U.S. Department of Transportation
Federal Highway Administration

REMELs and Sub-source Heights for the Traffic Noise Model

A SYNTHESIS OF THE STATE OF KNOWLEDGE AND SUMMARY OF NEEDS

FHWA-HEP-24-031| April 2024
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13. ABSTRACT (Maximum 200 words) This report identifies and describes the noise sources associated with highway noise and reviews the current measurement techniques for quantifying highway-related noise including wayside measurements, such as statistical isolated pass-by (SIP), the continuous-flow traffic time-integrated method (CTIM), beamforming and acoustical cameras, as well as proximal measurements including the close proximity method (CPX) and the on-board sound-intensity method (OBSI). Uses, strengths and weaknesses are discussed for each technique. This report also includes considerations on how measured data can be used to improve noise modeling in the Federal Highway's Traffic Noise Model (TNM) and provides an annotated bibliography.			
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Acronyms and Abbreviations

CPB	Controlled Pass-by
CPX	Close Proximity Method
CTIM	Continuous Flow Traffic Time-Integrated Model
DGA	Dense Graded Asphalt
DGAC	Dense Graded Asphalt Concrete
DLPA	Double Layer Porous Asphalt
FHWA	Federal Highway Administration
ICE	Internal Combustion Engine
OBSI	On-Board Sound Intensity
OGAC	Open Graded Asphalt Concrete
PA	Porous Asphalt
PCC	Portland Cement Concrete
REMELs	Reference Energy Mean Emission Levels
SIP	Statistical Isolated Pass-by
SMA	Stone Mastic/Matrix Asphalt
SPB	Statistical Pass-By (See Also CTIM)
SSB	Solid Safety Barrier
TNM	Traffic Noise Model

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1. Introduction

This document describes the main sources of highway traffic noise, identifies methods and standards for conducting noise measurements, summarizes current research using these methods, and discusses the current state the Federal Highway Administration's (FHWA) Traffic Noise Model's (TNM).

The focus of the TNM discussion is on traffic noise source heights and emission levels related to Heavy Trucks and different pavement types.

The report concludes by identifying research needs and recommendations for updating TNM. Updates to TNM will be focused on increasing accuracy and ensuring the model predicts levels as close to the real-world as possible.

1.1 Introduction to Highway Traffic Noise Sources

There are two[1] main sources of highway traffic noise that are typically measured and modeled:

- The noise emitted by the tire-pavement interface
- The noise due to the combustion process of internal combustion engines

The noise level generated by the tire-pavement interface will depend on the particular tire itself, while the noise generated by the engine combustion will depend on the specific engine and its use. For details on the sub-components of these sources, see **Section 2: Noise Sources**.

1.2 Introduction to Highway Traffic Noise Measurements

Measurements can be taken in two main ways to determine and characterize vehicle noise sources:

- At the vehicle utilizing the:
  - On-board sound intensity (OBSI) Method
  - Close proximity (CPX) Method
- At the roadside utilizing the:
  - Statistical isolated pass-by (SIP) Method
  - Continuous flow traffic time-integrated (CTIM) Method
  - Beamforming Methods
  - Acoustic camera[2] Method

Each technique has its own benefits and shortcomings and using a combination of methods may provide the most accurate and applicable data for inclusion in noise models. See also **Section 3: Measurements**.

[1] Aerodynamic noise is typically a small contributor to exterior roadway traffic noise and is typically aggregated into engine and tire-pavement noise. With the exception of reverse, gear trains can generally be neglected as roadway traffic noise source.
[2] Acoustic cameras utilize beamforming methods and a digital camera to overlay the estimated source levels with an image of the target source.

1.3 Introduction to Highway Traffic Noise Modeling

Acoustic modeling describes the types of sources that significantly contribute to roadway traffic noise and how their characteristics change when propagating between the source and the receiver. From a model development perspective, characterizing these sources and understanding how they are modeled is important for:

- Understanding potential research needs
- Determining how new data can be implemented in TNM
- Evaluating what potential impacts there would be when implementing new data

Typically, a **source-path-receiver**[3] model is used to model roadway traffic noise and to account for how mitigation strategies, such as noise walls, can help reduce the noise level near roadways. There are a variety of noise models available both from private companies and government entities around the world. This document focuses on the Federal Highway Administration's Traffic Noise Model (TNM). For more detailed information on how TNM models highway traffic noise in the context of the current discussion see **SECTION 4: NOISE MODELING: TNM ALGORITHMS .**

1.4 Introduction to TNM and Summary of Needs

FHWA developed TNM to account for noise emissions, divergence, and diffraction in modeling roadway traffic noise. The first version, TNM 1.0 was released in 1998. Since then, several updates have been made to the model to improve the usability and accuracy, and development continues.

Throughout this time, the original database of noise emission levels from TNM 1.0, defined by the Reference Energy Mean Emission Levels (REMELs), detailed in Annotated Bibliography reference **RLR_021**, have not changed. While the source heights themselves have also not changed, the modeled distribution of energy between the source heights has been updated to improve the model's accuracy.

However, over the last two decades, vehicles and pavements have evolved, new measurement technologies have been developed, and new research has been conducted that may help further improve the accuracy and physical representations of current traffic conditions in TNM. Updates to TNM will serve to identify and mitigate traffic noise impacts near roadways more effectively.

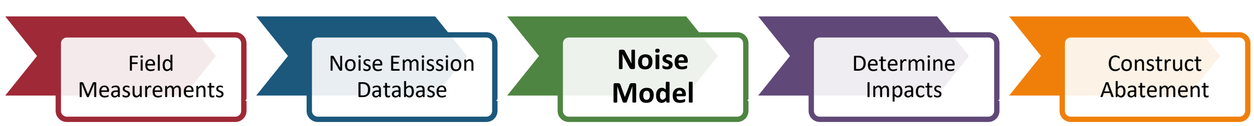

FIGURE 1 NOISE MODEL DEVELOPMENT AND USE PROCESS

To ensure proper reduction and abatement of project impacts, it is important to be able to model traffic noise levels at specific locations for noise sensitive land uses. Proper modeling in turn, depends upon a detailed noise emission database, which is developed using good field measurements. For more information on recommended next steps to accomplish these updates, see **SECTION 5: LITERATURE REVIEW SUMMARY**.

[3] Receiver is used to denote where the model calculates the final noise levels. The modeling input object 'receiver' corresponds to one or more real-world noise-sensitive locations called receptors.

2. NOISE SOURCES

Background Information on Highway Noise Sources

The main[4] sources of roadway traffic noise are tire-pavement noise and engine noise from internal combustion engine (ICE) engines. Several factors must be considered when describing these noise sources for use in modeling, during research projects, and during highway project development. These include:

1) The source geometry
2) The sound level as a function of frequency
3) How the source is measured
4) How the source is modeled

Both main noise sources are described with respect to these factors in more detail below. For information regarding factor 3, see **SECTION 3: MEASUREMENTS**; and for more information on how TNM currently models these sources, see **SECTION 4: NOISE MODELING: TNM ALGORITHMS** .

2.1 Tire-Pavement Noise

The noise level generated by the tire-pavement interface will depend on several mechanisms, including the tire itself (including the tread pattern and depth, the hardness of the tire and its size) as well as the tire load, the pavement type, and the speed that the vehicle is traveling.

Annotated Bibliography reference **RLR_054** describes several of these mechanisms:

- Tread Impact (Hammering)
- Air Pumping (Clapping)
- Stick-Slip (Sneaker)
- Stick-Snap (Suction Cup)
- Acoustic Horn (Horn)
- Helmholtz Resonance (Pop Bottle)
- Pipe Resonance (Pipe Organ)
- Sidewall Vibration (Pie Plate)
- Cavity Resonance (Balloon)

Donavan et al showed in **RLR_008** that these various mechanisms generate a distributed source around the tire, as shown in **FIGURE 2**. In order to obtain the necessary data to characterize these mechanisms in a model, the common practice is to use either wayside measurements and/or proximal measurements. For more details on the applicability of these methods to characterizing Tire-Pavement Noise, please see **SECTION 3.2.1.1: TIRE-PAVEMENT NOISE**.

[4] Aerodynamic noise tends to be a small contributor in comparison. In addition, artificial warning systems, such as those found on Electric Vehicles, may one day become significant, especially at low speeds, but they are beyond the scope of the current discussion.

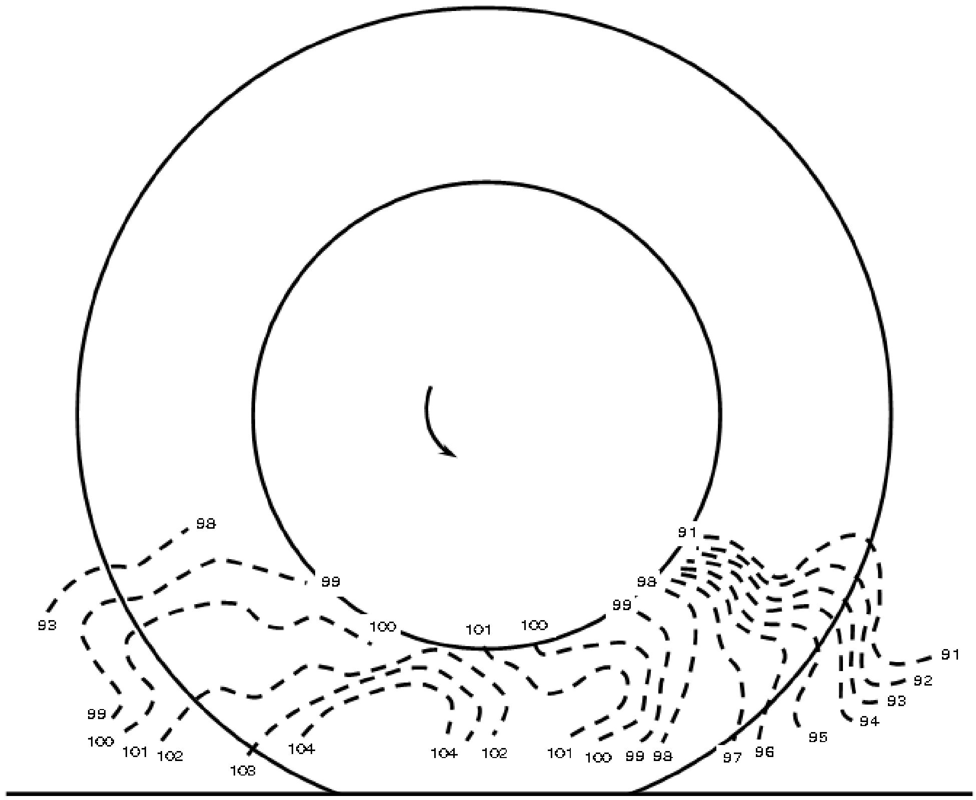

FIGURE 2 ISO-INTENSITY CONTOUR FOR CROS-BAR TREAD TIRE ON SMOOTH PAVEMENT IN 500 TO 1000 HZ FREQUENCY RANGE

(Photographic References: PR_01; note that the image was recreated for this report)[5]

When modeling noise at distances greater than 25 feet from the tire, it is the established practice to model these separate noise mechanisms as a single aggregated tire-pavement noise source. Typically, the source is set at ground level or just above the ground. In the case of TNM it is set at 10 centimeters (or about 4 inches) above the pavement in order to avoid numerical issues with zero-height sources. As such, tire-pavement noise is typically modeled as having a single source height and the level is modeled to be a function of frequency, speed, vehicle type, vehicle operating condition, and pavement type. Details of tire-pavement source modeling in TNM are presented in **SECTION 4.1: EMISSIONS: TNM EQUATIONS 3 TO 5**.

2.2 Engine Noise (ICE Engines)

Engine noise sources include all sound associated with the operation of an ICE. The noise generated by the engine combustion will depend on the engine design, intake and exhaust systems, engine load and operating speed. Most engine sources are radiated from the following components:

- valve cover (valve train)
- engine block (combustion, piston slap)

[5] Note, while the majority of the energy will be in the region of the tire closest to the pavement, the cavity resonance can excite the entire tire, thus for very large tires the highest portion of tire noise could be as high as 37.7 inches, e.g. for a 275-70R22.5 tire. However, the cavity resonance tends to be more significant to interior (vehicle occupant) noise than exterior (roadside) noise.

- air intake
- exhaust
- oil pan (various paths)
- accessories such as belts, pumps, and fans

Because the sound is radiated from sources inside the engine compartment and underneath the vehicle, the sound from the engine must first travel along various paths within the engine compartment. Sound can escape through seams around the engine hood, through the front grill, through the body panels, and from the wheel well and body underside. For an automobile, this means that engine noise can be coming from as low as a few inches above the ground for exhaust from automobiles and motorcycles to over five feet for some medium or heavy trucks and buses.

In order to obtain the necessary data to characterize these mechanisms in a model, the common practice is to use wayside measurements. For more details on the applicability of these methods to characterizing Engine Noise, please see **SECTION 3.2.1.2: ENGINE NOISE**.

The parameters that are used to model engine noise are the vehicle type, vehicle speed (as a proxy for engine speed and load), and the throttle condition for accelerating vehicles and for heavy trucks climbing steep road grades. Similar to the aggregation of the various sources of tire-pavement noise, the various noise sources from the engine (air intake, engine block, intake and exhaust manifolds, cylinder head cover, radiator fan, etc[6]) are aggregated into a single engine noise source when modeling a given vehicle. In turn, most of these vehicle parameters are aggregated across the national (or regional) vehicle fleet for each vehicle type. For more information on how TNM models engine noise, please see **SECTION 4.2 SUB-SOURCE HEIGHT SPLIT: TNM EQUATIONS 9 TO 11**.

Based on several beamforming studies of heavy trucks and analysis of short barriers, there is a need to investigate the engine/exhaust heights used in TNM, which may be overly conservative. **SECTION 5: LITERATURE REVIEW SUMMARY** provides more details on recent beamforming, short barrier studies, and OBSI measurements.

[6] The exhaust pipe exit is treated separately as it is spatially separated from the rest of the engine.

3. NOISE MEASUREMENTS

Background Information on Methods and Use

This section contains summaries of highway and vehicle noise measurement methods and a discussion on the application of these methods in the context of FHWA project development and model improvements. In the highway noise research program, noise measurements are mainly taken to:

- Characterize the noise emissions due to different pavement types
- Characterize the noise source heights for different vehicle types

There are a variety of possible measurement methodologies, techniques, and combinations of these to obtain the characterizations. The potential methods and techniques are described in more detail below.

3.1 Noise Measurement Methods

This section provides an overview of the most common measurement methods used for quantifying traffic related noise. Each method includes a short description of what it is, a photograph[7] showing the typical setup, an explanation of the appropriate uses, and a discussion of shortcomings of the method.

3.1.1 Statistical Isolated Pass-By (SIP) Method

The SIP Method is a type of wayside (roadside) measurement. The equipment is set up at a given distance perpendicular to the roadway. These measurements capture not only the tire-pavement noise, but also the engine and aerodynamic noise. SIP measurements are done with a single vehicle. This method is also known as the statistical pass-by method (SPB). It is defined in ISO 11819-1:1997(E).

3.1.1.1 EQUIPMENT SETUP

FIGURE 3 SIP METHOD EQUIPMENT SETUP
(Photographic References: PR_05)

[7] Each photograph contains a photographic reference ID starting with 'PR_', details for the given identification number can be found in the **PHOTOGRAPHIC REFERENCES** Appendix.

The setup usually involves multiple microphones at different heights and distances from the roadway.

3.1.1.2 Uses

Determining the influence of vehicle type, speed, operating condition and road surfaces on vehicle noise. Captures all vehicle noise sources. SPB measurements are often used to collect research-quality data. This method was used in collecting the original Reference Mean Energy Levels (REMELs) for TNM.

3.1.1.3 Caveats

All noise sources are included in the same measured sound pressure. Separating sound sources relies on modeling the site physical characteristics. Site and traffic requirements are highly prescribed. Also requires a large number of samples.

3.1.2 Continuous-Flow Traffic Time-Integrated Method (CTIM)

The CTIM Method is another type of wayside (roadside) measurement. Measurement equipment is set up at a given distance perpendicular to the roadway. Like the SIP/SPB it also captures tire-pavement, engine, and aerodynamic noise. However, CTIM wayside measurements are done with a continuous flow of traffic. This method is defined in AASHTO T 390:2020.

3.1.2.1 Equipment setup

Figure 4 CTIM Method Equipment Setup
(Photographic References: PR_04)

The equipment setup usually involves multiple microphones at different heights and distances from the roadway[8].

[8] For more information on the use of the CTIM Method on individual FHWA projects please see the Noise Measurement Handbook. For more information on the use of this method in validating the entirety of the TNM software itself please see the associated Validation Report for the latest version of TNM.

3.1.2.2 USES

Captures all vehicle noise sources. This method was used during model validation for the various TNM versions and is used for model setup validation on specific projects.

3.1.2.3 CAVEATS

Requires a long sample period. All noise sources are included in the same measured sound pressure. Separating sound sources relies on modeling the site physical characteristics. Site and traffic requirements are highly prescribed.

3.1.3 Beamforming

Beamforming is a third type of wayside (roadside) measurement. This method is newer than SIP or CTIM. Measurement equipment is set up at a given distance perpendicular to the roadway. Like other wayside measurements, it captures tire-pavement, engine, and aerodynamic noise. However, unlike the other wayside measurements, which require post-processing to separate the sources, Beamforming uses software with algorithms designed to separate the sources *in situ*. Wayside Beamforming measurements are done with a single vehicle. This method does not have a defined standard yet.

For more information on recent research and results using Beamforming, please see **SECTION 5.1 BEAMFORMING MEASUREMENTS**.

3.1.3.1 EQUIPMENT SETUP

FIGURE 5 EXAMPLE BEAMFORMING EQUIPMENT SETUP[9]
(Photographic References: PR_06)

[9] As this method has no set standard, the equipment can be set up in a variety of ways by the research team. This photograph provides on way it could be set up.

In this case, the equipment includes a multitude of microphones arranged in specific patterns. Since there is no standard yet, this section contains some extended discussion on the setup options and consequences.

The spatial *resolution* and frequency *range* of the array depend on the arrangement of the microphones. The spatial resolution is governed by the directivity pattern of the array, which is determined by size and pattern of the microphone distribution (much like a radio antenna). Low frequency localization depends on widely spaced microphones; thus, the low frequency limit is mostly controlled by the overall size of the array[10]. The high frequency localization depends on closely spaced microphones; thus, the high frequency limit is controlled mostly by how close some of the microphones are spaced.

3.1.3.2 Uses

Used to infer the level and origin of a noise source using a large number of simultaneous acoustic measurements.

3.1.3.3 Caveats

Results and use are dependent on the position of the microphones within the array, and the position of the array in relation to the roadway. Since there is no standard beamforming pattern or set of algorithms, different beamforming systems can produce different results for the same measured source. In addition, beamforming data can indicate 'ghost sources' of noise that do not correspond with reality, such as noise sources below the level of the ground.

3.1.4 Acoustical Cameras

Acoustical cameras are a combination method for wayside (roadside) measurement. This method combines beamforming with a digital camera and *in situ* processing software to create 'heat maps' of noise sources overlayed on an image of a given vehicle pass-by. Measurement equipment is set up at a given distance perpendicular to the roadway. Like other wayside measurements, it captures tire-pavement, engine, and aerodynamic noise. Acoustic camera wayside measurements are also done with a single vehicle. This method does not have a defined standard yet.

[10] Frequency limitations at both the low and high end for individual microphones exceed the range of typical microphone arrays. Therefore, individual microphone limitations are not considered in this discussion.

3.1.4.1 Equipment Setup

Figure 6 Acoustic Camera Method Equipment Setup
(Courtesy of Ivan Racic of the Arizona Department of Transportation)

3.1.4.2 Uses

To show acoustical impacts of various vehicle features and 'photograph' the noise source level and heights.

3.1.4.3 Caveats

As with beamforming, results and use are dependent on the position of the microphones within the array, and the position of the array in relation to the roadway. Since there is no standard beamforming pattern or set of algorithms, different beamforming systems can produce different results for the same measured source. In addition, beamforming data can indicate 'ghost sources' of noise that do not correspond with reality, such as noise sources below the level of the ground.

3.1.5 Close Proximity Method (CPX)

This is a type of source emission measurement (proximal) method; focused on the tire-pavement noise source. CPX measurements quantify sound intensity. These measurements are done with a single vehicle equipped with a reference tire. The measurement apparatus is attached near the tire itself. This method is defined in ISO 11819-2:2017(E).

3.1.5.1 Equipment setup

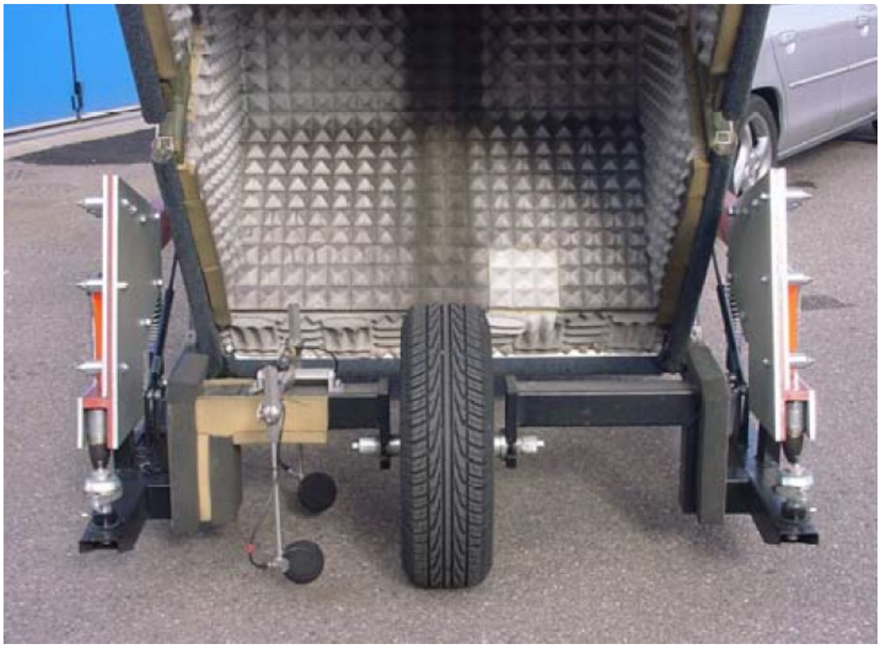

Figure 7 CPX Method Equipment Setup
(Photographic References: PR_03)

3.1.5.2 Uses

Comparison of the effects of different pavements on noise emissions.

3.1.5.3 Caveats

Do not account for path effects between the source (tire-pavement interface) and the receiver, nor do they provide any details on the source's engine or aerodynamic noise. CPX measurements also do not quantify sound pressure at reference locations, and assumptions must be made to convert sound intensity into sound pressure levels. Does not directly predict sound pressure at reference locations. Superseded by OBSI measurements in many cases.

3.1.6 On-Board Sound Intensity (OBSI) Method

OBSI is a type of source emission measurement (proximal) method; focused on the tire-pavement noise source. OBSI measurements quantify sound intensity generated by the tire-pavement interface. OBSI measurements are conducted using a single vehicle equipped with a standard reference tire. The measurement apparatus is attached to the vehicle itself [11]. This method is defined in AASHTO T 360-16:2020.

For more information on recent research and results using Beamforming, please see **Section 5.3 OBSI Measurements**.

[11] For OBSI, the microphones are setup as phase matched pairs in order to obtain intensity measurements.

3.1.6.1 EQUIPMENT SETUP

FIGURE 8 OBSI METHOD EQUIPMENT SETUP
(Photographic References: PR_02)

3.1.6.2 USES

Comparison of the effects of different pavements on noise emissions.

3.1.6.3 CAVEATS

Do not account for path effects between the source (tire-pavement interface) and the receiver, nor do they provide any details on the source's engine or aerodynamic noise. OBSI measurements also do not quantify sound pressure at reference locations, and assumptions must be made to convert sound intensity into sound pressure levels. Consistency between measurement systems is difficult to obtain due to complexity of the system and the measurement approach. System bias can be significant since typically only a single system (source) is used.

3.2 Applying the Measurement Methods

This section will focus on the application of each of the methods discussed above. The section is organized by methods that are used to obtain and quantify vehicle (source) emission data, and those that are used to characterize the height at which the emissions originate on a given vehicle type.

3.2.1 Methods to Characterize Vehicle Noise Source Emissions

Obtaining the correct data to characterize what sources exist on a given vehicle type and how much they contribute to the overall level is very important to understanding highway traffic noise and developing accurate models for use on project-level analyses.

3.2.1.1 TIRE-PAVEMENT NOISE

There are two types of measurements that are typically used to measure tire-pavement noise. The first of these are wayside measurements, conducted using microphones mounted on tripods at the side of a roadway with moving vehicles. These include SIP, CTIM, and Beamforming (and its associated Acoustic Camera technique). At high speeds the dominant noise source is the tire-pavement noise, thus wayside measurements are a good first approximation of tire-pavement noise.

The second type are proximal measurement methods. These include the CPX and the OBSI methods[12]. Both of these methods rely on mounting microphones close to the tire-pavement interface of moving vehicles. Proximal methods are used when the effects of a specific pavement need be examined. These measurements are taken much closer to the target noise source and as such, they are less susceptible to influence from other noise sources.

3.2.1.2 Engine Noise

Like tire-pavement noise, engine noise has historically been measured as part of an aggregate SIP or CTIM noise level. This works best at low speeds, when engine noise dominates over the other vehicle emission factors. In order to obtain the engine noise, assumptions about engine and tire-pavement source heights need to be made. Then data related to the geometry and ground type are used to infer (by using a set of direct and reflected acoustic rays) the relative contribution of both sources.

3.2.2 Methods to Characterize Noise Source Heights

Obtaining correct measurement data regarding the height of each noise source is critical to model development. The heights affect the path geometry and thus greatly influence the final noise level results in the model. The main method to obtain source heights today is Beamforming.

[12] Most recent research on tire-pavement noise utilizes OBSI measurements rather than CPX.

4. Noise Modeling: TNM Algorithms

Background Information on TNM Noise Sources and Heights

Several portions of TNM's code affect the modeled noise emission and the height of the noise emission sources. These are described briefly in this section to provide context on some of the interdependencies of various parts of TNM's code. For more information on TNM's algorithms see the Technical Manual for the associated TNM version.

4.1 Emissions: TNM Equations 3 to 5

Equations 3 to 5 in the TNM 3.1 Technical Manual are used to compute single event, maximum noise levels at reference location. The parameters A through Q in these equations account for differences due to:

- Vehicle Type (Auto, MT, HT, Bus, and Motorcycle)
- Pavement Type (Avg, PCC, DGAC, and OGAC)
- Throttle (Cruise, Full)
- Speed (Idle to X mph)
- Grade (+/- in 1% increments)
- Frequency (20 Hz to 20 kHz)

$$E_A(s_i) = (0.6214\, s_i)^{A/10} \cdot 10^{B/10} + 10^{C/10} \quad (3)$$

$$L_A(s_i) = 10 \cdot \log_{10}\big(E_a(s_i)\big) \quad (4)$$

$$L_{emis,\ i}(s_i, f) = (F_1 + 0.6214\, F_2 s_i)\,[\log_{10}(f)]^2 + (G_1 + 0.6214\, G_2 s_i)\,[\log_{10}(f)]^3 + (H_1 + 0.6214\, H_2 s_i)\,[\log_{10}(f)]^4 + (I_1 + 0.6214\, I_2 s_i)\,[\log_{10}(f)]^5 + (J_1 + 0.6214\, J_2 s_i)\,[\log_{10}(f)]^6 \quad (5)$$[13]

These equations work relatively well for spectra that do not change quickly from one-third octave band to the next, which is true for most conditions provided that the spectra do not contain strong tonal components. New values for each of these parameters can be added to handle new noise emission datasets. For more information, see **Section 6.3)**.

4.2 Sub-Source Height Split: TNM Equations 9 to 11

Historically, TNM has used three source heights: approximately four inches for the tire-pavement noise source, five feet for most engine noise, and twelve feet for heavy truck exhaust. To separate the energy in TNM between the different sources, the measured wayside data, along with some initial assumptions about source heights, were used to infer an energy split between tire-pavement noise and engine noise.

See References **RLR_011**, **RLR_012**, **RLR_021**, **RLR_024**, and **RLR_025** for more information and details.

[13] Equation numbers are given as they appear in the TNM 3.1 Technical Manual.

The original distributions, prior to TNM 2.5, are shown in **TABLE 1**.

TABLE 1: SOUND ENERGY DISTRIBUTION BETWEEN SUB-SOURCE HEIGHTS

Vehicle Type	Operating Condition	Percentage of Total Sound Energy at Upper Sub-source height: 1.5m (5 ft), except 3.66m (12 ft) for HT At Low Frequencies (500 Hz and below)	Percentage of Total Sound Energy at Upper Sub-source height: 1.5m (5 ft), except 3.66m (12 ft) for HT At High Frequencies (2000 Hz and above)
Autos	Cruise or Full Throttle	37%	2%
Medium Trucks & Buses	Cruise	57	7
Medium Trucks & Buses	Full Throttle	58	13
Heavy Trucks	Cruise	37	26
Heavy Trucks	Full Throttle	37	28
Motorcycles	Cruise or Full Throttle	58	13

Table recreated here; original source: Table 1, TNM 1.0 Technical Manual

During the development of TNM 2.5, the values of some of the parameters in these equations were updated to get better agreement between measured and modeled results. The new distributions from TNM 2.5 to the present are shown in **TABLE 2**.

*While these heights have not changed since TNM's development, the distribution of energy between these source heights **has** changed over time.*

In most cases the distributions to the upper source height either decreased or did not change significantly. However, the upper source height for heavy trucks did see a significant increase in upper source height energy. The fact that this produces better comparisons with measured data could indicate several things; however, as will be discussed later, it is not likely that this represents the actual physical characteristics of the noise distribution except in rare cases.

TABLE 2: SOUND ENERGY DISTRIBUTION BETWEEN SUB-SOURCE HEIGHTS

Vehicle Type	Operating Condition	Percentage of Total Sound Energy at Upper Sub-source height: 1.5m (5 ft), except 3.66m (12 ft) for HT At Low Frequencies (500 Hz and below)	Percentage of Total Sound Energy at Upper Sub-source height: 1.5m (5 ft), except 3.66m (12 ft) for HT At High Frequencies (2000 Hz and above)
Autos	Full Throttle	27%	4%
Autos	Cruise	27%	4%
Medium Trucks	Full Throttle	34%	11%
Medium Trucks	Cruise	35%	6%
Heavy Trucks	Full Throttle	57%	48%
Heavy Trucks	Cruise	57%	46%
Buses	Full Throttle	34%	11%
Buses	Cruise	36%	7%
Motorcycles	Full Throttle	28%	3%
Motorcycles	Cruise	28%	3%

Table recreated here; original source: Table 3, TNM 3.1 Technical Manual

Equations 9 to 11 in the TNM 3.1 Technical Manual (unchanged since TNM 2.5) are used to distribute the noise energy between two source heights for each vehicle type. For heavy trucks the two heights are at approximately 4 inches and 12 feet. For all other vehicles the two source heights are at approximately 4 inches and 5 feet.

$$r_i(f) = L + (1 - L - M)\left[1 + e^{(N \log_{10}(f) + P)}\right]^Q \tag{9}$$

$$E_{emis,i,upper}(s_i, f) = \left(\frac{r_i}{r_i + 1}\right) E_{emis,i} \tag{10}$$

$$E_{emis,i,lower}(s_i, f) = \left(\frac{1}{r_i + 1}\right) E_{emis,i} \tag{11}$$

There are several modifications that can be made to TNM to improve the accuracy and utility of these source heights. For more information, see SECTION 6.3.

.

4.3 Removing the Free Field Effect: Equations 12 and 13

Equations 12 to 13 in the TNM 3.1 Technical Manual are used to remove the free-field effect that is included in the measured data that were used to develop the emissions database.

$$E_{emis,\ i,\ upper,\ ff}(s_i, f) = m_{upper} \cdot E_{emis,\ i,\ upper} \tag{12}$$

$$E_{emis,\ i,\ lower,\ ff}(s_i, f) = m_{lower} \cdot E_{emis,\ i,\ lower} \tag{13}$$

5. Literature Review Summary

Current Research on Measurements and TNM Shortcomings

Recent research has mostly focused on the sub-source height energy emissions split, rather than on measuring the source emissions themselves. The height of each noise source is especially important for acoustic modeling because it affects the path geometry and can therefore have a significant effect on the results regarding impact and mitigation decisions. However, there has also been an interest in using source measurement techniques, such as OBSI, for a wider array of applications.

Several recent beamforming and barrier measurement research project analysts have argued that the engine/exhaust heights used in TNM may be overly conservative and that this is a question that should be investigated and resolved in near-term research[14]. This section summarizes research regarding both emissions and source heights especially related to OBSI, Beamforming, and Short Barrier measurements[15].

5.1 Beamforming Measurements

As previously discussed, Beamforming is a type of wayside measurement in which the ability to capture low and high frequencies is especially sensitive to the array's setup. **Figure 9** shows an example of a beamforming microphone array. Each small black sphere includes a microphone, so this array has 54 microphones distributed amongst the 9 arms. This array has a useable frequency range from 315 to 4000 Hz. The array would need to increase in diameter to be able to isolate the location of lower frequencies and would need some microphones spaced closer together to localize higher frequencies.

Figure 9 Beamforming Array and Single Sound Level Meter Measuring Vehicle Pass-by
(Photographic References: PR_06)

[14] FHWA is supporting an ongoing National Cooperative Highway Research Program (NCHRP) research project that seeks to collect data to support an update to the TNM noise emissions database and sub-source height settings.
[15] This section only provides a high-level summary of completed research.

Figure 10 shows the estimated sound pressure level obtained from a beamforming array overlayed with an image of a heavy truck during a pass-by. There are two images, one for each frequency (250 and 630 Hz). Note that the noise source changes depending on the frequency. The sound level profile is shown to the right of the image for each frequency.

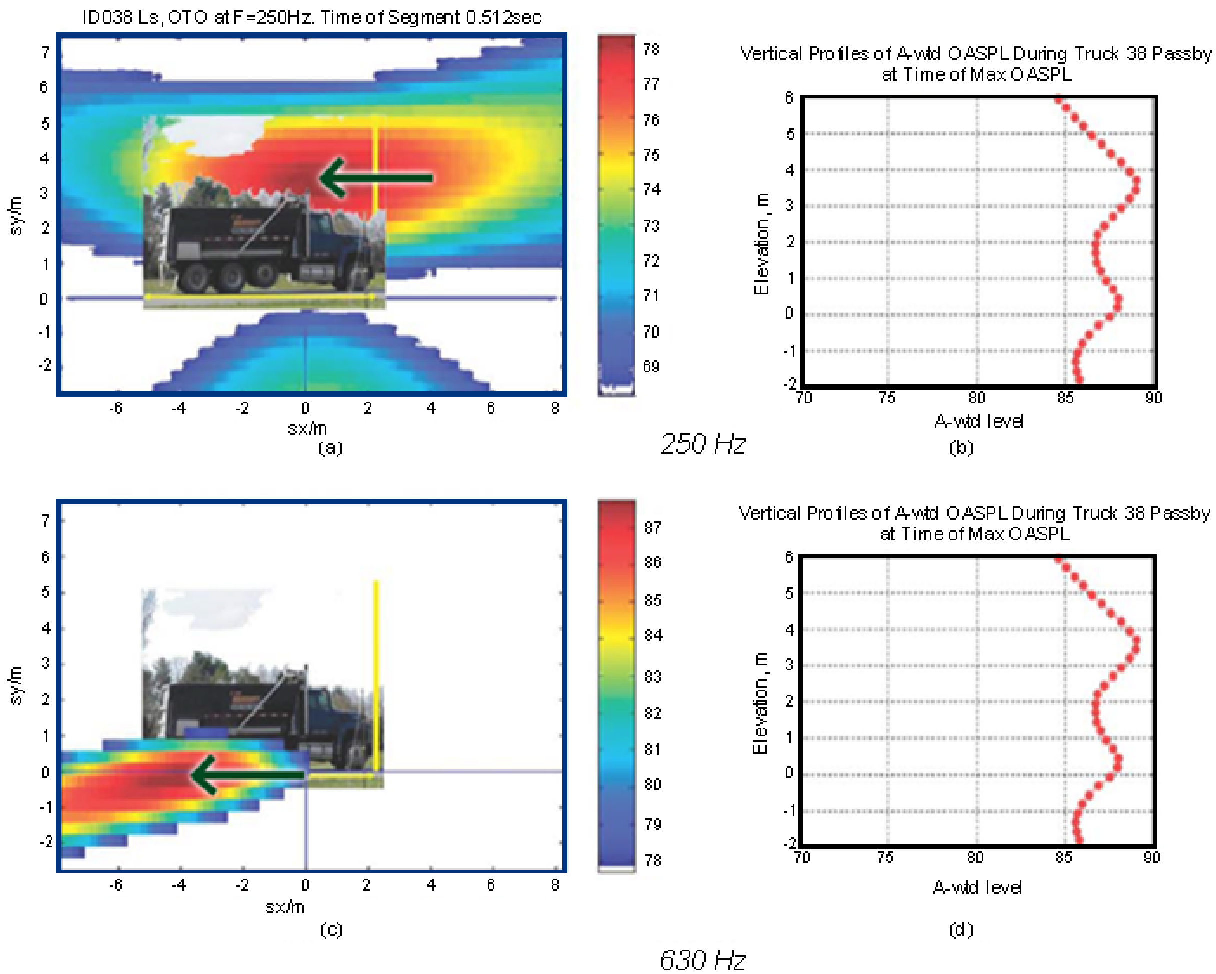

Figure 10 Source Images and Vertical Profiles for a Heavy Truck at Two Frequencies (250 & 630 Hz)
(Modified from an image in Annotated Bibliography Reference: RLR_009)

For both the 250 and 630 Hz images, there is a significant amount of noise indicated below the ground plane. This is due to the noise reflecting off the ground. This is a well understood phenomenon, but also illustrates that not all sound inferred from the beamforming algorithms represents actual noise. Another example is the noise that is imaged well above the exhaust stack. These ghost sources can be due to reflections or diffractions as well as limitations of the spatial resolution. Therefore, caution must be exercised when integrating the sound from the sound profile.

Figure 85 in NCHRP 635 (2009) shows the sound level profile as a function of height for 59 different heavy trucks. This figure illustrates the variation that can be found from one vehicle to the next. As can be seen, there is a wide variety of profiles, but most have lower sound levels around the stack height and more sound energy about a foot above the pavement. The relative amount of noise between these two source heights can depend on the pavement type as well as whether the vehicle has a modern catalytic converter.

Most beamforming studies have focused on heavy trucks, which are the only vehicles to have a 12-foot source in TNM. These beamforming studies have shown that some heavy trucks do have a source at approximately this height, while others do not. This indicates that TNM's source height allocation for heavy trucks could be improved by lowering this source height for some or all heavy trucks.

5.2 Short Barrier Measurements

With the interest in revisiting the source heights for heavy trucks, several researchers have also conducted insertion loss measurements of solid safety barriers (SSB) and low berms. The results show that short barriers could provide measurable noise reduction for heavy trucks since they will typically block the tire-pavement noise source.

Three documents were reviewed: *Measured Effect of Low-Height Solid Safety Barriers on Heavy Truck Noise* (**RLR_030**), *Truck Noise Shielding Analysis* (**RLR_031**), and *Acoustical Performance of Small Height Earthen Berms* (**RLR_040**). All three documents found that short barriers provided roughly 3 to 6 dB and sometimes more insertion loss for many cases where the line-of-site between the tire-pavement noise source and the microphone was blocked. The documents also found that modeling with TNM produced similar results. However, further research is recommended, see **SECTION 6.2.1 WAYSIDE NEEDS**.

5.3 OBSI Measurements

This section reviews recent research that made use of OBSI measurements and methodologies. It also includes discussion of the various issues related to consistency between measurement systems, correlation with wayside measurements and the categorization of pavement types based on OBSI measurements.

OBSI a modern method for conducting source emission measurements and is of great interest to State DOTs because it provides data focused on the tire-pavement noise source that was not available during the original data collection for TNM.

The use of OBSI measurements has greatly improved the efficiency by which noise emissions from various pavements can be collected and compared. For example, transversely tined Portland cement concrete (PCC), Dense-Graded Asphalt Concrete (DGAC) and Open-Graded Asphalt Concrete (OGAC) can be directly compared using this technique and it has been shown that there is a difference of about 15 dB between the quietest and the loudest pavements and that there can be a difference of about 10 dB between typical quiet and loud pavements.

There are three main questions that relate to the use of OBSI measurements to improve tire-pavement noise modeling in TNM.

- One, how can OBSI measurements be conducted such that noise levels are consistent regardless of what equipment and personnel are involved in the measurements? This question relates to consistency, which will be discussed in **SECTION 5.3.1**.
- Two, how can OBSI measurements be scaled such that noise levels due to tire-pavement noise at a reference location can be accurately predicted from the OBSI data? This question relates to calibration, which will be discussed in **SECTION 5.3.2**.

- The final question is, given a reliable method to utilize OBSI for quantifying pavement effects, how should data be organized such that pavements with similar physical and noise emission characteristics can be categorized together? This is discussed in **SECTION 5.3.3**.

5.3.1 Consistency

Consistency has been evaluated during several OBSI "rodeos", where several teams come together, with their own equipment and measure the same sections of roadway. The teams then compare their data and test various approaches to reduce the differences between teams. The results of this work are summarized in Table 7 of **RLR_034** as shown in **TABLE 3** below. The results showed that there was generally a maximum difference between teams of 2 to 3 dB. These results are good considering the complexity of the measurements, but also set a limit on minimum differences between pavement types that can be measured.

TABLE 3: TABLE 7 STATISTICS OF THE MAXIMUM DIFFERENCE BETWEEN TEST TEAMS ON PAVEMENT

Rodeo Event	Average Difference, dB	Standard Deviation, dB	Maximum Range, dB	Number of Teams
NC Rodeo Day 1	1.2	0.5	2.3	4
NC Rodeo Day 2	1.5	0.4	2.4	5
Mesa Rodeo	1.3	0.5	2.2	4
Texas Rodeo	1.3	0.4	2.0	3
Yuma Rodeo	1.3	0.4	2.1	2
NCAT Rodeo	1.4	1.1	2.9	2

Table recreated here; original source: Annotated Bibligraphy RLR_034

The last rodeo in North Carolina identified several causes of variation between the teams. The most significant difference was the test tire itself, when the same tire was used for all teams, the differences decreased by about 0.8 dB. As the test tires were already tightly specified, no further relationship to tread depth, hardness, or age could be identified that accounted for the 0.8 dB of variation.

After the specific test tire, the next largest contributor to variation was due to team-to-team differences, which accounted for about 0.3 dB. Beyond test tire and team, additional factors included speed control issues, differences in tire sensitivity to specific pavements, and combined tire/vehicle pavements interactions (**RLR_034**).

> *"In this study, applying correction factors for differences between tires did produce a reduction in the average variation between teams. However, developing a methodology for providing correction factors on an ongoing basis is problematic." (**RLR_034**)*

The authors suggested several procedural changes to the test methodology but were doubtful that these changes would be effective in reducing the variation. Thus, they also recommended computing an offset to account for differences, acknowledging that generalizing these correction factors required further investigation.

5.3.2 Calibration

During the development rodeos for the OBSI method, calibration methodologies were also examined. The main approach is described in **RLR_028** using OBSI and controlled pass-by (CPB) measurements:

> *"Normalization factors were determined by first determining the average difference between OBSI and CPB levels at each site and overall average for the 12 test sites. The average OBSI/CPB difference for each site was then subtracted from the average of all sites to determine the normalization factor for each site." (**RLR_028**)*

From this statement, the following equations are inferred:

$$A_i = \overline{\Delta}_{All\ Sites} - \overline{\Delta}_i \tag{A}$$

$$spl_{i,j} = OBSI_{i,j} - A_i \tag{B}$$

Where A_I is the normalization factor for a given site I, $\overline{\Delta}$ is the difference between OBSI and CPB measurements, *spl* is the sound pressure level that would be measured using CPB, I is the site counter and j is the measurement counter, such that I represents the i^{th} site and j represents the j^{th} measurement of the i^{th} site. Thus, this schema assumes that there is a generalizable difference between OBSI and CPB ($\overline{\Delta}_{All\ Sites}$), but there is also site-specific variation (which needs to be determined on a site-by-site basis) that should be added back into the relationship. Clarity is provided by expanding these equations as:

$$A_i = \frac{1}{\sum_{i=1}^{M} N_i} \sum_{i=1,j=1}^{M,N_i} \left(OBSI_{i,j} - CPB_{i,j}\right) - \frac{1}{N_i} \sum_{j=1}^{N_i} \left(OBSI_j - CPB_j\right) \tag{C}$$

$$spl_{i,j} = OBSI_{i,j} - \frac{1}{\sum_{i=1}^{M} N_i} \sum_{i=1,j=1}^{M,N_i} \left(OBSI_{i,j} - CPB_{i,j}\right) + \frac{1}{N_i} \sum_{j=1}^{N_i} \left(OBSI_j - CPB_j\right) \tag{D}$$

The effect of the last equation is to compute the wayside level as a standard level reduction based on average differences for a large number of sites between OBSI and wayside measurements (in this case CPB) and then add back in the average difference for the specific site. The idea being that there is a general relationship between OBSI and wayside results, but site-specific differences cause the levels to deviate. These site-specific differences could be due to, e.g., the presence of more engine noise, more high or low frequency components, and differences in effective flow resistivity (EFR), all of which represent true differences, as well as, e.g., errors in measured distance and deviations from expected EFR, which represent measurement errors.

It has been shown that this approach can remove the effect of a non-unity (m≠1) slope when the slope deviation is due to site differences. For example, in **RLR_028**, a regression slope of 1.31 was reduced to 1.06 using this method. It is presumed that the higher OBSI values were associated with specific sites, which is likely since site-specific pavements have a strong influence on measured OBSI levels.

This approach provides an alternate way of modeling the relationship between OBSI levels and wayside levels compared to a standard regression in that it provides a clear method for creating site-based corrections. However, it does not provide, without wayside measurements, the ability to accurately predict wayside levels since site-specific differences can be as large as 4 dB (Ref: **RLR_028**) and the variation of a specific site could significantly affect the computations if it is included or omitted.

If future research provides a means to quantify site-specific differences based on known parameters, e.g., frequency content, then it may be possible that this method could be used to determine tire-pavement noise emissions based solely on OBSI measurements. See **SECTION 6.1.3 OBSI MEASUREMENTS**.

5.3.3 Categorization

The final question related to the measurement of tire-pavement noise is the question of categorization. FHWA's TNM includes OGAC, DGAC, PCC and Average pavements. Of these available pavement types, OGAC tends to be the quietest, followed by DGA pavements, and ending with PCC pavements being the loudest of these three types. TNM's Average pavement type falls in the middle, as it is an average of these other real-world pavement types. **FIGURE 11** shows sound intensity level for a sample of pavements including porous asphalt, double layer porous asphalt, dense graded asphalt, stone mastic asphalt, and Portland cement concrete.

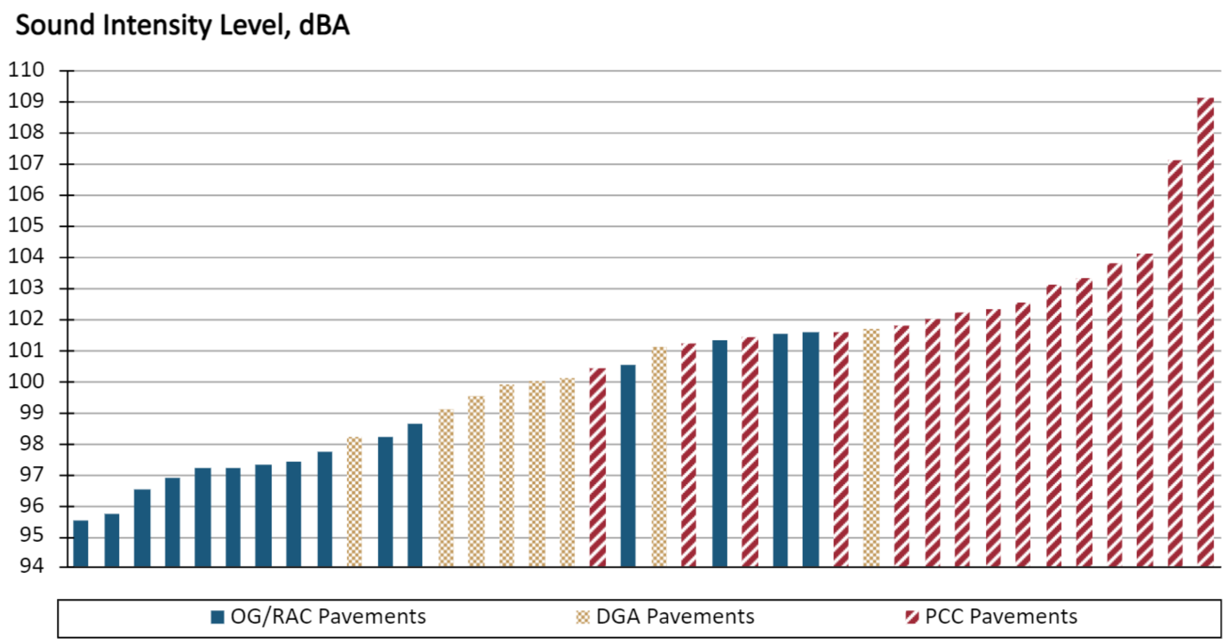

FIGURE 11 TIRE-PAVEMENT NOISE FOR REPRESENTATIVE, AT-GRADE HIGHWAY SURFACES AT 60 MPH
(Image recreated here, original source is Photographic References: PR_07)

This selection covers most of the range of sound intensity levels measured for pavements in use but there are many more that will also fall within this range. Some general trends that are consistent with TNM's categories can be seen:

- Porous asphalts are among the quietest[16]
- PCC tend to be the loudest

[16] Open-graded asphalt is used as a component in porous asphalts, but open-graded friction courses are also applied to non-porous base layers.

- Dense graded asphalts typically fall in the mid-range[17]

Although TNM's categories are generally consistent with these findings, and others throughout the literature, it is also apparent that there is still significant variation within each category. For example, there is about 10 dB difference between the quietest and loudest porous asphalt samples in **FIGURE 11**. The same can be said for PCCs in the figure, which also shows that there is about an 8 dB difference for DGAC.

While there exist many datasets with measured OBSI levels, a systematic method of correlating physical characteristics, e.g., aggregate size, aggregate material, void volume, binder chemistry, presence of expansion joints, etc. is needed to aid in classifying pavement categories with significant noise level differences. Several models have been proposed in academic papers, but none provide a practical method for creating categories without a priori knowledge of the noise emissions.

One other issue to consider when discussing pavement categories is the presence of strong tonal components. These typically occur due to periodic transverse textures in the pavement. These are most notable in transversely tined PCC; however, other pavements can also produce tonal noise. When this happens, the TNM regression equations for noise emissions are not capable of accurately modeling these tonal components because of the smoothing nature of the polynomial curve fits.

[17] Because of the texture of SMAs, they are typically between OGAC and DGAC in noise level; however, in this sample, SMA appears to be about equal to DGAC.

6. Recommendations and Needs

Data and measurements needed to improve TNM

The Federal Highway Administration developed and released the first version of TNM in 1998 to account for noise emissions, divergence, and diffraction in modeling roadway traffic noise. Since its inception, several updates have been made to the model to improve the usability and accuracy. These include general bug fixes to improve user experience, updated energy distributions to produce results that match measurements for the most important use cases, and with the 3.X series, a new code base that is easier to maintain and includes new, modern capabilities such as utilization of geo-referenced maps and parallel processing. As of this writing, the current version is TNM 3.2, released in 2024, that included new stationary sources, directivity and an emissions database for construction equipment noise.

Since the development of TNM's modeling algorithms and noise emission database, new technologies have been developed for quantifying tire-pavement noise, the dominant noise source in many roadway traffic noise scenarios, and for quantifying other vehicle noise source heights, such as engine noise. While TNM has been shown to validate well under most conditions, recent concerns about heavy truck source heights and the limited categories of pavement types have been expressed by various researchers and users.

While the research shows some validity to both concerns, the data do not currently provide sufficient information to enact comprehensive updates to TNM, therefore, the following steps are recommended to provide a path forward:

1) Develop best practices for traditional and new measurement techniques
2) Collect data on current roadway traffic noise emissions
3) Analyze data to determine optimal characterization of noise sources with respect to source heights and spectra in order to obtain most accurate results for primary use cases
4) Conduct sensitivity and validation analyses to confirm improvements and identify potential future improvements

6.1 Measurement Best Practices

Over the years, practical knowledge on measurement techniques have improved and new measurement techniques have been developed. While many best practices have been codified in standards and reports, some of these may need to be updated while others need to be developed.

6.1.1 Wayside Measurements

Wayside measurements are a traditional measurement technique with a well-developed process for taking measurements under various conditions. The quality of these data are well understood; however, TNM requires clean free-field data and wayside measurement data include ground effects. Historically the ground effects have been removed using TNM's own ground effects algorithms to "back out" the ground effects. This method provides a practical approach but can be influenced by discrepancies between the actual ground type at the site being modeled and the analyst's model input for ground type and geometry in the model. Therefore, consideration should be given to raising the measurement microphone to 10 or 15 above ground level to minimize ground effects in the measurements themselves.

Consider conducting wayside measurements using microphones fifteen feet above ground level.

Note that reducing the distance between the source and receiver has the potential of reducing ground effects, but there are practical and safety limitations related to decreasing this distance.

Another issue with wayside measurements is that they incorporate both the tire-pavement and engine (or exhaust) noise sources in a single value. Because TNM needs to model these sources separately, due to the different source heights, wayside data need to have the sources disaggregated. Historically this has been done by assigning source heights and then fitting proportional constants to the upper and lower sources to obtain a best match to measured data.

6.1.2 Beamforming Measurements

Recent research using Beamforming techniques have provided data to potentially help set more appropriate source heights in TNM for all prominent vehicle noise source heights[18]. However, more research is needed to determine the best method to quantize sources for modeling in TNM because, while beamforming provides the ability to spatially characterize noise sources, its application is relatively new to highway traffic noise modeling.

In addition, there are still usage issues that are not well controlled for in the methodology or accounted for in modeling. These include:

- Turbulence and other violations of assumptions inherent in the beamforming algorithms
- Low frequencies not captured by array
- Spatial leakage (i.e. Sources "appear" larger than the physical source)
- Apparent continuous 5 to 15 foot sources need to be modeled by a few discrete sources

The first of these issues can be improved by incorporating measurement protocols such as only conducting beamforming measurements when only one vehicle is present and turbulent effects from previous vehicles have died down.

Develop protocols to acquire clean beamforming measurements; and develop modeling and analysis techniques to account for beamforming limitations in frequency range and spatial resolution.

The latter three must be addressed by developing modeling techniques to account for shortcomings in range and resolution of the method. Spatial leakage, or ghosting, can occur from lack of spatial resolution. Some systems may already use algorithms that reject some ghost images or utilize post-

[18] See **Annotated Bibliography References** RLR_007, RLR_009, RLR_023, RLR_030, RLR_040, and RLR_045, and **Section 5.1 Beamforming Measurements** for more details.

processing of individual microphones in the array to help calibrate the levels, but this needs to be confirmed for the system used. To overcome the discrete nature of modeling, what is often done is to choose a few discrete sources that produce a combined level that matches the overall profile.

6.1.3 OBSI Measurements

OBSI measurements provide a very efficient method to quantify pavement differences. Further, these measurements correlate well to wayside measurements provided corrections can be developed for each site measured.

However, the metrics used for quantifying roadway traffic noise are relevant to "average" noise levels, which are a result of a wide range of vehicle types, engine types, pavement types and operating conditions. Wayside measurements are well suited for acquiring data that can be averaged to represent fleet level characteristics, but OBSI measurements rely on a standard test tire and (typically) a single vehicle over a limited speed range to collect data over a limited frequency range. Therefore, care needs to be taken when utilizing these data to infer average noise emissions for automobiles and it is not clear what types of inferences can be made for other vehicle types.

OBSI data should be considered as a supplemental data source to wayside data. OBSI data should not be used as the sole source for noise emission data.

As such, OBSI data should be considered as a supplemental data source to wayside data. For example, OBSI data are highly useful for identifying pavements with different tire-pavement noise. OBSI data, in conjunction with beamforming, may also be useful for determining what proportion of wayside energy should be allocated to tire-pavement noise and what portion should be allocated to engine or exhaust stack.

Continue development of a method to utilize OBSI data (including a reference pavement type that has full REMELs data) to provide a quick pavement adjustment method. This development needs to include work on reducing the limitations of the OBSI method in general as well as methods to model the adjustments.

It should be noted that some studies have shown the utility of using OBSI data referenced to a standard pavement as a method to quickly develop adjustments from the standard pavement for other pavement types. This approach is promising but has caveats.

6.2 Data Collection

Once measurement procedures have been updated to account for and utilize best practices, new highway traffic noise data can be collected in the field and subsequently used to improve highway traffic noise modeling in FHWA's TNM.

6.2.1 Wayside Needs

Wayside data needs to have the sources (engine and tire-pavement) separated to function in TNM. New methods are now available, such as beamforming and OBSI and these should be considered when determining the source proportions.

Utilize beamforming to inform source height selection and, in conjunction with OBSI and wayside measurements, determine the best proportionality constants for each source height.

A more comprehensive, parameterized comparison of single, pass-by events for a wide range of vehicles would be helpful for validating or exposing shortcomings of the TNM modeling algorithms with respect to source height and short barriers.

6.2.2 Beamforming Needs

Since ghosting can occur from lack of spatial resolution, it is perhaps reasonable to assume that true sources are thus best modeled at discrete locations of maximum sound level and then comparing the data to single microphone levels at equivalent locations. However, no known literature has evaluated that approach to assigning sources.

In addition, Beamforming has no set standard for equipment setup and use to obtain the desired results.

6.2.3 OBSI Needs

To determine tire-pavement noise emissions based solely on OBSI measurements, research should address the following questions:

- Stability of $\overline{\Delta}_{All\ Sites}$ parameter
    - Does $\overline{\Delta}_{All\ Sites}$ change significantly based on the site sampling?
    - Example values: Autos at 25 ft = 21.8 (**RLR_042**), 24.3 (**RLR_028**)
- Method to compute $\overline{\Delta}_i$
    - Is it frequency dependent?
    - For the many samples of the same type of site does it average to zero?
- How to account for different vehicle types

These questions need to be resolved for each vehicle type and as a function of frequency. Given the difference between the automobiles that are used to measure OBSI and heavy trucks it is especially important to understand how applicable calibrations are for different vehicle types. This method should be further developed to determine if it can be used for, at the very least, cases where traffic noise is dominated by automobile traffic. If correlations between OBSI and heavy truck wayside noise can be better quantified, then this method could potentially be generalized.

In addition, a systematic method of correlating physical characteristics is needed to develop a system to classify pavement categories. At the very least, more data are needed to determine the statistical distribution for a subset of pavements that describe a particular category. OBSI measurements are ideally suited for such a study.

6.2.4 Summary Needs

Data needs identify specific data that should be collected, and these data should be collected using the best methods from among CTIM/SPB, CPB, OBSI or Beamforming depending on the data type collected.

Collect traffic noise related data to improve FHWA's TNM noise emission database and to calibrate and validate the model.

New data that would support improving TNM are listed below.

- Maximum SPL at Pass-By (CPB, Beamforming) Tabulated Based on the Following Parameters
  - Vehicle Type (Automobile, Medium Truck, Heavy Truck, Bus, Motorcycle, Any New Vehicles)
  - Pavement Type (Avg, DGAC, PCC, OGAC, Any New Pavement Categories)
  - Throttle (Cruise, Full)
  - Speed (Idle to X MPH)
  - Grade (in +/- 1% Increments)
  - Frequency (20 Hz to 20 kHz)
  - Discrete Source Heights
- Tire-Pavement Noise (OBSI) Tabulated Based on the Following Parameters
  - Pavement Type (Avg, DGAC, PCC, OGAC, Any New Pavement Categories)
  - Speed (Idle to X MPH)
  - Frequency (20 Hz to 20 kHz)
- Calibration/Validation Data
  - Time Series Sample Data (CTIM, CPB)
  - With Barriers of Many Different Geometries (Xbarr/src, Xbarr/mic, Ybarr)
  - Flat Ground of Many Ground Types and Mic Distances
  - Other objects (ground zones, tree zones, terrain lines, etc.)

These data will support improving the noise emission database in TNM and will support validation and calibration of the model to obtain improved agreement between measurement and modeling.

7. Data Analysis and Implementation

This section discusses the potential updates that could be made to TNM based on new field measurements. The field data would need to be analyzed and formatted correctly for implementation in TNM. There are two main areas that could be updated in TNM to address and reflect current noise measurement research and practices. These are the vehicle emissions and the source heights. There are also other related areas and equations that would need to be updated depending on the changes made to the vehicle emissions and source heights.

7.1 Vehicle Emissions

New values of A through J in TNM Equations 3 to 5, could be added to account for a new pavement type or new vehicle type. These values would need to be computed for each new vehicle and pavement type pairing combined with each throttle condition and would need to be determined from measured data that included a wide range of speeds. However, TNM regression equations are not capable of accurately modeling tonal components. If tonal pavements are to be modeled more accurately, a new method of accounting for the tonal character would be needed. For example, the regression equations could be replaced with tabulated data that could be interpolated during processing. This would allow for greater differences between one-third octave bands.

Further research could also provide a better link between physical pavement characteristics and noise categories, but until that time, it may be useful to add “quiet” and “loud” versions of different pavements that can be selected based on initial OBSI measurements of a pavement.

7.2 Source Heights

Based on recent Beamforming research, TNM’s source height allocation for heavy trucks could be improved by lowering this source height for some or all heavy trucks. This is feasible but will require several modifications to TNM and will also require further study to make sure that TNM’s accuracy is not reduced and preferably improved with these modifications.

Considering the variance in source heights and emissions found by Beamforming studies (for details see Section 5.1 Beamforming Measurements), an analysis should be conducted to determine if multiple versions of the vehicle class should be created to account for different source heights, e.g., a local heavy truck with a high source and national heavy truck with no high source height, or if a single version should be used that is a compromise between the various source profiles.

There are currently three fixed source heights, these could be changed to different heights. For example, the engine source height could be lowered to 3 feet. The appropriateness of this would need to be evaluated by comparing not only measured source heights for a few vehicles, but testing would also need to be done to determine the best compromise since sports cars and buses are not likely to have the same source heights.

Another reasonable modification would be to redistribute the energy between the source heights as was done during the development of TNM 2.5. This may provide a more direct comparison with the physical location of sources but will require some additional analysis as it will likely, at least initially, decrease accuracy. This decrease in accuracy could likely be overcome by determining new areas of the modeling that are introducing variance between the measured and modeled cases.

Another option would be to make source heights specific to each vehicle class so that buses could have different engine heights than sports cars. This would increase the complexity of the code but is feasible.

Finally, more sources could be added for each vehicle. This would provide a finer spatial resolution but is not recommended since it would significantly increase the code complexity and computation time.

7.3 Additional Equations to Evaluate

In addition to equations 3 through 13, the parallel barrier analysis code will need to be reviewed to determine if there are any portions that need to be adjusted. The free field effect equations will also need to be updated if changes are made to the source heights or if the reference measurement locations change. This list is not exhaustive but contains the most likely areas of code that would need to be re-evaluated and tested.

7.4 Sensitivity Testing and Validation Analyses

With all of these potential changes, a new, comprehensive validation will need to be conducted to compare the new version of TNM against measured data. These data may include the historic data but will also require comparison of data from the contemporary fleet under standard and exceptional cases. These cases would examine, at a minimum propagation for:

1) Straight roads and flat ground
2) Receivers at increasing distance from the roadway
3) Receivers at various heights
4) Different ground types
5) With and without traditional barriers
6) With and without short barriers

Once these data are used to “fine-tune” the model, the automated consistency test suite (augmented with short barrier cases) would be used to evaluate differences between the previous and new versions of TNM to develop an understanding of expected changes in modeling results.

8. Annotated Bibliography

(RLR_001) Rules of Thumb on Pavement Noise by the American Concrete Pavement Association, published in 2006

The authors discuss various general rules that can be used to provide and intuitive sense of how pavement noise increases. This discussion includes details that may help categorize different PCC categories.

(RLR_002) Quiet Pavements: A Sustainable and Environmental Friendly Choice by M. Alauddin Ahammed and Susan L. Tighe, published in 2008

The authors provide a basic overview of pavement noise. It is a good primer with many good references but does not provide detailed information.

(RLR_003) Ground Tire Rubber and Trans-Polyoctenameras Asphalt Binder Additives by Robert Amme, published in 2004

The author presents in this slide deck information on different binders that are available. It provides some supporting material when considering rubberized asphalts for example.

(RLR_004) Tire-Pavement Noise Evaluation Using On-Board Sound Intensity (OBSI) Measurements by Douglas Barrett, published in 2010

The author presents in this slide deck information on measuring pavement noise. There are many similar presentations, so this does not provide any unique information.

(RLR_005) Accelerated testing of noise performance of pavements by H. Bendtsen, J. Oddershede, et al, published in 2012

The authors discuss the possibilities of predicting tire-pavement noise based on texture characteristics. While the paper discusses several ideas, there is no validation data and further work is need.

(RLR_006) Temperature Influence on Road Traffic Noise: Californian OBSI Measurement Study by H. Bendtsen, Qing Lu, et al, published in 2009

The authors discuss the effects of temperature on pavement noise measurements. A large data set is reviewed in order to draw several conclusions. Two important conclusions include: one, different pavements can have different sensitivities to temperature change, and two, noise variation due to different tires is significantly greater than noise variation due to temperature.

(RLR_007) Mapping Heavy Vehicle Noise Source Heights for Highway Noise Analysis (2017) by Paul R. Donavan and Carrie J. Janello, published in 2017

As of 2022, this is the latest major effort to describe a methodology to determine heavy truck source heights by using beam forming. The report also presents processes data to show continuous and discretized source heights. It should be noted that only heavy trucks are analyzed. Autos, for example, are not evaluated with this methodology. One of the key findings was that profiles were essentially independent of vehicle speed, pavement, operating conditions, and region, even though the statistical isolated pass-by (SIP) levels were dependent on these parameters.

(RLR_008) The Identification and Quantification of Truck Tire Noise Sources Under On-Road Operating Conditions by Paul R. Donavan and Lawrence J. Oswald, published in 1980

The authors discuss the distribution of noise over a tire. This is accomplished by using a scanning sound intensity probe. The results are some of the first in this area.

(RLR_009) Acoustic Beamforming: Mapping Sources of Truck Noise, by Yuriy A. Gurovich, Paul R. Donavan, et al, published in 2009

This report is the predecessor to RLR_007 and provides additional details into the methodology.

(RLR_010) Measurement of Highway Related Noise by Cynthia S. Y. Lee and Gregg G. Fleming, published in 1996

The authors discuss a methodology for the measurement of traffic noise sources. This report provides a comprehensive discussion of the standard measurement technique for REMELs data.

(RLR_011) Vehicle Noise Radiation - Effective Height and Frequency Measurements by R. N. Foss, published in 1976

The authors discuss how to estimate effective source heights and effective frequencies for a given Fresnel number. This is seminal work and provides a good historical perspective, but much of the modeling is more limited than current technology allows.

(RLR_012) Method for Measuring Vehicle Noise Source Heights and Subsource Spectra by Robert Coulson, published in 1996

The author discusses how to determine a single effective source height for a vehicle. The approach assumes two initial source heights at either the ground and 5 ft or 12 ft. (See also RLR_024.)

(RLR_013) Moving Source Beamforming On Road Vehicles by B&K, accessed in 2022

This is a product sheet published by B&K that is useful in understanding the parameter specifications and ranges for beam forming equipment. As the title implies, this data sheet is geared towards moving road vehicles.

(RLR_014) PULSE Beamforming System with 18-channel Sector Wheel Array by B&K, accessed in 2022

This is a product sheet published by B&K that is useful in understanding the parameter specifications and ranges for beam forming equipment.

(RLR_015) High-resolution Fly-over Beamforming Clustering Approaches to Automatic Modal Parameter Estimation by B&K, accessed in 2022

The authors discuss at an engineering level methods and technologies that can be used for determining noise sources on aircraft during fly-overs. This should still be considered a marketing tool, but the information is much more detailed and comprehensive. It provides very important information on how beamforming calculations are conducted for moving sources.

(RLR_016) Beamforming by B&K, accessed in 2022

The authors discuss at an engineering level methods and technologies that can be used for determining noise sources stationary objects. This should still be considered a marketing tool, but the information is much more detailed and comprehensive. It provides very important information on how beamforming calculations are conducted for stationary sources.

(RLR_017) PULSE Array Acoustics, Refined Beamforming Calculations by B&K, accessed in 2022

This is a product sheet published by B&K that is useful in understanding the parameter specifications and ranges for beam forming equipment.

(RLR_018) Moving Beamforming by B&K, accessed in 2022

This is a product sheet published by B&K that is useful in understanding the parameter specifications and ranges for beam forming equipment.

(RLR_019) Beamforming - Microphone Array Sound Localization by B&K, accessed in 2022

The authors overview some basic features of beam forming. This is a high-level slide deck with little detail.

(RLR_020) Case Study: Truck Noise Sources by Yuriy Gurovich, Kenneth Plotkin, et al, published in 2010

The authors present results from the NCHRP Report 635 (described in RLR_009).

(RLR_021) Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model by Gregg G. Fleming, Cynthia S. Y. Lee, et al published in 1995

The authors describe the process, data and results of the development of the 1995 REMELs database.

(RLR_022) Technical Noise Supplement to the Traffic Noise Analysis Protocol by Rudy Hendricks, Bruce Rymer, et al, published in 2013

The authors discuss general guidance for conducting noise measurements. The document does not go into useful details related to determining source heights or emission levels.

(RLR_023) Mapping Heavy Vehicle Noise Source Heights for Highway Noise by Carrie Janello and Paul R. Donavan, published in 2018

The authors summarize the approach and findings from NCHRP Report 842 (described in more detail in RLR_007).

(RLR_024) Vehicle Noise Source Heights & Sub-Source Spectra by Robert K. Coulson, published in 1996

The author discusses how to determine a single effective source height for a vehicle. The approach assumes two initial source heights at either the ground and 5 ft or 12 ft. (See also RLR_012.)

(RLR_025) Determination of noise source height Part 1: Measurement of equivalent acoustic source height above a reflecting surface by Glegg, published in 1990

This report provides information on the development of equations that are later used in RLR_012 and RLR_024 to determine an effective source height.

(RLR_026) Breaking Tall Barriers: An Alternative Approach to Reducing Highway Traffic Noise Impacts with Inexpensive Short Sound Walls by Bruce Rymer, published in 2020

The author describes some potential benefits of using lower barriers such as berms and safety barriers to reduce noise.

(RLR_027) Quieter Pavement Acoustic Measurement and Performance by Dana Lodico and Paul Donavan, published in 2018

The authors provide a comprehensive summary of the current studies and knowledge related to quitter pavements. This is a good reference document.

(RLR_028) NCHRP Report 630 Measuring Tire-Pavement Noise at the Source by Paul R. Donavan and Dana M. Lodico, published in 2009

The authors discuss the development and how to conduct OBSI measurements. This is the primary NCHRP report related to OBSI measurements. The main conclusion of this study was that OBSI is the most ideal method of measuring this type of noise, other methods like CPX create spectral distortion that skews the results and are more expensive.

(RLR_029) Measuring Tire-Pavement Noise at the Source: Precision and Bias Statement by Paul R. Donavan and Dana M. Lodico, published in 2011

The authors discuss methods for increasing the precision and reducing the bias of OBSI noise measurements. The main conclusion of this study was that precision of the OBSI measurements can be increased through adjustments for temperature and placing the microphone at a specified distance.

(RLR_030) Measured Effect of Low-Height Solid Safety Barriers on Heavy Truck Noise by Benjamin R. Sperry, Isam Khoury, et al, published in 2021

The authors discuss the effect that safety barriers have on the noise produced by vehicles. The main conclusion of this study was that solid safety barriers (SSBs) reduce noise substantially, and this needs to be taken into account when trying to create noise models.

(RLR_031) Truck Noise Shielding Analysis by Benjamin R. Sperry, Issam Khoury, et al, published in 2021

The authors discuss the noise shielding effect produced by solid safety barriers (SSBs). The main conclusion of this study was that SSBs substantially reduce the noise from heavy trucks and traffic, and so need to be modeled in the traffic noise model (TNM).

(RLR_032) Comparative OBSI Testing at the General Motors Proving Ground in Yuma by Paul R. Donavan, published in 2010

The author compares different OBSI measurements made at the same facility during the same experiment. The main conclusion of this study was that tire differences contributed a lot to differences between measurements, and temperature also had an impact.

(RLR_033) Comparison OBSI Testing Near Austin, TX: TxDOT Rodeo by Dana M. Lodico, published in 2010

The author discusses difference in OBSI measurements between teams following the same procedure and measuring the same thing. The main conclusion of this study was that tire tread variations and tire loading account for the majority of the differences between the different team's measurements.

(RLR_034) Comparative OBSI Testing in North Carolina: The North Carolina Rodeo by Paul R. Donavan, published in 2011

The author discusses using OBSI to measure tire-pavement noise. The main conclusion of this study was that there are minor differences between different groups measuring the same vehicle and pavement during repeated tests, but this is likely due to differences in tires tread wear.

(RLR_035) A New Road-Side Array Based Method for Characterization of Truck Noise During Passby by William K. Blake and Paul R. Donavan, published in 2008

The authors discuss the development of a new method for measuring pass-by noise by generating and using 2D sound maps of a vehicle. The main conclusion of this study was that this method is feasible and produces accurate results for both a controlled environment and on the highway.

(RLR_036) The Influence of Truck Tire Type and Pavement on Emission of Noise from Trucks under Highway Operating Conditions by Paul R. Donavan, published in 2007

The author investigates why quiet pavements do not reduce tire-pavement noise for heavy vehicles as much as they do for light vehicles. The main conclusion of this study was that truck tires have different treads that likely create more noise than light vehicles, in addition to the heavier loading placed on them.

(RLR_037) Tire Noise Generation and Propagation over Porous and Nonporous Asphalt Pavements by Paul R. Donavan, published in 2011

The author discusses the impact that pavement porosity has on tire-pavement noise. The main conclusion of this study was that while porous pavements significantly reduce noise, the age of the quiet pavement being studied is also an important factor that needs further study.

(RLR_038) Using Onboard Sound Intensity Measurements to Interpret Results of Traffic Noise Modeling by Dana M. Lodico and Paul R. Donavan, published in 2013

The authors discuss the impact that pavement type and condition have on tire-pavement noise, as these are not accounted for in the traffic noise model (TNM). The main conclusion of this study was that OBSI can be used to measure the difference between pavements and used to create a database that can be integrated into TNM.

(RLR_039) Truck Tires and Quieter Pavement Contribution to Roadside Noise Levels by Bruce Rymer and Paul Donavan, published in 2007

The authors study why quiet pavements don't work as well for trucks. The main conclusion of this study was that the use of aggressive transverse traction tread patterns on truck tire is a large part of the reason.

(RLR_040) Acoustical Performance of Small Height Earthen Berms by Lawhon and Associates, published in 2018

The authors document the effectiveness of various low berms. Conclusions are difficult to generalize, but the report does provide data that could be used for validation purposes.

(RLR_041) Effects of Aging on Tire–Pavement Noise Generation for Concrete Pavements of Different Textures by Paul R. Donavan and Bruce Rymer, published in 2011

The authors discuss how tire-pavement noise changes with age. The main conclusion of this study was that while tire-pavement noise did increase with age, there is no consistent trend that could be found.

(RLR_042) Estimation of Vehicle Pass-By Noise Emission Levels from Onboard Sound Intensity Levels of Tire–Pavement Noise by Paul R. Donavan and Dana M. Lodico, published in 2009

The authors discuss using OBSI to measure tire-pavement noise. The main conclusion of this study was that OBSI is an effective and accurate way to measure this type of noise, and the results showed that speed and sound level are directly correlated.

(RLR_043) Evaluation of Temperature Effects for Onboard Sound Intensity Measurements by Dana M. Lodico and Paul R. Donavan, published in 2012

The authors discuss the effect that temperature has on OBSI measurements. The main conclusion of this study was that while corrections don't need to be made for air density, they do need to be made for air temperature.

(RLR_044) Evaluation of Test Variables for Onboard Sound Intensity Measurements by Dana M. Lodico and Paul R. Donavan, published in 2009

The authors discuss ways to standardize OBSI measurements so they can be compared. The main conclusion of this study was that it's difficult to precisely determine what impacts OBSI measurements and find standardization factors.

(RLR_045) Measurement of Vertical Distribution of Truck Noise Sources During Highway Cruise Pass-Bys by Acoustic Beam Forming by Paul R. Donavan and Bruce Rymer, published in 2009

The authors discuss using beamforming to measure the vertical distribution of noise from heavy trucks. The main conclusion of this study was that noise generated was usually at or near the pavement surface, and tire-pavement noise was the majority of the noise generated.

(RLR_046) Investigations of Effects of Porous Pavement on Traffic Noise and Traffic Noise Prediction by Judith L. Rochat and Paul R. Donavan, published in 2013

The authors discuss the mechanism by which porous pavements reduce noise. The main conclusion of this study was that porous pavements absorb sound due to their texture, and the traffic noise model (TNM) should be modified to account for this effect.

(RLR_047) Noise Classification Methods for Urban Road Surfaces by Ulf Sandberg and Manfred Haider, published in 2006

The authors discuss various methods to measure noise from different pavements. This report includes an interesting discussion on the use of backing boards for measurements.

(RLR_048) Comparative Measurements of Tire / Pavement Noise Sources in Europe and the United States by Paul R. Donavan, California Department of Transportation, published in 2006

The author compares noise levels and sources of European and American pavements. The main conclusion of this study was that there is no real difference between average pavements in Europe and America, thought the quietest European pavements are slightly better than their American counterparts.

(RLR_049) Study on the Influence of Vehicle Sound Source Height on Traffic Noise Forecast by Xintan Ma and Guopeng Chang, published in 2018

The authors discuss the difference in predicted noise from models versus real life. The main conclusion of this study was that vertical noise source height influences the accuracy of results, and so models need to consider the type of traffic and the noise source height.

(RLR_050) Influence of Vehicle Sound Source Height on Traffic Noise Forecast and Sound Barrier Design by Xintan Ma and Guopeng Chang, published in 2018

The authors discuss the difference in predicted noise from models versus real life. The main conclusions of this study were the same as their previous paper, RLR_049, but with slightly more detail: essentially that noise source height influences the accuracy of results.

(RLR_051) Effect of Air Temperature, Vehicle Speed, and Pavement Surface Aging on Tire/Pavement Noise Measured with On-Board Sound Intensity Methodology by Daniel E. Mogrovejo Carrasco, published in 2012

The author discusses the impact that temperature, car speed and pavement age have on the tire-pavement noise generated. The main conclusions of this study were that noise slightly decreases as temperature increases, newer pavements are quieter than those older than 1-month, and that noise increases are directly correlated with speed increases.

(RLR_052) CTIM Wayside Noise Study for Virginia Quiet Pavement Pilot Project by J. Eric Cox, Christopher W. Menge, et al, published in 2012

The authors discuss the use and benefits of quiet pavement technology. The main conclusion of this study was that quieter pavements can reduce wayside noise levels by up to 11 dBA.

(RLR_053) Effect of Porous Pavement on Wayside Traffic Noise Levels by Paul R. Donavan, published in 2014

The author discusses the effect that porous pavements have on noise levels, specifically focusing on OGAC. The main conclusion of this study was that porous pavements can reduce wayside noise by up to 8 dB, and OBSI noise by 7.8 dB.

(RLR_054) The Little Book of Quieter Pavements by Robert Otto Rasmussen, Robert J. Bernhard, et al, published in 2007

The authors discuss sources and mechanisms by which tire-pavement noise is produced. This report is useful for understanding these underlying components that various measurement systems quantify.

(RLR_055) Reduction of vehicle noise at lower speeds due to a porous open-graded asphalt pavement by Paul R. Donavan, published in 2014

The author discusses the noise reduction that can be found through using porous OGAC. The main conclusion of this study was that noise measured using the statistical pass-by method was lowered by 9.2 dB for light vehicles, and 3-5 dB for heavy vehicles.

(RLR_056) Assessment of Highway Pavements for Tire/Road Noise Generation by Paul R. Donavan and Bruce Rymer, published in 2003

The authors discuss different methodologies for OBSI measurements. The main conclusion of this study was a methodology proposed by the authors, as well as the conclusion that OBSI is a viable technique for measuring pavement-tire noise.

(RLR_057) Virginia Quiet Pavement Implementation Program by Jose Gomez, published in 2012

The author discusses implementing quiet pavement technology in Virginia. The main takeaway of this report was information on the progress of the project.

(RLR_058) Evaluation of the Noise Characteristics of Minnesota Pavements by Douglas I. Hanson and Brian Waller, published in 2005

The authors discuss methods of creating quieter pavement surfaces. The main conclusion of this study was that there is a relationship between the pavement surface texture and the noise produced.

(RLR_059) Measurement of Tire/Pavement Noise in the Hot Mix Asphalt Technology periodical, published in 2005

The authors discuss different methods of creating quieter pavement surfaces. The main conclusion of this study was that a smaller top size for aggregate will lower the noise level, as pavement texture impacts noise.

(RLR_060) Roadway Noise Basics by the International Grooving & Grinding Association, published in 2013

The authors discuss the basics of noise and how it’s created for roads. There were no conclusions or takeaways in this report, it is simply an introduction to the subject.

(RLR_061) The Evaluation of Noise from Freely Flowing Road Traffic by D. R. Johnson and E. G. Saunders, published in 1967

The authors discuss the causes and levels of road noise in London, England. The main outcome of this study was results from the data measurement being used to create a simple mathematical model for predicting noise.

(RLR_062) The Virginia Quiet Pavement Implementation Program Under Section 33.2-276 of the Code of Virginia - Final Report by the Virginia Department of Transportation, published in 2015

The authors discuss the ongoing implementation of quiet pavement technology in Virginia. The main takeaway from this report is information on the progress of the project.

(RLR_063) Tire-Pavement Noise Measurement with the On-Board Sound Intensity (OBSI) Method by Erwin Kohler, published in 2011

The author discusses measuring pavement-tire noise with OBSI. The main conclusion of this study was that OBSI is an effective and accurate way to measure this type of noise.

(RLR_064) Surface Characteristics of Rigid Pavements in Florida by Hyung S. Lee, published in 2013

The author discusses measuring pavement surfaces. The main conclusion of this study was a proposed methodology for using lasers to measure pavement surface textures.

(RLR_065) The Effects of Tread Pattern on Tire Pavement Interaction Noise by Tan Li, Jianxiong Feng, et al, published in 2016

The authors discuss the impact that different tire tread patterns have on the pavement-tire noise produced. The main conclusion of this study was that while different tread patterns do change the level of noise, this change is marginal except when using very altered treads, such as snow tires.

(RLR_066) Synthesis of Current Research on Permeable Friction Courses: performance, Design, Construction, and Maintenance by Kai-Wei Liu, Allex E. Alvarez, et al, published in 2009

The authors discuss the design, performance, construction, and maintenance of porous concrete. This study had no major conclusions or findings.

(RLR_067) Virginia Quiet Pavement Implementation Program by Kevin K. McGhee, published in 2012

The author discusses implementing quieter pavements in Virginia. There were no findings or conclusions other than an update on the current progress of the program.

(RLR_068) Relationship Between Pavement Surface Texture and Highway Traffic Noise by Roger L. Wayson, published in 1998

The author discusses the relationship that exists between pavement texture and tire-pavement noise. The main conclusion of this study was that pavement texture can reduce noise, such as with porous or exposed aggregate surface pavements.

(RLR_069) Noise Policy and Guidance by Ronald J. Henke, published in 2011

The author discusses noise policy in the state of North Dakota. The report has no conclusion, as it is a state policy document.

(RLR_070) Guide to State Highway Road Surface Noise by the New Zealand Transportation Agency, published in 2014

The authors discuss methods to reduce and manage traffic noise in New Zealand. The main findings of this study were methods by which noise can be managed, and what causes it to increase.

(RLR_071) New HMA Products and Trends for NJDOT by the New Jersey Department of Transportation, published in 2008

The authors discuss different transportation projects currently underway in New Jersey. This presentation has no conclusion, as it is a list of projects.

(RLR_072) State-of-the-Art Review on Sustainable Design and Construction of Quieter Pavements—Part 1: Traffic Noise Measurement and Abatement Techniques by MD Ohiduzzaman, Okan Sirin, et al, published in 2016

The authors discuss reducing tire-pavement noise. The main conclusion of this study was that while surface texture can reduce this type of noise, the most effective method of noise reduction is still barriers.

(RLR_073) Principal Components Regression of Onboard Sound Intensity Levels by Aybike Ongel, Erwin Kohler, et al, published in 2008

The authors discuss reducing tire-pavement noise through use of open graded asphalt concrete (OGAC). The main conclusion of this study was that OGAC mixes do reduce noise, as other studies have shown.

(RLR_074) The Effect of Porous Road Surfaces on Radiation and Propagation of Tyre Noise by B. Peeters and A. Kuijpers, published in 2008

The authors discuss porous road surfaces, specifically focusing on the mechanism by which they reduce noise. The main finding of this study was a model created by the authors that can predict by how much porous surfaces reduce noise.

(RLR_075) Prediction of Noise from Laboratory Produced Pavement Slabs by Hans Bendtsen, Jens Oddershede, et al, published in 2012

The authors discuss methods by which pavement texture data can be used to predict the noise generated. The main finding of this study was that texture data, measured with a laser, can predict CPX and SPB noise levels.

(RLR_076) Propagation of Traffic Noise by Kenneth R. Agent and Charles V. Zegeer, published in 1981

The authors discuss the effect that several different variables have on the noise level generated by traffic. The main findings of this study were which variables and factors effect noise levels the most.

(RLR_077) The Language of Noise and Quieter Pavements by Robert Otto Rasmussen, Richard Sohaney, et al, published in 2010

The authors introduce the topic of noise and noise measurements. There are no conclusions or findings in this paper, as it is an introduction to the topic

(RLR_078) Tire/Pavement and Environmental Traffic Noise Research Study by Robert Otto Rasmussen, published in 2008

The author discusses methods by which tire-pavement noise can be reduced. The main conclusion of this study was that while further studies are needed, it’s likely that tire tread effects noise, and so switching to different patterns will lower the noise generated.

(RLR_079) Tire/Pavement and Environmental Traffic Noise Research Study by Robert Otto Rasmussen, published in 2012

The author follows up on their previous study (RLR_078) and continue to discuss methods for reducing tire-pavement noise. The main conclusion of this study was that quiet pavements are also an effective method for reducing this type of noise.

(RLR_080) Variability and Visualization of Tire-Pavement Noise Measurements by Robert Otto Rasmussen, Richard Sohaney, et al, published in 2011

The authors discuss characterizing tire-pavement noise and its variability. The main takeaway of this study was a methodology that can characterize tire-pavement noise.

(RLR_081) Effect of Diamond Grinding on Noise Characteristics of Concrete Pavements in California by Shubham Rawool and Richard Stubstad, published in 2009

The authors discuss the effect that diamond grinding has on pavement noise. The main conclusion of this study was that diamond grinding PCC pavements can significantly reduce tire-pavement noise generated.

(RLR_082) Demonstration of Using Quieter Pavement in Death Valley National Park by Judith L. Rochat and Michael Lau, published in 2013

The authors discuss quiet pavements and testing them in Death Valley. The main conclusion of this study was that re-affirming that quieter pavements are truly quieter and do reduce tire-pavement noise.

(RLR_083) Volpe Center Updates on Tire/Pavement Noise Studies by Judith L. Rochat, published in 2007

The author discusses the effect that pavement age has on tire-pavement noise generation. The main conclusion of this study was that modifications are needed to the Traffic Noise Model (TNM) to account for the aging effect.

(RLR_084) Tire/Pavement Noise Intensity Testing in Europe: The NITE Study and Its Relationship to Ongoing Caltrans Quiet Pavement Activities by Bruce Rymer and Paul Donavan, published in 2005

The authors discuss and compare tire-pavement noise levels in the United States and Europe. The main conclusion of this study was that pavement type has a significant effect on the noise level, with the authors finding up to a 10 dB reduction in noise for some pavement types.

(RLR_085) Traffic Noise Basics Fact Sheet by the South I805 Express Lanes Project, published in 2015

The authors introduce the topic of tire-pavement noise. This report has no conclusion, as it is and introduction to the topic of noise.

(RLR_086) Transportation Noise and Concrete Pavements: Using Quiet Concrete Pavements as the Noise Solution by Larry Scofield, published in 2009

The author introduces the subject of pavement noise. There were no findings or conclusions, as this paper is a brief introduction to the subject.

(RLR_087) State-of-the-Art Review on Sustainable Design and Construction of Quieter Pavements Part 2: Factors Affecting Tire Pavement Noise and Prediction Models by Okan Sirin, published in 2016

The author aggregates different sources and studies to discuss different variables and factors that affect tire-pavement noise. The main takeaway from this study was which variables or factors have been found to effect noise generation the most.

(RLR_088) Selection and Design of Quiet Pavement Surfaces by Andre de Fortier Smit, Manuel Trevino, et al, published in 2016

The authors discuss quiet pavement implementation. There were no major findings in this study other than an author recommended methodology for implementing quiet pavements.

(RLR_089) Experiences with CDOT's Quiet Pavement Research Program by Richard Sohaney, published in 2011

The author discusses the real-world use of quiet pavements, and their impact on noise. The main conclusion of this study was that noise generally increases with the age of the pavement and decreases as the temperature increases.

(RLR_090) Thoughts Regarding Tire-Pavement Noise by Michael A. Staiano, published in 2013

The author discusses using OBSI to measure noise. The main conclusion of this study was that OBSI can be used to accurately measure noise, as was shown in the US and Europe.

(RLR_091) Tyre-Road Noise Prediction: A Comparison Between the SPERoN and HyRoNE Models Part 1 by T. Beckenbauer, P. Klein, et al, published in 2008

The authors compare two different models for predicting tire-pavement noise. The main conclusion of this study was that both models are fairly accurate and can be used.

(RLR_092) New Research in Noise Reduction and Safety by George B. Way, published in 2011

The author discusses the use of quiet pavements in Arizona. The main conclusion of this study was that quiet pavement technology, such as open graded asphalt concrete (OGAC) can reduce noise levels by three to five dB.

(RLR_093) Research in Tire/Pavement Noise Reduction and Safety by George B. Way and Ali Zareh, published in 2012

The authors discuss the use of quiet pavements in Arizona. The main conclusion of this study was that open graded asphalt concrete (OGAC) can reduce noise levels by 3-5 dB.

(RLR_094) Modeling of Quieter Pavement in Florida by Roger L. Wayson, John M. MacDonald, et al, published in 2009

The authors discuss measuring the tire-pavement noise level generated by different pavements in Florida. The main conclusion of this study was that different pavement levels produce different sound levels, depending upon a wide range of factors such as age and texture.

(RLR_095) On-Board Sound Intensity (OBSI) Study by Roger L. Wayson, John M. MacDonald, et al, published in 2014

The authors discuss measuring the tire-pavement noise level generated by different pavements in Florida. The main finding in this study was a database created by the author, containing the noise levels of different types of pavements.

(RLR_096) Pavement Research in Florida: OBSI by Roger L. Wayson and John M. MacDonald, published in 2016

The authors discuss tire-pavement noise generated by different pavements in Florida. The main conclusions of this study were that profile depth, aggregate size, and the friction number of the pavement are all important parameters in tire-pavement noise.

(RLR_097) Concrete Pavement Surface Characteristics by Paul D. Wiegand, published in 2007

The author discusses the effect that pavement surface texture has on tire-pavement noise. The main conclusion of this study was that diamond grinding the pavement surface reduces noise.

(RLR_098) Concrete Solutions for Quieter Pavements on Existing Roadways by Paul D. Wiegand, published in 2006

The author discusses methods for creating quieter pavement surfaces, specifically focusing on diamond grinding. The main conclusion of this study was that diamond grinding is a realistic and effective method for reducing tire-pavement noise.

9. PHOTOGRAPHIC REFERENCES

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(PR_07) "Literature Review and Synthesis – Quantifying the Benefits of Noise Abatement Measures (Part 1) – Appendix B" AECOM.

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