile data points, taken every inch (centimeter), are averaged over a running 12-inch interval and stored as profile points for every 1, 2, or 6 inches (25, 50, 150 millimeters) of travel (Budras, 2001). Also, profilometers usually measure an index called mean profile depth (MPD) which is a little bit different from the MTD. The shortcoming of profilometers is that they are really expensive.
3.2.3. The Circular Texture Meter (CT Meter) ASTM E2157

Now the CT Meter is a stationary profilometer that uses a laser to measure the profile of a circle 284 mm (11.2 in) in diameter or 892 mm in circumference. The profile is divided into eight segments of 111.5 mm (4.4 in). The mean profile depth (MPD) is determined for each of the segments of the circle. The reported MPD is the average of all eight segment depths.

![Figure 3.2.1: A picture of CT Meter (Hanson, et al., 2004) (left) and of Segments of CT Profile (ASTM E2157-09, 2009) (right)](image)

Circular texture meter method is suitable for the calculation of the average macrotexture depth from profile data. The results of this calculation have proven to be useful in the prediction of the speed dependence of wet pavement friction or macrotexture. This method becomes less accurate when used on porous or grooved surfaces.

3.2.4. The Sand Patch Method (ASTM E965)

One of the oldest, most often used and relied on methods for measuring macrotexture of pavement surface is the Sand Patch Method (ASTM E965). Even today most other tests are referenced to the sand patch method. This test method determines the average depth of pavement surface over a region by smoothing an area with sand. The method is designed to provide an
average depth value of only the pavement macrotexture and is considered insensitive to pavement microtexture characteristics.

The Sand Patch Method test procedure involves spreading a known volume of material, sand or glass beads, on a clean and dry pavement surface, measuring the area covered, and subsequently calculating the average depth between the bottom of the pavement surface voids and the top of surface aggregate particles.

\[
Mean\ Texture\ Depth\ (MTD) = \frac{4V}{\pi D^2}
\]

(3.2-1)

Where:

\[ V \] – Sampling volume, in\(^3\) (mm\(^3\))

\[ D \] – Average diameter of the area covered by the material, in (mm)

Figure 3.2.2: Evaluation of macrotexture using the Sand Patch Method by NCAT member (Hanson, et al., 2004)
3.2.5. Conclusion

It could be concluded that there are inherent downsides with using these methods. For both methods, the sand patch and the circular track meter, one requires the stopping of traffic that creates road congestion, which in turn causes safety hazard for both, drivers and workers. In addition, the sand patch and circular track meter methods are time consuming. The smooth and
ribbed tire methods are destructive and expensive. Every time the test is performed the tire loses its surface threads; therefore, making the test expensive and less accurate. The laser-inertial profilometers require that external equipment be installed, which makes the vehicle longer and wider, creating inconvenience for the driver of the equipped vehicle and for other drivers on the road. Also, while the laser-inertial profilometers are extremely expensive they do not measure sound generation from tire-pavement interaction, therefore, they cannot be used to measure noise environment. On the other hand, the proposed method will not only provide needed macrotexture information but will also monitor road noise at a very low cost without the need for a system operator; hence, making it truly automatic.
4. SOUND GENERATION BY PAVEMENT TEXTURE

4.1. Introduction

Many studies have been performed on the effect of pavement macrotexture on the sound generated by the tire-pavement interaction with much success, many of which will be reviewed here. Most of the previous publications studied this research topic in order to see if varying the pavement surface parameters could diminish the noise that is created by the tire-pavement interaction without sacrificing safety. Yet, instead of trying to get rid of the noise, it is proposed to use it to monitor pavement parameters. In accordance with this goal the question of where to look in the Spectral Density of the sound signal to find pavement parameters that we are looking for and effect of temperature and wind on the Spectral Density are reviewed from published literature results to see how to better monitor MTD using noise generated by the tire-pavement interaction.

4.2. Frequency Range of the Spectrum that is Related to Macrotexture

Previous studies tried to correlate the A-weighted sound signal from the tire-pavement interaction to the roughness or macrotexture of the pavement without much success. Hence, the logical sequence is that correlation should be looked between certain frequency ranges of noise and texture. Consequently, one must look at relationship between sound signal and texture descriptors that have separate relationships with these mechanisms in order to have a chance of finding a good correlation of tire-pavement noise to MTD.

The earliest study that the author is aware of that tried to use noise generated by the tire-pavement interaction in a moving vehicle to monitor skid resistance or macrotexture was “Use of
tire noise as a measure of pavement macrotexture” by R. E. Veres et al. in 1975 (Veres, et al., 1975). They confirmed that macrotexture could in fact be measured by the noise generated in tire-pavement interaction if some improvements on the equipment and data processing are made. Yet, it was interesting that the authors of above mentioned paper found high correlation in the 1600 Hz. This seems to not conform to other studies that suggest that texture induced noise should be below 1000 Hz.

A study performed by Sandberg and Descornet measured tire-pavement noise third-octave band spectra for three tires at two speeds and for one tire at five speeds on a number of surfaces (Sandberg, et al., 2002). They made regression calculations, for all tires and speeds, using each pavement surface as one data point in the regression of noise on texture. The outcome of these calculations was the correlation between noise and texture spectral bands for all possible combinations of sound frequencies and texture wavelengths (Sandberg, et al., 1980). They found that “sound pressure levels at low frequencies, below 1 kHz, increase with texture amplitude when considering texture within the texture wavelength range of 10 – 500 mm” and that “sound pressure levels at high frequencies, above 1 kHz, decrease with texture amplitude when considering texture within the texture wavelength range of 0.5 – 10 mm”. They were able to separate the average frequency spectra over all surfaces to three mechanisms: the pavement texture impact in the frequency range below 800 Hz, the tread impact in the frequency range of 800 to 1200 Hz, and the air displacement mechanism in the higher part of the spectrum, above 1200 Hz (Sandberg, 1987). This is supported by numerous studies such as (Clapp, et al., 1983), (Nelson, et al., March 1993), (Anfosso-Ledee, et al., January 2002), and others. Therefore, we can conclude that the signal at a frequency below 800 Hz is due to the road asperities impacting
the tire and this is the frequency range where one should find reasonable correlation of MTD to the noise generated by the tire-pavement interaction.

Other studies also showed that as tread pattern of a tire becomes smoother the high frequency mechanism becomes less dominant and vice versa for the low frequency mechanisms. It could be concluded that sound pressure levels at low frequencies are the ones most important for detecting and monitoring pavement surface parameters like macrotexture using the noise generated by the tire-pavement interaction. This is because macrotexture impacts the tire which creates sound, and the more dominant this impact mechanism is the better correlation one should get of the tire-pavement generated noise to MTD.

4.3. The Temperature and Wind Effect

Currently, it is generally agreed that temperature’s effect on noise is about -1 dB per 10°C; therefore, a temperature coefficient of -0.1 dB/°C. This means that as the temperature increases 10° C the noise measured in dB would decrease by 1 dB. It has also been shown in previous published articles that this ‘Temperature Coefficient” is significantly influenced by the pavement type, tire type, and speed. Also, temperature coefficient has different value in the Spectral Density. Yet, it could be concluded that a temperature coefficient of -0.05 dB/°C is reasonable over the lower frequency range of interest.

It has been reported that any experiment studying noise generated by tire-pavement interaction under a moving vehicle should be performed when wind speeds are less than 5 m/s (Sandberg, et al., 2002). This is because wind has a high influence in the lower frequency and would create a lot of background noise. The slower the vehicle travels the more cautious one should be about
wind effect. Also, wind effect will be a function of vehicle’s speed but previous research has confirmed that this would only cause serious interference at speeds above 120 km/h.

4.4. Tire-Pavement Noise Generating Mechanisms

It also seems appropriate that a review be made of different reported mechanisms responsible for the sound generation by the tire-pavement interaction so that the reader better understands the physics responsible for the sound. Firstly, it has been reported that the tire-pavement generated sound starts to dominate over other vehicle noise for regular passenger cars for speeds of 20 km/h and higher. A state of the art report published in 1994 described three discrete mechanisms in tire-pavement sound production. These mechanisms are tire vibrations, air resonance, and accelerated water droplets (Brite, et al., 1994). Due to the different nature of mechanism of tire vibration and air resonance, these two mechanisms create sound in different frequency bands. Air resonance mechanism creates sound in the higher frequency range due to the geometry of tire tread and the physics of the mechanism. We shall explore these areas to see what significance they have on monitoring MTD.

Air pumping mechanisms are those that are responsible for compressing or pushing the air through or from the tire tread and pavement cavities. Air resonance is caused by the pipe resonance (dihedral formed by the tire-pavement contact geometry), Helmholtz resonance, and tire pocket air pumping (Wayson, 1998). Also, the Horn effect could amplify the sound by 20 dB. The amplification starts at about 300 Hz and has its maximum around 2 – 3 kHz but is substantial over the entire range of importance for A-weighted tire-pavement sound. This could prove vital for the monitoring of pavement characteristics. Also, it has been shown that the width
of the tire influences the Horn effect: the wider the tire the greater the Horn effect. The air resonant radiation has most of its energy concentrated in the frequency range 1000 – 2500 Hz.

It seems that the impact mechanisms are the ones that are of interests in our case. There are two types of categories of tire vibration reported in the literature: radial and tangential. Tangential vibrations are caused by frictional forces and stick-slip motions (Wayson, 1998). On the other hand, radial vibrations are caused by the impact of the tire tread pattern, the impact of the road surface textures, and adhesion of the stick-release from contact of the tire and pavement surface. In the forefront of the tire the tread element or the texture irregularity pushes into the tire, toward the rotational center, while at the rear of the tire the tire tread and texture irregularities are pushed out of the tire (Sandberg, et al., 2002). The distortion caused by this mechanism and the associated induced forces create forced and free vibrations which propagate on the surface of the tire tread and sidewall; however, the vibrations are quickly attenuated as they propagate along the tire circumference (Erixon, 1998). Since the pavement texture average distance between aggregates is usually greater than the average distance of tire tread, the two impact mechanisms could be separated.

When water is present, water noise of the accelerated droplets becomes important. Very little is known about the mechanisms responsible for sound generation on wet surfaces. Some authors have reported that the presence of water increases noise from 0 – 15 dB compared to dry condition. Tire-pavement interaction could cause many different reactions from the water on the pavement surface: it may cause the water to eject in a jet, displace in the form of splashing, or break adhesion bonds between rubber and water at the trailing edge. It seems that water on pavement surface creates noise around 2 kHz range.
5. **Experiment and Data Collected**

5.1. **Experiment Performed**

To validate the concept that macrotexture could be monitored through the sound generated by the tire-pavement interaction, experiments were performed at the National Center for Asphalt Technology (NCAT) facility. NCAT facility is divided into 46 pavement sections. 30 of the pavement sections are designed with superpave mix design, 6 with porous mix design like open-grade friction course (OGFC) or porous friction course (PFC), and 7 with stone-matrix asphalt (SMA) mix design. NCAT contained 3 other pavements with proprietary designs that could not be put into the above categories (Saykin, et al., 2011). One of those sections did not have MTD rating. Therefore, in this thesis, a reference to “all” NCAT test sections refers to the 45 sections that have an associated MTD rating. To study the effect of macrotexture of different pavement types on the sound generated by the tire-pavement interaction, four categories are created: superpave, porous, SMA, and “all”. This will give the reader a better understanding of the data that was gathered for different pavements and microphone set ups (Saykin, et al., 2011). The test vehicle was equipped with directional microphones under the body that recorded the sound as the van drove over NCAT pavement sections (Figure 5.1.1). NCAT pavement sections were driven on in a continuous fashion with manual pavement section separations. Also, NCAT pavement sections contained many different pavement surface damages like boreholes, raveling, rutting, and others that distorted the microphone signal (Saykin, et al., 2011).
5.2. Data Collected

A typical time history plot of the signal received by the microphones and the associated frequency domain plots could be seen in Figure 5.2.1. The spectral density was estimated through the Welch’s Method (Welch, 1967), with the magnitude measured in units of dB with a reference of 20 µPa. Welch’s method is an improvement to the standard periodogram spectrum estimating methods in that it reduces noise in exchange for reducing frequency resolution. The method splits the signal in 50% overlapping segments and then windows each segment. Then using discrete Fourier transform and computing the squared magnitude of the result, periodogram is calculated. The individual periodograms are then time-averaged (Welch, 1967).
Figure 5.2.1: Example of Time History Plot (left) and Sound Pressure Level Plot (right) with approximate chosen frequency band (Saykin, et al., 2011)

Figure 5.2.2: Energy values attained by Eq. 1.3-3 are plotted against given MTD values. Correlation is determined through Eq. 1.3-10
6. MTD Monitoring - Analysis of the NCAT test Section

6.1. Introduction

For years the DOTs of different states have been measuring MTD of pavement surface with the Sand Patch Method (ASTM E965). This test although accurate for what it was designed to do it is very time consuming and relies on human judgment. Due to the weakness of this method many have tried different methods to accelerate and automate the macrotexture monitoring. Unfortunately, most of these other methods are expensive for the DOTs. Some researchers tried to measure MTD through the sound generated by the tire-pavement interaction. Their success was limited to only one or two different types of pavements, after which the correlation dropped down as to make the proposed model unreliable. Therefore, parametrical experiments were conducted that included many different pavement construction types and microphone configurations, to see if macrotexture could be monitored using the sound generated by the tire-pavement interaction.

6.2. The Chosen Frequency Ranges for the Optimal Tire-Pavement Noise to MTD Correlation

Before regression or correlation analysis could be performed it is necessary to figure out what part of the acoustical signal should be used to find correlation to macrotexture. During the literature search, described in Chapter 4 of this report, it was found that many experts in the field found some positive correlation of tire-pavement noise to MTD in the lower part of the spectral density and some negative correlation of tire-pavement noise to MTD in the higher part of the spectral density (Sandberg, et al., 2002). It was found that the correlation for the 45 NCAT
sections which included porous, stone-matrix, and hot-mixed asphalt and many different ages
and pavement damages did exist in the lower and to a much lesser extent in the higher part of the
spectral density. To better affiliate the reader with the data and results presented below it is
needful to present some of the issues and benefits of the data collected.

NCAT facility has 46 pavement sections. It has about 30 pavement sections that were designed
with superpave mix design, 6 with a porous mix design like OGFC or PFC, and about 7 with a
SMA mix design. NCAT contained 3 other pavements with proprietary designs that could not be
put into the above categories; therefore, those pavements will not be taken into account unless
“all pavement” sections are referred to. That is, when we refer to all NCAT test sections it means
that 45 sections are referred to because one did not have an MTD rating. The following
discussion will break up the correlations into the superpave, porous, SMA, and “all” categories.
This will give the reader a better understanding as to the data that was gathered for different
pavements from the microphone set up. Some of the issues that the reader has to keep in mind
are that in some of the sections there were many bore holes. These really polluted the signal and
lowered the correlation for the SMA and other sections. Therefore, different runs with the same
configuration and with the same microphone and the same pavement section could have different
correlation. Why? Because during one run we managed to avoid the bore holes and other
damages while during another run that was not the case. This means that microphone signal for
each run could be considered random Also, the wild life was very loud sometimes and no doubt
contributed to lowering the correlation of the tire-pavement generated sound to the MTD of
pavement section.

The following studies are based on the correlation coefficient as calculated in chapter one of this
thesis. To find out what frequency range is best suited for monitoring MTD the author created
contour plots that show correlation coefficient as functions of the integration range. The x-axis shows the minimum of the integration range while the y-axis shows the maximum part of the integration. The author used these plots to find out what integration range should be used for correlating sound to MTD. It should be noted that these contour plots varied from run to run but a pattern could still be seen.

6.2.1. The Higher Frequency Range Correlation to the MTD

From the literature we see that many researchers have reported that many noise generating mechanisms in the tire-pavement noise generation exist in the higher part of the spectrum. Many of the mechanisms that act in the higher part of the spectrum relate to air displacement mechanisms. The most reported of these mechanisms are air pumping, air resonance like Helmholtz resonators, and acoustical amplifications like horn effect. None of these mechanisms explain the whole picture but embellish our understanding of the noise generation in a frequency range above 1000 Hz. These mechanisms deal with air displacement and radiation under the tire-pavement interaction and they dominate around 1000 Hz to 5000 Hz of the spectral density. The difficulty arises from the fact that we have an irregular pavement surface and irregular tire surface both of which contribute to the air displacement and compression under the tire-pavement interaction, interfering with each other. This creates a difficulty in finding a correlation of the tire-pavement interaction sound to the MTD of pavement because the signal in this range carries the contribution from the tire, the road surface, and many other undocumented sources. For example, it was shown from other literature that the tread impact of the tire on the pavement surface acts in the 800 to 1200 Hz but the transversal vibration of the tread to its own axis also creates noise in the higher part of the spectrum. To try to get rid of the unwanted noise from the
correlation, a frequency range was chosen above 1500 Hz. This would eliminate some of the tread impact but not all. Also, this would not eliminate other background noise that acts in this region.

As mentioned above, the correlation that is sought is a correlation of the energy through the integration of the spectral density of the acoustical signal in specific frequency range and of Fourier Series constants, specifically \( a_0 \), in the same frequency range to the MTD of pavement surface. For the correlation of the MTD index to the energy and \( a_0 \) of the tire-pavement generated sound configuration A at 50 mph was chosen with microphone 5. The reason for this is that microphone 5 was pointing to the tire-pavement interaction contact patch zone. This is thought to give the best chance for finding a correlation because the microphone was about 2 inches above ground and the waves from the higher part of the spectrum have short wavelengths; therefore, to catch them it would be beneficial to have the microphone close to the contact patch. When all of the NCAT test sections were taken a moderate correlation of energy to MTD of 0.63 was achieved (Figure 6.2.1).

From the plot below it could be seen that the variance, which is the square of the correlation coefficient, is quite small. Variance could be explained as how much of the noise could be explained by the tire-pavement interaction or more precisely by the tire-MTD of pavement interaction. The variance is quite low for the higher part of the spectrum which tells us that in the higher part of the spectrum, from 1500 to 4400 Hz, other sources rather than our MTD interaction with the tire dominate our signal. This does not say that there is no significant correlation of the noise generated by the tire-pavement interaction to the MTD index of pavement surface. What this tells us is that we were not successful in removing the background noise in this frequency range. Hence, higher frequency range does not provide satisfactory
correlation of tire-pavement generated sound to MTD. One should look into a different part of the spectral density to find reasonable correlation.

Figure 6.2.1: Plot shows how the correlation coefficient depends on the minimum and maximum frequency in the frequency range for the energy integration for microphone 5 at 50 mph in configuration A, run 3.

6.2.2. The Lower Frequency Range Correlation to the MTD

In the literature many researchers have reported that many tire-pavement sound generating mechanisms exist in the lower part of the spectrum. Many of the mechanisms that act in the lower part of the spectrum relate to impact mechanisms. The most reported of these mechanisms are the tire tread impact and the texture of pavement surface impact. These mechanisms deal with pressing the tire tread against the pavement surface or pressing the texture of pavement surface against the tire tread and they dominate around 100 Hz to 1000 Hz of the spectral density. The difficulty arises from the fact that we have an irregular pavement surface and irregular tire surface both of which contribute to the impact under the tire-pavement interaction;
but it turns out that they do so at different frequencies. Never the less, it is still difficult to find a correlation of the tire-pavement interaction noise to the MTD of pavement because the signal in this range carries the contribution from the tire cavity, wind, engine and transmission, and the road surface.

Some of the questions that are discussed are: the reliability of correlation coefficients and what frequency ranges give the best correlation? To answer these questions and to attain a better understanding, contour plots were used. A plot shown below for microphone 5 at 50 mph for configuration A reveals very interesting features. It shows that if we take 45 NCAT sections the best correlation to MTD of those sections would really depend on the maximum frequency of the frequency range and very little on the minimum frequency. It is very interesting that the contour for the correlation in the range of 0.75-0.80, dark brown color, is wide and tall. This seems to imply that this correlation is reliable. This also shows where to look in the spectral density for the best correlation.

Below, in Figures 6.2.2, 6.2.3, and 6.2.4, we have the contour plots for 3 runs. It could be seen that overall, run 2 and 3 had better correlation for all of the NCAT test sections. This is because for runs 2 and 3 we did not hit many of the bore holes that were present in the track but for run 1 we did. This effect is seen much better when the NCAT test sections are broken up into pavement types. The more pavement surface damages that we hit, with the tire of the vehicle, the less correlation we achieved. Yet, these plot show that there is moderate correlation of tire-pavement generated sound to MTD when all of the pavement types are considered. When one limits the sample to one particular pavement type the correlation improves significantly.
Figure 6.2.2: The colorbar shows the color representation of correlation coefficients achieved for particular frequency range for microphone 5 at 50 mph in configuration A, run 3.

Figure 6.2.3: The colorbar shows the color representation of correlation coefficients achieved for particular frequency range for microphone 5 at 50 mph in configuration A, run 2.
From the graphs below we see that each type of pavement construction has its own contour plot trend. Even though each run did not have similar correlation coefficient values, the trends still could be seen. For the superpave mix design pavement type it is seen that the correlation of the noise generated by the tire-pavement interaction is really dependent on the maximum of the frequency range and not on the minimum. It is seen that for the superpave section run 2 had the best correlation while run 3 was also very good and stable. From the three plots, Figures 6.2.5, 6.2.6, and 6.2.7, it could be said that for the best and stable correlation the maximum of the frequency range should be around 400 Hz while the minimum part of the frequency range should be around 25 Hz. For the porous pavements it is seen that run 1 had terrible results. This is due to the fact that during run 1 a lot of boring holes were hit in the porous pavement sections. This is further confirmed by the fact that for the other two runs the correlations were excellent. As for
the superpave test sections, the porous sections seem to have the best correlation when the maximum part of the frequency range is around 400 Hz. Also, the minimum of the frequency range does not affect the correlation for porous types of pavement; therefore, for the minimum of the frequency range a value of 25 Hz seems reasonable. From SMA pavement type, a maximum correlation of about 0.85 was attained for 60-200 frequency range in run 3. This correlation is thought to not be reliable enough because it does not repeat itself. It is seen that a high correlation for the SMA pavements is achieved if the maximum of the frequency range would be around 400 Hz. The minimum of the frequency range seems to not affect the correlation of the tire-pavement generated noise to the MTD pavement surface index.

Figure 6.2.5: The colorbar shows the color representation of correlation coefficients achieved for particular frequency range for microphone 5 at 50 mph in configuration A, run 3, and taking into account only Superpave pavements.
Figure 6.2.6: The colorbar shows the color representation of correlation coefficients achieved for particular frequency range for microphone 5 at 50 mph in configuration A, run 2, taking into account only Superpave pavements.

Figure 6.2.7: The colorbar shows the color representation of correlation coefficients achieved for particular frequency range for microphone 5 at 50 mph in configuration A, run 1, taking into account only Superpave pavements.
Figure 6.2.8: The colorbar shows the color representation of correlation coefficients achieved for particular frequency range for microphone 5 at 50 mph in configuration A, run 3, taking into account only Porous pavements.

Figure 6.2.9: The colorbar shows the color representation of correlation coefficients achieved for particular frequency range for microphone 5 at 50 mph in configuration A, run 2, taking into account only Porous pavements.
Figure 6.2.10: The colorbar shows the color representation of correlation coefficients achieved for particular frequency range for microphone 5 at 50 mph in configuration A, run 1, taking into account only Porous pavements.

Figure 6.2.11: The colorbar shows the color representation of correlation coefficients achieved for particular frequency range for microphone 5 at 50 mph in configuration A, run 3, taking into account only SMA pavements.
Figure 6.2.12: The colorbar shows the color representation of correlation coefficients achieved for particular frequency range for microphone 5 at 50 mph in configuration A, run 2, taking into account only SMA pavements.

Figure 6.2.13: The colorbar shows the color representation of correlation coefficients achieved for particular frequency range for microphone 5 at 50 mph in configuration A, run 1, taking into account only SMA pavements.
6.2.3. Frequency Range Conclusion

The highest correlation that was achieved was 0.96 for porous pavement. This shows a strong correlation of sound generated by the tire-pavement interaction and MTD. In conclusion, it could be said that there exists an optimal range in the spectral density for correlation of tire-pavement noise to MTD of the test sections. This range will be preferably in the lower part of the spectral density (40 to 400 Hz). This is due to the fact that the impact mechanisms that act in the lower part of the spectrum give a much better correlation of tire-pavement noise to pavement’s MTD than do the air displacement and air compression mechanisms that dominate in the higher part of the spectrum. One possible reason for a good correlation in the lower frequency range is that of resonance. When the aggregate impacts the tire tread repeatedly and in a consistent way this creates resonance. This is further amplified by the resonance of the vehicle used. This seems to be supported by a classical equation of

\[ f = \frac{c}{\lambda} \]  

(6.2-1)

Where  
\( f \) = frequency  
\( c \) = sound speed, 340 m/s  
\( \lambda \) = wave length

For example, the distance from the ground to the underbody of the vehicle is about 50 cm, this gives us a resonant frequency of about 680 Hz. Also, if we take the length of the vehicle to be about 6 meters then the resonant frequency will be about 57 Hz. Obviously, this resonant frequencies are not exact but a very rough measurement of the frequency range that should be resonating. From the same simple equation it could be seen that our texture impact should also be acting in this frequency range. Hence, we see an amplification of this frequency range and the data about pavement surface characteristics could be elicited. Also, a lot of the background noise
sources dominate in the higher part of the spectrum while leaving the lower part pretty much untouched. The only serious signal polluter in the lower frequency range is the wind. This is being said from practical point of view and not from theoretical since the air displacement and air compression mechanisms if acted in a perfect environment where there is no background noise and absolutely nothing but the air mechanisms acting could possible give the author a better correlation, but this perfect environment will hardly be reached in real life. Therefore, if one wants to monitor MTD of pavement through the use of the sound generated from the tire-pavement interaction one will have to use the lower part of the spectrum, preferably below 800 Hz, which agrees very well with the other published results.

6.3. Optimum Microphone Location

In trying to detect MTD of a pavement through the sound generated by the tire-pavement interaction, it is important to know where to place your microphones. The height of the microphones above the surface of the road and the exact location of the microphone relative to the underbody of a vehicle will have a big effect on monitoring the MTD or macrotexture of the pavement. According to the VOTERS project none of the sensors, including the microphones, should be visible to the public. This is a hard task since we know from literature that the closer we have our microphones to the contact patch of the tire and pavement surface the better information about pavement surface we should get in our signal.
6.3.1. Horizontal Location of Microphones

At the NCAT test track, five microphones were placed under the underbody of a vehicle. This configuration was numbered configuration A. The reason for placing the microphones in different locations along the underbody of the vehicle was to see how sound generated by tire-pavement interaction in a moving vehicle correlated to the MTD of the pavement section under the vehicle’s chassis. Some very interesting results were found. Different microphones gave different correlation to the MTD. The best microphone seems to be microphone number 4, which is the one in front of the rear tire. It was obvious that the microphones that were near and pointed towards the contact patch, microphones 4 and 5, should get the highest correlation but it was a total surprise that microphone 3 also had substantial correlation to the MTD of the pavement sections. For the sake of comparison the speed will remain constant at 50 mph for this discussion.

The first microphone to be analyzed was microphone 5, which was the microphone behind the rear tire, pointing towards the contact patch, and being about 2 inches from the ground. This position is promising because it tried to isolate unwanted noise and capture as much of the sound related to the macrotexture as possible. The benefit of this position is that the correlation of the tire-pavement interaction sound to the pavement’s MTD was consistent. In the favorable frequency range of 40 to 400 Hz each run provided a correlation over 0.725. While an average correlation of the tire-pavement sound to the MTD was 0.794. This is extremely high considering the variability of the pavement surface structures and their associated conditions with all of the interfering noise of a moving vehicle. What was really amazing was that when only superpave pavement mix design sections were used with different surface features the correlation of vehicle
tire-pavement generated sound to MTD of the section increased to 0.901. Therefore, microphone 5 alone provides very satisfactory findings.

Microphone 4, which is in the front of the rear tire, showed a little better correlation than microphone 5. Overall, it seems to the author that the microphones around the tire receive a lot of their signal from the tire-pavement interaction. This is not surprising because the microphones were quite close to the contact patch. So close in fact that the author was worried that the microphones would be damaged by the debris flying off the tires and by the pavement surface. The Table 6.3.1 below shows all the correlations of energy to MTD that were achieved for the configuration A microphones.

Table 6.3.1 The average correlation of microphone data to the MTD of pavement sections for configuration A setup at 50 mph

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Pavement Type</th>
<th>Microphone 1</th>
<th>Microphone 2</th>
<th>Microphone 3</th>
<th>Microphone 4</th>
<th>Microphone 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 to 400</td>
<td>All Sections</td>
<td>0.198</td>
<td>0.584</td>
<td>0.697</td>
<td>0.800</td>
<td>0.794</td>
</tr>
<tr>
<td>40 to 400</td>
<td>Superpave</td>
<td>0.299</td>
<td>0.713</td>
<td>0.786</td>
<td>0.896</td>
<td>0.901</td>
</tr>
</tbody>
</table>

Another very interesting factor is that the microphones between the tires, microphones 1, 2, and 3, have an increasing correlation of the tire-pavement noise to the MTD of the section. The reason for this is that even though the front tire also generates the same noise relating to the tire-pavement interaction there exist other noise sources that act in the lower part of the spectral density: sources such as the engine and transmission. These sources interfere with the tire-pavement noise signal and the correlation drops. What is interesting is that microphone 2, which is located equal distance from the front and rear tire, the two tire-pavement noise sources, still gets higher correlation than microphone 1. Another reason for this could be that the cavity that is
formed under the vehicle’s chassis helps to propagate the sound generated from the tire contact patch. It is interesting to note that microphone 3 received an overall lower pressure signal than did microphone 4 and 5 but still achieved impressive correlation. This seems to confirm the fact that tire-pavement generated sounds propagated throughout the underbody of the vehicle.

Overall, it could be safely said that microphones 3, 4 and 5 are good choices for microphone location in regards to the correlation of the tire-pavement generated sound to MTD but microphones 4 and 5 are probably the better choice from a point of view of that our system TEASe should have as little amount of sensor showing as possible. The correlation of the sound signal in microphones in array to the MTD should be explored because the noise signal from the tire-pavement interaction carries information of the pavement surface far enough to reach microphone 2 and 3. The action of the horn effect could be the noise amplification that makes this possible. If this is true, could our microphones be placed higher and still achieved the same correlation?

6.3.2. Vertical Location of Microphones

To test the height impact on the microphones, microphones 4 and 5 from configuration A and 2 will be compared. In the previous section we studied the effect of the location of microphones under the chassis of a vehicle on the correlation of the tire-pavement generated sound to the MTD of a pavement surface. It was found that microphones around the rear tire, microphones 4 and 5, had the best and very stable correlation of the tire-pavement generated sound to the MTD. It is now of interest to discuss the effect of the height of microphones above ground to the correlation of tire-pavement generated sound to the MTD. Here we will compare configuration 2
and configuration A. Configuration A and its results are discussed in detail in the previous section. Configuration 2 was chosen as a comparison to configuration A because configuration 2 had microphone 4 and 5 at 15 inches above ground. This allowed the author to compare the height effect more closely because microphones 4 and 5 have about the same correlation of noise to the MTD of pavement.

The first microphone to be analyzed is microphone 5, which was the microphone behind the rear tire, pointing towards the contact patch, and being about 15 inches from the ground. It was the author’s hope that the horn effect which we have shortly discussed in the previous section would carry the desired signal to the microphone. In the favorable frequency range of 40 to 400 Hz each run provided a correlation over 0.637. While an average correlation of the tire-pavement generated sound to the MTD was 0.678. This is extremely high considering the variability of the pavement surface structures and their associated conditions with all the interfering noise of a moving vehicle. What was really amazing was that when only superpave pavement mix design sections were used with all their different surface features the correlation of vehicle tire-pavement related signal to MTD of the section increased to 0.773.

Microphone 4, which is in the front of the rear tire, showed moderate correlation of the tire-pavement sound to the MTD of pavement surface. One might say that the height of the microphones, for the microphones located in the front and back of rear tire, has very little effect on the correlation of tire-pavement noise to the pavement surface MTD. Some reasons that microphone 4 did not do some much better than microphone 5 might be that microphone 4 was located in a cavity under the chassis of the vehicle, which distorted the signal; on the other hand, microphone 5 had no such cavities to deal with.
Overall, it seems to the author that the microphones around the tire receive a lot of their signal from the tire-pavement interaction even at a fair distance from the ground. This is probably due to the horn effect helping to propagate the sound generated by the tire-pavement interaction. This is quite surprising because the author did not think that the acoustic signal from the contact patch would travel that far and still carry the needed information. One must understand that at this height the microphones are receiving not only the acoustical signal from the contact patch but from the muffler, the engine, the transmission, the wind, and other noise sources from the surrounding environment that pollute the signal. Yet, with this entire noise pollution the microphone 5 was still able to produce significant results. The Table 6.3.2 below shows all the correlations that were achieved for configuration 2 with microphones 4, and 5. What helped to achieve the correlation coefficients might be the pavement aggregate penetrating or imprinting into the tire causing a radial wave to develop that would go around the tire and radiating to the close proximity the information about the pavement surface; hence, helping microphone 4 and 5 to receive more needed information (Erixon).

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Pavement Type</th>
<th>Microphone 4</th>
<th>Microphone 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 to 400</td>
<td>All Sections</td>
<td>0.640</td>
<td>0.741</td>
</tr>
<tr>
<td>40 to 400</td>
<td>Superpave</td>
<td>0.689</td>
<td>0.773</td>
</tr>
</tbody>
</table>

Overall, it could be safely said that microphones 4 and 5 are all good choices for microphone location in regards to the effect of the height on the correlation of the tire-pavement generated sound to MTD, although microphone 5 is the best location. Through this study it has been shown that it seems possible to hide the microphones under the vehicle’s chassis and still be able to

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monitor the MTD of pavement surface through the sound generated by the tire-pavement interaction.

6.4. The Speed Effect

Experiments at NCAT test track tested each configuration at three different speeds, at 32, 54, and 80 km/h (20, at 35, and at 50 mph). At each speed there were three runs; therefore, for each configuration there were 9 total runs. This amount of runs at different speeds allowed the author to compare the effect of speed on the correlation of the sound generated by tire-pavement interaction to the MTD of pavement. For this parametric study configuration A, with which the reader is already familiar, was chosen as the configuration of choice for determining the effect of speed. Since it was already established that microphones 3, 4 and 5 are the best correlated microphones to the MTD, only microphones 3, 4 and 5 are compared in this study.

Two approaches for determining the effect of speed on correlation of MTD and sound generated by the tire-pavement interaction are presented. The first strategy is to keep the frequency range constant with speed. This assumes that the aggregate impact acts in the same frequency range irrespective of speed. The other approach is to change frequency range with speed. This assumes that sound generated by the tire-pavement interaction follows the Eq. 6.2-1.

For the speed regression analysis the author selected the runs with the best correlation to show what could be achieved in the best case scenario, especially if one would give extra effort to managing wind noise. The reason for this is that of noise. One could dismiss the other runs with lower correlation coefficient values by simply stating that they are more polluted with noise;
hence, are not as correct for determining the relationship of MTD to energy. The author performed linear regression analysis on best runs for the three microphones.

Figure 6.4.1: Change in Correlation Coefficient with Speed for Microphone 5 at Configuration A taking into account (a) All Pavement Sections, (b) Superpave Pavement Sections only, (c) Porous Pavement Section only, and (d) SMA Pavement Sections only.

From Figure 6.4.1 it could be established that adjusting the frequency range gives on average better results than keeping the frequency range constant. For the case with only the porous pavement sections and SMA pavement sections the correlation coefficients were not very stable due to the fact that there was few of the pavement section, but the second approach still seems to be performing better than the first approach. This trend repeats itself for different microphones.
Overall, it could be said that the second approach seems to be more correct and some variation of the above stated equation should be developed to take into account the speed effect.

Another interesting feature could be seen from fitting a best fit line through a linear regression at different speeds and comparing them. As shown in Figure 6.4.2, the data supports linear equation for different speeds but the slope coefficient of the equations changes with the speed. This suggests that energy and speed are interrelated. It could also be seen that the intercept of the equations changes with speed.

![Figure 6.4.2: The plot shows data from microphone 5 from configuration A at different speeds with best fit curves and their equations. The equations show how much the slope changes with speed.](image)

Overall, at 50 mph outstanding results were achieved. If we take all of the NCAT sections, a correlation of noise generated by the tire-pavement interaction to the MTD of a pavement surface of 0.800 was achieved. What is really impressive is the fact that a correlation of 0.901 was achieved when we considered only pavements that where designed by the superpave method. This is due to the fact that a lot of data was collected, and this data added stability to the outcome since it helped to remove any outliers in the noise. Yet, the adjusted $R^2$ was just as high as $R^2$. One the other hand, pavements that were designed as open grade friction course (OGFC) and
porous friction course (PFC), both under the OGFC subscript, were much fewer in numbers, only 6. This caused the data and outcome to be less stable. Nevertheless, outstanding results were still found. A correlation of 0.982 was found for the OGFC pavements.

<table>
<thead>
<tr>
<th>Table 6.4.1: The correlation of microphone data to the MTD of pavement sections for configuration A setup at 50 mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>40 to 400</td>
</tr>
<tr>
<td>40 to 400</td>
</tr>
<tr>
<td>40 to 400</td>
</tr>
<tr>
<td>40 to 400</td>
</tr>
</tbody>
</table>

During the experiments at NCAT the vehicle constantly maintained a 1600 rpm for 35 and 50 mph runs. In the eyes of the microphone, this should create the same disturbance from the engine but since we are traveling at a slower speed the wind effect should be smaller. The correlation of the microphones fell at 35 mph compared to 50 mph. Microphone 3 seems to be inconsistent due to the fact that the wind might have affected microphone 3 much more than the other two microphones. Overall, we see that decreasing speed by 15 mph did not change the results much. The reason for the drop in the correlation of sound generated by tire-pavement interaction to the MTD is probably that the pavement aggregate were not pushed into the tire belt with as high of an impulse as in the case of 50 mph runs.

<table>
<thead>
<tr>
<th>Table 6.4.2: The correlation of microphone data to the MTD of pavement sections for configuration A setup at 35 mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>40 to 300</td>
</tr>
<tr>
<td>40 to 300</td>
</tr>
<tr>
<td>40 to 300</td>
</tr>
<tr>
<td>40 to 300</td>
</tr>
</tbody>
</table>
To complete the study on the effect of a speed of a vehicle on the correlation of sound generated by the tire-pavement interaction to the pavement surface MTD we will look at the results from the 20 mph runs. During these runs the engine was at a higher rpm. This creates more noise and vibration in the vehicle. Since the vehicle traveled at a slower speed the wind effect should have been much lower.

The fact that the engine worked at a higher rpm is seen in the results. The correlation for the SMA and OGFC pavements in microphones fell dramatically. This comes to no surprise because we know that the engine creates vibrations at a lower frequency, at which we are interested. This causes significant pollution of our acoustical signal; therefore, diminishing the correlation of the tire-pavement generated sound to the MTD of pavement surface. Also, we know from published results that the noise coming from tire-pavement interaction starts to dominate the acoustical signal only after 13 mph speed (Sandberg and Ejsmont). The correlation in microphone 4 and 5 of the sound generated by the tire-pavement interaction to the MTD of pavement surface was negatively affected by the reduction of speed. This is because the impulse of the aggregate hitting the tire belt was lower. Overall, we see that this caused a small decline in the correlation for pavements which had less aggressive aggregates protrusion.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Pavement Type</th>
<th>Microphone 3</th>
<th>Microphone 4</th>
<th>Microphone 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 to 200</td>
<td>All Sections</td>
<td>0.708</td>
<td>0.778</td>
<td>0.803</td>
</tr>
<tr>
<td>40 to 200</td>
<td>Superpave</td>
<td>0.755</td>
<td>0.840</td>
<td>0.858</td>
</tr>
<tr>
<td>40 to 200</td>
<td>OGFC</td>
<td>0.484</td>
<td>0.466</td>
<td>0.698</td>
</tr>
<tr>
<td>40 to 200</td>
<td>SMA</td>
<td>0.725</td>
<td>0.515</td>
<td>0.595</td>
</tr>
</tbody>
</table>

Table 6.4.3: The correlation of microphone data to the MTD of pavement sections for configuration A setup at 20 mph
In conclusion, it could be stated that the frequency at which MTD “acts” in the acoustical signal changes with speed. Also, it seems that the speed has an effect on the correlation of the sound generated by the tire-pavement interaction to the MTD of pavement surface. It seems that the higher the speed of a traveling vehicle the higher the correlation, but not by much and not for all of the microphones. The speed study also showed that microphone 3 could have a surprisingly high correlation if one eliminates the noise coming from the wind. Also, for microphones 4 and 5 the correlation is less affected by the speed of the vehicle. This is because microphones 4 and 5 are located far from the engine; therefore, the rpm of the engine has a small effect on the microphones. Also, the microphones 4 and 5 are more protected from the wind being located behind and in front of the rear tire. We can conclude that microphone 4 and 5 should be our primary choice for microphone location in order to achieve the best correlation of sound generated by the tire-pavement interaction to the pavement surface MTD. Also, one could use the found optimal frequency range and modify Eq. 6.2-1 as follows

\[ f_2 = \frac{0.3 \times (v - 8.94)}{\lambda} + 200 \]  

(6.4-1)

Where:

- \( \lambda \) = the distance between the pavement maximum aggregate, assumed to be approximately 0.02 m
- \( v \) = the speed of the vehicle, m/s, valid from 8.94 to 22.32 m/s (32 to 80 km/h)
- \( f_2 \) = the upper limit of energy integration, Hz

Also, for our vehicle and tested roads, MTD could be estimated from

\[ E(MTD) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \]  

(6.4-2)

Where:

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\[ \beta_0 = 0.9173 \text{ constant from regression analysis} \]
\[ \beta_1 = -0.1396 \text{ constant from regression analysis} \]
\[ \beta_2 = 4.23 \times 10^{-4} \text{ constant from regression analysis} \]
\[ x_1 = \text{speed of the vehicle in km/h} \]
\[ x_2 = \text{energy level from microphone, dB – Hz} \]

This equation gives an overall error of 7.9% when averaged over all tested roads with the 2010 Chevrolet Express Van. This study was performed under speeds of 32 to 80 km/h; hence, \( x_1 \) is only valid under this speed range. Also, \( x_2 \) in this equation should be determined by using microphone located in position 5 of configuration A. In determining \( x_2, f_2 \) is determined by Eq. 6.4-1 and \( f_1 \) is always kept constant at 40 Hz.

## 6.5. The Microphone Array Effect on the Correlation of Noise to MTD

It now seems that the idea of microphones used in array should be discussed. The tables below were formed using microphone 3, 4, and 5. The best of runs were used to represent the data that these microphones will receive. Also, different microphone arrangement was tried to see if combining different microphones would improve the correlation of sound generated by the tire-pavement interaction to the MTD of pavement surface. Also, it was of interest to show that the correlations that were received were stable. The adjusted \( R^2 \) values are also shown to show if the addition of an extra microphone really improves the correlation. We also see that if the pavement type is limited to a very similar pavement surface the correlation increases dramatically. This will become very significant when performing actual monitoring since the pavement types do not change in a particular state or small country as much as they did at NCAT. When comparing Table 6.5.1 and 6.5.2, one will notice that the adjusted explained variance does not improve when one considers all pavements and only superpave pavements for microphones used in array to that of solo microphone. Yet, for porous and SMA pavements improvement could be seen. It
seems logical to conclude that if enough data is presented, like in all and superpave pavements, one only needs one microphone to successfully monitor MTD of pavement. Therefore, we conclude that by using microphone 4 or 5 by itself it is very possible to do a continuous, constant, and accurate monitoring of the pavement MTD index through the sound generated by the tire-pavement interaction.

Table 6.5.1: The explained variance and adjusted explained variance

<table>
<thead>
<tr>
<th>Pavements</th>
<th>microphone 3</th>
<th>microphone 4</th>
<th>microphone 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$ adj</td>
<td>$R^2$</td>
<td>$R^2$ adj</td>
</tr>
<tr>
<td>All</td>
<td>0.4745</td>
<td>0.4864</td>
<td>0.6323</td>
</tr>
<tr>
<td>Superpave</td>
<td>0.6049</td>
<td>0.6185</td>
<td>0.7964</td>
</tr>
<tr>
<td>Porous</td>
<td>0.0863</td>
<td>0.269</td>
<td>0.9153</td>
</tr>
<tr>
<td>SMA</td>
<td>0.4338</td>
<td>0.5282</td>
<td>0.3719</td>
</tr>
</tbody>
</table>

Table 6.5.2: The explained variance and adjusted $R^2$ for microphones in array

<table>
<thead>
<tr>
<th>Pavements</th>
<th>Microphone 3, 4, 5</th>
<th>Microphone 3, 4</th>
<th>Microphone 3, 5</th>
<th>Microphone 4, 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$ adj</td>
<td>$R^2$</td>
<td>$R^2$ adj</td>
<td>$R^2$</td>
</tr>
<tr>
<td>All</td>
<td>0.6189</td>
<td>0.6449</td>
<td>0.626</td>
<td>0.643</td>
</tr>
<tr>
<td>Superpave</td>
<td>0.794</td>
<td>0.8153</td>
<td>0.7889</td>
<td>0.8035</td>
</tr>
<tr>
<td>Porous</td>
<td>0.986</td>
<td>0.9944</td>
<td>0.9869</td>
<td>0.9921</td>
</tr>
<tr>
<td>SMA</td>
<td>0.6023</td>
<td>0.8012</td>
<td>0.5865</td>
<td>0.7244</td>
</tr>
</tbody>
</table>
7. **CONCLUSION**

7.1. **Proposed Equation**

Through this parametrical study of correlating energy of sound generated by the tire-pavement interaction to the MTD index of pavement surface it was shown that it is possible to monitor macrotexture through an acoustical signal. It was found that there exists an optimal range in the Spectral Density from about 40 to 400 Hz at 50 mph. Also it was shown that in noisy situations keeping the frequency band from 40 to 400 Hz while changing speeds gave stable results. Yet, the data seems to show that with the change of speed the frequency band should also change, and in situations with less noise this gave a much better correlation. Also, it was confirmed that the higher the speed of a traveling vehicle the higher the correlation. It was shown that microphones around the tire receive a lot of their signal from the tire-pavement interaction even at a fair distance above the ground. It could be observed that raising the microphones about 13 inches lowered correlation of energy to MTD by about 13 percent on average. It was shown that microphone positions 4 or 5 are the best choice for microphone location in monitoring macrotexture. Therefore, it is concluded that by using only microphone position 5 it is very possible to do a continuous, constant, and accurate monitoring of the pavement macrotexture through the sound generated by the tire-pavement interaction.

Also, this study should be carried on further to study the effects of water being present on pavement surface, tire size, and pavement temperature on macrotexture monitoring through the sound generated by the tire-pavement interaction. In addition to monitoring macrotexture, this technique could be used simultaneously to monitor the environmental impact of vehicle noise.
8. REFERENCES


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