A DERIVATION OF AN EMPIRICAL EQUATION FOR ESTIMATING THE ACOUSTICAL SHADOW ZONE LENGTH OF ROADWAY NOISE BARRIERS

by

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ABSTRACT

The objective of this research was to derive an empirical equation that estimates the acoustical shadow zone length (SZL) of roadway noise barriers. The acoustical shadow zone is the area behind a noise barrier of reduced sound levels, generally to some stated level at or near background. The ability to predict the SZL can be used as a method to evaluate the performance, and possibly the design, of roadway noise barriers. The current federally required roadway noise model is the Federal Highway Administration (FHWA) Traffic Noise Model (TNM). TNM uses insertion loss (IL) to evaluate the effectiveness of a barrier. Insertion loss is the difference in sound level between the "no barrier" and the "with barrier" case. One major limitation with TNM is that the reported IL does not take into account how background noise levels influence the mitigated sound levels. Background noise can be defined as the noise present at a barrier location in the absence of roadway noise. The shadow zone represents a region behind the noise barrier where the barrier is effective at reducing noise levels and takes into account how background noise affects the IL and thus the SZL. The inclusion of background noise becomes significant in evaluating barrier effectiveness because as the distance from the barrier increases, background noise begins to overtake roadway noise as the dominate noise source.

The derivation of the empirical equation began by collecting in-situ noise measurements at 18 noise barrier locations across Florida. The measured noise data was supplemented by noise data obtained from computer modeling. After a sufficient quantity of measured and modeled IL data was obtained, a contour of equal IL (IL = 5 dB[(A]) was plotted for each barrier location. The area defined by the contour is called the shadow zone. All the SZLs were statistically compared to several variables that were expected to influence it. Regression modeling showed

that the background noise level, noise barrier height, the distance from the roadway to the noise barrier, and percent of heavy truck traffic volume were statistically significant as useful predictors of SZL. Two empirical equations were derived, one from linear regression and one from polynomial regression, and are referred to as the Shadow Zone Equations as shown below.

1. $SZL_l = 626.5 - (13.1)(L_{99}) + (7.5)(H_{EFF}) + (2.0)(D_R)$

   Where: SZL_l = Shadow zone length as derived from linear regression (feet)

   L_{99} = Background noise level (dB[A])

   H_{EFF} = Effective noise barrier height (feet)

   D_R = Distance from the noise barrier to the center of the roadway (feet)

2. $SZL_p = 4{,}561.9 + 11.6(L_{99}) - 181.4(H_{EFF}) - 139.5(D_R) + 140{,}606.5(HT) + 9.6(L_{99})(H_{EFF}) + 4.1(L_{99})(D_R) - 5{,}637.0(L_{99})(HT) - 1.3(H_{EFF})(D_R) + 4{,}835.3(H_{EFF})(HT) + 980.3(D_R)(HT) - 3.1(L_{99})^2 - 11.0(H_{EFF})^2 - 0.5(D_R)^2 - 93{,}408.0(HT)^2$

   Where: SZL_p = Shadow zone length derived from polynomial regression (feet)

   L_{99} = Background noise level (dB[A])

   H_{EFF} = Effective noise barrier height (feet)

   D_R = Distance from the noise barrier to the center of the roadway (feet)

   HT = Fraction of heavy trucks operating on roadway (0-1.0)

To Mr. John F. Sheehan, who saw more in me than

I saw in myself, and that has made all the difference.

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LIST OF ACRONYMS/ABBREVIATIONS

ANSI	American National Standards Institute
dB	Decibel
dB(A)	A-weighted decibels
DV	Dependent variable
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
Hz	Hertz
IL	Insertion loss
IV	Independent variable
L_{90}	Sound pressure level exceeded 90% of the time
L_{99}	Sound pressure level exceeded 99% of the time
L_{eq}	Equivalent sound pressure level
mks	Meter-kilogram-second
μPa	Micropascal
Pa	Pascal
RMS	Root mean square
SLA	Sound level analyzer
SPL	Sound pressure level
SZL_l	Shadow zone length as derived from linear regression
SZL_p	Shadow zone length as derived from polynomial regression
TNM	Traffic Noise Model®

CHAPTER ONE: INTRODUCTION

Currently, the most common way to evaluate the effectiveness of roadway noise barriers is to determine the parameter known as insertion loss (IL). The IL is the sound level difference between the "without barrier" and the "with barrier" cases at a specific point behind a noise barrier. One limitation with this method is that the effectiveness of a barrier is known only at a specific point behind a barrier and only for a specific level of effectiveness (specific value of IL). Knowing the value of IL only at a specific point behind a noise barrier yields no indication as to what the IL is at some point closer to or farther from the barrier. It would be beneficial to know the effectiveness of a noise barrier at any point behind the barrier (the effective range of a noise barrier) since noise sensitive locations, such as dwellings and places of worship, are typically located at various locations behind a noise barrier. In order to determine the noise barrier effectiveness at reducing noise levels at each of these locations the IL must be measured or modeled at multiple locations and this technique must be repeated every time a different noise barrier location is evaluated. If many IL points were known at various distances and at various heights above the ground behind a noise barrier, a contour of equal IL could be estimated. This contour would describe the effectiveness of a noise barrier not just for a particular point in space but for an entire area behind the noise barrier. This area behind the noise barrier, defined by the contour, which begins at the top of the noise barrier and extends some distance from the barrier before reaching the ground, is called the shadow zone. The shadow zone is the area behind a noise barrier of reduced sound levels. Any noise sensitive location that lies within the shadow zone, regardless of its location behind the barrier, is said to receive a specific value of IL that may meet or exceed some stated criterion. This eliminates the need to measure or model every noise sensitive location to determine its IL. Any noise sensitive location that lies outside the shadow zone is said to receive less IL than the stated criterion. In other words, the barrier is not considered effective for these noise sensitive locations. So, the most important and difficult aspect of shadow zones is predicting how far they will extend from the noise barrier. Shadow zone contours can be developed for multiple noise barrier locations, and an analysis can be performed to find a relationship between the shadow zone lengths (SZLs) and the variables known to influence it. Once that relationship is determined, and found to be statistically significant, it can be applied to other similar noise barrier locations to determine that barrier's unique shadow zone length. The objective of this research was to define this relationship, in the form of an easy to use equation, so that it could be used to predict the length of roadway noise barrier shadow zones. The criterion used was defined as the IL = 5 dB(A) for the purposes of evaluating barrier effectiveness, barrier design, and providing a graphical representation of a barrier's effective range. The reason for selecting this criterion is explained in the next chapter.

The first part in developing the shadow zone equation was to develop a method to plot the shape of the shadow zone. This was done by obtaining measured sound levels at various noise barrier locations. From the measured sound levels at various points behind the barrier, IL was calculated (see Chapter 2). Since the number of measured IL points was not sufficient to determine the shadow zone shape, computer modeling was used to determine IL at additional locations behind the barrier to supplement the measured IL data points. Once a sufficient number of IL points from field measurements and modeling were obtained, a contour of equal IL was plotted using contouring software. The contour criterion chosen was equal to an IL of 5 dB(A). This contour defines the shape and length of the 5 dB(A) shadow zone. The SZL was estimated for several noise barrier locations across Florida.

The last part in developing the shadow zone equation was to conduct a multiple regression analysis to determine if the SZL could be estimated using a certain set of variables known, or expected, to have an influence on the SZL. The variables included in the regression analysis were background noise levels, barrier height, distance from the noise source to the barrier, fraction of heavy truck traffic volume, and the average traffic speed. The statistical analysis produced two equations, one based on a linear regression model and the other based on a polynomial regression model, that were statistically significant as useful tools for estimating the SZL of roadway noise barriers. These regression models are called the Shadow Zone Equations.

CHAPTER TWO: LITERATURE REVIEW

This chapter discusses the terminology and concepts that are necessary to establish an understanding of roadway noise barrier shadow zones and the method developed to estimate their lengths. There is also a discussion on the methods used to collect and analyze noise data. The chapter ends with a review of another research work also devoted to estimating shadow zone lengths.

Fundamentals of Applicable Acoustics

Noise is defined as unwanted sound. Highway noise is an example of unwanted sound. The measure of sound is expressed in units of decibels, dB, as defined in Equation 1.

$$\text{SPL (dB)} = 10\log_{10}\left(\frac{P_{RMS}}{P_{REF}}\right)^2 \qquad (1)$$

Where: SPL = Sound pressure level (dB)

P_{RMS} = Measured root mean square pressure (μPa)

P_{REF} = Reference root mean square pressure (20 μPa)

The decibel is based on a logarithmic scale that encompasses the wide dynamic range of sound pressure fluctuations that the human ear has an ability to perceive. The sound pressure levels the human ear can detect ranges from the threshold of hearing (20 μPa) to the threshold of pain (63 Pa). The corresponding range in decibels is 0 to 130 dB.

The normal hearing range covers frequencies from 20 to 20,000 Hz. Since the human ear is not equally sensitive to all frequencies (highest sensitivity between 200 to 10,000 Hz), weighting schemes have been developed that approximate the way the human ear responds to noise. The most commonly used weighting scheme for outdoor community noise is called the A-weighted scale. Sound levels expressed in A-weighted decibels use the notation dB(A). Time-varying noise levels are often expressed in terms of an acoustic average noise metric known as the equivalent sound pressure level, L_{eq}. The L_{eq} is the noise level that if held constant over a period of time would contain the same acoustical energy as the actual measured fluctuating noise level over the same time period. The L_{eq} is mathematically defined by Equation 2.

$$L_{eq} = 10\log_{10}\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} 10^{\frac{L(t)}{10}}\,dt\right] \tag{2}$$

Where: L_{eq} = Equivalent sound pressure level (dB[A])

$L(t)$ = Sound pressure level at any time t

t_1 = Beginning of noise measurement

t_2 = End of noise measurement

To understand the concept of an acoustical shadow zone, it is also important to understand how a noise barrier works to reduce noise levels. The sound approaching a noise barrier is reduced on the opposite side of the barrier by absorption, reflection, transmission and diffraction as shown in Figure 1.

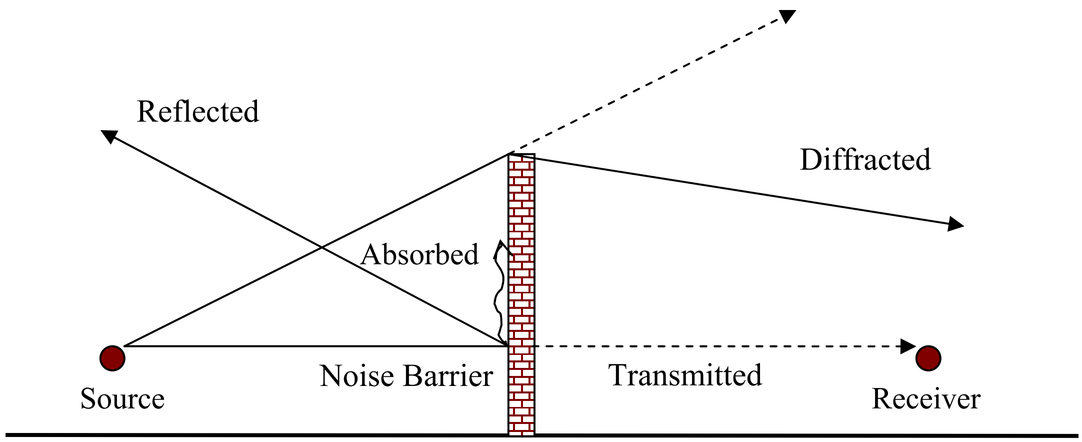

Figure 1: Barrier Reflection, Absorption, Transmission, and Diffraction

Reflected sound "bounces" off the surface of a barrier and is usually only a concern when it affects receivers (noise sensitive locations) on the opposite side of the noise source. The amount of sound absorbed by a noise barrier is commonly expressed in the industry as a frequency dependent absorption coefficient (α), which is a measure of the ratio of the energy absorbed to the amount of incident energy and the unit of measure is called Sabines, and may be related to the overall frequency range by use of a derived term called the noise reduction coefficient (NRC). An NRC of zero means the barrier is totally reflective, whereas an NRC coefficient of 1.0 means the barrier is totally absorptive. The NRC is the arithmetic average of the absorption coefficients at 250 Hz, 500 Hz, 1,000 Hz, and 2,000 Hz.

Some of the sound incident on the barrier face will be transmitted through the barrier to the receiver. Typically, with barrier material of sufficient mass per area (4 lbs/ft^2 or more) and no gaps, the sound transmitted through a noise barrier will be at least 20 dB(A) below the sound that goes over or around the barrier. Since decibels are on a logarithmic scale, the transmitted noise levels are two orders of magnitude less and considered negligible.

Diffraction is the phenomenon by which noise is attenuated by a noise barrier. Diffraction is the ability for sound waves to bend around corners, or in the case of noise barriers, the ability to bend over the top or travel around the ends of the barrier and propagate to receivers on the other side. This ability to diffract, or bend, over the top of a noise barrier is frequency dependent. Lower frequencies (long wavelengths) diffract over the top of a barrier easily whereas higher frequencies (short wavelengths) bend less. As shown in Figure 2, instead of sound traveling directly from the source to the receiver, called the direct path (segment c), the sound must travel up and over the top of the barrier, then bend or diffract downward toward the receiver, called the diffracted path (segments a & b).

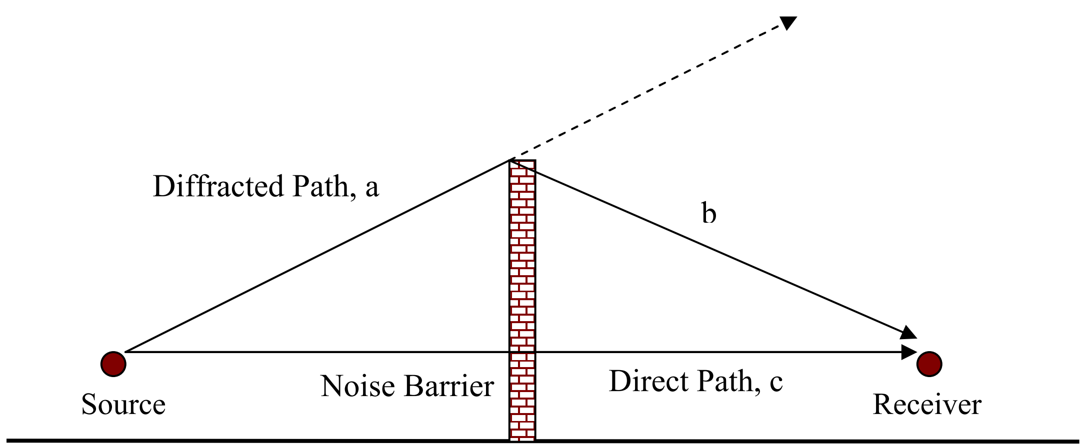

Figure 2: Diffracted and Direct Path

The difference between the diffracted path and the direct path is called the path length difference, δ, and is often used as a surrogate for the real attenuation variable—the angle the wave must turn. The variable that combines both frequency and path length difference is the dimensionless quantity called the Fresnel number (N). The Fresnel number is used in predicting the attenuation provided by a noise barrier and is calculated using Equation 3.

$$N = 2\,\frac{\delta}{\lambda} = 2\,\frac{f\delta}{c} \qquad (3)$$

Where: N = Fresnel number

δ = Path length difference = a + b - c (distance)

λ = Wavelength (distance)

f = Frequency (Hz)

c = Speed of sound (distance/time)

Insertion loss differs from barrier attenuation in that IL not only takes barrier attenuation into account but also shielding, ground effects, transmission loss, reflections, flanking noise, and to a lesser extent, atmospheric refraction. The definition for IL is given by Equation 4.

$$IL = SPL_{before} - SPL_{after} \qquad (4)$$

Where: SPL_{before} = Sound pressure level before barrier (or without barrier)

SPL_{after} = Sound pressure level after barrier (or with barrier)

Kurze and Anderson [1] developed an equation for IL, shown in Equation 5, and applies to a single vehicle at its closest point to the receiver.

$$IL = 5dB + 20\log\frac{\sqrt{2\pi N}}{\tanh\sqrt{2\pi N}} \quad \text{for } -0.2<N<12.5 \tag{5}$$

Where: IL = Insertion loss (dB[A])

N = Fresnel number

From this equation, it can be seen that when a barrier just breaks the line of sight from source to receiver (i.e., $\delta = 0$, thus N = 0) the IL is 5 dB(A) with a theoretical maximum IL of 24 dB(A) for N = 12.5. Also evident is that some attenuation occurs even before the line of sight is broken. A negative N means that the receiver is in the illuminated zone and a positive N means that the receiver is in the shadow zone. From the equation for N and IL, as δ increases, so does the barrier attenuation. If all other parameters stay the same, IL increases as well. Also, as frequency increases, so does IL. A form of this equation is used in the Federal Highway Administration (FHWA) Traffic Noise Prediction Model [2]. For N values greater than unity, Equation 5 can be approximated using Equation 6.

$$A_d = 10\log_{10}(3 + 20N) \tag{6}$$

Where: A_d = Attenuation due to diffraction (dB[A])

N = Fresnel number

The FHWA Traffic Noise Model (TNM) [3] uses the diffraction theory developed by DeJong [4]. This theory was based on work done by Pierce [5] and Jonasson [6] and accounts for impedance discontinuities and wedge diffraction. The DeJong approach, as implemented in TNM, is shown in Equation 7.

$$D = \frac{Re^{-i\frac{\pi}{4}}}{L\sqrt{\pi}} e^{ik(L-R)} e^{-i\chi^2} F(\chi) \tag{7}$$

Where: D = Diffraction coefficient (dimensionless)

R = Direct-line distance from source to receiver (distance)

L = Propagation path length (distance)

k = Wave number (inverse distance)

$F(\chi)$ = Fresnel integral (dimensionless)

Since a roadway is a line source, the amount of IL will vary as distance changes from the point closest to the receiver, a summation of IL along the entire line source needs to be calculated using Equation 8.

$$IL_{total} = 10\log_{10}\frac{1}{\pi}\int_{\theta L}^{\theta R} 10^{IL_{\theta}/10} d\theta \tag{8}$$

Where: θR = Angle formed to the right of the straight line between source to receiver

θL = Angle formed to the left of the straight line between source to receiver

IL_{θ} = The insertion loss any angle θ (dB[A])

The other parameter that affects N, and thus the IL, is wavelength or frequency as shown in Equation 3. As the speed of air molecule vibration (frequency) changes, so does the noise spectra as shown in Figures 3 and 4 [7]. As vehicle speed increases, the sound pressure level for low frequency (about 500 Hz or less) and high frequency octave bands (about 3,000 Hz or greater) decreases. For the mid-range frequencies, the sound pressure level increases or remains constant. Since frequency varies with vehicle speed, the speed variable was included in the shadow zone analysis.

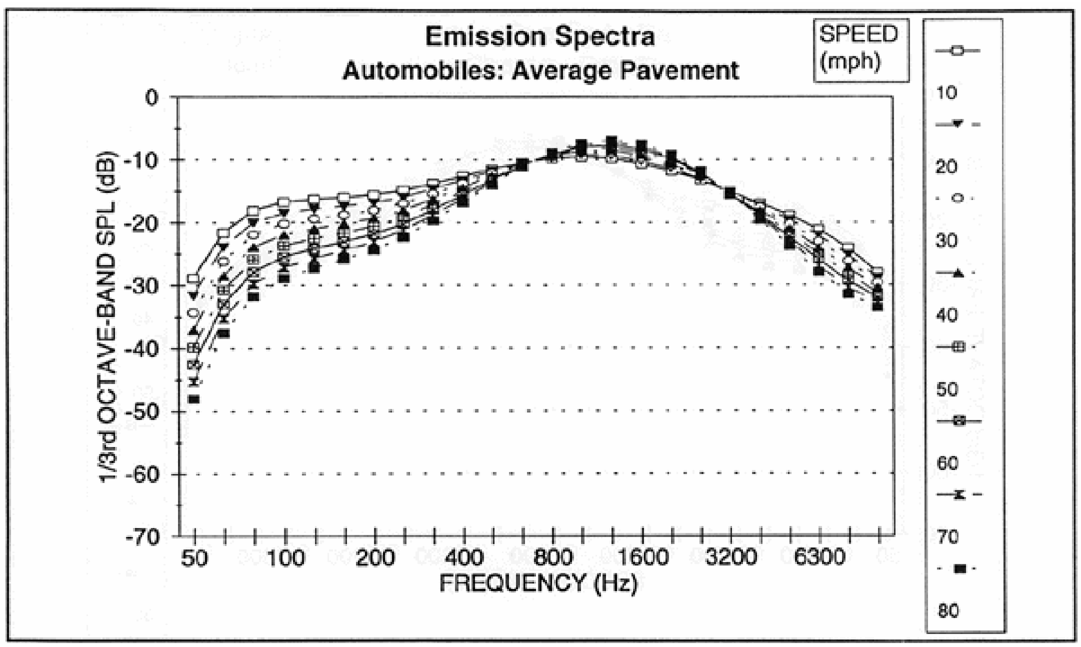

Figure 3: Emission Spectra for Automobiles [7]

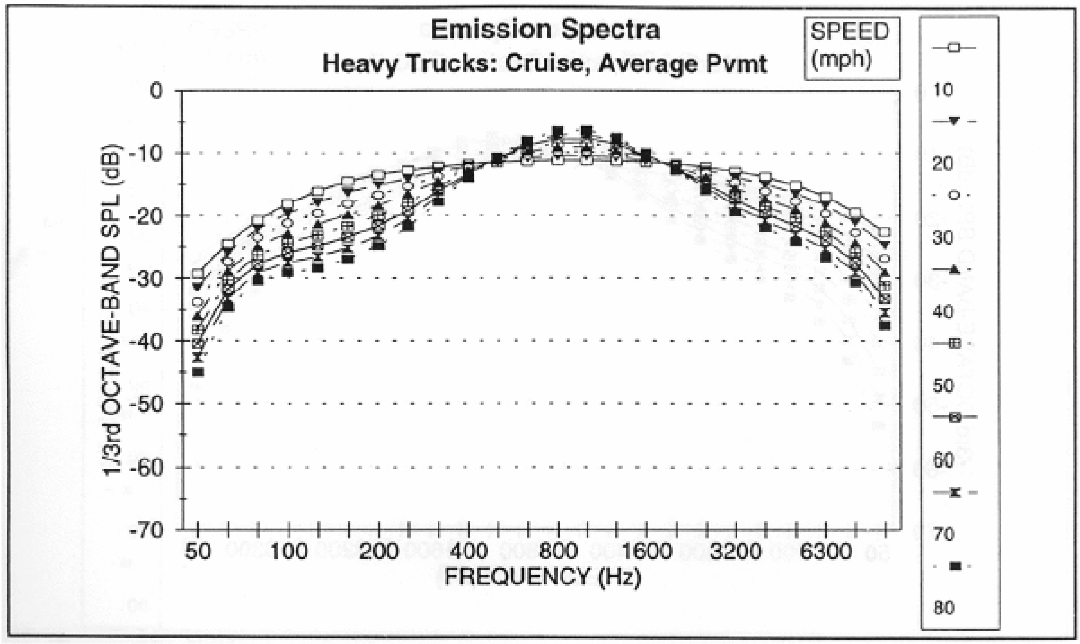

Figure 4: Emission Spectra for Heavy Trucks [7]

As was shown in Figure 5, on the receiver side of the noise barrier, there is an area of decreased noise levels called the acoustical shadow zone. Above the shadow zone is an area called the illuminated zone. In the illuminated zone, there is no reduction in noise associated with the noise barrier because the noise travels above the barrier and does not need to pass around it, thus does not experience barrier absorption, reflection, transmission, and diffraction. The imaginary boundary that separates the shadow zone from the illuminated zone is called the line of sight. This is the straight line path between the source and the top of the noise barrier. However, due to diffraction and scattering, sound will penetrate into the shadow zone causing it to decrease with distance from the barrier. Another factor contributing to the decrease in the shadow zone is background noise. This is the noise level on the receiver side of the noise barrier that does not include the noise from the source. This background noise is also the acoustic floor because the reduced noise level resulting from the noise barrier can never go below the background noise level.

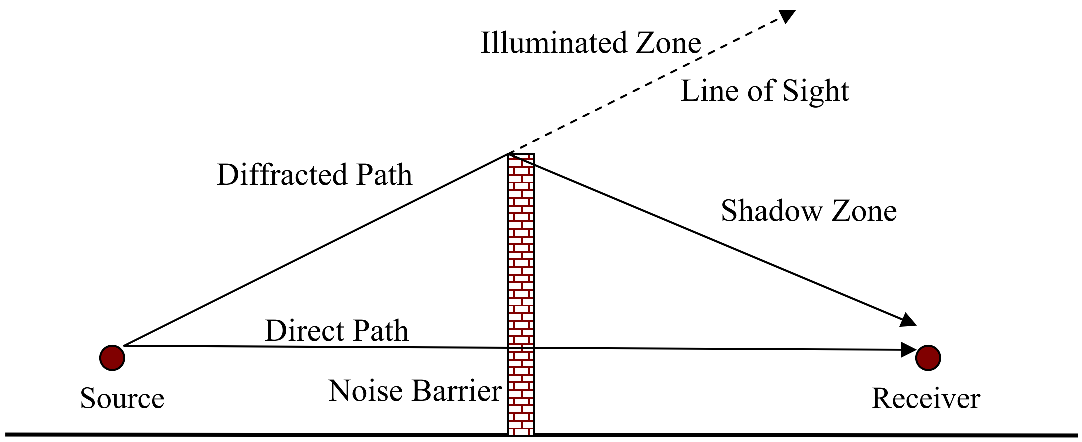

Figure 5: The Illuminated and Shadow Zones

Sound emitted from a line source, such as a roadway, will be emitted to the receiver in the shape of a cylinder around the source (roadway). Since a line source is an infinite number of point sources, spreading occurs for each point as the circumference of a circle. As the sound travels, the sound energy is distributed along an ever increasing area and a receiver is exposed to only a part of the total sound energy. How much sound energy reaches a receiver is dependent on distance. The farther the source is from the receiver, the more the sound energy is spread over a greater area. This reduction in sound due to distance between the source and receiver is called attenuation due to geometric spreading and is defined in Equation 9 for a line source.

$$A_{geo} = 10\log_{10}\left(\frac{D_1}{D_2}\right) \tag{9}$$

Where: A_{geo} = Attenuation due to geometric spreading (dB[A])

D_1 = Distance from the source to point 1

D_2 = Distance from the source to point 2

From this equation, A_{geo} is 3 dB(A) per doubling of distance for a line source. Note that for point sources, such as a single vehicle driving on the roadway, spreading occurs in a spherical shape, not a circle and the terms in parenthesis would be squared and the equation would yield 6 dB(A) per doubling of distance.

The ground can affect the noise propagating over it either negatively or positively. An acoustically soft surface will react with the wave and attenuate the sound. Acoustically soft surfaces are those with porosity and include grass and loose gravel. Acoustically hard surfaces, which do not allow the wave to enter the surface will not reduce noise and include surfaces such as asphalt and water. The cause for this is that a sound wave incident upon the ground surface will reflect off the ground at the angle of incidence, rather than be absorbed, and will propagate to the receiver along with the direct wave. Depending on the phase and amplitude of the reflected wave as compared to the direct wave there may be destructive interference or constructive interference effects on the wave resulting in a change in the sound level. There are various methods used to calculate the attenuation due to ground effects.

The simplest ground effect method is the alpha factor method. This method was used by FHWA prior to the development of a newer, more advanced model [2]. This method incorporates the ground attenuation with the geometric spreading term of Equation 9 and is shown below in Equation 10.

$$A_g = 10\log_{10}\left(\frac{D}{D_o}\right)^{1+\alpha} \tag{10}$$

Where: A_g = Attenuation due to geometric spreading and ground effects (dB[A])

D = Distance from source to receiver of interest

D_o = Distance from source to reference receiver

α = Alpha factor (= 0 for hard ground, = 0.5 for soft ground)

From Equation 10, for propagation over hard ground, ground effects are negligible and equal to 3 dB per doubling of distance. For propagation over soft ground, sound pressure level is attenuated an additional 1.5 dB(A) per doubling of distance.

Another method to calculate attenuation due to ground effects comes from Beranek [8]. Equation 11 was empirically derived and includes a term for vertical geometry.

$$A_g = 4.8 - \left(2\frac{h_m}{d}\right)\left(17 + \frac{300}{d}\right) \tag{11}$$

Where: A_g = Attenuation due to geometric spreading and ground effects (dB[A])

h_m = Average source height and receiver height (meters)

d = Distance from source to receiver (meters)

Additional methods have been developed to calculate ground attenuation such as Chessell's [9] ground absorption model that is currently used in the new FHWA model, TNM [3]. This method computes the reflection coefficient. Chessell included the work of Delaney and Bazley [10] who defined ground impedance by a single parameter called flow resistivity, σ.

Embleton et al. [11] expanded this work by conducting measurements and determining an empirical relationship between ground type and σ. The reflection coefficient equation implemented in TNM is shown in Equation 12 below [7].

$$Q = R_p + F(w)\,(1-R_p) \tag{12}$$

Where: Q = reflection coefficient of a spherical wave from a surface (dimensionless)

$R_p = \dfrac{\sin\varphi - \dfrac{Z_o}{Z}}{\sin\varphi + \dfrac{Z_o}{Z}} =$ Reflection coefficient of a plane wave from a surface (dimensionless)

F(w) = Ground wave function (dimensionless)

φ = Angle of incidence

Z_o = Air impedance (dimensionless)

Z = Ground impedance (dimensionless)

The ground impedance equation implemented in TNM is shown in Equation 13 below [7].

$$Z = \left[1 + 0.051\left(\frac{f}{\sigma}\right)^{-0.75} + 0.077\left(\frac{f}{\sigma}\right)^{-0.73} i\right] Z_o \tag{13}$$

Where: Z = Ground impedance (dimensionless)

f = Frequency (Hertz)

σ = Effective flow resistivity (mks rayls)

Z_o = Air impedance (dimensionless)

Meteorology can also affect sound propagation, primarily through the phenomena of refraction. Refraction is the bending of sound waves due to wind and temperature gradients. Receivers upwind from a noise source tend to hear less sound from the source because sound waves tend to refract upwards. Conversely, receivers downwind from the noise source hear an increase in sound because sound waves refract toward the ground. Temperature gradients affect sound refraction by causing sound waves to refract upward during a normal temperature lapse rate resulting in a decrease in sound levels. Conversely, during an inversion, sound waves are refracted towards the ground resulting in an increase in sound levels. As can be seen, the waves tend to bend toward the colder regions. Other meteorological phenomena include atmospheric absorption and turbulence. When present, both contribute to reduce sound levels.

Data Collection and Analysis

The opportunity to study roadway noise barrier shadow zones occurred during the Florida Department of Transportation (FDOT) sponsored research on the effectiveness of noise barriers [12][13]. The purpose of these barrier effectiveness studies was to evaluate IL for in-situ noise barriers across Florida. There were a total of 18 noise barrier locations evaluated between the two FDOT studies. The noise barrier locations are shown in Table 1 and are assigned an alphabetical name for simplicity.

Table 1
Noise Barrier Locations [12][13]

Location Name	Location	Roadway Noise Source
A	Jacksonville	I-95
B	Jacksonville	I-295
C	Daytona Beach	SR 5A
E	Brandon	I-75
F	Clearwater	SR 636
G	St. Petersburg	SR 682
H	Ft. Lauderdale	I-95
I	Deerfield Beach	I-95
J	Miami	I-295
K	Tamiami	US 41
L	Hialeah	SR 924
M	Wildwood	SR 44
N	Maitland	SR 414
O	Ft. Lauderdale	I-95
P	Boynton Beach	I-95
Q	Palm Beach Gardens	I-95
R	Palm Harbor	SR 586
S	New Port Richey	SR 54

Note: Location D was excluded due to insufficient measured data points.

The primary goals of the FDOT barrier effectiveness studies were to determine if Florida noise barriers were performing as modeled and if they met expected effectiveness. FDOT's minimum design goal for noise barrier IL is a minimum of 5 dB(A) at the first row receivers (noise sensitive locations such as houses) with an overall design goal of 10 dB(A) or more [14]. Although not the purpose of these studies, it was soon realized that much of the data collected could be used to study shadow zones.

The method used to determine IL was the American National Standards Institute (ANSI) indirect method [15]. This method was used since all the noise barriers were already in place. The method suggests the use of a noise model, such as TNM, to predict the sound levels that would exist if the barrier was not in place. It should be noted that there were three barrier locations where sound levels were able to be measured without the influence of the noise barrier. At Site H, in Ft. Lauderdale, sound levels were measured beyond the end of the barrier. At Site R, in Palm Harbor, sound levels were measured on the opposite side of the roadway from the barrier. Finally, a location in Longwood (designated Site T in the Florida barrier effectiveness study [13]) currently does not have a noise barrier in place but one will be built in the near future. As such, it was possible to measure the sound pressure level without the barrier at this location. Without a barrier there is no IL, so Site T was not included in this research.

Noise measurements were collected at each noise barrier location and the list of equipment used to conduct these measurements is provided in Appendix A. Microphones were arranged in an array as shown in Figure 6 and is based on ANSI procedures [15]. Although the ANSI procedure was written using metric units, they have been converted to English units here.

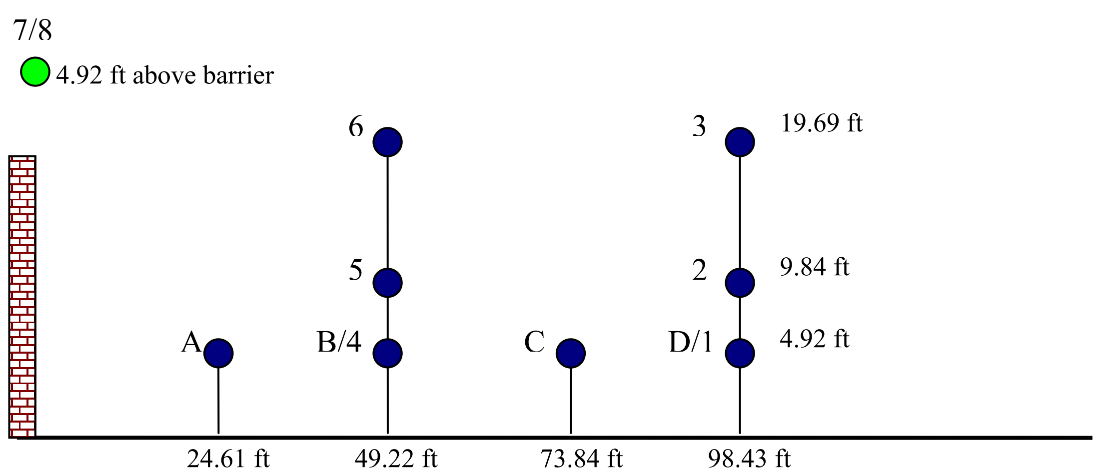

Figure 6: Microphone Positions

The blue circles represent microphone locations behind the barrier and placed at about 5, 10, and 20 feet above the ground and at increments of about 25 feet from the noise barrier so that the last column of microphones was approximately 100 feet from the noise barrier. Two "reference" microphones, represented by the green circle, were placed about 5 feet above the noise barrier in the illuminated zone to measure the "without barrier" noise levels. Two microphones were placed at this location for quality assurance purposes. The microphones labeled with numbers (i.e., 1, 2, etc.) mark the locations of the Ivie Electronics one-third octave band analyzers. The microphones labeled with letters (i.e., A, B, etc.) mark the location where Metrosonics db308 broadband (A-weighted) sound level analyzers (SLA) were placed and used concurrently to collect overall A-weighted sound levels. Microphones "B" and "4" share the same location as do microphones "D" and "1". The purpose of collocating was for quality assurance. Four sample runs of 20 minutes in duration were conducted at each barrier location. Concurrently, traffic volume counts and speeds were obtained for each vehicle class (automobiles, heavy trucks, medium trucks, buses, and motorcycles). Unusual or interfering noise events such as aircraft flyovers and barking dogs were noted so they could be further analyzed and, if necessary, removed during the data analysis phase. Meteorological data was also collected during the sample runs and included wind speed, wind direction, temperature, and relative humidity.

After collecting the noise data, various data reduction techniques were performed through a series of quality assurance (QA) checks. Once the data was reduced, the equivalent sound energy (L_{eq}), IL, and correction factors were calculated for each microphone for each noise barrier location. Additionally, the background noise level (L_{99}) was calculated for each location. The first QA check was removing interfering events, such as aircraft flyovers, from the measured noise data. These events were removed from the data if they were identified as outliers. Outliers were identified as measured noise levels that lied outside 2 standard deviations (2σ) from the mean. This criterion was chosen because statistically about 95% of all observations from a normally distributed population should lie within 2σ.

The next QA check compared A-weighted levels supplied directly from the Ivies with that derived from one-third octave data. The two A-weighted levels should correlate closely and this QA check determined just how close they correlated and the results helped to determine which A-weighted levels (the levels supplied directly by the Ivies or derived from the one-third octave data) would be used for further computations. An example of this QA check is shown in Figure 7. Each point is the difference between the A-weighted levels derived from one-third octave data and the A-weighted levels obtained directly from the Ivies. As depicted, the A-weighted levels directly from the Ivies are consistently higher than those derived from the one-third octave data. This disparity suggests that one of the two A-weighted levels may be in error and perhaps should not be used and that an additional QA check should be conducted.

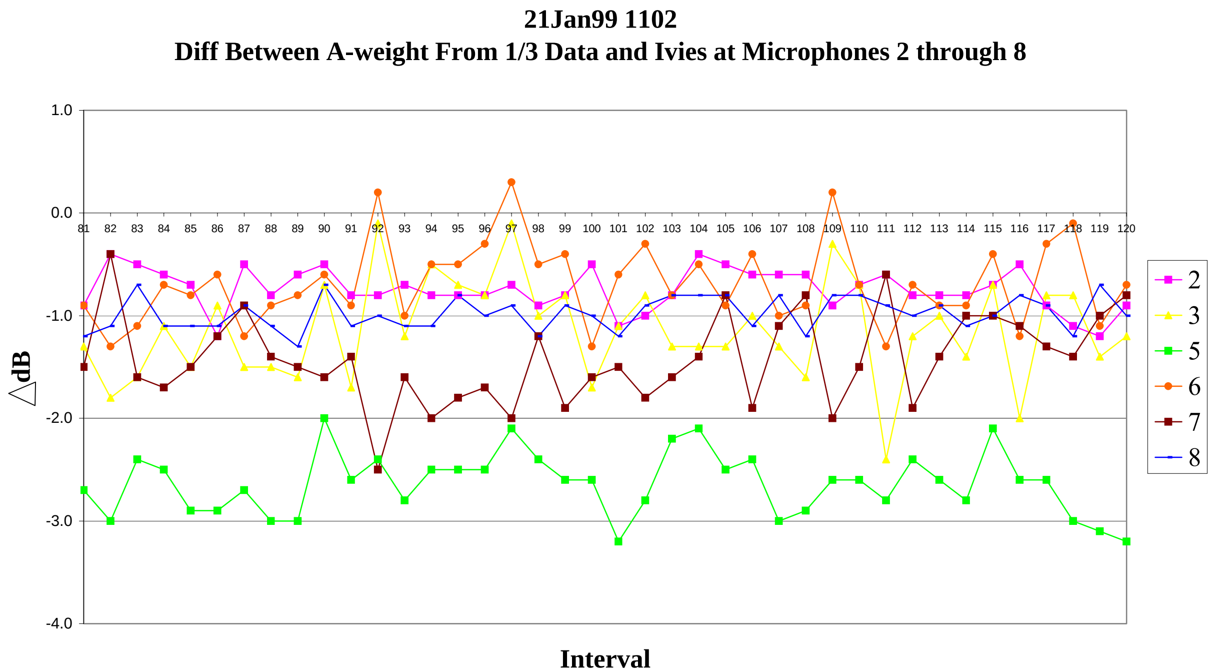

Figure 7: Difference Between A-Weighted Levels Obtained From Ivies and One-Third Octave Data

The next QA check was the comparison of the A-weighted levels between Ivies 7 and 8. These two Ivies were located adjacent to each other above the barrier and their readings should correlate closely. This QA check was done to ensure reliability of the non-attenuated noise measurements. An example of this QA check is shown in Figure 8 and shows that Ivies 7 and 8 tracked closer together for A-weighted values derived from one-third octave data than those directly from the Ivies. As a result of this, along with the findings of the previous QA check, A-weighted levels for further computations and analysis should be those derived from one-third octave data and those supplied directly from the Ivies should be discarded. In addition, data points that exceeded 2 dB(A) between Ivies 7 and 8 were discarded.

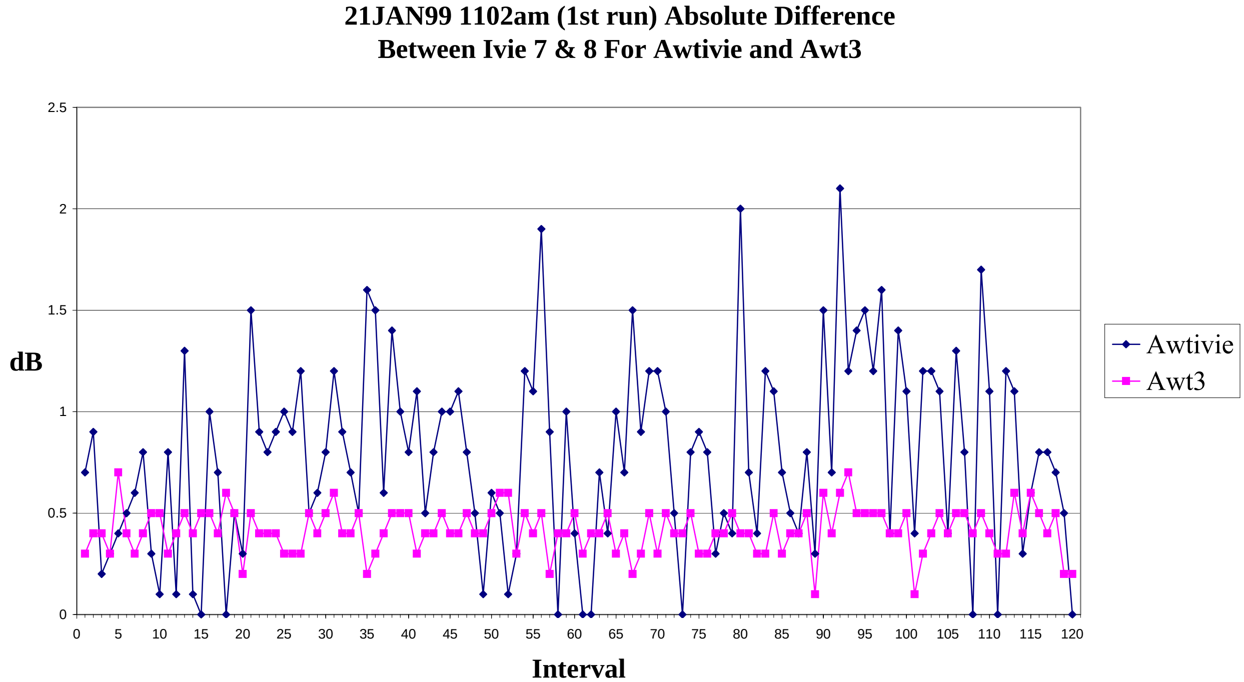

Figure 8: A-Weighted Noise Level Difference Between Ivies 7 & 8

The next QA check was the comparison of Ivies 1 and 4 A-weighted levels with their adjacently located Metrosonics unit, D and B, respectively. Since the Metrosonics units were located adjacent to each of these Ivies, their readings should correlate closely. This QA check was done to ensure reliability of the attenuated noise measurements. An example of this QA check is shown in Figure 9 and showed that the A-weighted levels derived from the one-third octave data tracks closer with the Metrosonics data than the A-weighted levels supplied directly from the Ivies. This is further evidence that A-weighted data reported directly from the Ivies should be discarded and that the A-weighted levels derived from the one-third octave data should be used for further computations.

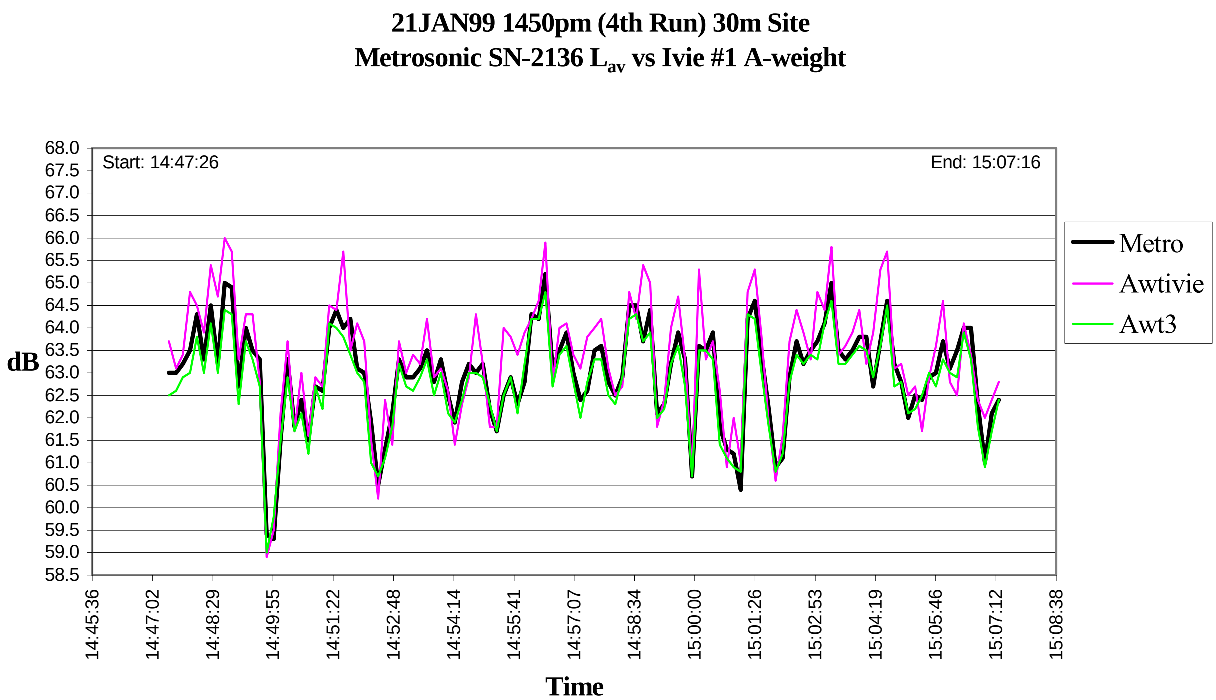

Figure 9: Comparison of A-Weighted Noise Levels Between Ivies and Metrosonics

The next QA check was to plot the A-weighted levels of each Ivie to detect any aberrant readings. An example of this QA check is shown in Figure 10 and shows that the noise levels from Ivies 1 and 4 are suspect. For this particular run, the data recorded by Ivies 1 and 4 were discarded.

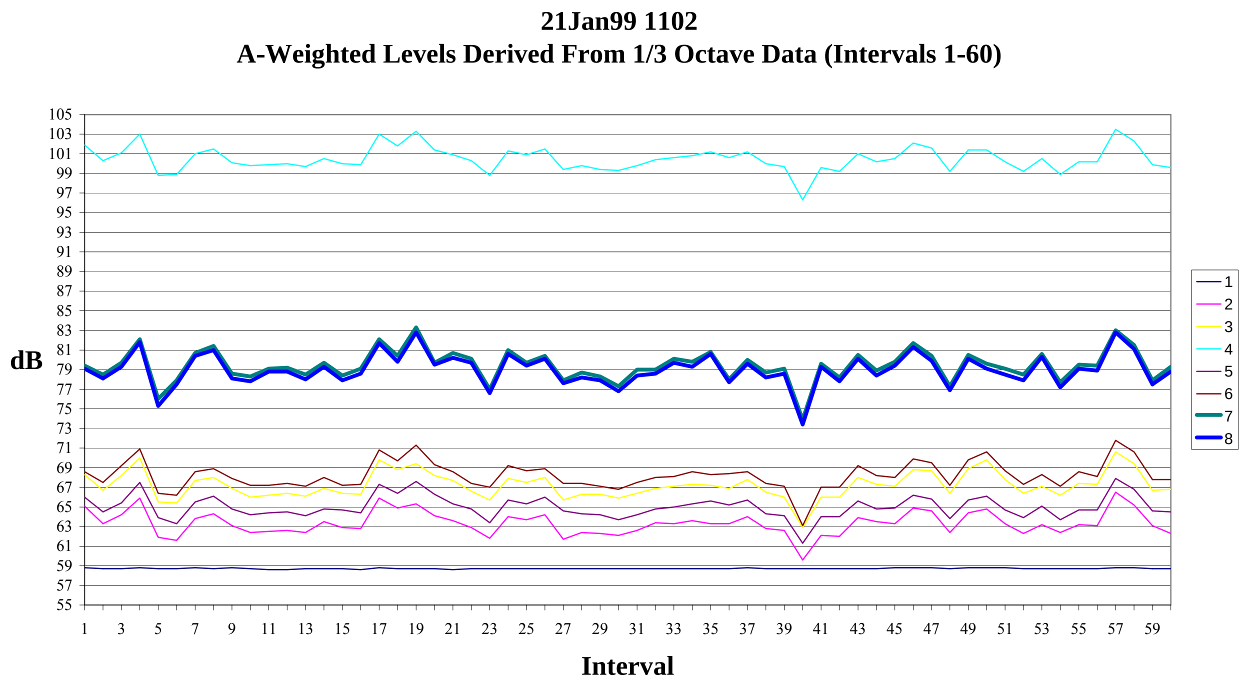

Figure 10: A-Weighted Levels of All Ivies

The final QA check was to analyze the frequency spectra at Ivies 1 through 6 as compared to the reference microphones (Ivies 7 and 8). An example spectra is shown in Figure 11. The top spectra curve was measured at the reference microphone location and the bottom spectra curve was measured at the Ivie 1 location. The example spectra curves showed the reduction in noise level as a result of the noise barrier. As expected, the reduction is not as great for lower frequencies (long wavelength) as it is for higher frequencies (short wavelengths) since lower frequencies diffract over the top of the noise barrier more efficiently. Also observed was the phenomena of ground attenuation which occurred at low frequencies between 100 and 1000 Hz. This extra attenuation was not seen in the reference microphone spectra which is located high above the ground.

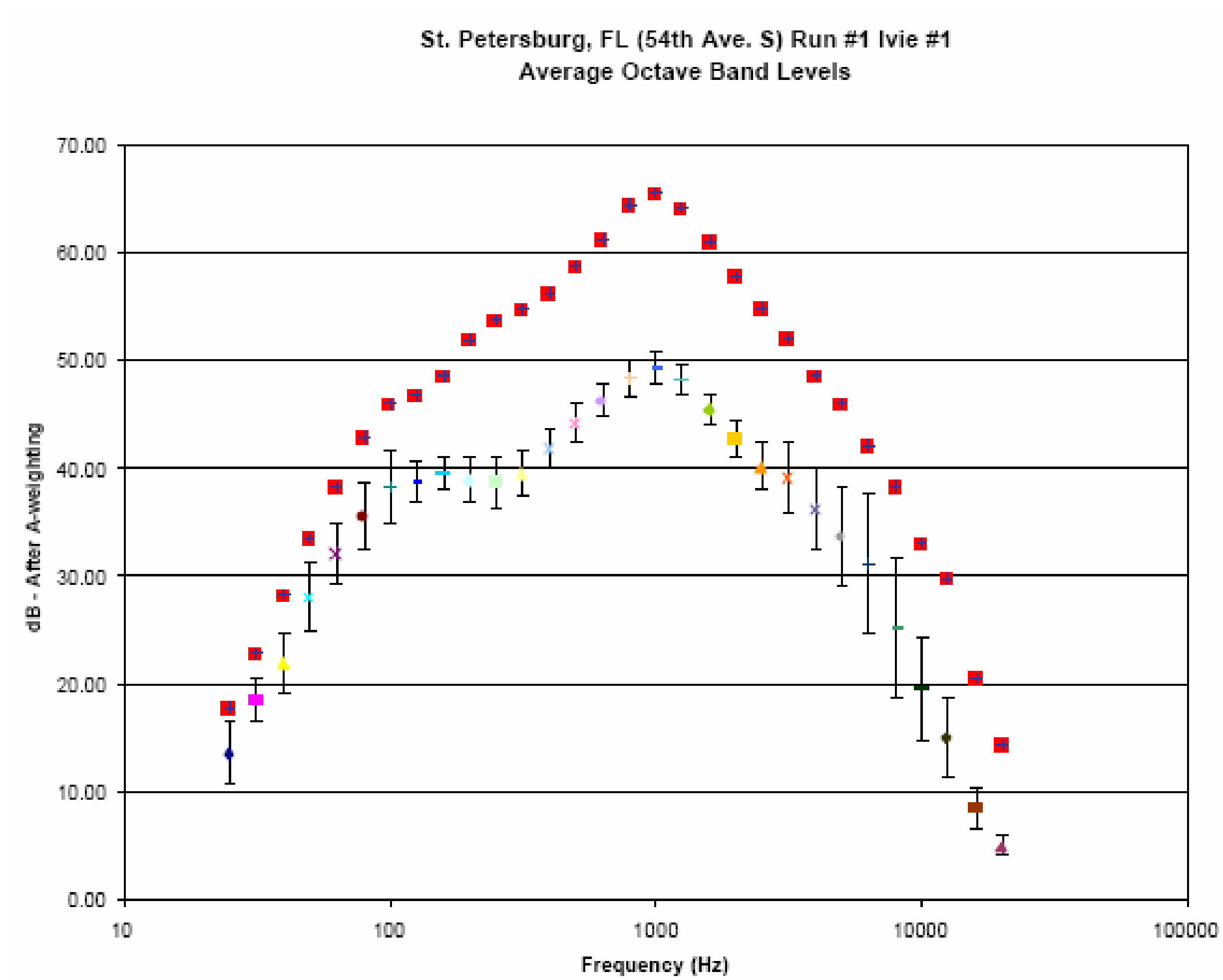

Figure 11: Typical Frequency Spectra Comparison.

Once the data reduction of the measured data was completed, the average sound levels were calculated for each 20 minute sampling period and for each noise barrier location. The results are shown in Appendix B.

Other Shadow Zone Research

MacDonald, Wayson, El-Aassar, and Berrios [16], also investigated the development of empirical equations for predicting the SZL behind roadway noise barriers and was published during, but independently of, the shadow zone research contained herein. Much of the data used by MacDonald et al. also came from the Florida noise barrier effectiveness studies [12][13], however the methodology used to estimate the SZL varied significantly. Four SZL prediction methods were developed and their average prediction error was calculated. The method with the lowest average error in SZL was the "regression with background source" method. This method was developed by estimating the location and strength of a simulated background source. This was combined with regression modeling to relate the change in sound level, as compared to the reference position (see Figure 6), at any position behind the noise barrier. The variables used in the regression model to determine the location of the edge of the shadow zone included vertical and horizontal geometry, background noise level, and the fraction of traffic volume that is heavy trucks. From this, multiple expressions were developed and one, a regression equation, was developed to estimate the SZL as shown in Equation 14.

$$SZL = 616.5 + (2.2)(Barrier) - (9.6)(L_{90}) + (1.3)(Road) - (530.5)(HT) \quad (14)$$

Where: SZL = Shadow zone length behind barrier (feet)

Barrier = Height of barrier (feet)

L_{90} = Background sound level (dB[A])

Road = Distance from barrier to roadway centerline (feet)

HT = Fraction of heavy trucks operating on roadway (0-1.0)

Equation 14 predicts the length of the 5 dB(A) shadow zone (away from the barrier ends to avoid the effects of flanking noise). This means the predicted SZL included all levels of IL from 5 dB(A) on up, which is the same shadow zone that is the focus of this research. The 5 dB(A) SZL indicates how far from a noise barrier that an IL of at least 5 dB(A) occurs. The 5 dB(A) shadow zone is of particular importance because it is the FDOT minimum noise reduction design goal for noise barriers [14].

Rover measurements, at locations beyond approximately 100 feet from the noise barrier were used to develop and evaluate the method of locating the position and strength of a generic background source. The method of determining the location and strength of the background source involved an automated residual minimization technique. The technique varied the location of a virtual background point source, its distance behind the barrier and above the ground plane, and also varied its strength. Under each scenario, the superposition of the background source, the change in sound level between the reference position and each microphone, barrier location, and the average error for all microphones was computed. The background source location and strength that produced the minimum average error for all locations and microphones was chosen as the optimum location and strength of a virtual background source.

The shadow zone equation, Equation 14, produced a $R^2 = 0.701$ when predicting SZL and had an average error of 31 feet. The next section offers an alternative method to derive the shadow zone equation.

CHAPTER THREE: METHODOLOGY

This section describes the methodology used to develop an empirical equation that estimates the acoustical shadow zone length (SZL) of roadway noise barriers (here on out referred to as the *shadow zone equation*). Typically, a roadway noise barrier is evaluated in terms of insertion loss (IL) as discussed in Chapter 2.

The acoustical shadow zone as defined in this research represents an area behind the noise barrier where the IL at any location within the shadow zone is greater than zero. Given sufficient IL points, the shape of the shadow zone can be estimated. The shadow zone of interest is the area behind the noise barrier where every point within that area receives an IL of 5 dB(A) or greater. The 5 dB(A) shadow zone is of particular interest because this is the Florida Department of Transportation's (FDOT's) criterion to establish benefited receivers. FDOT and other states also use this as the minimum design for constructing noise barriers [14]. A hypothetical 5 dB(A) shadow zone can be graphically displayed as shown in Figure 12.

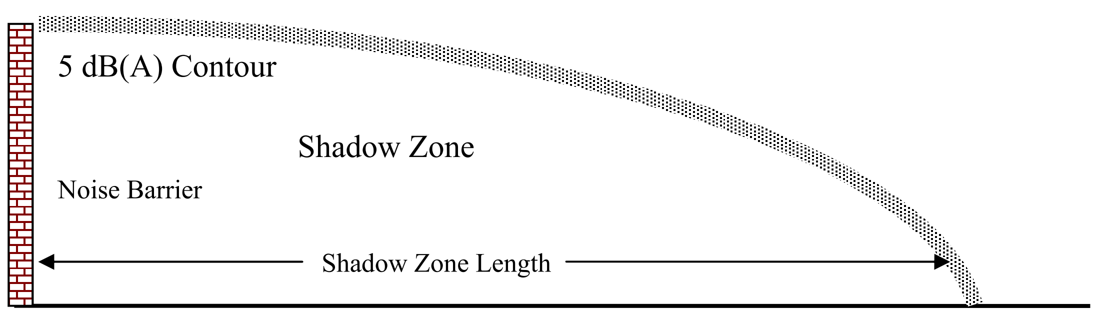

Figure 12: Graphical Display of the 5 dB(A) Shadow Zone

Every location along this line is where an IL of 5 dB(A) is predicted to occur. Everywhere inside the defined boundaries of the line the IL is predicted to increase whereas everywhere outside the defined boundaries of the line the IL prediction decreases. If a noise sensitive location, such as a residence or place of worship, lies within the 5 dB(A) shadow zone it is said that the location is receiving at least 5 dB(A) of IL. Noise sensitive locations outside the 5 dB(A) shadow zone are receiving less IL. As such, the ability to predict the SZL can be a tool to evaluate the effectiveness of a noise barrier and to identify those receivers receiving a benefit in an easy to understand graphical representation as opposed to the more difficult to interpret IL values at a single point. Additionally, the methodology used to predict the shadow zone incorporates the effects of background noise, as will be discussed. The IL values reported by the Federal Highway Administration (FHWA) Traffic Noise Model (TNM) [3] assume that the only noise source is the roadway, but in the real world, background noise is always present. Background noise comes from sources other than the roadway. Background noise sources can include anything from the wind blowing through the trees to the hum of residential air conditioning units. This background noise can affect the actual IL. Near the barrier, roadway noise is high enough that background noise has little to no effect on IL. However, as the distance from the barrier increases, background noise levels add more significantly to the overall noise level and affect IL. The shadow zone takes this effect into consideration and provides a more realistic depiction of noise barrier performance at increasing distances from the barrier.

The 5 dB(A) contour was created using commercially available contouring software. The contour was based on IL values from a combination of both in-situ noise measurements and modeled noise levels obtained from TNM, as will be discussed in the *Shadow Zone Data Points* section. All the modeled noise levels using TNM were conducted at the UCF Community Noise

Lab. From these IL values, the 5 dB(A) contours were plotted for each of the 18 roadway noise barrier locations located across Florida that were part of the FDOT noise barrier effectiveness studies [12][13]. From these contours, each SZL was determined. Finally, a regression analysis was performed on both the SZLs and the variables that affect it to develop the shadow zone equation.

Shadow Zone Data Points

In order to plot the 5 dB(A) contours, sufficient IL data points were first required. These points were defined with an X, Y and Z value in a plane. The X and Y value define the location of the IL point behind the noise barrier. The X value was the distance from the barrier and the Y value was the distance above the ground. The Z value was the IL, in dB(A). The challenge in creating the 5 dB(A) contours was to determine where behind the noise barrier IL points had to be located, how many IL points were needed, and what IL values to assign to them. This was ultimately solved through the use of field measurements, computer modeling, engineering judgment, and trial and error. To determine what IL points were required, it was necessary to first analyze the shape of an ideal shadow zone as shown in Figure 13. The ideal shadow zone revealed clues as to where the actual shadow could be and where it cannot be. Clearly, the ideal shadow zone is bounded to the left by the noise barrier and bounded below by the ground. It was expected that the actual shadow would share these same boundaries. Above the ground, the ideal shadow zone is bounded by the line-of-sight. The line-of-sight is where the noise barrier just breaks the straight line view from the noise source to the top of the noise barrier. Below the line of sight is the acoustical shadow zone where IL values are greater than zero. Above the line of sight is the illuminated zone where there is no IL. Finally, the shadow zone is bound at some distance to the right of the barrier; it does not extend indefinitely.

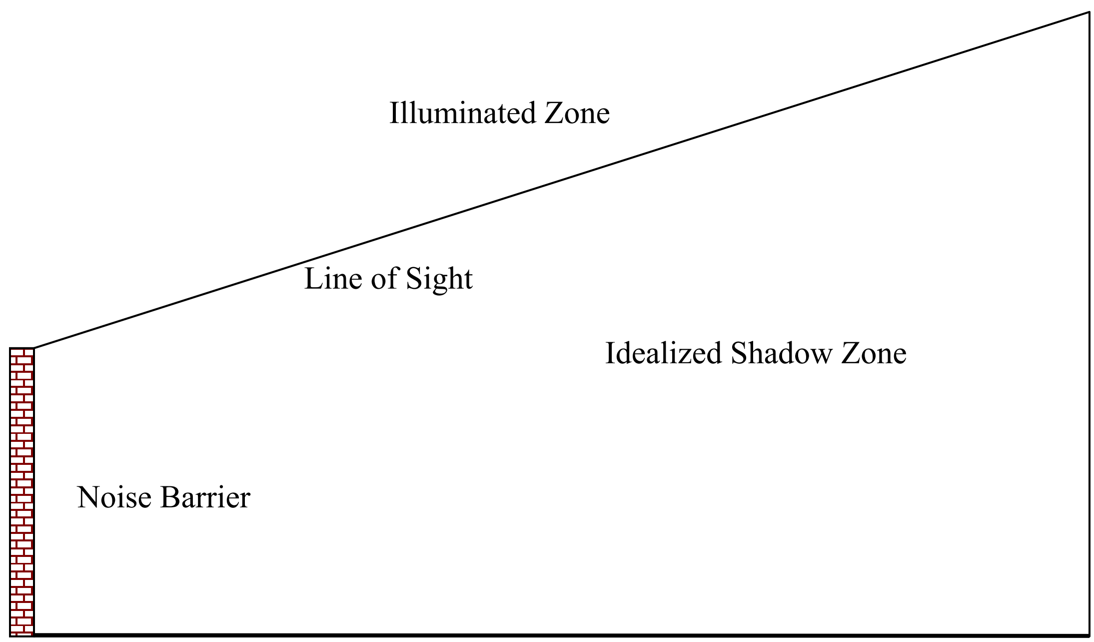

Figure 13: Ideal Shadow Zone

With the boundaries of the shadow zone identified, the next step was to develop IL points from which the 5 dB(A) contours could be developed. These steps included obtaining IL values from in-situ measurements and computer modeling.

Shadow Zone Microphone Points

The first IL points developed to predict the shadow zone were those at the microphone positions. The IL values at these locations were determined using the ANSI indirect method [15]. These IL locations are shown in Figure 14.

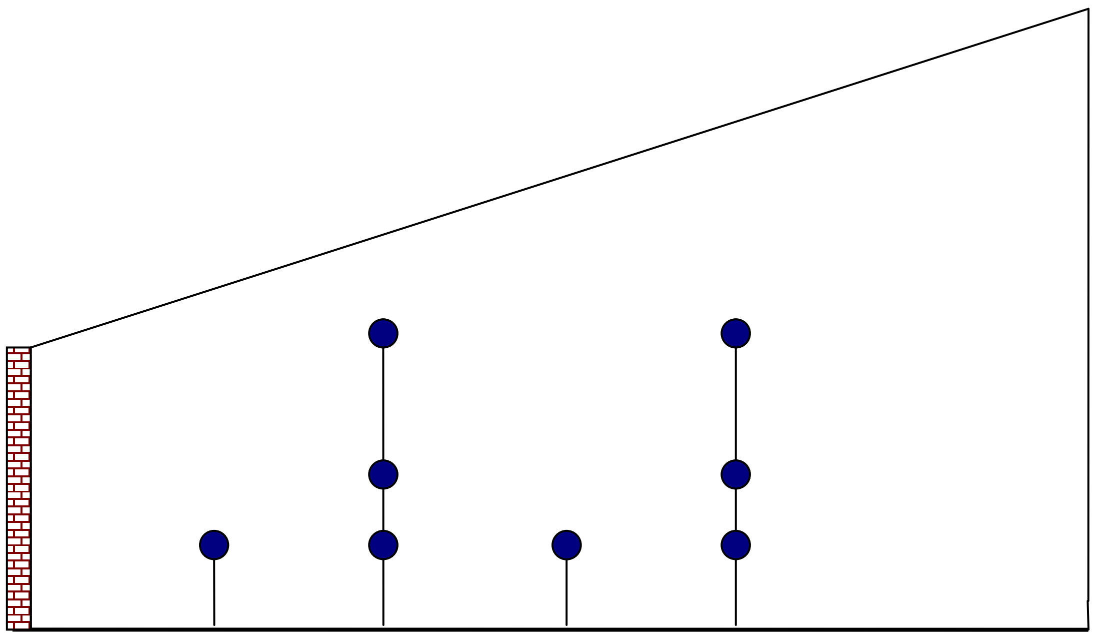

Figure 14: Insertion Loss Points at the Microphone Locations (heights as shown in Figure 6)

These locations correspond to Ivies 1 through 6 and Metrosonics A and C. The propagation loss error correction factor was calculated as shown in Equation 15 based on the ANSI method (15). Computed values are shown in Appendix C.

$$CF_{prop} = (TNM_{ref\ SPL} - TNM_{Ivie\ SPL}) - (Meas_{ref\ SPL} - Meas_{Ivie\ SPL}) \quad (15)$$

Where: CF_{prop} = Propagation loss error correction factor (dB[A])

$TNM_{ref\ SPL}$ = Sound pressure level as predicted by TNM at the reference microphone position (Ivies 7 and 8) (dB[A])

$TNM_{Ivie\ SPL}$ = Sound pressure level as predicted by TNM at Ivies 1 though 6 and Metrosonics A and C (dB[A])

$Meas_{ref\ SPL}$ = Sound pressure level measured by microphones 7 and 8 (dB[A])

$Meas_{Ivie\ SPL}$ = Sound pressure level measured at Ivies 1 though 6 and Metrosonics A and C (dB[A])

Propagation loss is the difference between the reference sound level at the barrier compared to the sound level at any location behind the barrier. It is a property that takes into account geometric spreading, ground effects, diffraction, and atmospheric effects. The propagation loss error corrects the modeled IL as shown in Equation 16.

$$IL_{corr} = IL_{TNM} - CF_{prop} \quad (16)$$

Where: IL_{corr} = Corrected insertion loss at Ivies 1 though 6 and Metrosonics A and C (dB[A])

IL_{TNM} = Insertion loss as predicted by TNM

CF_{prop} = Propagation loss correction factor (dB[A])

However, these IL values did not provide enough points required to plot a shadow zone contour and therefore, must be supplemented by additional IL points as discussed next.

Shadow Zone Start Points

Although the IL points at the microphone positions helped to describe the shape of the actual shadow zone inside the boundaries of the ideal shadow zone, there was a lack of IL points that would determine where the actual shadow zone begins. In other words, although the left boundary of the actual shadow zone is the noise barrier, IL values were needed to determine where along the height of the noise barrier the contour would begin. The reference microphone position, the green point in Figure 15, was located to purposely avoid diffraction effects and was too far above the barrier to help with this determination. For this reason, it was necessary to model several points using TNM. It is a commonly recognized thumb rule that an IL of 5 dB(A) will be observed when a noise barrier just breaks the line of sight between the source and the receiver. From this, it was expect that the 5 dB(A) contour would begin somewhere near the top edge of the barrier. In order to determine the approximate location of the 5 dB(A) contour, IL values were calculated directly behind the barrier starting at 5 feet above the ground to the reference microphone position in 1 foot increments as shown by the purple points in Figure 15. The IL at these points was the difference between the measured reference sound level and the modeled sound level at each of the purple points. These calculated IL points were corrected for the difference between the measured reference sound level and the modeled sound level at the purple point located at the same height as the reference microphones.

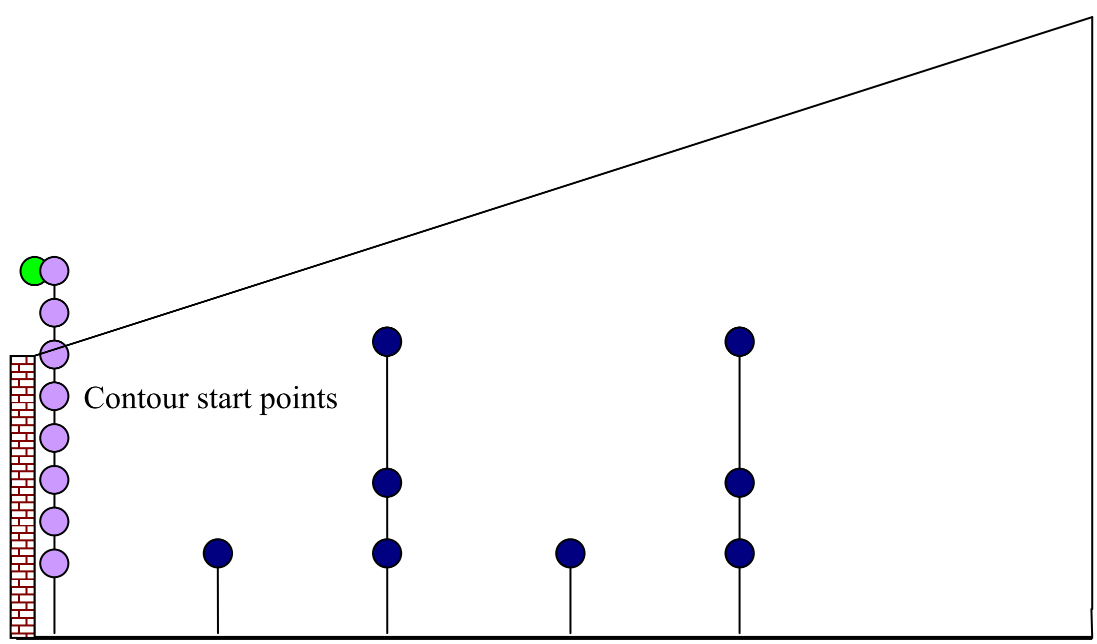

Figure 15: Contour Start Points

Shadow Zone Upper Boundary Points

The next step was to define the upper boundary of the shadow zone. The upper boundary was defined earlier to be at the border between the ideal shadow zone, where IL equals some non-zero value, and the illuminated zone where the IL equals zero. This border is also known as the line of sight. We know the shadow zone cannot cross the line of sight and enter the illuminated zone where the IL equals zero. So, in order to find this boundary, TNM was used again to determine where the IL just became equal to zero and is represented by the yellow points as shown in Figure 16. Three such points were determined at distances of 25, 50 and 100 feet from the noise barrier.

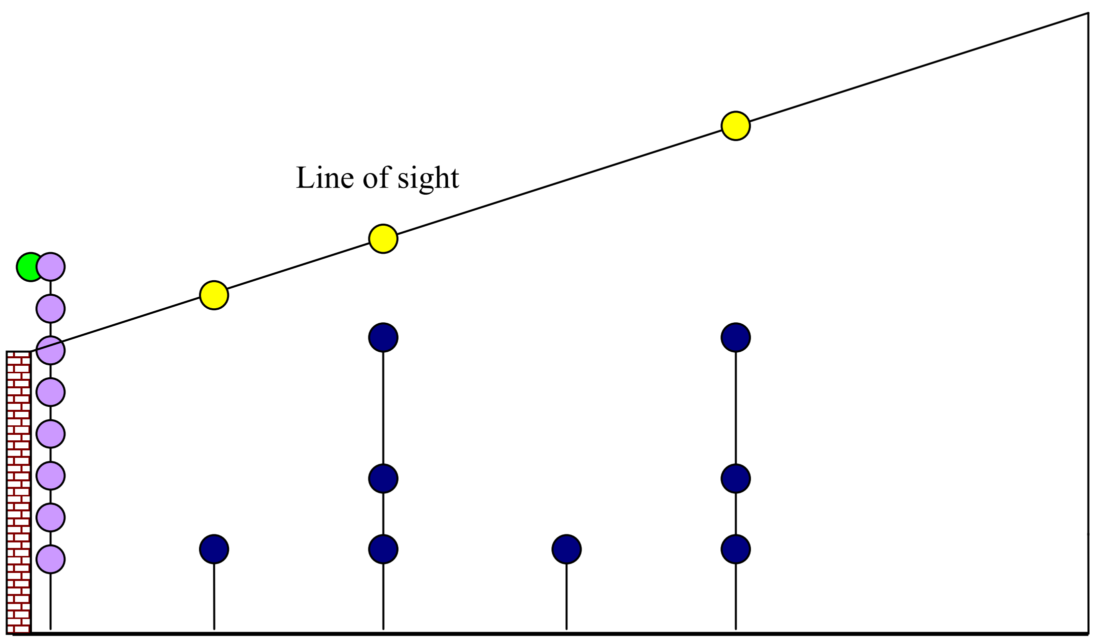

Figure 16: Line of Sight Points

The angle of the line of sight varies depending on the height of the sources (vehicles). Of particular concern are the exhaust stacks of heavy trucks. The source height for heavy truck stacks is defined as 12 feet in TNM. This can cause the line of sight to be flatter than that shown in Figure 16, which is based on a source height of zero feet (tire/pavement interface). If the stack height is above the barrier then the line of sight could actually angel downwards, which will result in a shorter SZL.

Shadow Zone Termination Point

In order to determine where the shadow zone ends, the location to the right (receiver side) of the barrier where IL equals zero needed to be determined. Insertion loss will equal zero where the noise level of the source equals the background noise level. Background noise levels are the sound pressure levels present in the absence of the source, which in this case is highway traffic. The source could not be eliminated from the measurements therefore the background levels at each noise barrier location had to be assumed. It was assumed (with concurrence from FDOT) that background noise levels were approximately equal to the L_{99} at the Ivie 1 microphone position. The L_{99} is the noise level exceeded 99% of the time during a measurement period and since heavily traveled roadways were used this was appropriate. The values for L_{99} are shown in Table 2.

Table 2
Estimated Background Noise Levels Using L_{99} (dB[A]) [12][13]

Location Name	L_{99}	Location Name	L_{99}
A	60	K	46
B	59	L	54
C	52	M	40
E	57	N	46
F	48	O	57
G	53	P	53
H	60	Q	50
I	60	R	43
J	62	S	49

Then using TNM, it was determined how far from the barrier this noise level occurred. This point represents the approximate distance to where IL equals zero and the distance where the actual shadow zone does not extend. This is represented by the red point in Figure 17.

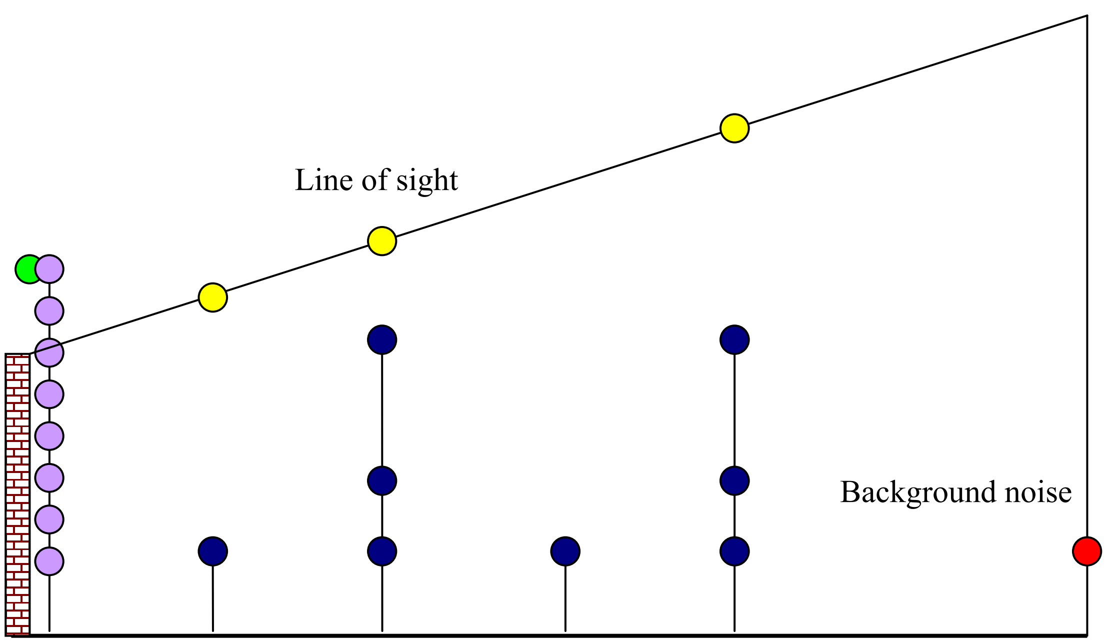

Figure 17: Background Location

The background level was adjusted for the absolute error at the Ivie 1 position. The absolute error is the difference between the predicted SPL as determined by TNM and the measured SPL as measured by Ivie 1. The absolute error was used instead of the propagation loss error as a correction factor because the propagation loss error requires both a measured and modeled sound pressure level at a particular point. However, there is no measured value for background; it is an assumed value (L_{99}). Given the measured data available, the only method to correct TNM's estimation of the background location was to apply the difference between the measured and modeled sound pressure level at the microphone closest to the estimated background location, which was Ivie 1. The general form of the absolute error equation is shown in Equation 17.

$$C_{AE} = SPL_{Pred} - SPL_{Meas} \tag{17}$$

Where: C_{AE} = Absolute error correction factor at any microphone position (dB[A])

SPL_{Pred} = Sound pressure level as predicted at that microphone position (dB[A])

SPL_{Meas} = Sound pressure level as measured at that microphone position (dB[A])

For example, if the L_{99} value at Ivie 1 is 55 dB(A) and the C_{AE} is -0.5, this means that TNM is under predicting the SPL at Ivie 1 by 0.5 dB(A). Thus, we can assume that TNM will also under predict the background SPL by the same amount. Since the distance from the barrier where the L_{99}, or background, value occurs will be determined by TNM, the background value is adjusted by the amount of the correction factor and is 55.5 dB(A).

It should be noted that the point behind a noise barrier where TNM predicts traffic noise to equal background noise (L_{99}), there are two sources present: the traffic noise and the background noise. Therefore, the total sound pressure level at that point is the summation of the two sources. Since the two sources are at the same sound pressure level, the true level at the background location is actually 3 dB(A) higher than the assumed background level of L_{99}. So, it may appear that TNM should be used to determine the location of the L_{99} + 3 dB(A) location to determine where traffic level drops to background levels. This was not taken into account when determining the location of background due to the uncertainties associated with the appropriateness of using L_{99} as background and TNM's accuracy in predicting sound pressure levels over long distances. However, this could be further explored as a possible way to improve the prediction of shadow zone lengths.

Supplemental Data Points

Through trail and error, it was still determined that the number and locations of IL data points were insufficient to characterize the shadow zone contour within the boundaries established. Using TNM, supplemental IL points were added, as shown in Figure 18 as orange points. These points were located approximately 25 and 75 feet from the noise barrier and at heights corresponding to the microphone heights of 10 and 20 feet. The modeled IL values were adjusted by applying a propagation loss error correction factor, CF_{prop}. This factor attempts to increase the accuracy of the modeled IL based on the measured noise data. For the orange points between the two Ivie towers, the propagation loss correction factor applied was the average of those calculated for the microphones on either side of them. For the orange points located closest to the barrier, the correction factor applied was that calculated for the microphone to the right of them. The final result is a grid of IL points that now can be contoured.

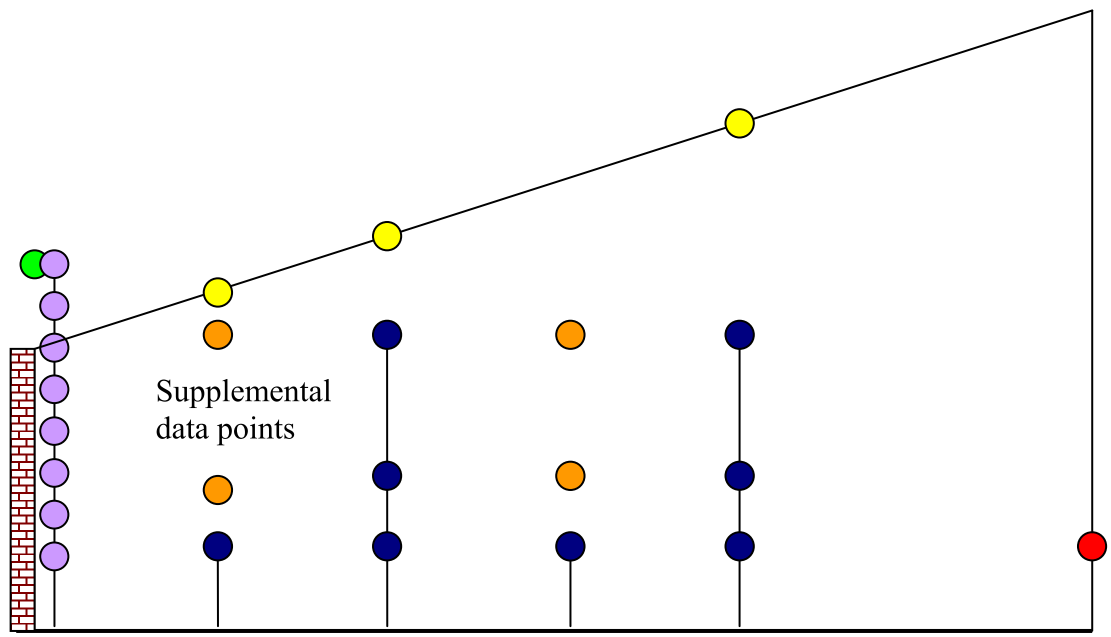

Figure 18: Supplemental Data Points and Final Insertion Loss Grid

Contouring the Insertion Loss Data Points

Once the IL data points were created for all the locations, the 5 dB(A) shadow zone contour was created using commercially available contouring software. After the 5 dB(A) contours were created, the distance from the noise barrier to the where the contours reach the ground were noted. These distances are shown in Table 3.

Table 3
Shadow Zone Lengths [12][13]

Location Name	Shadow Zone Length (feet)
A	200
B	141
C	254
E	362
F	130
G	73
H	243
I	150
J	90
K	489
L	157
M	320
N	157
O	316
P	445
Q	390
R	251
S	305

The contouring software provided several gridding methods to choose from. Gridding produces a regular array of data points by interpolating or extrapolating the original data. The grid is then used to generate a contour. By understanding how the actual shadow zone should look like, and from trail and error, it was determined that the radial basis multiquadric function produced contours that made sense and were the most consistent from location to location. This gridding method is flexible and useful for gridding most types of data sets. This method is an exact interpolator and honors the original input data during contouring. The contouring property called anisotropy was adjusted to a value of 1.6. Anisotropy is a ratio that controls how much weighting is given to points along one axis versus points located on the other axis. An anisotropy ratio equal to 1.0 means that equal weighting is given to points on both axes. A ratio other than one means that more (or less) weighting is given to points along one axis versus points located along another axis. If the X and Y coordinates are the same scale (i.e., X = 1unit and Y = 1 unit) then the anisotropy should be set to 1.0. However, for the array of IL values (i.e., the data point positions in Figure 18), the spatial variability in the horizontal plane was 25 feet and in the vertical was an average of 15 feet, which is a ratio of approximately 1.6 and thus the need to adjust the anisotropy. An example shadow zone contour is shown in Figure 19. From this figure, the SZL was predicted to be 200 feet.

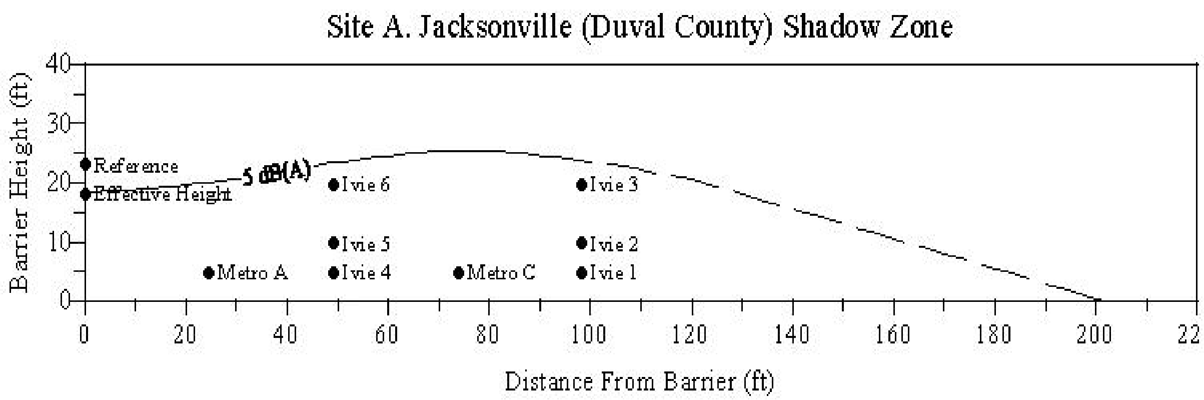

Figure 19: Example Shadow Zone Contour

Developing the Shadow Zone Equation

With the SZLs of all the noise barrier locations estimated, a relationship between this variable, known as the dependent variable (DV), and other significant variables, known as independent variables (IV), was statistically analyzed. The DV was the length of the noise barrier acoustical shadow zone. The IVs chosen were those that were expected to significantly affect the shadow zone and are shown in Table 4.

Table 4
Independent Variables

Independents Variables Expected to Affect the Shadow Zone
Background (L_{99})
Effective Barrier Height
Distance from Roadway to Noise Barrier
Percent Heavy Trucks
Average Speed

The values used for the multiple regression analysis for each of the IVs can be found in Chapter 4. The background levels, as estimated using L_{99}, were chosen since background noise levels effect how far a shadow zone extends. The other variables listed in Table 4 affect IL. As discussed in Chapter 2, IL is influenced by the Fresnel number (N). The N is a function of the horizontal and vertical geometry between source-barrier-receiver (path length difference, δ) and also of frequency. Any variable that causes a change in the traveled path of the noise vector or the frequency will also change the IL, and thus the shadow zone. The term "effective barrier height" is the distance above the ground plane of the receivers to the top edge of the barrier.

Of these variables, the one that may not be obvious as to how it affects the shadow zone is Percent Heavy Trucks. Heavy trucks emit a significant amount of sound energy from their stacks which are located higher above the ground than where other vehicle classes emit their sound energy. TNM uses two sub-source heights for vehicles. They are 0 and 12 feet for heavy trucks, and for all other vehicle classes the sub-source heights are 0 and 5 feet. This difference in sub-source heights affects N and thus IL. In order to determine if this difference relates to SZL, this variable was included in the analysis. It should be noted that the percentage of heavy trucks was used as an IV instead of using the number of heavy trucks since IL is not affected by changing the quantity of a source but by changing the distribution of the sub-source heights. This can be proven using TNM and the results are shown in Tables 5 and 6.

Table 5
Affect of Changing the Number of Heavy Trucks on Insertion Loss

Number of Heavy Trucks (#/hour)	Insertion Loss (dB[A])
1	11.8
10	11.8
100	11.8
1,000	11.8

Table 6
Affect of Changing the Fraction of Heavy Trucks on Insertion Loss

Fraction of Heavy Trucks (0 to 1.0)	Insertion Loss (dB[A])
0.001	13.5
0.01	13.4
0.1	12.6
1.0	11.8

From Table 5, assuming a 14 foot tall barrier, as the number of heavy trucks varies and everything else remains constant, the IL remains constant. If the IL remains constant, then the shadow zone is not affected. From Table 6, as the fraction of heavy trucks varies, the IL changes as it decreases as the fraction of heavy trucks increases. Since IL changes, then the shadow zone will be affected, thus the reason why the fraction of heavy trucks is used instead of the number of heavy trucks as the independent variable. Both observations hold true regardless of barrier height.

With the SZL estimated for 18 noise barriers and the values for the associated IVs computed, the relationship between the two were evaluated using multiple regression. Multiple regression answers the question, “What is the best predictor of SZL?” A scatter plot of the individual IVs versus SZL was created in order to detect any type of relationship. Since this provided no strong evidence of how they are related, both a linear and polynomial regression analysis was used to relate the DV to the IVs. A linear regression model is in the form shown in Equation 18.

$$Y = A + B_1X_1 + B_2X_2 + B_3X_3 + \ldots \qquad (18)$$

Where: Y = Shadow zone length (dependent variable)

A = Value of Y when Xs are zero

B = Coefficients of the independent variables

X = Values of the independent variables

The polynomial regression model for two independent variables is in the form shown in Equation 19.

$$Y = A + B_1X_1 + B_2X_2 + B_3X_1X_2 + B_4X_1^2 + B_5X_2^2 \qquad (19)$$

Where: Y = Shadow zone length (dependent variable)

A = Value of Y when Xs are zero

B = Coefficients of the independent variables

X = Values of the independent variables

So, given the values of X (independent variables) for any existing or proposed noise barrier, the value Y (shadow zone) can be predicted. The model that shows the strongest relationship between X and Y will be called the *Shadow Zone Equation*.

Several assumptions had to be made in order to use a multiple regression analysis. It was assumed that the distribution of values (the residuals, or the difference between the predicted values and the observed values) from the prediction of the model is random and approximately Gaussian (normally distributed). A normal probability plot was created in order to inspect the distribution of the residuals. A test for outliers among the residuals was also conducted since a single outlier can bias the regression line. Other assumptions included that the variance of the data from the prediction model was the same for all values of the IVs, all the IVs are correct and that any experimental error affects only the DV, and all the data points are independent.

The multiple regression analysis attempts to fit a line through a number of points by minimizing the squared deviations of the observed points to the line. This is called least squares estimation. The R^2 value, or the coefficient of determination, is a prediction of how properly the equation fits a set of data and tells what fraction of the sample variation that is attributable to one or more of the IVs. For example, if the R^2 value is 87%, this means that 87% of the shadow zone variation is attributable to, or can be explained by, one or more of the IVs. The remaining 13% is attributable to residual variability or some other IV that was not included in the analysis. The adjusted multiple coefficient of determination, R^2_a, can also be used to determine model adequacy. The R^2_a takes into account sample size and the number of independent variables and represents a more conservative indication of model adequacy than R^2.

An analysis of variance was conducted using Fisher's F-test. This indicated whether the IVs of the regression model were useful for predicting the SZL. If the observed significance level of the F-test, given as the P-value, is small, it can be concluded that at least one of the independent variable coefficients is nonzero and the model is useful for predicting the SZL. In this case, the null hypothesis is rejected in favor of the alternative, both of which are defined below.

H_o: The IV coefficients = 0, or the slope of the regression line is zero.

H_a: At least one IV coefficient ≠ 0, or the slope of the regression line is not zero.

In addition to analyzing the model as a whole for the ability to predict the SZL, the individual IVs were analyzed to determine their usefulness in the model. This was done by inspecting the P-values associated with each IV. If the P-value is small, the IV contributes significantly to the regression model. If the P-value is large, the IV contributes no more to the model than would pure chance. Using a significance level of 0.05, a P-value less than 0.05 means the IV made a statistically significant contribution. A P-value greater than 0.05 means that the IV was not statistically significant and can be removed from the regression analysis.

It should be noted that *location K* was removed from the regression analysis. As was shown in Table 3, the SZL was predicted to be 489 feet. This length far exceeded any of the other noise barrier locations, and given the location parameters, this value was considered unreasonable. This location had two peculiarities associated with it that could have attributed to the abnormally long SZL. First, a traffic signal controlled the flow of vehicles on the roadway that the noise barrier was shielding and, secondly, the microphones were located near the end of the barrier and also near a gap in the barrier for the community's entrance.

In summary, the steps followed in deriving the methodology for developing an empirical equation that estimates the SZL of roadway noise barriers were:

- Obtain in-situ and modeled noise measurements at noise barrier locations across Florida to determine IL at specific locations behind the barriers.
- Determine IL at additional locations behind the barriers through computer modeling to provide the necessary number of points to plot the shadow zone.
- Develop a regression model that relates the shadow zone length to a number of independent variables.

CHAPTER FOUR: FINDINGS

The results of the methodology used to estimate the shadow zones for all the noise barrier locations are shown in Table 7. The shadow zone length (SZL) represents the dependent variable (DV) in the multiple regression analysis. Also shown in the table are the independent variables (IV) and their values for each noise barrier location. The regression analysis was used to determine if the IVs were able to predict the DV. If the IVs prove statistically significant in predicting the SZL then the multiple regression model can be used to predict the SZL of any noise barrier with IVs that are within a reasonable range of those used in the regression model. This regression model was called the *Shadow Zone Equation*. This was done by analyzing scatter plots of the SZL versus each of the IVs, analyzing the R^2 value of the regression model, analyzing the P-value of each IV, the P-value of the model as a whole, and finally analyzing the residuals. Location K was not included in the regression analysis due to its unreasonable SZL as discussed in the previous chapter.

Table 7
Values for the Independent Variables and the Dependent Variable for the Multiple Regression Analysis

Location	**Background**	**Effective Barrier Height**	**Distance from Road to Barrier**	**Percent HT**	**Average Speed**	**Shadow Zone Length**
	L_{99} (dB[A])	H_{EFF} (feet)	D_R (feet)	HT (%/100)	V_{AVG} (mph)	SZL (feet)
A	60	18.5	97	0.0463	64.5	200
B	59	13.5	141	0.104	69.0	141
C	52	14.5	84	0.006	49.5	254
E	57	41	81	0.0983	68.0	362
F	48	11	74	0.0111	36.5	130
G	53	7.3	51	0.0056	43.0	73
H	60	14.5	123	0.057	58.5	243
I	60	13.1	139	0.0631	58.5	150
J	62	18	55	0.01	56.5	90
K	46	11	74	0.0039	46.0	489
L	54	25.3	70	0.0741	58.5	157
M	40	9.4	53	0.13	46.5	320
N	46	11.6	60	0.03	41.5	157
O	57	14.5	120	0.05	59.0	316
P	53	18.4	145	0.06	57.5	445
Q	50	19.3	145	0.064	65.0	390
R	43	7.7	60	0.01	48.0	251
S	49	11	65	0.01	37.0	305

The scatter plots showing the relationship between the SZL and each of the individual IVs are shown in Figures 20 through 24. The purpose of the scatter plots was to determine how the SZL and the IVs are related. By visual inspection, there appears to be no relationship. The data was fitted to a linear and second-order polynomial (quadratic) line and the R^2 value was computed.

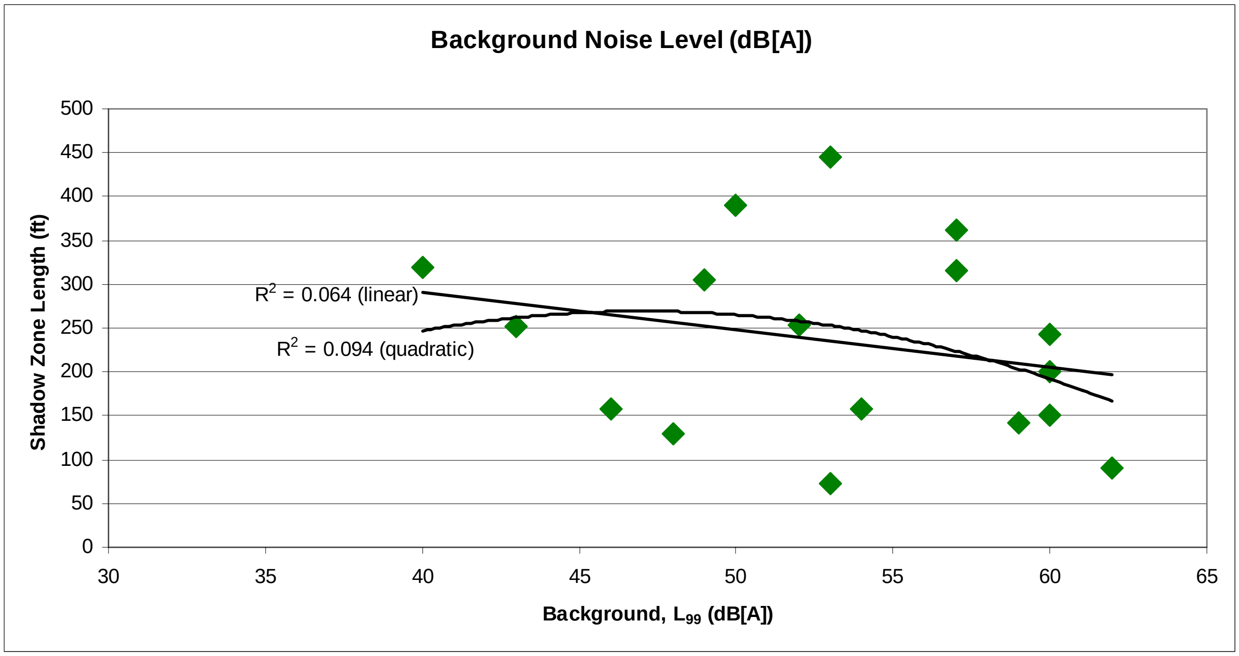

Figure 20: Scatter plot of Shadow Zone Length Versus Background Noise Level (L_{99})

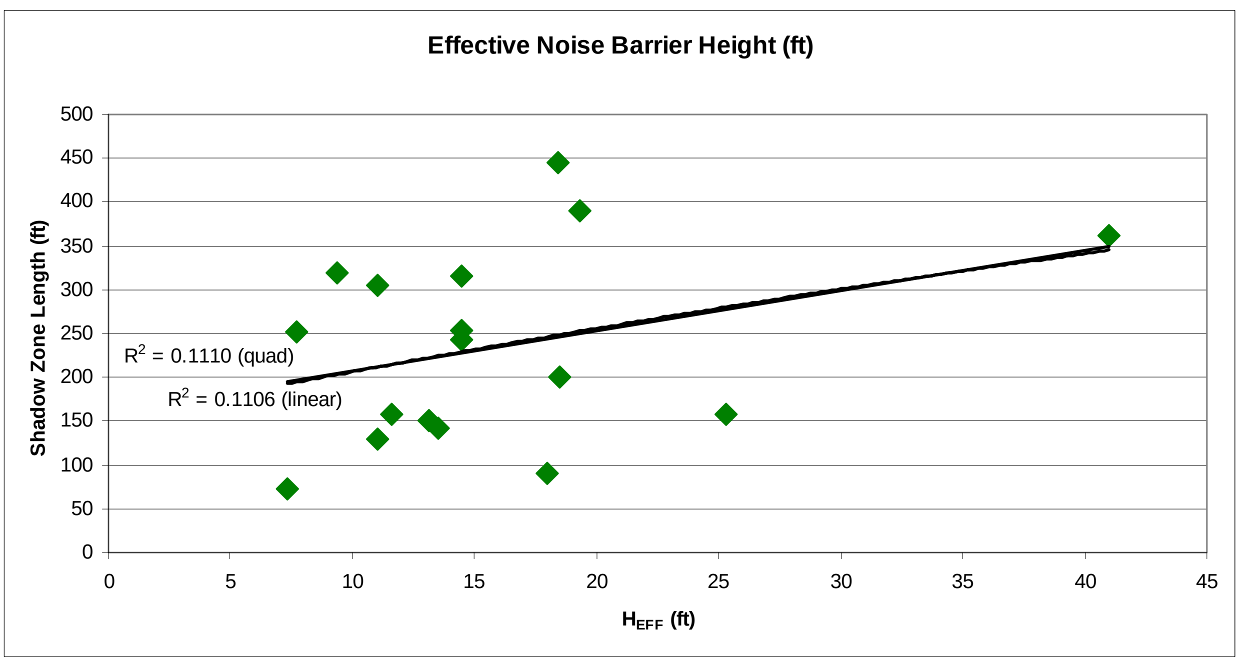

Figure 21: Scatter plot of Shadow Zone Length Versus Effective Noise Barrier Height

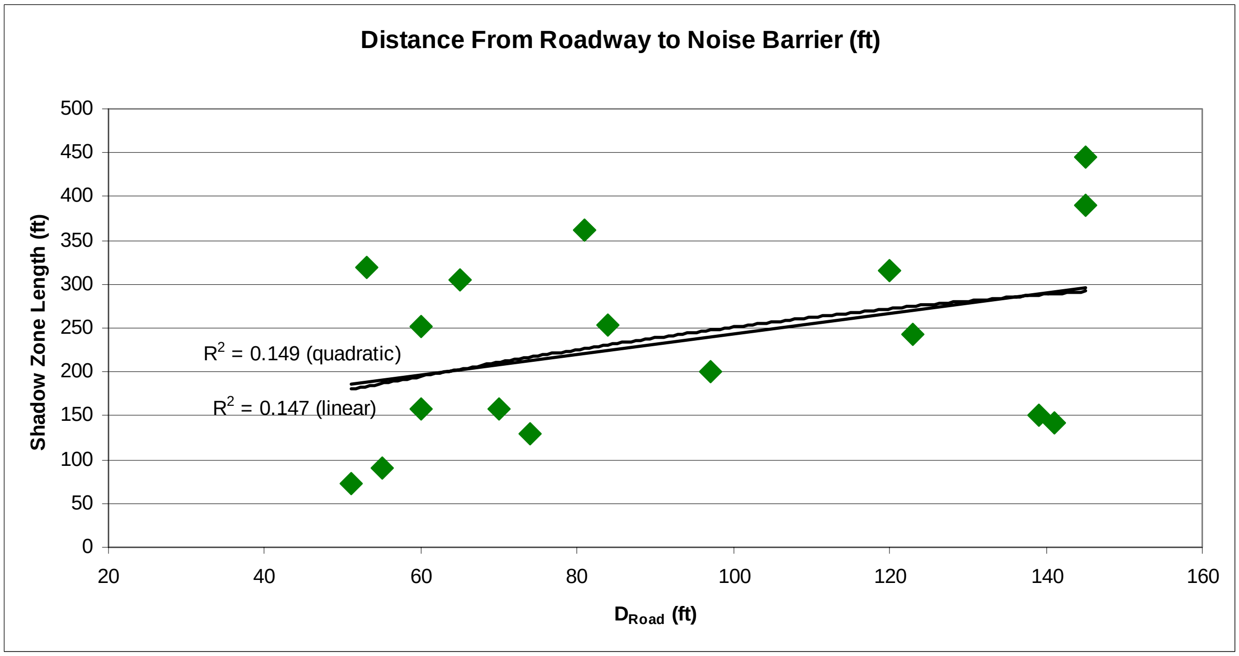

Figure 22: Scatter plot of Shadow Zone Length Versus Distance From Roadway to Noise Barrier

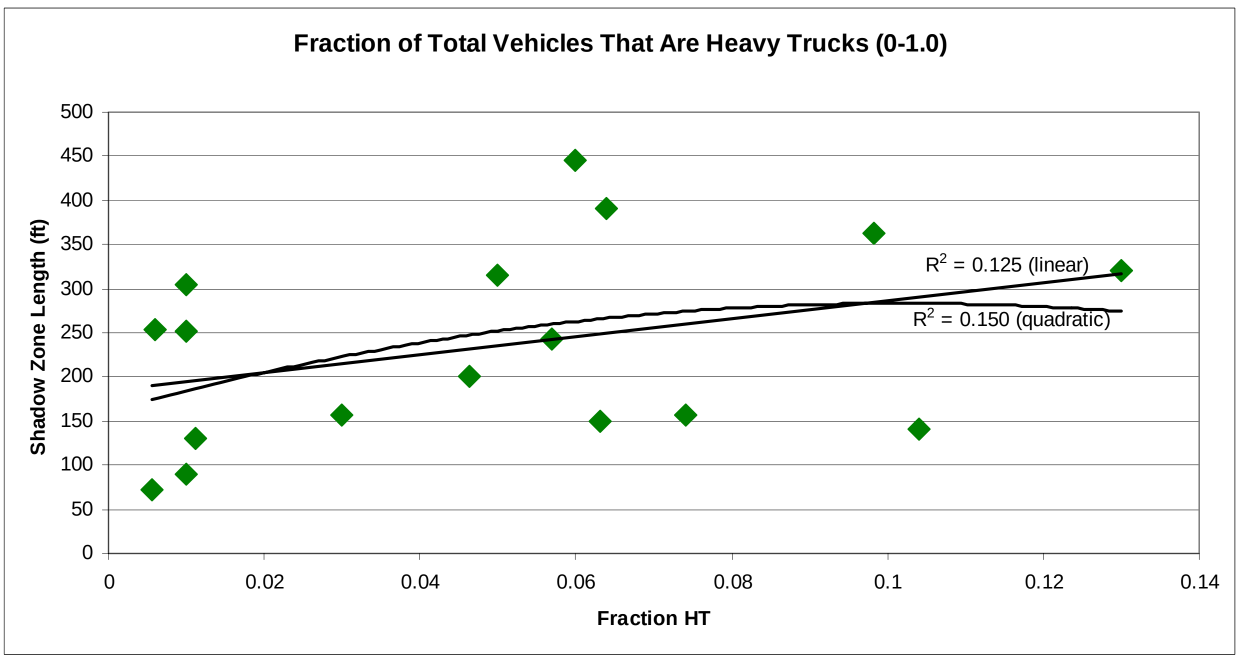

Figure 23: Scatter plot of Shadow Zone Length Versus Fraction of Heavy Trucks

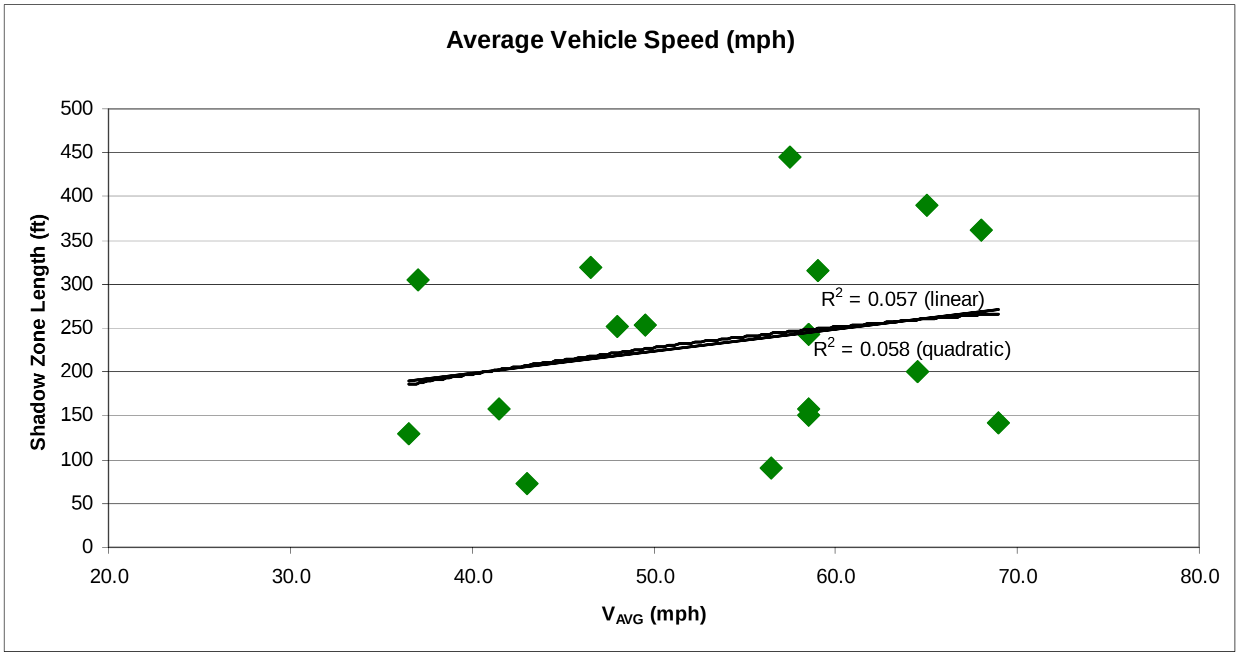

Figure 24: Scatter plot of Shadow Zone Length Versus Average Vehicle Speed

From the scatter plots, there is no strong linear or quadratic relationship between SZL and any of the individual IVs although the quadratic line fit the data slightly better than the linear line. The fact that there were no strong relationship between the SZL and any of the IVs suggests that no one IV heavily influences the length of the shadow zone but, in fact, it is a combination of IVs that contribute to the SZL. A multiple regression analysis was performed to determine if this was true and since it was not clear how the shadow zone and the IVs relate, both a linear and polynomial regression was analyzed.

The results of the multiple linear regression analysis utilizing all the IVs are in Table 8. Of note are the P-values for the IVs. The high P-values for Percent Heavy Trucks and Average Speed are large. This means that these IVs are not useful for predicting the shadow zone equation. Additionally, the 95% confidence intervals for the coefficients of these three IVs include both positive and negative values. This cannot be since these IVs either increase or decrease the SZL and cannot do both. As such, these IVs were eliminated from the regression model.

Table 8
Multiple Linear Regression Results for All Independent Variables

R^2	0.64				
Adjusted R^2	0.47				
Term	**Coefficient**	**SE**	**p**	**95% CI of Coefficient**	
Intercept	652.5180	177.8173	0.0037	261.1449	to 1043.8912
Background, L_{99} (dB[A])	-13.8366	4.8498	0.0157	-24.5111	to -3.1622
Effective Barrier Height, H_{EFF} (ft)	8.1885	3.5552	0.0418	0.3635	to 16.0135
Distance from Barrier to Road, D_R (ft)	2.1659	0.8126	0.0220	0.3774	to 3.9544
Percent Heavy Trucks, HT (%/100)	-328.6942	759.7441	0.6736	-2000.8794	to 1343.4911
Average Speed, V_{AVG} (mph)	0.0803	4.5032	0.9861	-9.8313	to 9.9919

Source of variation	SSq	DF	MSq	F	p
Due to regression	121892.352	5	24378.470	3.86	0.0289
About regression	69469.531	11	6315.412		
Total	191361.882	16			

The regression analysis was conducted again, excluding Percent Heavy Trucks and Average Speed, with the results shown in Table 9. All three IVs are significant with P-values less than 0.05.

Table 9
Multiple Linear Regression Results for Statistically Significant Independent Variables

R^2	0.63				
Adjusted R^2	0.54				
Term	**Coefficient**	**SE**	**p**	**95% CI of Coefficient**	
Intercept	626.5190	157.6940	0.0016	285.8417	to 967.1962
Background, L_{99} (dB[A])	-13.0959	3.4831	0.0024	-20.6206	to -5.5711
Effective Barrier Height, H_{EFF} (ft)	7.4785	2.5331	0.0112	2.0061	to 12.9509
Distance from Barrier to Road, D_R (ft)	2.0154	0.5838	0.0043	0.7542	to 3.2765
Source of variation	**SSq**	**DF**	**MSq**	**F**	**p**
Due to regression	120310.847	3	40103.616	7.34	0.0040
About regression	71051.035	13	5465.464		
Total	191361.882	16			

The R^2 value is 0.63. This means that 63% of the variability in the SZL can be attributed to one or more of the three IVs. The regression line is shown in Figure 25. The observed significance level of the F-test is small with a P-value of 0.004. This means that at least one coefficient of one of the IVs is not equal to zero and the null hypothesis (H_o) can be rejected. Based on these results, it can be said that the regression model is useful for predicting SZL. The average error of the regression model in predicting the actual SZL was 55 feet with a range of about ± 100 feet from the actual SZL. The model under-predicted the shadow zone for 10 of the noise barrier locations and over-predicted the shadow zone for the remaining 7 locations.

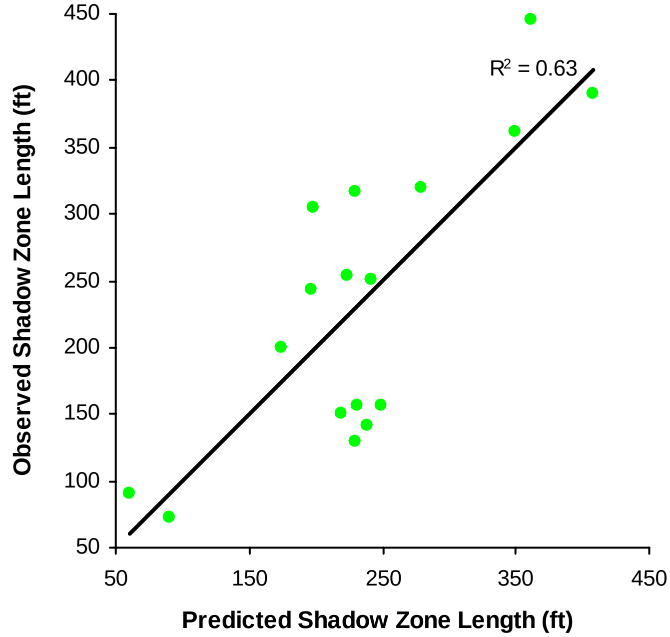

Figure 25: Regression Line of Observed Versus Predicted Shadow Zone Length as Derived from Linear Regression

A check of the assumptions underlying the linear regression was made. The residuals were plotted against the predicted value of the SZL as shown in Figure 26. From the figure, it was difficult to determine the presence of unequal variances. More data points would be required to make this determination. So, it was assumed the variances of the residuals were the same for all settings of the IVs. The histogram was used in determining the normality of the residuals. The figure showed that the distribution of the residuals were not perfectly normal, nor was it severely skewed. Again, due to lack of data points, and also since regression is robust with respect to normality, it was assumed that the assumption that the random error is normally distributed is satisfied. Also evident from the residuals plot, was that all the points lie within ± 1.5σ. This means there were no outliers that could influence the regression analysis.

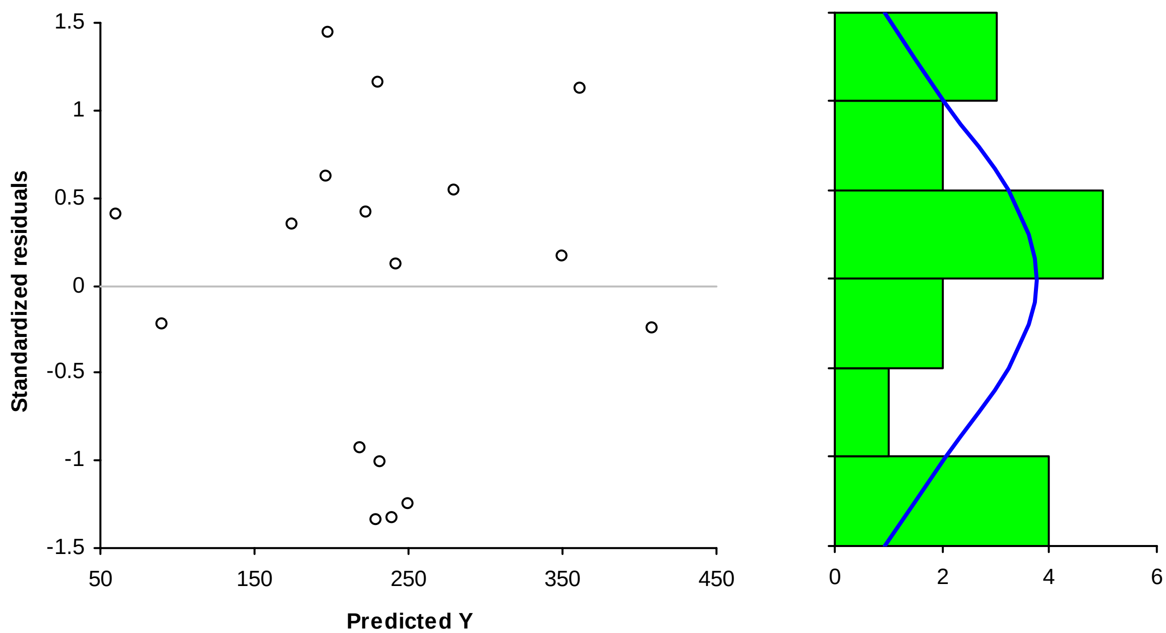

Figure 26: Plot of Residuals from the Linear Regression Model

The relationship between the SZL and the IVs was also evaluated using a polynomial regression model to the second-order (quadratic) in an attempt to improve on the R^2 value. A second-order polynomial is the highest order polynomial that can be analyzed based on the number of samples. It was determined that the same three IVs used in the linear regression model plus the Fraction of Heavy Trucks variable, HT, provided the best fit. The inclusion of HT in the polynomial regression model yielded a higher R^2 and a smaller P-value for the F-test. The results of the polynomial regression analysis utilizing these four IVs are shown in Table 10.

Table 10
Second-Order Polynomial Regression with Four Independent Variables Results

R^2	0.98				
Adjusted R^2	0.80				
Term	**Coefficient**	**SE**	**p**	**95% CI of Coefficient**	
Intercept	4561.92	3440.66	0.32	-10242.02	19365.86
Background, L_{99} (dB[A])	11.60	127.20	0.94	-535.71	558.92
Effective Barrier Height, H_{EFF} (ft)	-181.41	112.87	0.25	-667.03	304.21
Distance from Barrier to Road, D_R (ft)	-139.53	45.67	0.09	-336.02	56.97
Percent Heavy Trucks, HT (0-1.0)	140606.51	42118.57	0.08	-40615.04	321828.07
$(L_{99})(H_{EFF})$	9.56	2.82	0.08	-2.60	21.71
$(L_{99})(D_R)$	4.06	1.26	0.08	-1.35	9.48
$(L_{99})(HT)$	-5636.99	1731.04	0.08	-13085.05	1811.06
$(H_{EFF})(D_R)$	-1.26	0.52	0.13	-3.48	0.96
$(H_{EFF})(HT)$	4835.30	1597.17	0.09	-2036.76	11707.36
$(D_R)(HT)$	980.31	314.39	0.09	-372.38	2333.00
L_{99}^2	-3.08	1.37	0.15	-8.96	2.81
H_{EFF}^2	-11.03	3.52	0.09	-26.16	4.11
D_R^2	-0.48	0.16	0.09	-1.16	0.20
HT^2	-93407.95	41013.25	0.15	-269873.69	83057.79
Source of variation	**SSq**	**DF**	**MSq**	**F**	**p**
Due to regression	186645.840	14	13331.846	5.65	0.1603
About regression	4716.042	2	2358.021		
Total	191361.882	16			

The R^2 value for the polynomial regression is 0.98. This means that 98% of the variability in the SZL can be attributed to one or more of the four IVs. The regression line is shown in Figure 27. The observed significance level of the F-test is large with a P-value of 0.16. This means that the H_o (all the IV coefficients = 0) cannot be rejected. This means that there is insufficient evidence (at $\alpha = 0.05$) to indicate that the model is useful for predicting SZL. The average error of the regression model in predicting the actual SZL was 13 feet with a maximum error of about 32 feet from the actual SZL.

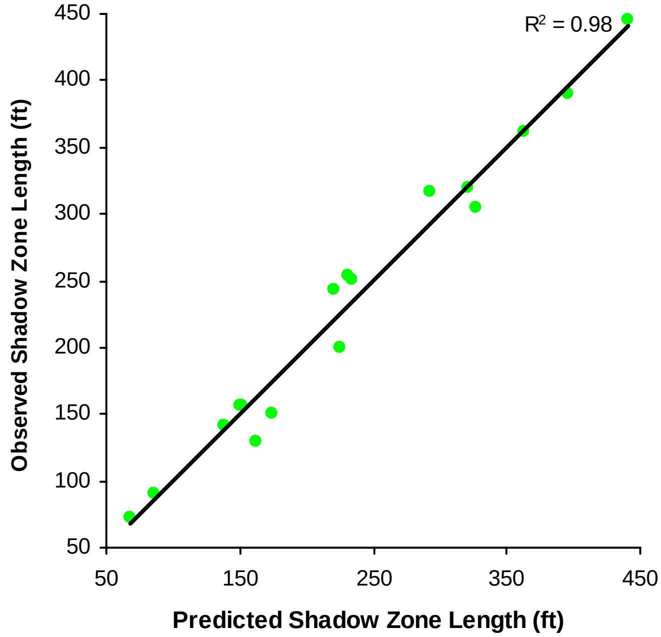

Figure 27: Regression Line of Observed Versus Predicted Shadow Zone Length as Derived from Polynomial Regression

From the graph of the residuals shown in Figure 28, the assumptions that the residuals are normally distributed with mean 0, with constant variances, and are independent can be reasonably satisfied.

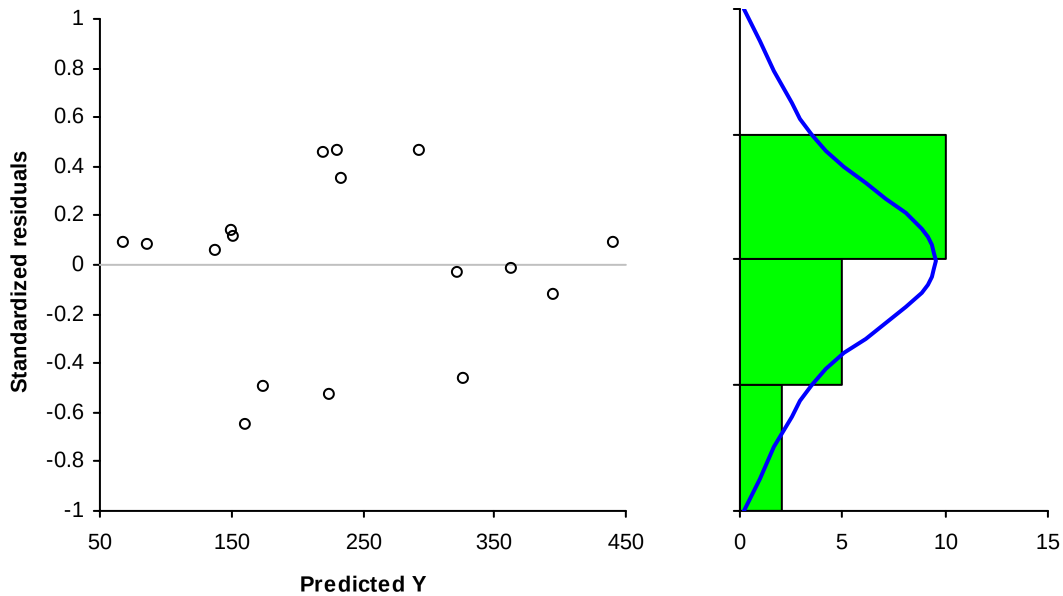

Figure 28: Plot of Residuals from the Polynomial Regression Model

Based on the R^2 results of the multiple linear and polynomial regression analyses, it can be assumed that both regression models are useful in predicting noise barrier SZLs. The linear model provided a $R^2 = 0.63$ and the polynomial model provided a $R^2 = 0.98$. Clearly, the polynomial model fitted the data better than the linear model. The error of prediction for the models is shown in Table 11.

Table 11
Error of Prediction of the Shadow Zone Length (feet)

Location	Linear Regression	Polynomial Regression
A	27	26
B	96	3
C	32	22
E	13	1
F	98	32
G	16	4
H	48	22
I	67	24
J	31	4
L	92	5
M	41	2
N	74	7
O	87	23
P	85	4
Q	16	6
R	10	17
S	108	22
Average Error	55	13

However, when using the F-test to make inferences about the overall adequacy of the models to predict SZL, only the linear model was significant. For the computed F value of 7.34 for the linear regression model, the observed significance level (P-value = 0.004) of the F-test shows that the H_o can be rejected at $\alpha = 0.05$. This means that at least one of the IVs is nonzero, thus the linear regression model is useful for predicting SZL. The observed significance level (P-value = 0.16) for the polynomial regression model shows that the H_o cannot be rejected at $\alpha = 0.05$, thus not considered useful for predicting SZL.

Based on the high R^2 of the polynomial regression model and the significance of the F-test for the linear regression model, two Shadow Zone Equations are presented based on both regression models. The Shadow Zone Equation based on the linear regression model is shown in Equation 20 and that based on the polynomial regression model is shown in Equation 21.

$$SZL_l = 626.5 - 13.1(L_{99}) + 7.5(H_{EFF}) + 2.0(D_R) \tag{20}$$

Where: SZL_l = Shadow zone length as derived from linear regression (feet)

L_{99} = Background noise level (dB[A])

H_{EFF} = Effective noise barrier height (feet)

D_R = Distance from the noise barrier to the center of the roadway (feet)

$$\begin{aligned} SZL_p = {} & 4{,}561.9 + 11.6(L_{99}) - 181.4(H_{EFF}) - 139.5(D_R) + 140{,}606.5(HT) + \\ & 9.6(L_{99})(H_{EFF}) + 4.1(L_{99})(D_R) - 5{,}637(L_{99})(HT) - 1.3(H_{EFF})(D_R) + \\ & 4{,}835.3(H_{EFF})(HT) + 980.3(D_R)(HT) - 3.1(L_{99})^2 - 11.0(H_{EFF})^2 - \\ & 0.5(D_R)^2 - 93{,}408.0(HT)^2 \end{aligned} \tag{21}$$

Where: SZL_p = Shadow zone length as derived from polynomial regression (feet)

L_{99} = Background noise level (dB[A])

H_{EFF} = Effective noise barrier height (feet)

D_R = Distance from the noise barrier to the center of the roadway (feet)

HT = Fraction of heavy trucks operating on roadway (0-1.0)

The predicted SZLs derived from Equations 20 and 21 and those derived from MacDonald et al. [16] were compared to the observed SZLs as derived from the methodology in Chapter 3 and are shown in Figure 29.

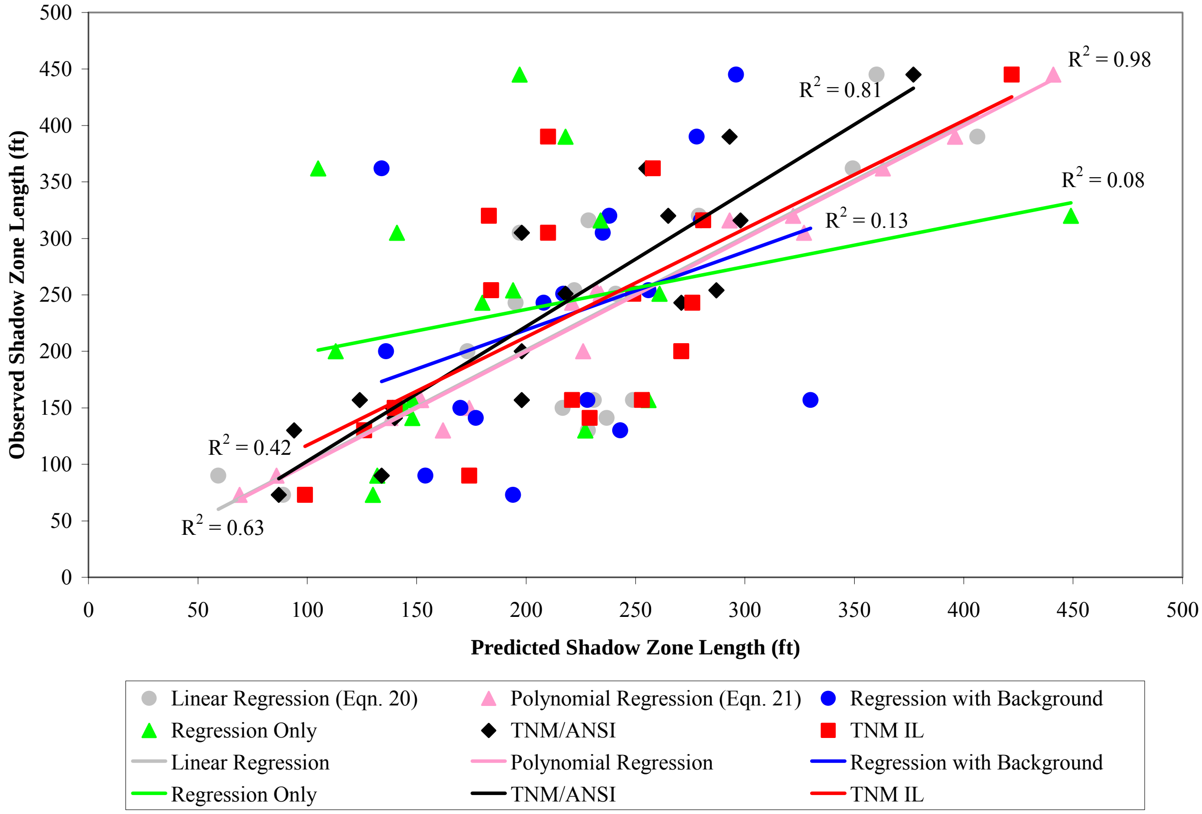

Figure 29: Scatterplot of Observed Shadow Zone Lengths vs. Predicted Shadow Zone Lengths

The polynomial regression model fits the observed data points the best with a $R^2 = 0.98$ followed by the TNM/ANSI method developed by MacDonald et al. with $R^2 = 0.81$. The linear regression model was next with a $R^2 = 0.63$. This indicates that the polynomial regression model provides better results than any of the other methods.

As an attempt to validate both shadow zone equations (Equations 20 and 21), they were compared to the four independently derived observed SZLs as calculated by MacDonald et al. (Equation 14). These observed SZLs were partly derived from rover measurements that identified the distance from the barrier to where background noise levels were reached at four noise barrier locations. In order to conduct the comparison, both shadow zone equations had to be modified so that they excluded the four sites that MacDonald et al. had derived SZLs for. The predicted SZLs from the modified shadow zone equations are compared to the observed SZLs as derived from MacDonald et al. in Figure 30.

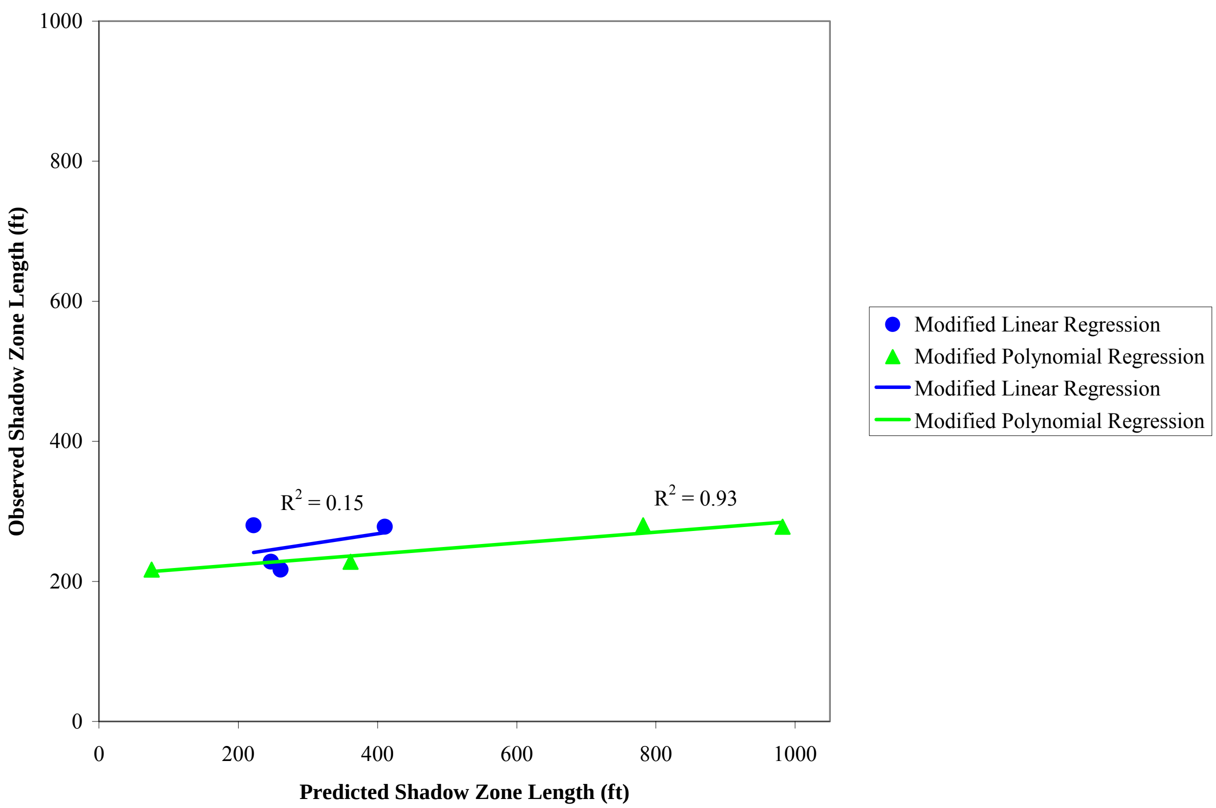

Figure 30: Scatterplot of Observed Shadow Zone Lengths as Derived from MacDonald et al. vs. Predicted Shadow Zone Lengths as Derived from Linear and Polynomial Regression at Four Barrier Locations.

As shown, there is a poor relationship between the modified shadow zone equations and the observed shadow zones developed by MacDonald et al. Despite the high R^2 for the modified polynomial regression model there is obviously no relationship between the predicted and observed values. For example, the farthest right modified polynomial regression data point shows an observed SZL = 278 feet and the predicted SZL = 982 feet. Based on these results, the shadow zone equations do not validate when compared to the observed SZLs developed by Equation 16 of MacDonald et al. Additional testing against independently derived observed shadow zone lengths will be required in order to fully validate the two shadow zone equations.

CHAPTER FIVE: CONCLUSION

The purpose of this research was to develop an empirical equation that could predict roadway noise barrier shadow zone lengths (SZLs). Two empirical equations, called the Shadow Zone Equations, were successfully derived and statistically proven as useful tools for estimating SZL. This research, through individual effort and team participation, was accomplished through a combination of field work, computer modeling, data analysis, gridding and contouring, and statistical analysis. The actual SZLs derived from the methodology in Chapter 3 and the SZLs predicted by the shadow zone equations are shown in Table 12.

Table 12
Actual and Predicted Shadow Zone Lengths (feet)

Location	Actual	Linear Regression (Equation 20)	Polynomial Regression (Equation 21)
A	200	173	226
B	141	237	138
C	254	222	232
E	362	349	363
F	130	228	162
G	73	89	69
H	243	195	221
I	150	217	174
J	90	59	86
L	157	249	150
M	320	279	322
N	157	231	152
O	316	229	293
P	445	360	441
Q	390	406	396
R	251	241	234
S	305	197	327
Average Error Of Prediction		55	13

In the development of the shadow zone equations, it was learned that vehicle speed was not important in predicting the SZL. The SZL can be predicted using only 3 variables under the linear regression model: barrier height, background noise level, and distance from the roadway to the noise barrier. A fourth variable, percent heavy trucks, improved the statistical results in predicting the SZL using polynomial regression.

Suggested improvements would be to enhance the microphone array that was used to measure noise levels at in-situ noise barriers. Additional microphones would provide a better coverage of measured noise levels and would eliminate the need to estimate IL based on computer modeling, which can lead to errors. Additional towers should be placed beyond 100 feet from the barrier. Additional microphones should be placed at various heights above the ground. Of course, practical locations will be a problem since barriers have only been built in residential areas and the structures could interfere with ideal microphone placements and offer unwanted shielding affects. A series of microphones should be placed at increasing distances from the barrier in the expected area of where the background level becomes the dominant noise source in an attempt to find the location of zero IL. Another improvement would be in the selection of noise barrier locations. The usefulness of some of the barriers locations, although adequate for noise barrier evaluation close to the barrier, was questionable for shadow zone research which requires evaluating a barrier at distances much farther away. Specific examples of problem locations for shadow zone study were those where the microphone array was set up near the end of the barrier or near an opening in the barrier such as required for access roads. FDOT prescribed the locations and perhaps better locations could have been found. Both the measured and modeled noise levels can be affected by noise flanking around the ends of the barrier degrading the length of the estimated shadow zone. Also, some of the locations had side streets on the receiver side of the barrier whose noise also degraded the length of the estimated shadow zone. Any such feature at a noise barrier location that can artificially degrade the estimated shadow zone will result in a regression model (shadow zone equation) that will tend to underestimate the length of predicted shadow zones. Additionally, for some locations, the microphone array had to be placed in between homes resulting in either the measured noise levels being lower than actual due to shielding or possibly higher than actual due to reflections. This can cause the estimated shadow zone to be different had the microphones been placed away from any type of shielding or reflective surface. The shielding provided by the first row of dwellings lowers the sound levels measured and predicted at the second and third row of homes. This additional shielding reduces noise levels which would be equivalent to a taller barrier without shielding. At such locations, the estimated shadow zone will be longer than actual. A shadow zone equation based on such locations would tend to overestimate the length of predicted shadow zones.

The shadow zone equations developed as the objective of this research should undergo continued validation against independently derived shadow zone lengths. However, doing so would require a level of effort and time suitable for another research project. The shape of the shadow zone is dependent primarily on IL and background noise levels. Ideally, it would be preferred to measure noise levels at a location without a barrier then take measurements again once a barrier is constructed (as is planned for Site T from the Florida barrier effectiveness study [13]) or take measurements near, but away from, the noise barrier to obtain the “without barrier” noise levels provided the terrain is the same as that behind the barrier (as was done for Sites H and R). The ability to do so would provide a direct IL determination for a noise barrier location. Although this study utilized measured IL data, it was based on the indirect method of measuring

IL and not the recommended direct method. However, it is difficult to identify locations that currently have no noise barrier but eventually will.

Since the background noise level plays a large role in determining the SZL, the indirect method to predict IL may be sufficient. For this study, background noise levels were assumed to be equivalent to the L_{99} value at the Ivie 1 microphone position (100 feet from the barrier). It may be beneficial to try L_{90} as the background value, as was done by MacDonald et al., and recalculate the regression model. To validate if whether L_{90} or L_{99} is a good estimate of background levels, actual background noise levels need to be measured. It would be ideal to measure noise levels at a noise barrier location where all traffic has stopped, but this is not feasible. An array of microphones should be placed at varying distances from the noise barrier where the dominate noise source changes from traffic noise to background noise. A plot of L_{eq} versus distance from the barrier would show where the noise level drops off to a relatively constant level. This is where the background noise is approximately 9 dB(A) above the traffic noise because of the logarithmic nature of decibels (dB). The location where the traffic noise just equals the background noise is the edge of the shadow zone. The location of this edge is where the measured noise level equals the background noise level plus 3 dB(A). The location where this occurs can then be compared to the modeled locations of the L_{90} and L_{99} values to determine which descriptor best approximates background or if a different statistical descriptor, L_X, should be used as background. Regardless, there are several issues that make determining the location and strength of the background noise level difficult:

- The L_X value will vary from true background depending on what type of roadway facility is present at that location. If the roadway is an uninterrupted flow highway the L_X value will be higher than for a signalized arterial roadway, which may have traffic lulls due to signalization, thus the background could be overestimated for locations next to uninterrupted flow highways. In this case, L_{90} or other metrics would be better than L_{99}.

- Trying to determine the location of background may require taking measurements within a neighborhood which itself may contain unusual noise sources that interfere with the actual background noise (e.g., dogs barking, construction noise, etc.).
- It is difficult to pinpoint the location where the background noise level is reached since noise levels change very little over long distances.
- Actual background noise levels vary with time of day and day of week.
- There is a high level of uncertainty in correlating the measured background noise levels to the TNM predicted location of background because the predicted location can be 500 to 700 feet behind the noise barrier and TNM's accuracy has not been validated at such distances.

Another suggested improvement to the estimation of SZL includes giving consideration to the TNM predicted location of background and how the traffic and background noise combine to create a higher sound pressure level than either one alone at that location. A 3 dB(A) difference at the background location may affect the SZL, but should only be considered after investigating more important issues such as improving the method used to determine background (as opposed to assuming it is equal to L_{99}) and validating TNM at the distances it predicts the background to occur.

APPENDIX A: FIELD EQUIPMENT LIST [12]

Equipment		Serial Number
Metrosonics		2134
db308 Sound Level Analyzers		2136
		2137
		2143
		2146
Ivie Electronics	Unit 1	805X034
IE 30A Audio Analyzers	Unit 2	805C418
	Unit 3	805C861
	Unit 4	805C392
	Unit 5	805C246
	Unit 6	805C372
	Unit 7	805C415
	Unit 8	805B325
	Unit 9	805C850
	Unit 10	805C840
	Unit 11	805C859
	Unit 12	992C986
Ivie Electronics	Unit 1	138
IE 3P Preamplifiers	Unit 2	137
	Unit 3	166
	Unit 4	120
	Unit 5	135
	Unit 6	102
	Unit 7	104
	Unit 8	117
	Unit 9	144
	Unit 10	146
	Unit 11	145
	Unit 12	125
CL-304 Calibrator		2219
GenRad Sound Level Calibrators		2411
		911642015
		9146545009
		2365
Aspirated Thermometers		41342a
		41342b
R.M. Young		UV02192
UVW Anemometers		UV02193
instruNet Model 100		
Analog/Digital Input/Output System		43514
Campbell Scientific		
CR23X Micrologger		2055

Vehicle	Radiator water level Tire air pressure Van gasoline level
Portable Sound Analyzers	Metrosonics Calibrator Tripods Heavy duty tape Wind screens Mic holders
Sound Analyzer System	Ivies GenRad multi-frequency calibrators Stands Mics/Preamps Wind screens Cables
Power Supply	Small generator Large generator Gasoline tank Wooden boards/wall Lead blanket Hi-voltage extension line Low-voltage extension line
Meteorology Equipment	Campbell data acquisition unit Tripods Anemometer Pulley system Compass Psychrometer
Data Acquisition Equipment	Laptop AC adapter Inverters (2) Car battery (2) Charger
Communication Equipment	Walkie-talkies (2) Charger unit
Personal Accessories	Safety vest Water Ice Cooler

APPENDIX B: MEASURED NOISE LEVELS [12][13]

Ivie Measured Noise Levels (L_{eqA}) Locations A through H

Location	Run	1	2	3	4	5	6	7	8
A. Jacksonville	1	-	63.5	67.6	-	65.2	68.5	79.8	79.3
	2	63.0	63.4	67.5	-	65.3	68.6	80.1	79.8
	3	62.8	63.3	68.2	-	65.4	68.6	79.9	79.6
	4	62.9	63.4	68.4	-	65.5	68.8	79.9	79.6
	Avg	62.9	63.4	67.9	-	65.3	68.6	79.9	79.6
B. Jacksonville	1	-	65.6	66.8	64.3	66.1	69.4	76.1	77.1
	2	-	66.2	67.0	64.7	66.5	70.0	76.2	77.5
	3	64.0	66.4	67.0	64.7	66.6	69.7	76.1	77.5
	4	63.3	66.3	69.3	64.1	66.6	69.9	76.2	77.5
	Avg	63.7	66.1	67.7	64.5	66.5	69.8	76.2	77.4
C. Daytona	1	55.3	56.9	61.9	57.6	59.2	-	-	73.0
	2	55.7	57.1	61.2	56.7	58.2	-	-	73.3
	3	55.8	57.4	61.7	58.3	59.4	-	-	74.2
	4	55.9	57.8	62.2	58.9	60.0	-	-	74.3
	Avg	55.7	57.3	61.8	58.0	59.2	-	-	73.7
E. Brandon	1	62.1	63.1	65.5	62.3	63.4	64.6	83.1	83.1
	2	61.3	62.3	64.3	61.2	62.0	62.8	82.9	83.5
	3	63.0	64.0	66.1	63.0	64.6	65.2	83.5	84.0
	4	64.5	65.4	67.6	64.5	65.8	66.3	83.2	83.8
	Avg	62.9	63.9	66.0	62.9	64.2	64.9	83.2	83.6
F. Clearwater	1	54.9	56.4	61.7	55.4	57.1	65.5	72.8	72.0
	2	56.0	57.6	63.4	56.5	58.2	66.5	72.3	71.5
	3	55.6	57.4	63.4	56.3	58.1	65.8	71.4	71.5
	4	54.8	55.8	64.8	55.4	57.0	65.6	71.7	72.1
	Avg	55.4	56.9	63.5	55.9	57.6	65.9	72.1	71.8
G. St. Petersburg	1	56.5	57.7	59.3	58.0	58.7	-	71.1	70.4
	2	56.9	58.1	60.1	58.4	59.1	-	71.4	71.0
	3	57.2	58.4	60.5	58.8	59.2	-	71.1	71.2
	4	57.1	58.5	60.7	58.9	59.4	-	71.3	71.0
	Avg	56.9	58.2	60.2	58.5	59.1	-	71.2	70.9
H. Ft. Lauderdale	1	64.9	67.1	69.5	66.5	66.2	72.7	81.0	80.6
	2	64.4	66.9	70.7	66.2	66.3	72.6	80.9	80.6
	3	64.1	66.6	69.7	66.0	66.3	72.7	81.1	80.7
	4	63.3	65.8	68.8	65.4	65.7	72.1	81.0	80.4
	Avg	64.2	66.6	69.7	66.0	66.1	72.5	81.0	80.6

Ivie Measured Noise Levels (L_{eqA}) Locations I through O

Location	Run	1	2	3	4	5	6	7	8
I. Deerfield Beach	1	63.2	65.1	69.3	65.1	66.4	72.2	79.0	78.4
	2	62.9	64.9	69.0	64.8	66.2	71.9	79.2	78.6
	3	63.3	65.4	69.3	65.0	66.4	72.1	79.1	78.5
	4	63.1	65.3	69.3	65.0	66.4	72.1	79.1	78.5
	Avg	63.1	65.2	69.2	65.0	66.4	72.1	79.1	78.5
J. Miami	1	64.7	64.9	66.9	65.2	66.0	69.5	80.7	80.2
	2	64.9	65.2	67.1	65.6	66.3	70.0	81.0	80.2
	3	65.2	65.3	67.3	65.9	66.6	70.2	81.3	80.7
	4	65.4	65.4	67.4	65.8	66.7	69.9	81.2	80.8
	Avg	65.1	65.2	67.2	65.6	66.4	69.9	81.1	80.5
K. Tamiami	1	52.6	54.4	58.3	55.4	56.5	62.6	73.6	-
	2	53.0	54.0	58.0	55.3	56.6	62.5	73.5	-
	3	53.1	54.1	58.8	55.9	56.9	63.0	74.1	-
	4	53.3	54.2	58.4	55.8	57.0	62.8	74.6	-
	Avg	53.0	54.2	58.4	55.6	56.8	62.7	74.0	-
L. Hialeah	1	58.1	76.7	61.9	58.5	59.4	61.8	76.7	-
	2	58.2	76.6	62.3	58.8	59.9	62.1	76.6	-
	3	58.8	76.8	62.9	59.3	60.7	62.9	76.5	-
	4	58.7	77.2	63.1	59.6	60.9	63.3	77.0	-
	Avg	58.5	76.8	62.6	59.1	60.3	62.6	76.7	-
M. Wildwood	1	49.5	51.1	57.2	53.1	53.8	61.3	69.5	69.8
	2	50.9	53.8	59.5	54.0	55.8	61.2	70.6	70.5
	3	51.7	52.5	59.7	54.4	55.4	62.0	71.1	70.3
	4	51.7	53.2	58.8	52.3	57.1	62.0	70.5	70.8
	Avg	51.0	52.7	58.8	53.4	55.5	61.6	70.4	70.3
N. Maitland	1	NA	53.9	55.8	54.7	54.6	NA	69.7	NA
	2	NA	53.9	56.5	54.7	54.5	NA	71.0	NA
	3	NA	56.0	57.6	55.7	56.4	NA	71.7	NA
	4	NA	54.7	56.6	55.2	55.8	NA	70.6	NA
	Avg	NA	54.6	56.6	55.1	55.3	NA	70.8	NA
O. Fort Lauderdale	1	63.0	65.0	NA	64.7	66.1	NA	NA	80.0
	2	63.2	65.1	NA	64.5	66.2	NA	NA	80.0
	3	63.7	65.6	NA	66.2	66.7	NA	NA	80.2
	4	NA	NA	NA	NA	NA	NA	NA	NA
	Avg	63.3	65.2	NA	65.1	66.4	NA	NA	80.1

Ivie Measured Noise Levels (L_{eqA}) Locations P through S

Location	Run	1	2	3	4	5	6	7	8
P. Fort Lauderdale	1	57.2	58.7	NA	58.7	59.3	64.1	77.3	77.6
	2	58.7	59.8	NA	59.0	59.6	64.4	77.3	77.4
	3	59.1	60.0	NA	59.2	59.9	64.6	77.9	78.0
	4	59.3	60.0	NA	59.4	60.2	65.2	78.2	78.2
	Avg	58.6	59.6	NA	59.1	59.8	64.6	77.7	77.8
Q. West Palm Beach	1	54.3	56.6	61.1	57.4	58.5	64.1	76.1	78.1
	2	54.7	57.0	61.6	57.2	58.6	64.1	75.9	76.0
	3	55.8	58.2	62.8	58.5	59.4	65.2	76.0	76.0
	4	56.2	58.9	63.4	58.4	59.9	65.4	76.4	77.8
	Avg	55.3	57.7	62.2	57.9	59.1	64.7	76.1	77.0
R. Palm Harbor	1	NA	55.8	NA	57.6	61.1	NA	69.6	70.1
	2	NA	55.7	NA	57.3	61.6	NA	69.6	70.6
	3	NA	56.5	NA	58.4	62.1	NA	68.7	70.5
	4	NA	56.5	NA	56.7	60.2	NA	69.0	68.9
	Avg	NA	56.1	NA	57.5	61.3	NA	69.2	70.0
S. New Port Richey	1	55.3	55.3	56.5	56.3	55.5	60.4	70.5	70.2
	2	56.0	56.4	57.1	57.0	56.4	59.3	69.7	70.7
	3	58.5	58.4	59.8	58.4	58.5	60.4	70.8	72.0
	4	56.4	56.8	58.1	57.0	56.7	58.8	70.9	71.1
	Avg	56.5	56.7	57.9	57.2	56.8	59.7	70.5	71.0

APPENDIX C: PROPAGATION LOSS ERROR CORRECTION FACTORS [12][13]

	Ivies						Metrosonics	
Location	**1**	**2**	**3**	**4**	**5**	**6**	**A**	**C**
A. Jacksonville	2.7	2.2	4.6	n/a	4.0	3.3	4.0	3.5
B. Jacksonville	3.4	4.2	0.1	4.0	3.5	-1.9	5.1	3.3
C. Daytona	-1.5	-1.5	-1.3	-0.6	-1.1	n/a	-0.7	0.2
E. Brandon	0.7	0.4	0.1	1.0	1.1	0.0	-1.7	0.5
F. Clearwater	2.0	-1.2	1.1	1.3	-1.1	-0.3	0.7	2.1
G. St. Petersburg	1.0	-0.6	-2.7	0.6	-3.2	n/a	1.4	0.8
H. Ft. Lauderdale	1.2	2.2	1.5	3.0	1.1	0.2	2.0	1.1
I. Deerfield Beach	0.6	0.3	0.1	2.6	1.8	-1.5	4.6	2.4
J. Miami	0.3	-1.3	-1.7	0.8	0.2	-0.8	1.6	0.5
K. Tamiami	2.1	1.8	-1.6	-0.4	-0.7	-2.4	1.0	2.2
L. Hialeah	2.3	n/a	3.0	2.7	3.3	3.2	1.9	3.4
M. Wildwood	-1.1	-1.5	-0.7	-0.2	-1.2	-2.6	2.3	3.5
N. Maitland	3.9	2.8	1.4	2.6	0.9	n/a	1.8	4.0
O. Fort Lauderdale	0.8	1.5	n/a	2.0	1.8	n/a	n/a	n/a
P. Fort Lauderdale	2.0	1.5	n/a	0.6	0.5	-0.4	3.7	1.8
Q. West Palm Beach	-0.8	-0.2	0.4	-0.2	-0.1	0.2	-0.1	1.0
R. Palm Harbor	1.7	-1.2	n/a	-0.1	-3.0	n/a	n/a	n/a
S. New Port Richey	1.2	0.0	-1.0	0.5	-2.1	-2.7	0.6	n/a

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