PAVEMENT CONDITION EVALUATION USING FIELD DATA OF SURFACE DEFLECTION AND TIRE-PAVEMENT NOISE

By

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ABSTRACT OF THE THESIS

Pavement Condition Evaluation using Field Data of Surface Deflection and

Tire-Pavement Noise

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Pavements are used in roads, bridges, parking lots, runways, and driveways to provide a smooth surface with adequate coefficient of friction for quick and efficient transportation. Pavement deterioration occurs due to overuse of the pavement materials, traffic loading, weather uncertainties, surface distresses and other environmental factors. It is essential to maintain and enhance the durability of the pavement structure to increase its service life. Flexible and rigid pavements are the two types which are commonly used. Several mixture types, materials and preservation treatments are used to increase the strength and durability of pavement. Since pavement construction and maintenance is a thriving industry, there are several testing methods and software which are used to record pavement performance and find new ways to make it cost-effective and sustainable.

Pavement surface deflections measurement is one of the methods which is used to determine the bearing capacity of the pavement. Falling Weight Deflectometer (FWD) is one of the most commonly used devices to measure surface deflections and is considered effective to backcalculate the pavement layer moduli. However, one of the disadvantages of using FWD is that it is a stationary measuring device which leads to traffic disruptions while collecting the data. TSD is newly developed device which measures the surface deflections at traffic speed. In order to incorporate TSD deflections into pavement management systems (PMS), it is essential to compare it with FWD to check whether TSD is reliable. In this study, methods like Multiple Regression Analysis, Limit of Agreement (LOA), Backcalculation of layer moduli using BAKFAA software and Correlation of surface deflections with surface distress were performed for both the devices. Lastly, it was evident that there needs to be significant increase in the amount of research studies and experiments before TSD can replace FWD and can be fully implemented in the pavement management systems.

In addition to surface deflection, tire - pavement noise method is another way of determining pavement performance. In this study further analyses were performed on tire-pavement noise for flexible pavements like Dense Graded Asphalt, Stone Mastic Asphalt, and Open Graded Friction Course using On-Board Sound Intensity (OBSI) method. The factors like temperature, aging of pavement, surface distresses and pavement preservation techniques were analyzed to determine their effects on the tire-pavement noise. In conclusion, it was observed that the Open Graded Friction Course (OGFC) was quietest pavement.

Keywords: Pavement, TSD, FWD, surface distress, deflection, backcalculation, tire-pavement noise, OBSI

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1 Introduction

1.1 Background

Pavements are durable surfacing of road which transfers loads to the sub – base and underlying soil. People use roads, bridges, parking lots, runways, and driveways for transportation. These modes make transportation quick, efficient, and cost – effective over a short distance. One of the major differences between developed and an underdeveloped nation is that the former has better quality of pavement structure when compared with the latter. The construction and maintenance of pavement is one of the thriving industries in the world. In addition to facilitating people to reach their destination, there is an increase in the use of different road networks for freight shipping.

With an increase in the use of roads, the pavement structure should provide smooth ride to the commuters. Some of the characteristics of an ideal pavement are as follows:

- Smooth surface with adequate coefficient of friction
- Sufficient thickness to distribute the load of the vehicles
- Durable with an efficient drainage system
- Cost – effective and sustainable

There is a significant increase in the number of research experiments using different materials and techniques to achieve the aforementioned qualities. The pavement industry is an advancing industry since billions of dollars have been spent on maintenance and construction. In the United States, approximately 2.5 million miles of roads are paved out of the total 4 million. In 2014, the federal government spent around $27 billion for operation and maintenance of roads and the state government spent around $165 billion for highways including national, state, and local roads, bridges, and tunnels.

One of the major factors which play an important role in pavement deterioration is the environmental factor. Weather uncertainties, increase in traffic volume count, degradation of pavement materials and declining pavement quality due to age lead to pavement distresses. Regular maintenance and rehabilitation can increase the service life of the pavements by decelerating the deterioration process of the pavements. However, maintenance and rehabilitation in most cases are expensive and have drawbacks on the environment. In order to enhance sustainability, innovative construction techniques and different materials are being tested and used to construct new pavements. For developing and/or using any maintenance or rehabilitation techniques on existing pavements, it is necessary to know the structural condition of each of those pavements. Several destructive and non – destructive tests are being performed on paved roads by collecting samples for laboratory tests or performed on site using different instruments. These tests are conducted to determine different factors and conditions related to each pavement layer.

In this study, pavement condition evaluation of New Jersey highways was conducted using the calibrated field data of surface deflection and tire-pavement noise. Surface deflections are majorly used to determine structural bearing capacity and load transfer of flexible and rigid pavements. Deflection measurements can also be used to determine the layer stiffness and subgrade resilient modulus. Pavement deflection measurements are non – destructive and different testing equipment like Falling Weight Deflectometer (FWD), Light Weight Deflectometer (LWD), Heavy Weight Deflectometer (HWD), Traffic Speed Deflectometer (TSD) are being used to measure surface deflections. Amongst them, Falling Weight Deflectometer (FWD) is considered as the most common and effective non-destructive testing device. Since FWD is stationary measuring device, it causes traffic disruption during deflection measurement. In addition, collecting reasonable amount of data is time consuming. To increase the testing efficiency and minimize traffic disruption and potential risk during testing, Traffic Speed Deflectometer (TSD) was developed. TSD measures deflection continuously and records the pavement deflection while travelling at a speed of 50mph. Since TSD is relatively new, it is essential to compare it with old and most common deflection measuring devices. This helps to evaluate the extent of this new device, reliability and whether it can replace the old device.

Moreover, this study also evaluates tire-pavement noise using different factors along with surface deflection. Noise is an undesirable and an unwanted sound which is considered to have adverse health effects on humans. People residing in urban areas are affected the most since they are continuously exposed to transportation noise by vehicles, trains, and aircrafts. According to the World Health Organization, noise that exceeds 65 dB(A) during the day and 55 dB(A) at night have adverse effects on human health. Exposure to prolonged or excessive noise has been shown to cause wide range of health problems. Interrupted sleep is the most common problem that continues to affect creativity, memory, judgement and makes you feel tired. Additionally, roads are one of the main causes of noise pollution. The sources of road traffic noise are the power unit noise, the aerodynamic noise, and the tire – pavement noise. This study focuses on the tire – pavement noise which occurs due to the tire-pavement interaction. The acoustic performance of pavement surface is affected by environmental conditions and over time due to heavy traffic and surface distress. As tire – pavement noise is one of the major causes of noise pollution, it becomes obligatory to understand the change in the acoustic data of different pavements of different mixture types over the course of time. To obtain quieter pavements, it is necessary to reduce the pavement noise at the design level. As most of the noise is generated at tire-pavement interface, the selection of appropriate materials becomes essential. Long term monitoring of pavement can assist in selection of quieter materials. The continuous collection of tire-pavement noise will result in increased knowledge about the behavior of the pavement over the years which might lead to mitigation of the tire – pavement noise in the future.

1.2 Objective and Scope

In terms of surface deflection evaluation, the objective is to determine whether the information collected by Traffic Speed Deflectometer (TSD) for flexible pavement is appropriate and reliable. This can be achieved by comparing it with the structural condition information collected by Falling Weight Deflectometer (FWD). The results obtained from this analysis will help to decide if data collected with TSD can be implemented in the pavement management system (PMS) process.

The study also involves comprehensive discussion on the On-board Sound Intensity (OBSI) testing, data collection and data processing. Furthermore, analysis of the processed OBSI data is conducted using factors like different mixture type, temperature, aging, and surface distress. The results will help to determine quieter pavement with respect to the above-mentioned factors. It will also help to decrease the tire-pavement noise at design level.

Chapter 2 Literature Review

2.1 Pavement Deflection Measurement

2.1.1 Traffic Speed Deflectometer (TSD)

Generally, trucks are used with heavy rear single-axle load of 100kN equipped with dual wheel on each side. The Traffic Speed Deflectometer (TSD) is mounted on the truck. The deflectometer has Seven Doppler lasers that are mounted on servo-hydraulic beam. A reference laser is positioned at 3.6 m in front of the rear axle, away from the deflection bowl. Four lasers mounted on the beam record vertical deflection velocity under one of the dual wheel assemblies and the other three lasers record deflection velocity in front of the rear axle. In order to keep the lasers at constant height, the beam moves in opposite direction of the truck. (Flintsch et al., 2012 and Katicha et al., 2014)

The deflectometer records the reading while moving at a speed of 50 mph. The deflection velocity is produced (mm/s) while calibrating the measurements. It is then divided by the instantaneous survey speed (m/s) to give deflection slope (mm/m) as output (Ferne et al., 2009).

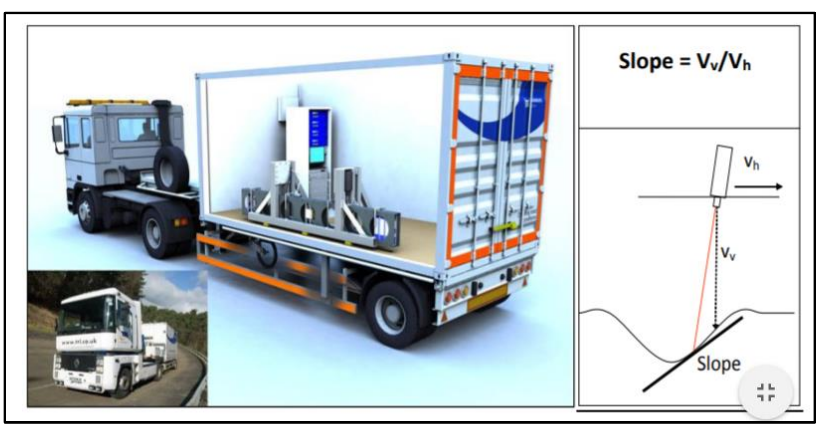

Figure 1 TSD equipment and operating method (Katicha et al., 2014)

2.1.2 Falling Weight Deflectometer

The FWD measures deflection by applying load pulse that simulates the load of rolling wheel of the vehicle to the pavement. A circular plate of 300mm diameter is placed on the pavement surface and a weight is dropped on it to produce load. The weights used are 6000 lbs. (27kN), 9000 lbs. (40kN) and 12000 lbs. (53kN) The deflections sensors called geophones are mounted radially from the center of the load plate and record pavement deflection at various radial distances (0, 200, 300, 450, 600, 900, 1200 and 1500 mm). The data obtained from this test is primarily used to estimate pavement structural condition by backcalculating layer moduli and to predict the future load bearing capacity of the pavement (Katicha et al., 2014).

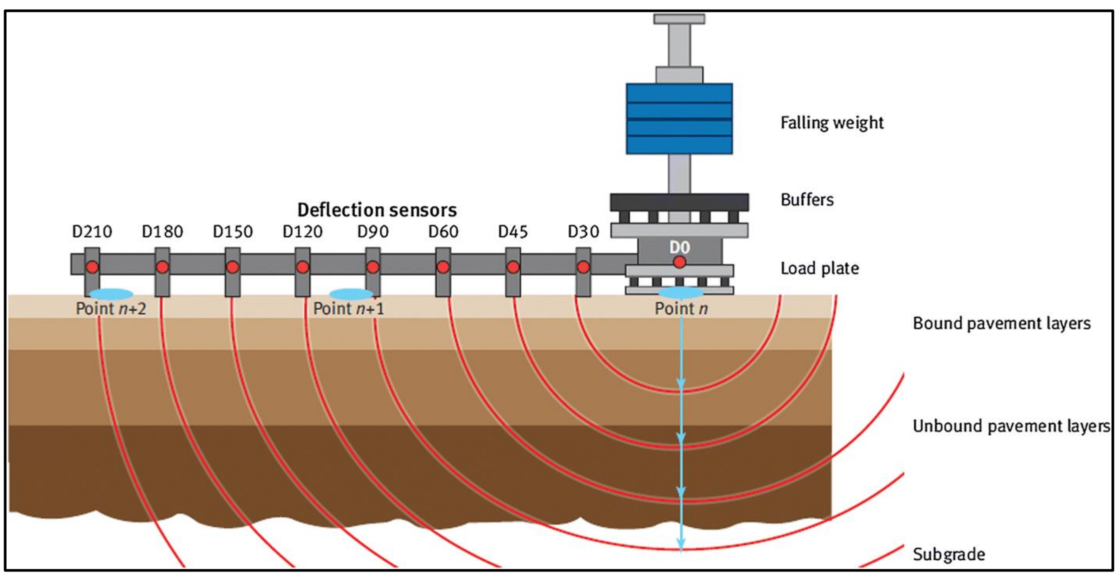

Figure 2 Deflections measuring approach by FWD

2.2 Pavement Condition Evaluation Using TSD and FWD

There are significant differences between the loading mechanism of TSD and FWD. Each device measures different quantities. These differences (TSD measures deflection slope while FWD measures deflection) were the reason a study converted the deflection measurements to the structural curvature index (SCI) and the base damage index (BDI) (Katicha et. al. 2014). A significant bias was found between the two devices using the Limit of Agreement (LOA) method. The study also recommends using LOA method to compare TSD and FWD. Furthermore, another study compared TSD and FWD measurements using ANOVA and Limit of Agreement (LOA) method and concluded that the deflection measurements are statically different due to loading characteristics and load type (Zihan. 2019). For backcalculation, there are several software available to obtain pavement layer moduli. Therefore, it is necessary to find some software that calculates accurate and consistent modulus values. EVERCAL, a backcalculation software showed highest accuracy and consistency when compared to MODULUS and BAKFAA using FWD test data (Ahmed. 2010). An attempt to compare FWD and spectral analysis of surface waves (SASW) was made by using several backcalculation methods. BAKFAA was concluded to be effective in estimating PCC moduli along with ELMOD method (Ellis 2008). Majority of the software are used for FWD deflections. Hence, it is required to incorporate TSD measurements into backcalculation analyses. One of the studies used 3D-Move models to accurately estimate the surface deflections when compared to field measurements. It concluded that the estimated deflection and field measurements were in good agreement under TSD loading. Later, with the help of Artificial Neutral Network, TSD deflections were converted to corresponding FWD deflections to allow the backcalculation of layer moduli using TSD deflections as predicted FWD deflection (Elseifi et. al. 2019). To further integrate the TSD in backcalculation analysis, velocity method (3D-Move software) and deflection method using WESLEA analysis tool were used to obtain layer moduli of flexible pavement. The velocity method using 3D-Move had more advantages. However, results showed that backcalculated layer moduli obtained from deflection method were comparable with results from velocity method (Nasimifar et. al. 2016).

Due to the difference in loading operation, the TSD measured deflections could be sensitive to surface irregularities like pavement distresses and roughness (Flinstsch et. al. 2013). A report showed that the distribution of effective structural number (SNeff) calculated from TSD and FWD measurements had relatively good consistency. Hence, the structural information derived from TSD can be successfully used instead of the information derived from FWD for network level pavement application (Katicha et. al. 2020). Further correlation between the surfaces distresses like rutting and cracking with surface curvature index (SCI300) were conducted. The results showed weak correlation between SCI300 and cracking an average value of 0.06 for all the tested roads and even weaker correlation between SCI300 and rutting with an average value of 0.04 (Katicha et. al. 2020). Surface distress like cracking and cement-treated base crushing may result in significant bump in FWD deflection basin which can cause error in backcalculation analysis (Xie et. al. 2015).

2.3 Pavement Noise Measurement

Standardized noise measurement gives an idea about the range of noise levels produced by different pavements over the course of time to design quiet and durable pavement surfaces.

The following are some of the objectives of tire/pavement noise testing:

- Reduce noise generation by existing pavements using different preservation methods.
- To design new pavements with materials that produce minimum noise.
- To determine the health impacts of tire – pavement noise in Life Cycle Analysis (LCA).

2.3.1 Field Measurements

Field Measurements includes methodologies like Statistical Pass-by (SPB), Controlled Pass-by, Close Proximity etc. A detailed overview of these activities has been given as follows:

Statistical Pass-by (SPB)

The Statistical Pass – by (SPB) method measures noise of vehicles that pass by using sound level meter (SLM). This instrument is placed at the distance of 25 ft and height of 4ft (ISO Standard 11819-1, Europe) or at distance of 50 ft and height of 5 ft (FHWA, US) from the centerline of the travel lane. Random samples of typical vehicle class are measured one at a time. It is also required to record the speed and the type of vehicle which is measured.

Statistical Pass-by Index (SPBI) is computed after analyzing the data. This index can be used to compare different pavements.

In this method, traffic noise such as engine, exhaust, and aerodynamic noise is clarified. It also considers the variation occurred due to vehicles in the same class. The following aspects must be considered when selecting sites:

- Terrain
- Low traffic volume
- Minimum background noise
- Absence of acoustic reflective surface

One of the drawbacks observed is that this method is time consuming and the results might vary depending on the traffic mix. Secondly, the number of pavements that can be tested with this method economically when considering the above aspects is low.

Figure 3 Statistical Pass-by (SPB) testing method

Controlled Pass – by (CPB)

The Controlled Pass – by method requires the same setup as SPB. In this method, one or few selected vehicles are used for testing. The vehicles are driven at a designed test sign with specific speed. There are no standards available for this testing method.

The CPB method is less time consuming than SPB. However, it contains similar limitations as that of SPB while selecting sites. This method does not include the variation occurring due to vehicles of the same class. Since it requires less traffic volume, few pavements can be tested, and insufficient data will be available for the comparison of various pavements.

Close Proximity (CPX)

In close proximity (CPX) method, the sound levels are measured at the tire/pavement interface. A trailer is used for testing. The instrument consists of microphones and an acoustical chamber (hood). The microphones are placed eight inches from the center of the tire and four inches above the surface of the pavement (ISO Standard 11819-2). The acoustic chamber is placed over the microphone to eliminate the wind noise and other traffic noise. The measurements are recorded in moving traffic speed.

CPX method is quick and enough data can be collected as there are few restrictions. This method measures sound pressure by standard sound level meter and can monitor the pavement condition. Since the measurements are recorded on trailer with limited set of tires, the variation occurring due to different types of traffic is not accounted for.

Figure 4 Close Proximity testing equipment

Close Proximity Sound Intensity (CPI)

The CPI measures sound intensity instead of sound pressure. Measuring sound intensity is smoother and more sophisticated than sound pressure as it determines basic parameter of sound. It is similar to CPX. The sound intensity is measured by using two microphones located near the rear tire of the trailer. The intensity probe consists of 2.5 mm diameter microphones and preamplifiers spaced 16 mm apart. It is protected with foam windshield. An acoustic chamber is not required due to the nature of the sound intensity. The measurements can be recorded at normal traffic speed. Therefore, sufficient data can be recorded and analyzed for studying the variations of different pavements.

Figure 5 Close Proximity Sound Intensity testing equipment

On-Board Sound Intensity (OBSI)

This method was developed in early 1980s in the U.S. by General Motors Corporation and recently introduced into the pavement community (Donavan and Lodico 2009). It measures sound intensity at the source (just above the pavement) using microphones in sound intensity probe at two principle locations (leading and trailing). The configuration is mounted to the outside of the vehicle and near the tire-pavement interface. A-weighted sound intensity levels in dBA are reported as results.

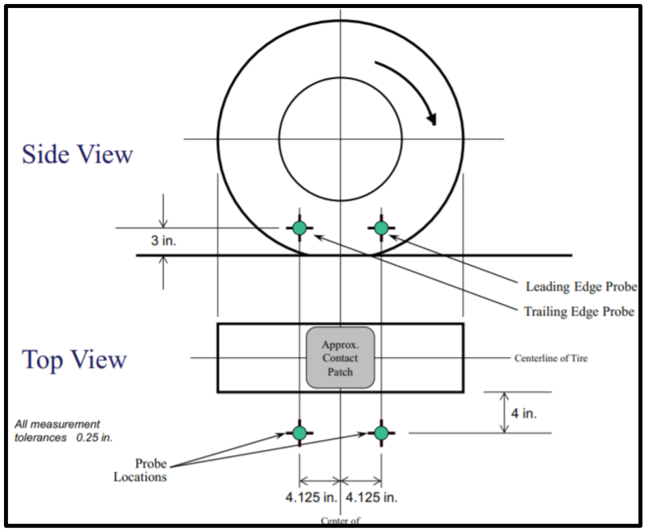

Figure 6 On-Board Sound Intensity (OBSI) apparatus

The factors which need to be controlled during testing are as follows:

1. <u>Vehicle speed</u>: The AASHTO TP 76-12 OBSI states that 60mph (96km/h) should be used. However, if the situations do not permit testing with the required speed, it should be noted in the report for all the sound intensity levels. The other acceptable speeds are 45, 35 and 25 mph (72, 56 and 40 km/h respectively). If brakes are applied during the measurement period, the data should not be valid.

2. <u>Test Tire Type</u>: The Standard Reference Test Tires (SRTT) should be used for the testing. During cold weather the tire shall be inflated to 30 ± 2 psi. All the stones should be removed from the tire as it can affect the noise measurement.

3. <u>Miscellaneous noise</u>: During the measurement period, the data can be affected by other background noises like vehicles passing by, construction sites, propulsion noise etc. The operator should record the measurements without any external disturbance to get accurate results.

The OBSI method requires less time, and sufficient data that can be collected at normal traffic speed. Various research in the pavement field has been conducted using the OBSI noise data.

2.3.2 Laboratory Measurements

Impedance Tube Absorption Testing

The impedance tube is used for testing acoustic absorption or transmission loss of material. The tube is made of aluminum and is 40 inches long with 4 – inch diameter. There are three holes made on the side of the tube to insert two microphones and one speaker is mounted at one end of the tube. The speaker generates broadband noise. At the other end of the tube, specimen holder is attached to hold the pavement core sample.

Prior to performing the test, the tube is calibrated using an open cell foam target. Post calibration, 4-inch mold is placed into the receiver and loaded into the tube. Materials that are found under the pavement layer are placed at the back of the core sample to simulate real pavement. Pink noise is played into the tube and the noise that gets reflected from the composite pavement is recorded to digital file.

This is one of the destructive measurement methods. However, the mold can be used to evaluate the pavement noise based on the mix design before the construction of the section. This method can also be used to measure the permeability, air voids and their effects on the acoustic performance over time.

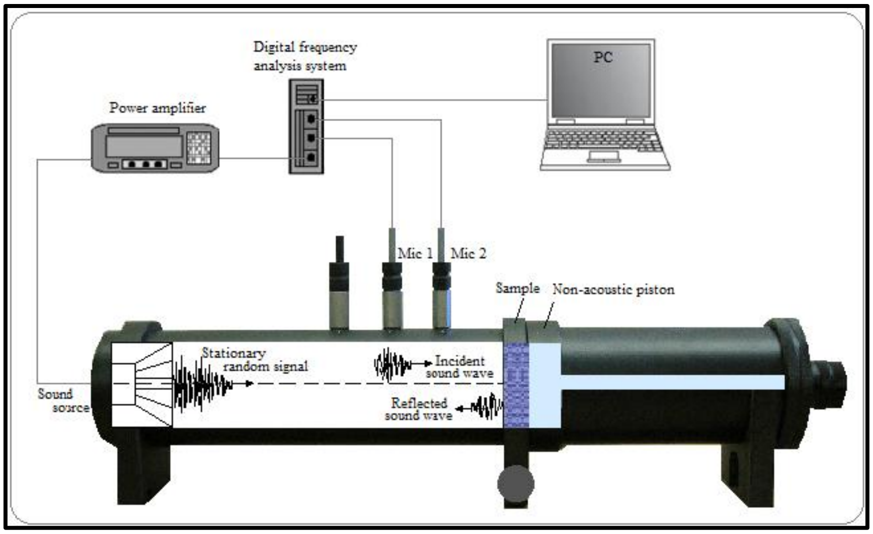

Figure 7 Impedance Tube Absorption Testing methodology

Tire-Pavement Test Apparatus (TPTA)

The Tire-Pavement Test Apparatus (TPTA) is laboratory method to test tire-pavement noise on pavement drums. The apparatus contains stationary pavement drum, and a pair of rolling tires is used on it. It has many advantages over other laboratory techniques. The specimen can produce accurate measurements like the field measurement techniques with sample size of 4 m in diameter. The rolling tires can speed up to 30 mph and load of 1000 lbs. can be mounted on.

Figure 8 Tire-Pavement Test Apparatus (TPTA) testing

2.4 Factors affecting tire-pavement noise

2.4.1 Temperature

When tire-pavement noise is collected, temperature should be recorded as it has significant impact on the measured noise data. During noise testing using Statistical Passby (SPB) method, the air temperature varied from 5 °C to 30 °C and 1 dBA reduction in noise levels were observed for every 10 °C increase in air temperature for dense bituminous pavements and 0.6 dBA decrease for porous pavements (Ledee and Pichaud 2007). Another study showed similar results with downward trend between temperature and noise for both HMA and PCC surface types (Donavan and Lodico 2009). Rough-textured pavement surfaces are affected significantly with temperature as compared to smooth-textured surfaces (Sandberg and Ejsmont 2002, Sandberg 2002).

2.4.2 Aging

With an increase in traffic volume, surface distresses and environmental conditions, changes in the acoustic data over times was observed. The change varies depending on the type of pavements tested. Many studies have been conducted to monitor the data over time using different survey methods like Close-Proximity Method (CPX), Statistical Pass-by Methods (SPB), Controlled Pass-by (CPB), On-Board Sound Intensity (OBSI).

One of the studies in Texas used OBSI testing method on Open-Graded Friction Course (OGFC) pavement sections to determine whether the pavements quietness can be sustained over time. The results showed that old OGFCs were louder with an average of 99.8 dBA, the average noise produced by medium sections were 98.9 dBA, and the average noise of new sections were 98.7 dBA. The tire-pavement noise was louder by approximately 1 dBA for old sections than the medium and new sections (Trevino and Dossey, 2009).

A case study in Qatar (Sirin et al., 2018) examined changes in the noise of dense graded asphalt (DGA) pavement over time using OBSI method. From the Figure 9, it can be concluded that the DGA pavement generates louder noise with age with an approximate increase of 3.5dBA. Colorado DOT (Hanson and Waller, 2006) conducted three-year study on tire/pavement noise on 14 Hot Mix Asphalt (HMA) and 15 Portland Cement Concrete (PCC). It was concluded that OGFC is the quietest pavement with an average increase of 1.9 dBA. PCC was observed to be the loudest since the beginning of its service life, at noise level of 97.5 dBA and the level increased by 1 dBA every year. A 10-year performance study of tire-pavement noise on Open-Graded Asphalt Concrete (OGAC) concluded that the noise increased by 0.1 dBA each year and the OGAC pavement got louder by 1.5 dBA over 10 years (Illingworth and Rodkin, 2011).

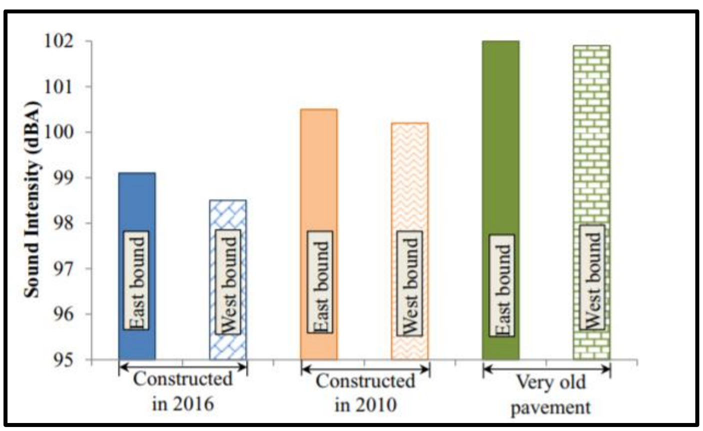

Figure 9 Effects of aging of OGFC pavement on tire-pavement noise (Sirin et al, 2018)

2.4.3 Mixture type

For evaluating effectiveness of different mixture types (Ponniah et al., 2010), five trail sections were selected to examine the noise levels of various asphalt mixes. The sound intensity levels increase with increase in speed. The pavement A (open-friction course) recorded the lowest sound intensity levels at all speeds followed by pavement C (single rubberized open graded mix), pavement D (SMA), pavement B (single open grade mix) and pavement E (control section) (see Table 1).

Table 1 Sound intensity level for five types of pavement (Ponniah et al., 2010)

Pavement Type	Sound Intensity Level, dBA					
	Speed, kph	Leading Edge	Trailing Edge	Average	Difference	Average Difference
(1)	(2)	(3)	(4)	(5)	(6) =(3-4)	(7)
Pavement A	60	90.2	86.8	88.9	3.4	2.53
	80	93.6	91	92.5	2.6	
	100	96.1	94.5	95.4	1.6	
Pavement B	60	94.3	91.6	93	2.7	2.50
	80	96.9	94.1	95.8	2.8	
	100	98.9	96.9	98	2	
Pavement C	60	92.1	89.6	91	2.5	2.37
	80	94.5	91.9	93.4	2.6	
	100	97	95	96.1	2	
Pavement D	60	92.4	90.1	91.4	2.3	2.33
	80	95.5	93	94.5	2.5	
	100	98	95.8	97.1	2.2	
Pavement E	60	93.3	92.6	93	0.7	0.37
	80	97.3	96.8	97.1	0.5	
	100	99.8	99.9	99.9	-0.1	

The tire/pavement noise of different pavement surfaces were evaluated based on surface characteristics (Liao et al., 2014). The tire – pavement noise of different pavement surfaces were evaluated based on surface characteristics (Liao et al., 2014). Surface characteristics were measured quarterly on Impervious pavements (Fine-graded and Coarse- graded Superpave and Stone Mastic Asphalt) and Open-graded pavement (Open-Graded Friction Course). Linear regression analysis method was used to evaluate single pavement surface characteristics on noise levels. Dominance analysis method was used to evaluate multiple surface characteristics on noise levels. Post evaluation, it was concluded that the surface texture increases noise levels on impervious pavements at frequencies below 1600Hz. On open-graded asphalt pavements, the porosity decreases the noise levels at every frequency.

The evaluations of pavement noise were conducted using Close Proximity Method (CPX) on 42 pavements in New Jersey (Bennert et al, 2005). The surfaces used for testing were Hot Mix Asphalt (HMA) and Portland Cement Concrete (PCC). It was concluded that the OGFC pavement mixed with crumb rubber with finest aggregate gradation produced lowest noise (96.5 dBA at 60 mph) and 12.5mm SMA mix produced the loudest tire/pavement noise (100 dBA at 60 mph). The PCC surfaces were tested to be the loudest with transverse tined surfaces at 106.1 dBA.

2.4.4 Surface distress

When the road surface is exposed to heavy traffic and changing weather conditions, distress appears on the road surface which affects the tire/pavement noise. A study confirmed that the distresses have relevant effect on the noise data (Elisabete et al., 2019). 21 road sections were selected which consists of Gap Graded Asphalt (CGA), Asphalt Concrete (AC) and Gap Graded Asphalt Rubber (CGAR) and two distress were chosen-

Alligator cracking and raveling. CPX method was used to collect the noise measurements. The figure below shows the A-weighted noise levels for alligator cracking (ACR) and raveling (R) and non-distressed pavement section (N) for all the pavement types. It is obvious that the non-distressed section generates less noise at all speeds when compared with the distressed section. The impact of distresses on the noise is higher at low speeds. Raveling has limited to no impact on noise on GGA pavement. However, for AC and GGAR pavements raveling generates more noise than alligator cracking.

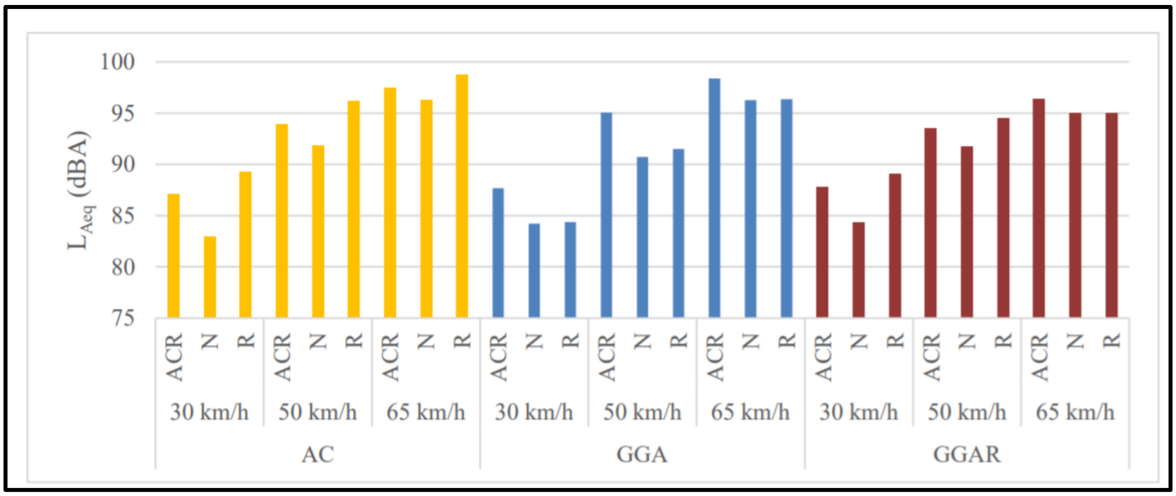

Figure 10 Effects of surface distress on tire-pavement noise (Elisabete et al., 2019).

A series of noise measurements were conducted using CPX by European SILENCE project (Qing et al., 2010). Asphalt pavements with different distresses were considered. The results show that there was an increase of 2-3 dBA on 6 m long section of alligator cracking as compared to the section with no distress on the same pavement.

Chapter 3 Analysis of Traffic Speed Deflectometer (TSD) Measurements

3.1 Data Collection and Analysis

3.1.1 Data Collection

Initially, the deflection measurements at offset 0 mm (D0) for FWD and TSD for several New Jersey routes were plotted to obtain good correlation between the two measurements. The deflection at offset 0 mm was used for selection of routes as the deflection is maximum at the point of loading. The routes selected for performing the analysis were Route 9 (northbound) from milepost 32.47 - 43.81; Route 17 (northbound) from milepost 4.56- 8.85, Route 40 (eastbound) from milepost 50.25- 51.62, I-80 (eastbound) from milepost 67.0 - 69.0 and Route 35 (southbound) from milepost 50.5-58.

The TSD deflections were obtained from data analyzed by Muller and Roberts approach. The deflections were recorded with 10341 lbs. (46kN) moving load. Deflections at 0, 100, 200, 300, 450, 600, 900 (mm) were collected for each milepost. The measurements for TSD deflections were taken at approximately 0.005 mile and temperature corrected to 68°F. The deflections measured by FWD were obtained from the Michael Baker International report. The deflections were normalized at wheel load of 9000 lbs. (40 kN). The FWD measurements were collected at approximately 0.05 mile (+/- 250’) and temperature corrected to 68°F. The TSD deflections were averaged over 0.1 mile to obtain measurements at similar locations as that of FWD.

3.1.2 Multiple Linear Regression Analysis

Multiple Linear Regression is one of the statistical methods used to predict dependent variable with one or more independent variables. It estimates the relationships between dependent variable and one or more independent variables. The mathematical representation of multiple linear regression is:

$$\boxed{\mathbf{y = a + bx1 + cx2 + dx3}}$$

Where,

y = dependent variable

x1, x2, x3 = independent variables

a = intercept

b, c, d = slope

In this project, FWD is the dependent variable and TSD, Core thickness, Effective Structure Number, HMA Modulus and Subgrade Resilient Modulus are considered as the independent variables. The HMA Modulus and Subgrade Resilient Modulus present in the Michael Baker International report were backcalculated using MODULUS software. The Core thickness was considered as one of the independent variables. It is required to have core thickness of each measurement location. Since core thickness for few mileposts were collected and GPR thickness was obtained for every milepost, linearity was derived between the core and the GPR thickness to calculate the core thickness for every milepost.

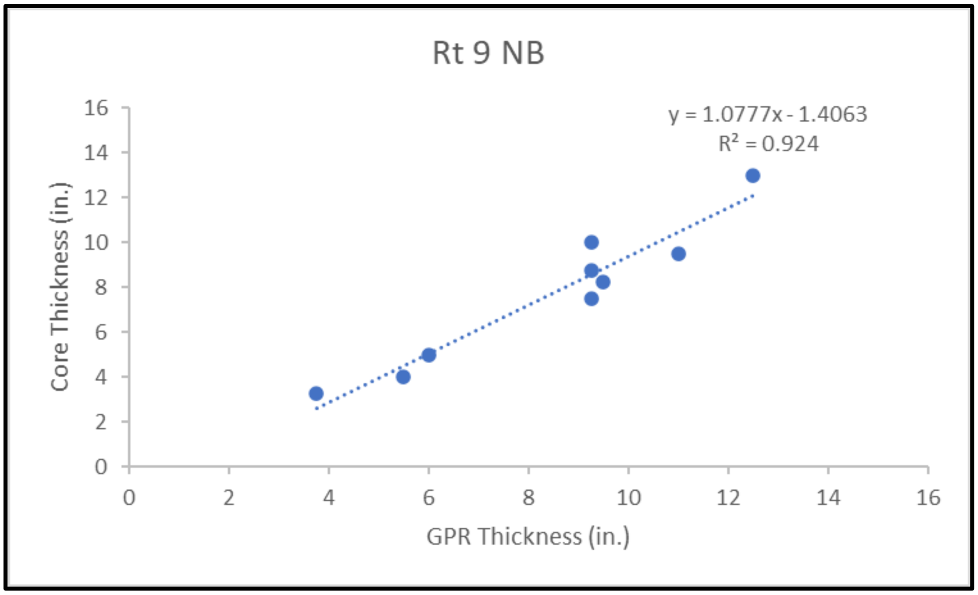

Figure 11 Scatter plot between Core thickness and GPR thickness for Rt 9 NB

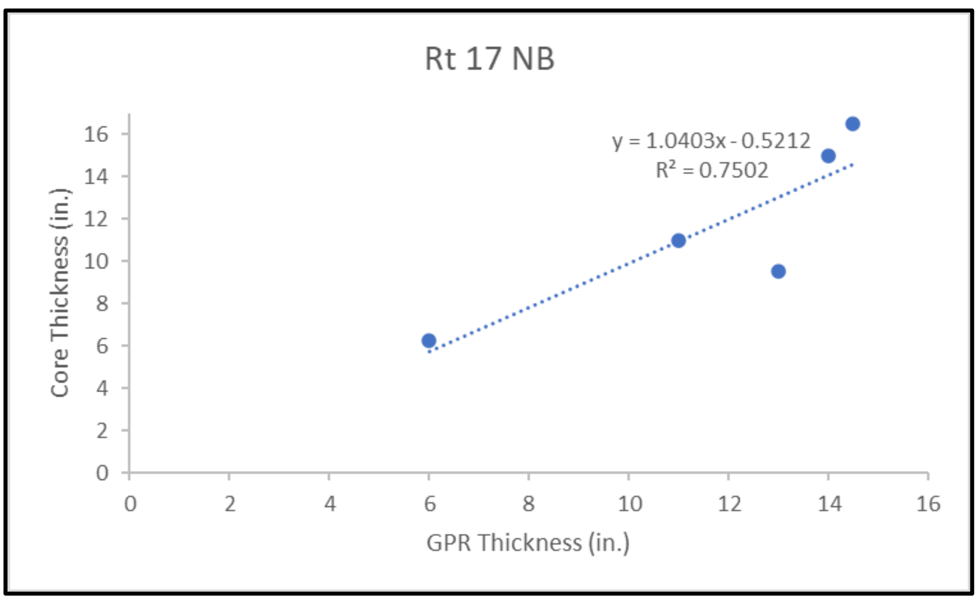

Figure 12 Scatter plot between Core thickness and GPR thickness for Rt 17 NB

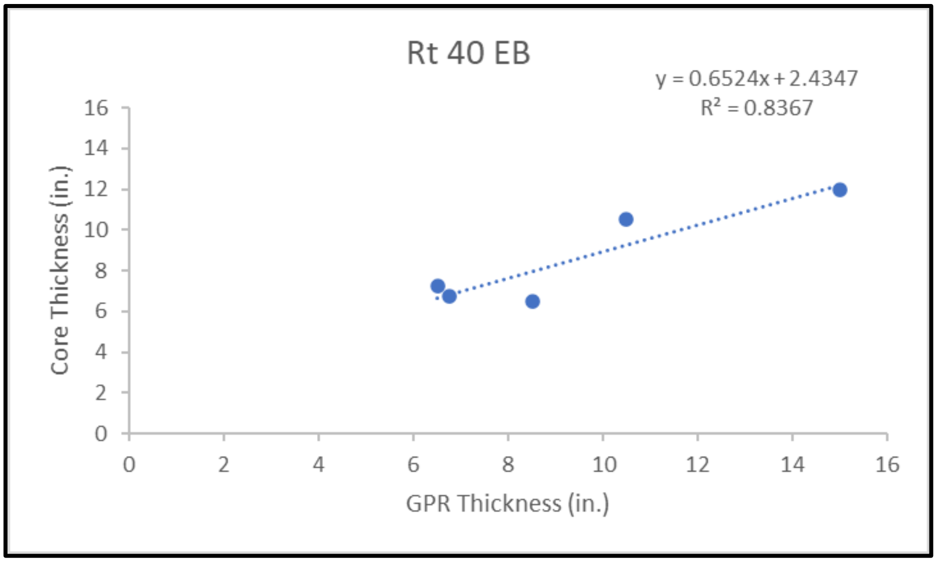

Figure 13 Scatter plot between Core thickness and GPR thickness for Rt 17 NB

Data from Rt 9 (Northbound), Rt 7(Northbound) and Rt 40 (Eastbound) was combined to perform the regression analysis. In this method, the values of the independent variables were normalized with the help of data transformation. The offsets at 0, 300, 450, 600, 900, 1200 and 1500 mm from the point of load application (D) were considered. The regression models for these offsets were obtained.

Table 2 Regression Model and R square for predict FWD deflections at each section

Offset (mm)	Regression Models	R square obtained
D0	y = -0.934 -0.012*√(x1) -0.0103*√(x2) +1.298/√(x3) -0.004*√(x4) +2.899/Log(x5)	0.97
D300	y= -1.072 -0.0005*(x1) +0.0054*√(x2) +0.814/√(x3) -0.001*√(x4) +3.47/Log(x5)	0.95
D450	y = -1.0453 -0.006*log(x1) +0.104*√(x2) +0.574/√(x3) -5.2E-05*√(x4) +3.469/log(x5)	0.93
D600	y = -0.933 -0.028*√(x1) +0.012*√(x2) +0.436/√(x3) +0.001*√(x4) +3.148/log(x5)	0.90
D900	y = -0.675 +0.005*Log(x1) +0.005*√(x2) +0.132/√(x3) +0.0002*√(x4) +2.66/log(x5)	0.93
D1200	y = -0.475 +0.0001*log(x1)+0.001*√(x2) +0.015/√(x3) -4.2E-05*√(x4)+2.031/log(x5)	0.97
D1500	y = -0.342-0.002*log(x1) +3.69E-05*√(x2)-0.002/√(x3) -9.7E -05*√(x4)+1.531/log(x5)	0.96

Where,
y = FWD Dn (mm) (n=0,300,450,600,900,1200,1500 respectively)
x1= TSD Dn (mm) (n=0,300,450,600,900,1200,1500 respectively)
x2= Core Thickness (in.),
x3= Effective Structure Number,
x4 = HMA Modulus (ksi),
x5 = Subgrade Resilient Modulus (psi)

Using linear regression, the R square values are calibrated as 0.97, 0.95, 0.93, 0.90, 0.93, 0.97, 0.96. These values are closer to 1 which indicates perfect positive relationship and better fit. From the results, it is interpreted that there is strong linear relationship between the dependent and independent variables.

Furthermore, multiple regression analysis was performed using only two independent variables, TSD deflections and Core thickness. This analysis was conducted to verify whether similar results were obtained if limited parameters are available. However, the results shown in table were not as good as the previous analysis. The R square values for offsets at 0, 300, 450, 600, 900, 1200 and 1500 mm were 0.61, 0.53, 0.37, 0.24, 0.12, 0.06, 0.06, respectively using only TSD deflection and core thickness as independent variables.

Table 3 Regression Model and R square for predict FWD deflections at each section

Offset (mm)	Regression Model	R Square
D0	$y = 0.17 + 0.648*\sqrt{(x1)} - 0.01*\sqrt{(x2)}$	0.62
D300	$y = 0.118 + 0.79*\sqrt{(x1)} - 0.06*\sqrt{(x2)}$	0.53
D450	$y = 0.424 + 0.178*\sqrt{(x1)} - 0.027*\sqrt{(x2)}$	0.37
D600	$y = 0.06 + 0.48*\sqrt{(x1)} - 0.02*\sqrt{(x2)}$	0.24
D900	$y = 0.195 + 0.06*\log(x1) - 0.003*\sqrt{(x2)}$	0.12
D1200	$y = 0.085 + 0.01*\log(x1) + 0.004*\sqrt{(x2)}$	0.06

D1500	y = 0.05 +0.006*log(x1) +0.002*√(x2)	0.06

Where,
y = FWD Dn (mm) (n=0,300,450,600,900,1200,1500 respectively)
x1= TSD Dn (mm) (n=0,300,450,600,900,1200,1500 respectively)
x2= Core Thickness (in.)

3.1.3 Limit of Agreement (LOA) method

Each device has different way of conducting the tests and measures different quantities. TSD measures deflection slope and FWD measures deflection. The limit of agreement (LOA) method is used to assess the agreement between the two devices.

The Limit of Agreement methodology was performed on three different routes (US-9 NB, US-17 NB, US-40 EB). Two sets of analysis for each route were conducted. The first LOA analysis was performed with the raw FWD-TSD data and the second set was analyzed using the SCI300 (i.e., D0-D300) data. The first step was to evaluate LOA by plotting the difference (FWD-TSD) versus the average ((FWD+TSD)/2. Then, the difference (FWD SCI300 -TSD SCI300) versus the average ((FWD SCI300 + TSD SCI300)/2) was plotted.

The 95% (Confidence Interval (C.I.) Limit of Agreement lies between the upper and the lower lines as shown in Figure 14, Figure 15, and Figure 16. This shows that the data between these two lines agree with each other 95% of the time with measurement error. The distance between the bias and the points show the measurement error. The farther the point from the bias line, the greater will be the measurement error. The points that lie outside of the 95% LOA can be interpreted as true change since it is greater than the measurement error.

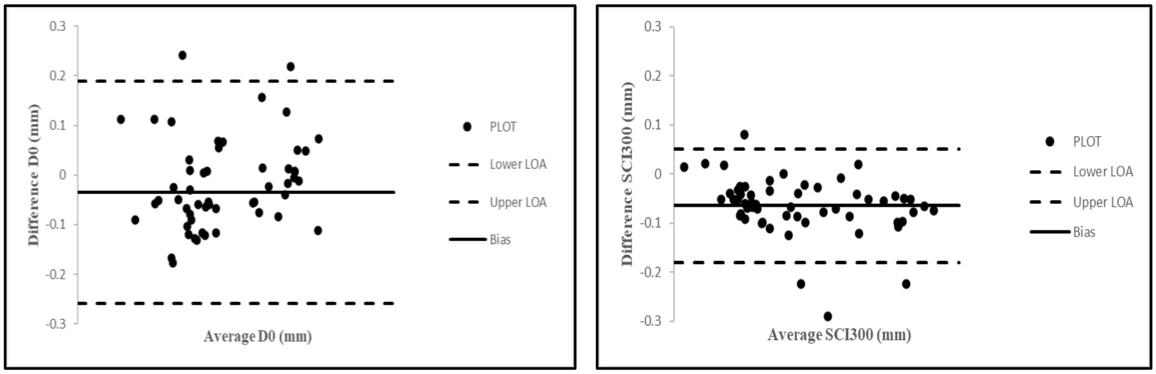

Figure 14 LOA between FWD and TSD for D0 and SCI300 for Route 9 NB

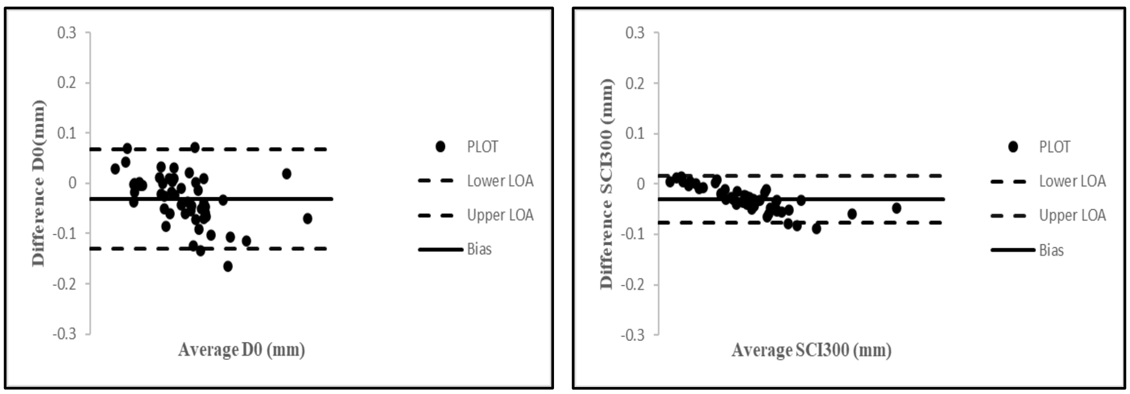

Figure 15 LOA between FWD and TSD for D0 and SCI300 for Route 17 NB

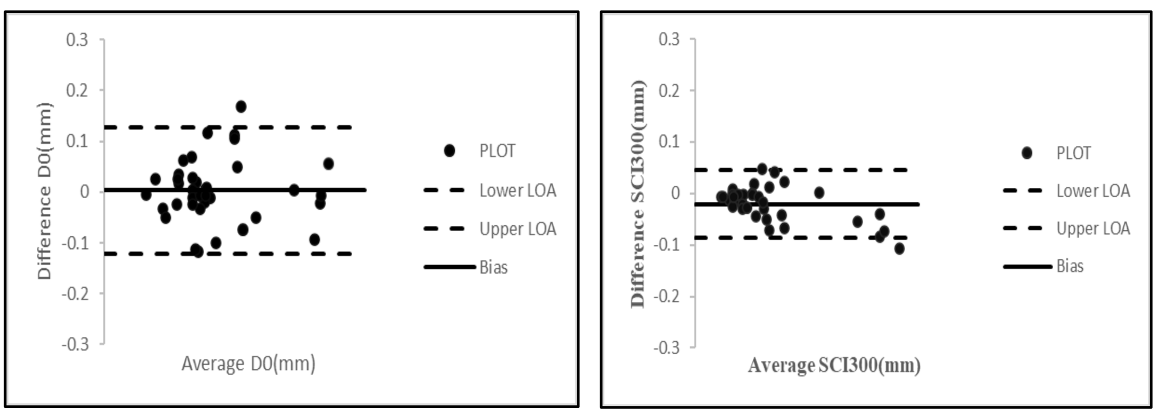

Figure 16 LOA between FWD and TSD for D0 and SCI300 for Route 40 EB

Table 4 Values obtained using Limit of Agreement method

Route		Upper LOA (mm)	Lower LOA (mm)	Bias (mm)	Standard Deviation (mm)
Rt 9 (NB)	**D0**	0.19	-0.26	-0.03	0.11
	SCI300	0.05	-0.18	-0.06	0.06
Rt 17 (NB)	**D0**	0.07	-0.13	-0.03	0.05
	SCI300	0.02	-0.08	-0.03	0.02
Rt 40 (NB)	**D0**	0.13	-0.12	0.00	0.06
	SCI300	0.05	-0.09	-0.02	0.03

From the above result Table 4, it is evident that for Rt 9 NB and Rt 17 NB, the standard deviation is high as compared to the mean. This shows that the data is spread out over wider range. However, for Rt 40 NB, the standard deviation is slightly lower than the other two routes. This shows that for Rt 40 NB the data is closer to the mean of the set.

3.1.4. Backcalculation analysis

"Backcalculation" is an analysis of pavement layer moduli by using pavement deflections measured by various deflection devices such as FWD and TSD. Additionally, it calculates surface deflection and attempts to match it with the measured deflections. In this iterative process, the assumed layer moduli (stiffness) are adjusted until the calculated deflection closely matches the measured deflection within permissible Root Mean Square Error (RMSE) between 1 to 2 percent.

The TSD deflections were collected at 0, 100, 200, 300, 450, 600 and 900 mm. In order to use TSD deflections in backcalculation, deflections at offsets 1200 and 1500 mm were required. The deflections at these offsets were predicted by plotting deflection versus offset for each location. The equation from exponential function was used as it fits the deflection curve the best. BAKFAA is one of the software programs for Backcalculation of pavement layer moduli used by Federal Aviation Administration. It uses layered elastic analysis program LEAF and downhill multidimensional simplex minimization method that minimizes the function RMS (mils) between the measured and calculated deflections. It can backcalculate up to 10 pavement layers. Each measurement requires inputs like Seed moduli, Poisson's ratio, interface parameters and layer thickness (see Figure 17). To assist the user there are recommended seed moduli ranges (see Table 5) for pavement layers. The FWD measured deflections can be loaded through files or can be entered manually. The radius of the plate used is 5.91 inches, the plate load is kept at 10341 lbs. (all the deflections were normalized to 10341 lbs.). The seed modulus was assumed from the reference table (see Table 5), Poisson's ratio was assumed to be 0.35, interface parameter's value was kept as 1.0 (default). The layer thickness was derived from the FWD reports. Data locations obtained from the regression analysis and measured FWD were randomly selected for backcalculation.

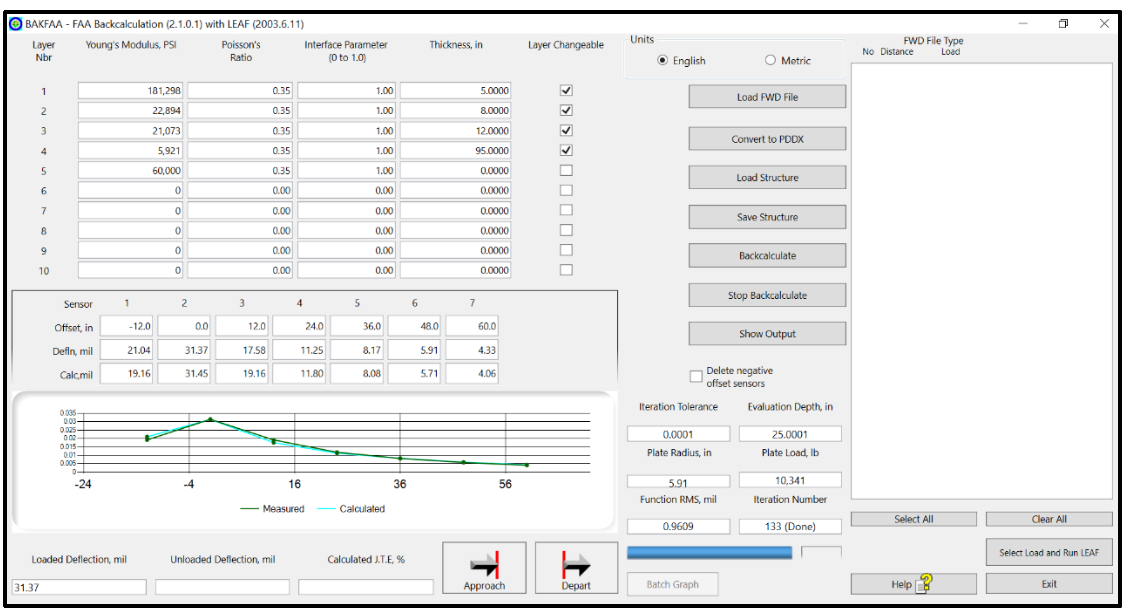

Figure 17 BAKFAA Interface

Table 5 Recommended seed moduli (BAKFAA help menu)

Typical Modulus Values and Ranges for Paving Materials			
Material	**Low Value, PSI(MPa)**	**Typical Value, PSI(MPa)**	**High Value, PSI(MPa)**
Asphalt Concrete	70,000 (500)	500,000 (3,500)	2,000,000 (14,000)
Portland Cement Concrete	1,000,000 (7,000)	5,000,000 (35,000)	9,000,000 (60,000)
Lean-concrete Base	1,000,000 (7,000)	2,000,000 (14,000)	3,000,000 (20,000)
Asphalt-treated Base	100,000 (700)	500,000 (3,500)	1,500,000 (10,000)
Cement-treated Base	200,000 (1,400)	750,000 (5,000)	2,000,000 (14,000)
Granular Base	10,000 (70)	30,000 (200)	50,000 (350)
Granular Subbase or Soil	5,000 (30)	15,000 (100)	30,000 (200)
Stabilized Soil	10,000 (70)	50,000 (350)	200,000 (1,400)
Cohesive Soil	3,000 (20)	7,000 (50)	25,000 (170)

The backcalculation process includes few trial runs by adjusting the seed modulus to minimize the RMSE between the BAKFAA calculated deflections and measured deflections. This software program is based on deflections measured by Falling Weight Deflectometer (FWD). Therefore, FWD measured deflections and TSD measured deflections, as equivalent FWD deflections (see Table 2) are used to backcalculate the layer modulus of the pavement. The tables below show the backcalculated modulus for the four layers of the pavement. The correlation coefficients obtained were 0.87, 0.78, 0.13 and 0.27 for AC layer, base layer, subbase, and subgrade, respectively.

Table 6 Backcalculated modulus for Layer 1 -Asphalt Concrete

Route	Milepost	Layer 1 (AC)			
		Thickness (in.)	Seed Modulus (ksi)	FWD Backcalculated Moduli (ksi)	
				Measured	Predicted
9 NB	32.47	9	200	155	268
9 NB	32.67	9	200	218	298
9 NB	32.81	9	500	371	345
9 NB	33	9	500	658	886
9 NB	43	9.5	500	343	378
9 NB	43.52	8.75	500	721	597
40 EB	50.51	7.65	500	519	306
40 EB	51.04	7.98	500	448	250
40 EB	51.53	7.65	500	1621	531
17 NB	4.7	13	500	1304	1889
17 NB	5.02	13	500	1434	1117
17 NB	5.55	7	200	514	483
17 NB	8.02	14.56	500	620	521

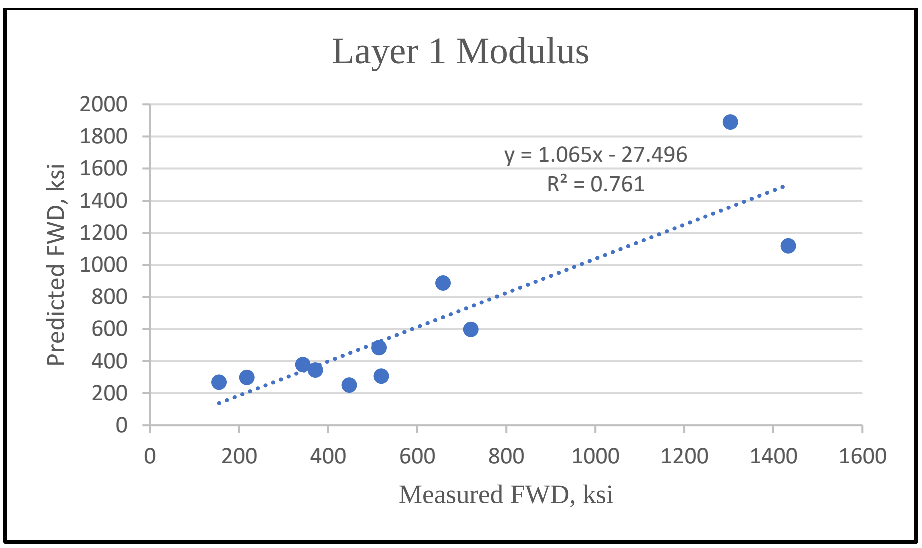

Figure 18 Layer 1 plot between Measured and Predicted FWD modulus

Table 7 Backcalculated modulus for Layer 2 - Base

Route	Milepost	Layer 2 (Base)			
		Thickness (in.)	Seed Modulus (ksi)	FWD Backcalculated Moduli (ksi)	
				Measured	Predicted
9 NB	32.47	8	150	33	10
9 NB	32.67	8	100	9	8
9 NB	32.81	8	500	5	8
9 NB	33	8	200	47	10
9 NB	43	6	200	130	16
9 NB	43.52	6	200	287	230
40 EB	50.51	6	30	29	42
40 EB	51.04	6	30	42	54
40 EB	51.53	6	30	175	143
17 NB	4.7	6	30	50	115
17 NB	5.02	6	30	21	83
17 NB	5.55	6	10	43	40
17 NB	8.02	6	30	1	5

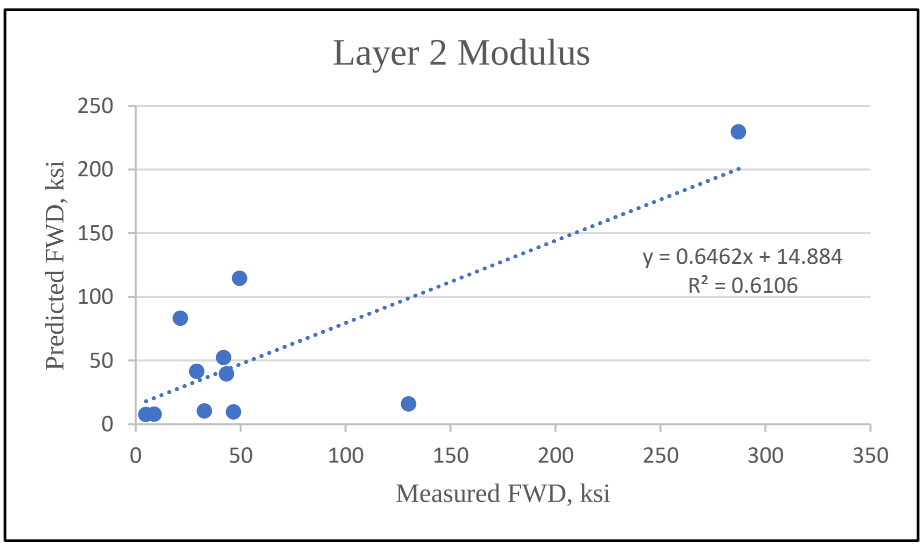

Figure 19 Layer 2 plot between Measured and Predicted FWD modulus

Table 8 Backcalculated modulus for Layer 3 - Subbase

Route	Milepost	Layer 3 (Subbase)			
		Thickness (in.)	Seed Modulus (ksi)	FWD Backcalculated Moduli (ksi)	
				Measured	Predicted
9 NB	32.47	N /A	N /A	N /A	N /A
9 NB	32.67	N /A	N /A	N /A	N /A
9 NB	32.81	N /A	N /A	N /A	N /A
9 NB	33	N /A	N /A	N /A	N /A
9 NB	43	6	30	4	48
9 NB	43.52	6	30	2	7
40 EB	50.51	6	15	10	13
40 EB	51.04	6	15	15	21
40 EB	51.53	6	15	5	8
17 NB	4.7	6	15	51	1
17 NB	5.02	6	15	19	43
17 NB	5.55	6	5	38	24
17 NB	8.02	6	15	15	14

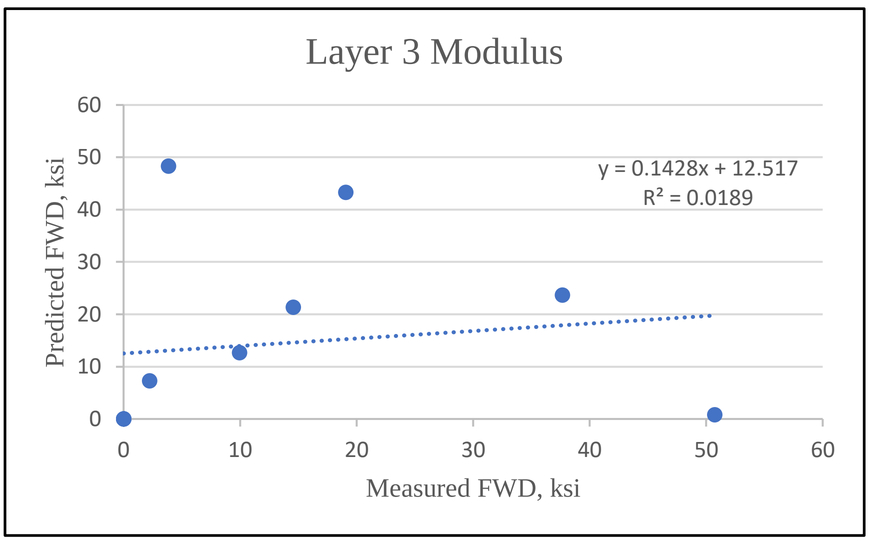

Figure 20 Layer 3 plot between Measured and Predicted FWD modulus

Table 9 Backcalculated modulus for Layer 4 – Subgrade

Route	Milepost	Layer 4 (Subgrade)		
		Seed Modulus (ksi)	FWD Backcalculated Moduli (ksi)	
			Measured	Predicted
9 NB	32.47	30	29	28
9 NB	32.67	50	16	17
9 NB	32.81	50	42	37
9 NB	33	50	25	28
9 NB	43	50	37	28
9 NB	43.52	50	40	28
40 EB	50.51	50	23	23
40 EB	51.04	50	37	38
40 EB	51.53	50	27	24
17 NB	4.7	50	25	75
17 NB	5.02	50	23	18
17 NB	5.55	10	17	18
17 NB	8.02	50	55	29

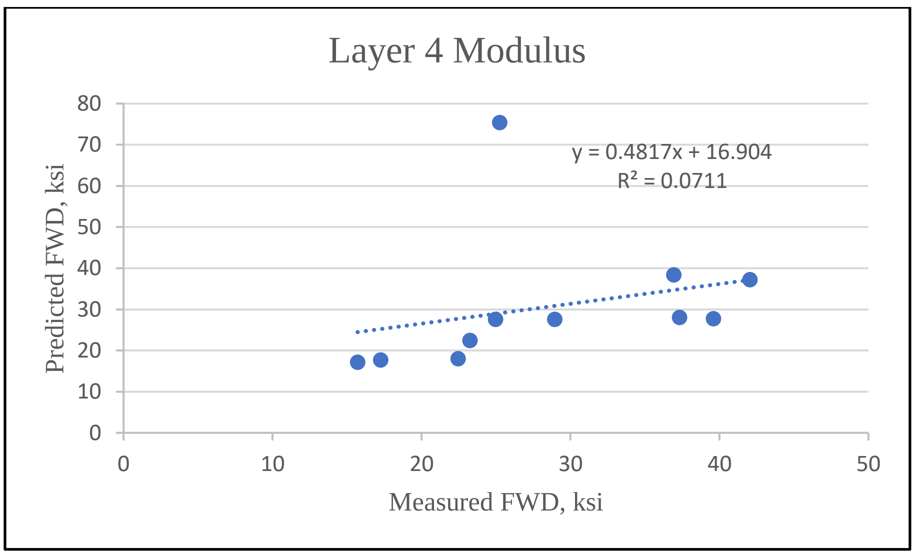

Figure 21 Layer 4 plot between Measured and Predicted FWD modulus

3.1.5 Pavement condition evaluation with FWD and TSD deflections

Some of the common factors which cause deterioration of pavement are weather uncertainties, aging of materials, traffic etc. This results in pavement distresses like cracking, rutting, raveling, potholes, etc. The common distresses observed on asphalt pavement surfaces are fatigue(pattern) cracking, longitudinal and transverse cracking, and rutting. The surface deflection measured by different deflectometers would depend on the physical condition of the pavement. This means that pavement distresses can affect the results of the measured deflection.

In this study, correlations between pavement distress and deflection indices (Surface Curvature Index) were obtained to further investigate the relationship between FWD and TSD. According to Rada et al. (2016), the recommended deflection indices are as follows:

Table 10 Recommended Deflection indices (Rada et al. 2016)

AC Thickness	Index	Device Precision (Percent)	Device Accuracy (Percent)	Model Uncertainty (Percent)	Model R^2
Between 3 and 6 inches	DSI_{4-12}	9	8	16	0.88
	SCI_{12}	11	18	15	0.90
	DSI_{4-8}	10	12	13	0.92
	TS_4	14	11	13	0.91
Greater than 6 inches	DSI_{4-12}	9	8	13	0.97
	DSI_{8-12}	9	7	12	0.98
	SCI_{12}	11	18	14	0.96
	DSI_{4-8}	10	12	17	0.95
	TS_8	9	15	17	0.94
	TS_{12}	10	21	17	0.96
	AUPP	11	13	15	0.97
Unknown	DSI_{4-12}	9	8	22	0.97
	SCI_{12}	11	18	20	0.97

Surface Curvature Index (SCI300) best reflects the AC layer of flexible pavement as it is based on radial distances of 0 and 304.8 mm (0-12 inches) (Rada et al. 2016). Hence, SCI300 is considered to perform correlation analysis with pavement distresses like Pattern Cracking, Longitudinal and Transverse Cracking, and Rutting. The FWD and TSD deflections were collected in the year 2016 and 2017, respectively. In order to get the appropriate correlation, the pavement conditions considered for analysis were from the same timeframe.

The correlation analysis between structural condition and surface conditions were performed for both FWD and TSD and are given below:

Table 11 Correlation between surface deflection and pavement distresses

Route	SCI300 and Pattern Cracking		SCI300 and Rutting		SCI300 and Longitudinal Cracking		SCI300 and Transverse Cracking	
	FWD	TSD	FWD	TSD	FWD	TSD	FWD	TSD
Rt 9 NB	0.55	0.60	-0.09	-0.13	0.36	-0.08	-0.02	0.46
Rt 40 EB	0.44	0.52	0.08	-0.30	0.38	0.44	0.28	-0.27
Rt 17 NB	-0.16	0.01	-0.20	0.24	0.14	0.01	-0.16	-0.32
Rt 35 SB	0.33	-0.14	0.00	0.20	0.38	0.04	-0.18	-0.27
I-80 EB	0.49	0.17	-0.15	0.36	-0.48	0.14	0.27	-0.18
All Roads	0.33	0.23	-0.07	0.08	0.15	0.11	0.04	-0.12

Table 12 Correlation between the change in surface deflections and distresses for 2016-2017

Correlation with change in $SCI300_{TSD-FWD}$				
Route	**Pattern Cracking (2016-2017)**	**Rutting (2016-2017)**	**Longitudinal Cracking (2016-2017)**	**Transverse Cracking (2016-2017)**
Rt 9 (NB)	0.06	0.20	-0.14	0.15
Rt 40 (EB)	-0.14	-0.07	0.24	-0.28
Rt 17 (NB)	0.35	0.26	-0.05	-0.21
Rt 35 (SB)	-0.16	-0.10	0.07	-0.01
I-80 (EB)	0.04	0.14	0.37	0.03

In general, correlation between SCI300 and pattern cracking was moderate to weak (see Table 11). The highlighted values show moderate correlation for both FWD and TSD deflectometers for US 9 (NB) and US 40 (EB). The average of all roads for pattern cracking is 0.33 and 0.23 for FWD and TSD, respectively. This is the highest amongst other distress correlations. The positive and negative values within the same distress type indicates that the amount of cracking observed on the road is not good indicator of the road's structural condition. (Samer. W et al., 2020). From the Table 12 it can be interpreted that the difference between FWD (SCI300) and TSD (SCI300) has weak correlation with the change in the pavement condition for the years 2016 to 2017.

3.2 Summary

In this study, surface deflections measured with Falling Weight Deflectometer (FWD) and Traffic Speed Deflectometer (TSD) were considered for the analysis. Falling Weight Deflectometer is stationary measuring device and Traffic Speed Deflectometer is continuous measuring device at traffic speed. In this study, the FWD data was collected from the Michael Baker International report and TSD deflections were obtained from by analyzing data through Muller and Roberts approach. After the required missing data points were found, an in-depth data analysis was conducted. In order to compare the deflections obtained from both the devices, different methodologies like Multiple Linear Regression Analysis, Limit of Agreement (LOA), Backcalculation and Evaluation of Structural Condition were used. In addition, other methods are required for better and an in-depth evaluation to decide whether TSD can replace FWD and can be implemented successfully in pavement management systems.

Chapter 4 Analysis of Tire-Pavement Noise

4.1 Pavement Noise Data Collection and Analysis

4.1.1 Data Collection

In this study, we have considered and performed the On-Board Sound Intensity (OBSI) test to collect the noise data. The detailed methodology of the aforementioned OBSI testing has been discussed below.

The On-Board Sound Intensity (OBSI) method was adopted to measure the tire – pavement noise for the study of effects of aging on tire – pavement noise. As discussed earlier, OBSI measures the sound intensity at the source (tire-pavement interface) with the help of microphones. The sound intensity measurement is made over 440 ft (134.1 m) test section as per AASHTO TP 360-16 (6) which is approximately equivalent to 5 seconds measurement at speed of 60 mph (96 km/h). The equipment is mounted on Standard Reference Test Tire (SRTT) as shown in Figure 22. The right lane of each section was considered for testing to provide consistency when comparing with other sections. The Brüel & Kjaer Pulse system was utilized to record and process the data during testing. As per AASHTO TP 76-12 (8), minimum of three test runs are required for each point (location) and the difference between the measurements should not differ by more than 0.5 dBA.

Figure 22 On-Board Sound Intensity (OBSI) Equipment

Figure 23 Standard Reference Test Tire (SRTT) Tread

Before testing, the date, time, hardness of the tire (SRTT), vehicle type, microphone calibrations have to be recorded. Post testing, environmental input such as barometric pressure (Hg), wind speed (mph), air temperature (°F), pavement temperature (°F), tire temperature (°F), tire pressure (psi), longitude, latitude, elevation (ft) are recorded. Durometer is used to record the hardness of the tire (ASTM D 2240 and F 2493). Precision acoustic calibrator 1000 Hz is used to calibrate the microphones before and after the test.

4.1.2 Data Processing

After collecting the measurements, the data is processed using MATLAB GUI (Graphical User Interface). During the process, one-third octave band with center frequency between 400 Hz to 5000 Hz graphs for PI index and coherence of sound pressure for each measurement is produced. The measurements are considered good, if the criteria for PI index and coherence in one-third octave band are fulfilled as per AASHTO TP-76-12(6). The results obtained after processing the data contain overall sound intensity levels and sound intensity levels in one-octave bands with center frequency from 400 to 5000 Hz and environmental data are collected while testing. The processed information is compiled in pgAdmin database and Microsoft Excel.

4.1.3 Selection of data

The routes selected were from New Jersey's highway system. The study is focused on the three common pavement types in New Jersey which are as follows:

- Open Graded Friction Course (OGFC)
- Stone Mastic Asphalt (SMA)
- Dense Graded Hot Mix Asphalt (DGA)

The analysis was conducted on the basis of the tests results produced over the period of 10 years (2010-2019).

4.1.4 Temperature Correction factors

To evaluate the tire/pavement noise level, it is necessary to normalize the sound intensity data to 68°F (20°C). The temperature correction factor selected was -0.04dBA/°F (NCHRP project 1-44). The temperature was measured during testing with the Kestrel® 4300 weather tracker.

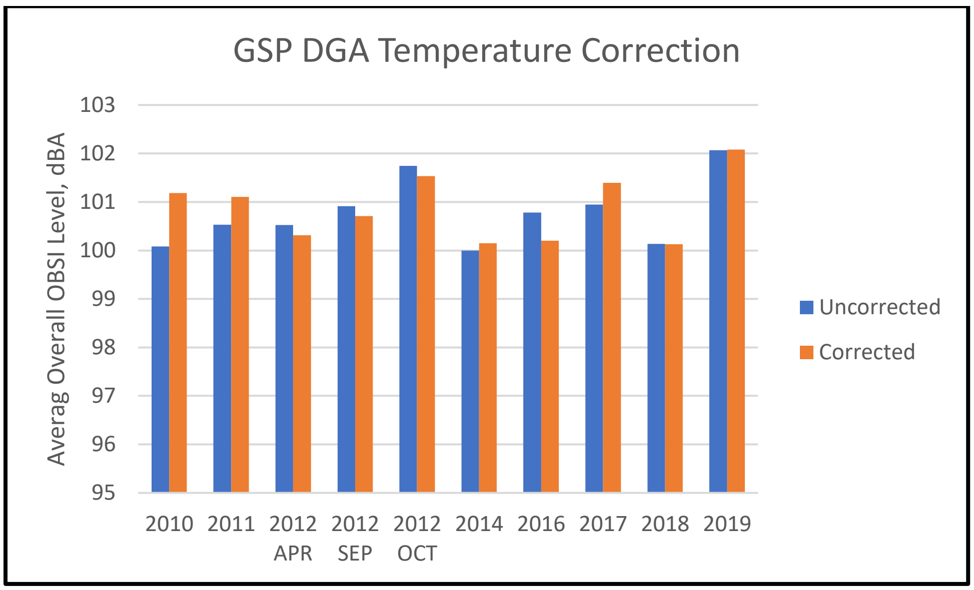

Figure 24 GSP MM 97-102 uncorrected noise levels vs corrected noise levels

The above Figure 24 shows differences in the noise levels when correction factors are applied. The GSP DGA section was measured three times in the year 2012 and it shows steady rise in the noise levels every time it was tested in that year. As the temperature decreases from April to October in 2012, the noise levels increase from 101.2 dBA to 104 dBA. From 2010 to 2019 the noise level for this DGA pavement did not increase more than 102 dBA which shows that the pavement is frequently maintained.

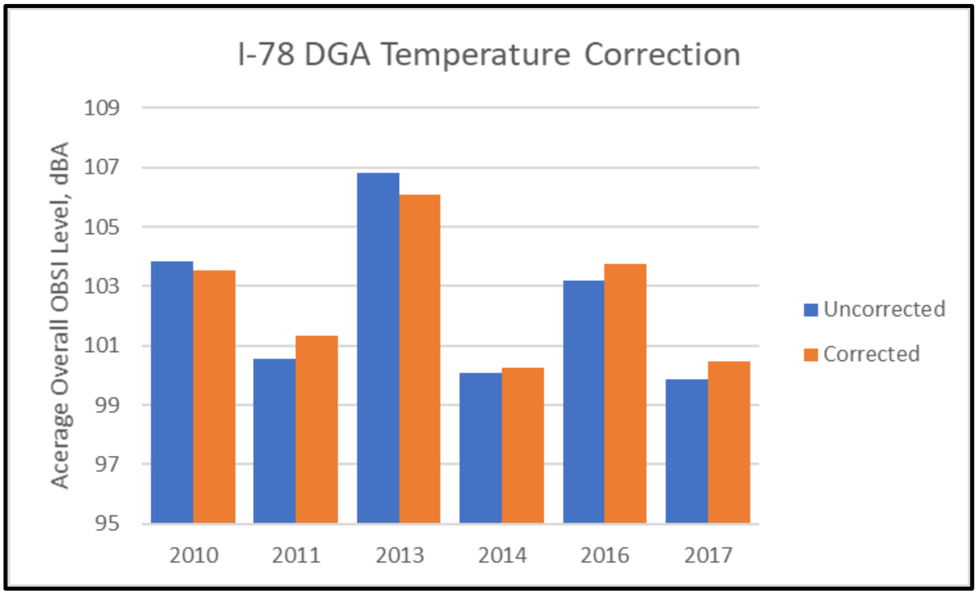

Figure 25 I-78 MM 18-26 uncorrected noise levels vs corrected noise levels

This pavement section (Figure 25) was measured from the year 2010 to 2017. The noise levels are observed to be highest for the year 2013 at 106.06 dBA after correction. There was significant drop (approximately 6 dBA) from the year 2013 to 2014 i.e., from 106.06 dBA to 100.27 dBA. One of the conclusions which can be drawn is that the pavement must have gone under maintenance at that time. For the year 2017, the noise levels were observed to have decreased by 3 dBA from the year 2010.

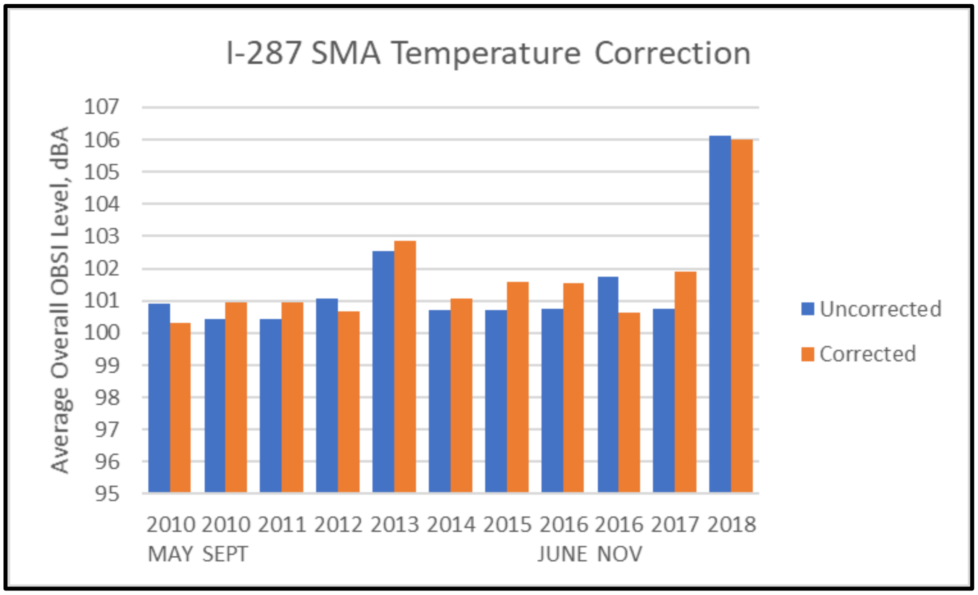

Figure 26 I-287 MM 58-60 uncorrected noise levels vs corrected noise levels

The measurements for the I-287 SMA (Figure 26) section do not show significant changes from the year 2010 to 2017. The difference in the noise levels before and after temperature correction is less. The range of noise levels are consistent between the range of 100 dBA to 102 dBA. However, there was an increase (approximately 2 dBA) in noise from 2012 to 2013. The noise level spiked 4 dBA from the year 2017 to 2018 which could be due to multiple surface distresses. The increase in AADT would have also influenced the drastic change in the noise.

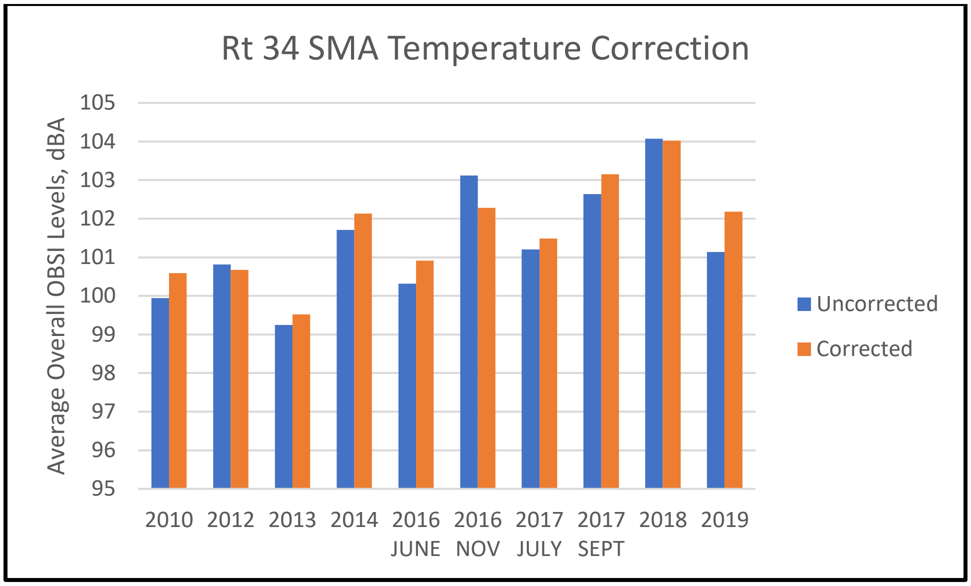

Figure 27 Rt 34 MM 9-10.5 uncorrected noise levels vs corrected noise levels

The above Figure 27 shows that an increase in the tire – pavement noise is non-linear over the years. However, there is no significant decrease or increase in the noise levels in the following years. The highest noise recorded was 104 dBA in 2018. However, the noise remains constant before and after temperature correction. For 2016, the noise levels measured in June and November show difference of more than 1 dBA. Furthermore, for the year 2017 it follows similar trend. This shows that at lower temperatures the noise increases and vice versa.

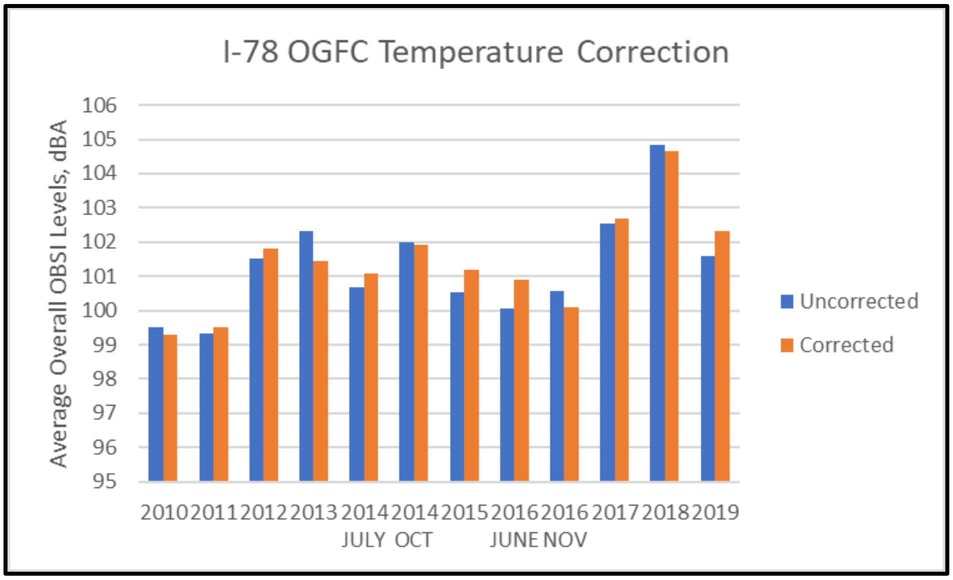

Figure 28 I-78 MM 34-43 uncorrected noise levels vs corrected noise levels

For the I-78 section, the effects of temperature follow the same trend as the other section. However, as the testing was conducted in 2016 for June and November, the noise levels recorded were 100.9 dBA and 100 dBA, respectively. With an increase in the temperature, the noise level is also increasing and vice versa.

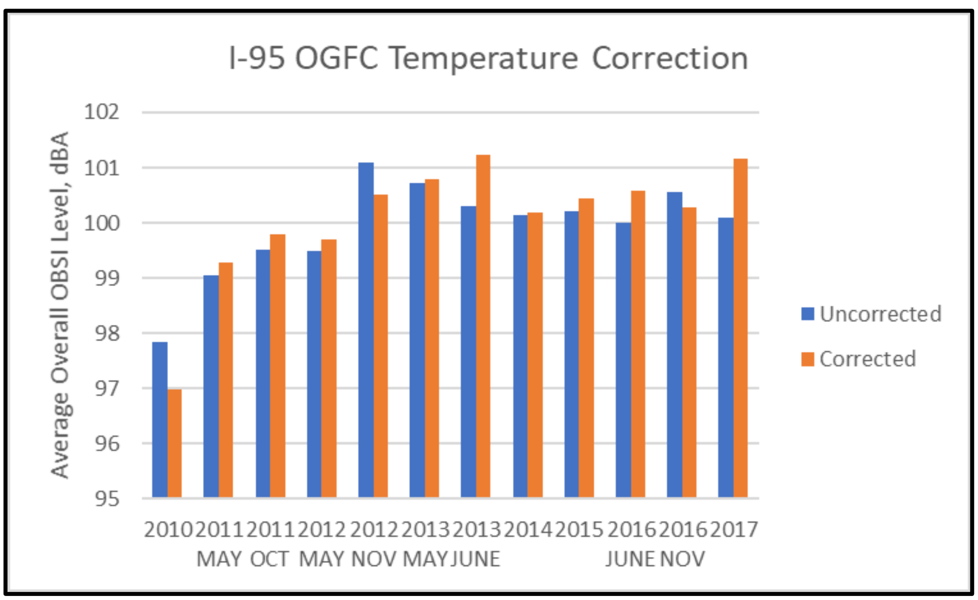

Figure 29 I-95 MM 4-8 uncorrected noise levels vs corrected noise levels

There were two tests conducted almost every year from 2010 to 2017 for the I-95 OGFC section as shown in Figure 29. The temperature effects are evident from the figure. The noise levels recorded during summer months are lower than the noise levels recorded in winter months for 2011 and 2012. In 2013, the measurements were taken within a span of one month and it showed significant increase in the noise levels from 101.7 dBA in May 2013 to 101.2 dBA in June 2013. The reason behind the increase in noise could be pavement dampness or clogging of pores.

4.2 Factors affecting tire-pavement noise

4.2.1 Temperature

The temperatures need to be normalized to reference ambient air temperature of 68°F. This will facilitate in comparison of different sections of various pavement types. According to an investigation by Ledee and Pichaud, there is 1 dBA decrease in noise levels for every 18°F increase in the temperature for dense bituminous pavements and 0.6 dBA reduction for porous pavements. The Figures 30 to 36 show significant difference in the noise levels for the same section with a change in the air temperature. The measurements plotted were recorded in same year (within a span of 4 to 6 months). For SMA, the tire-pavement noise decreased by 0.3 - 0.7 dBA with 10°F increase in temperature. For OGFC pavement, it decreased by 0.4 – 1.0 dBA with 10°F increase in the temperature.

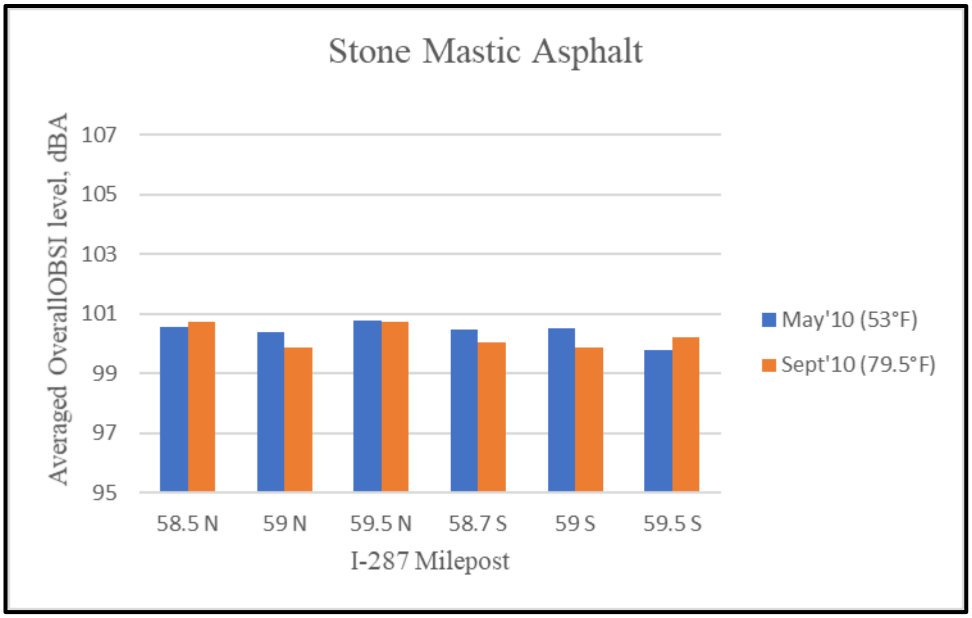

Figure 30 Temperature effect for I-287 in 2010

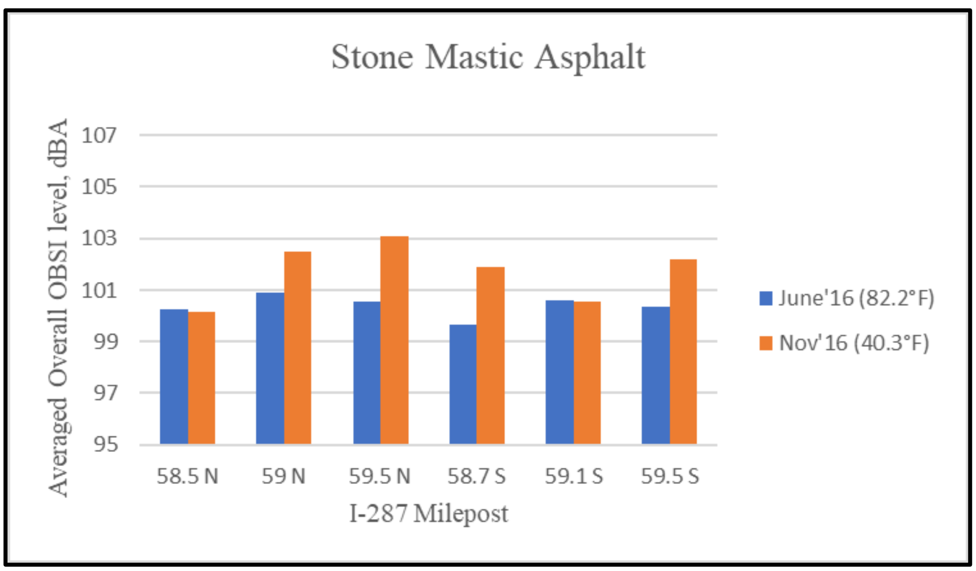

Figure 31 Temperature effect for I-287 in 2016

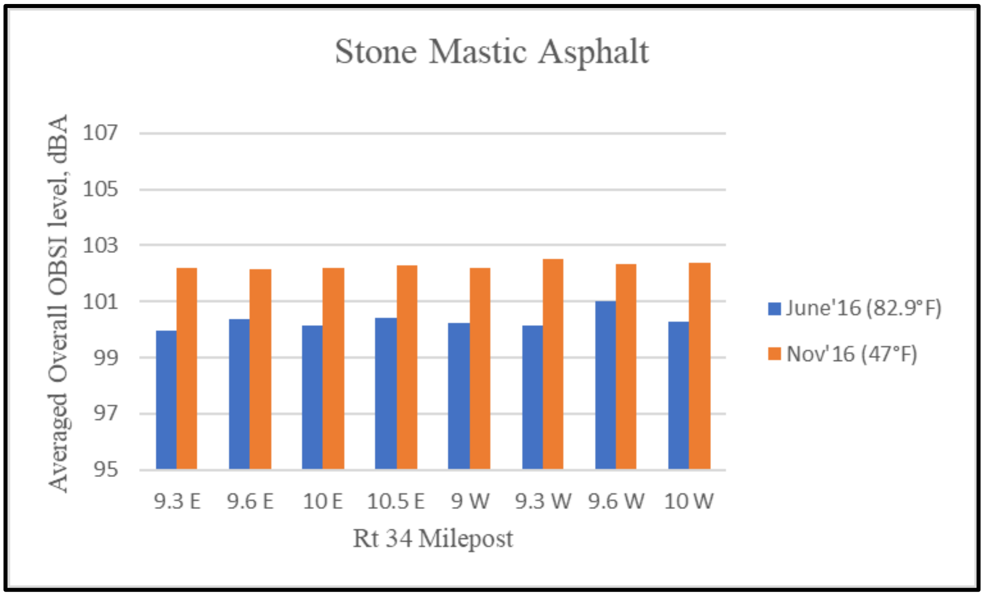

Figure 32 Temperature effect for Rt-34 in 2016

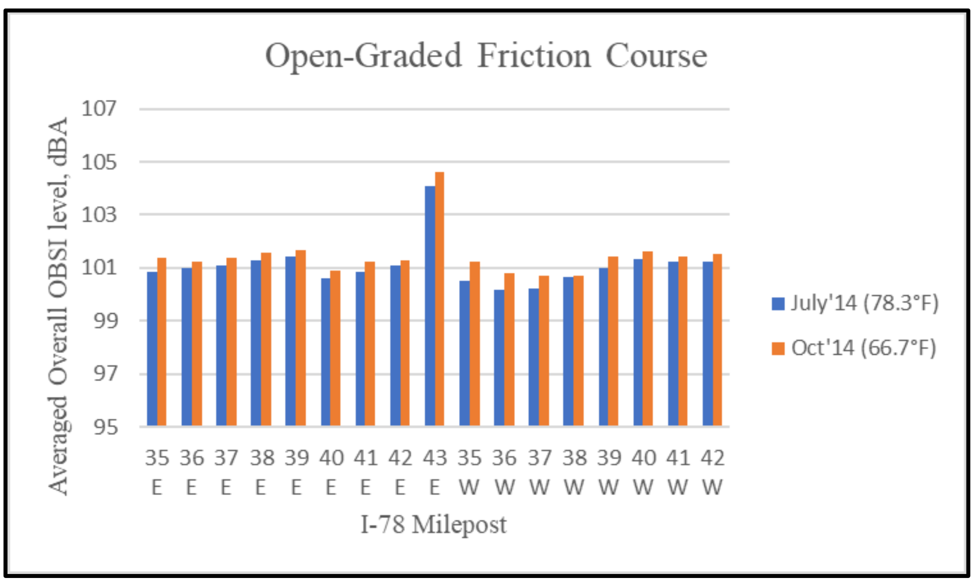

Figure 33 Temperature effect for I-78 in 2014

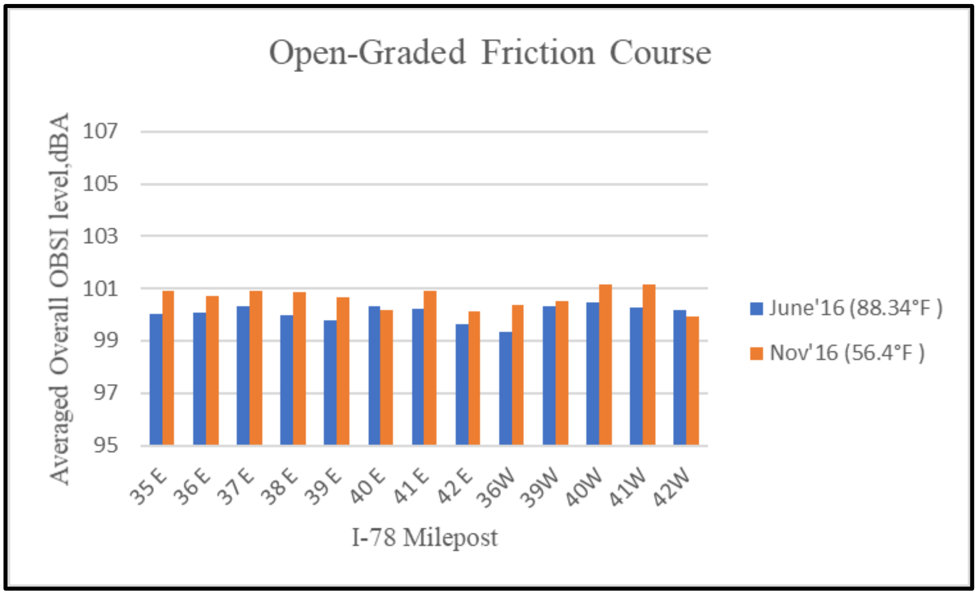

Figure 34 Temperature effect for I-78 in 2016

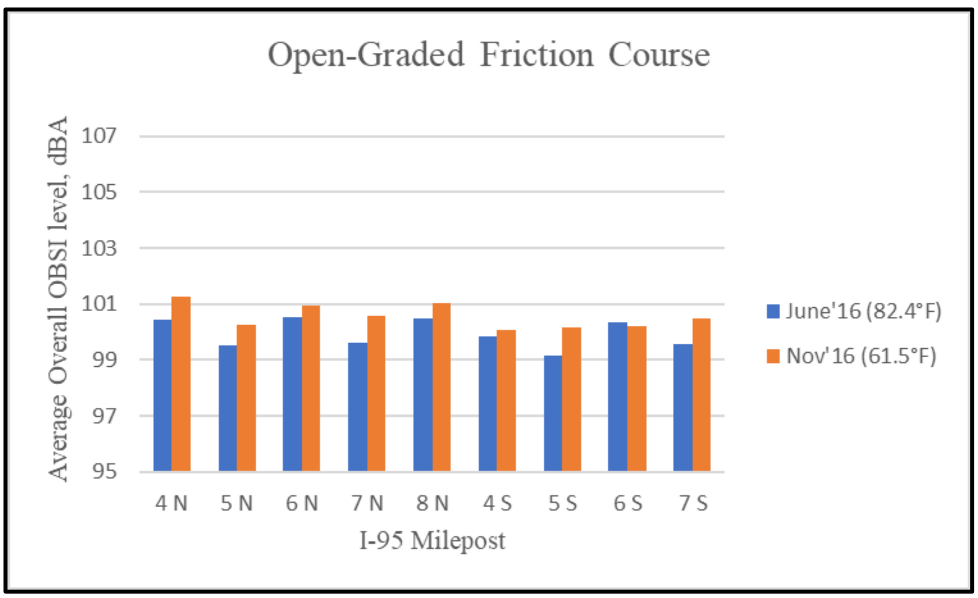

Figure 35 Temperature effect for I-95 in 2016

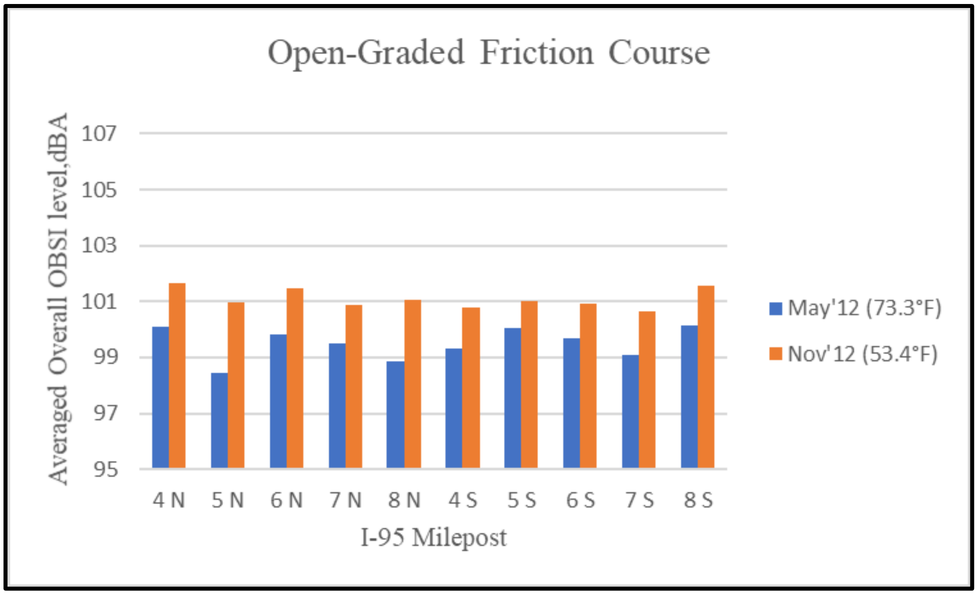

Figure 36 Temperature effect for I-95 in 2012

4.2.2 Aging of Pavement

The aging effects of pavement surface is not the same for all the pavement types. This section will show the changes in the noise level for each section over 10 years and compare the A-weighted frequencies and one-third octave bands with other pavement types for better understanding.

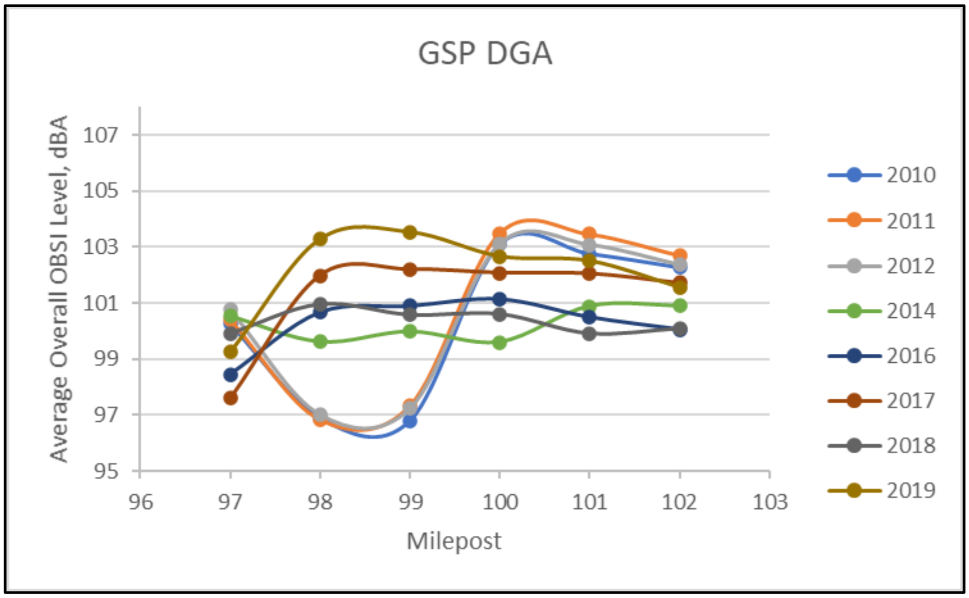

Figure 37 GSP (North) MM 97-102 noise levels from 2010-2019

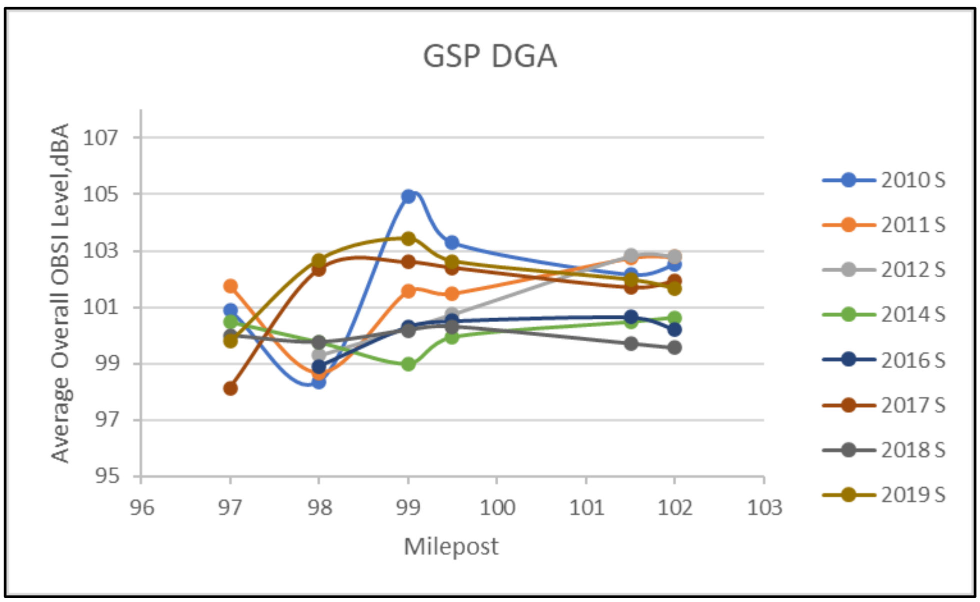

Figure 38 GSP (South) MM 97-102 noise levels from 2010-2019

The Figure 37 shows the changes in the noise level of the GSP North section of pavement type DGA for the year 2010 to 2019. The noise increased from 98 dBA in 2010 to 102 dBA in 2017. There was significant drop of noise level (approximately 2 dBA) from 2017 to 2018. This could be due to construction of new pavement surface.

This GSP south section as shown in Figure 38 does not show a similar trend like the north section. In the year 2010, the noise levels recorded were highest for some mileposts. However, there was significant drop of noise from 2017 to 2018 (of about 2 dBA) which is similar to the north section. This confirms the construction of new pavement layer between the testing period. The overall increase of noise levels was observed for both the sections of GSP DGA pavement.

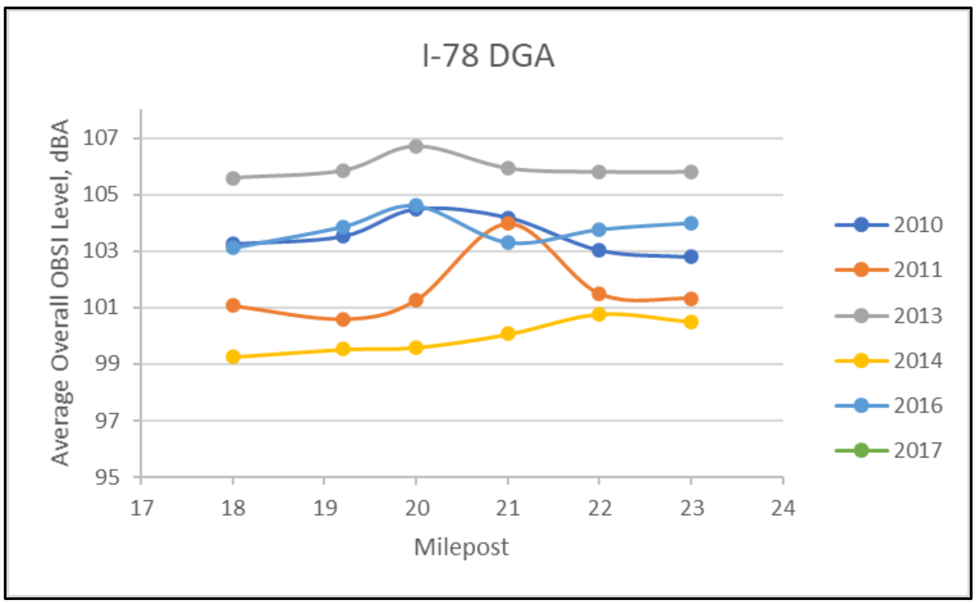

Figure 39 I-78 (East) MM 18-23 noise levels from 2010-2017

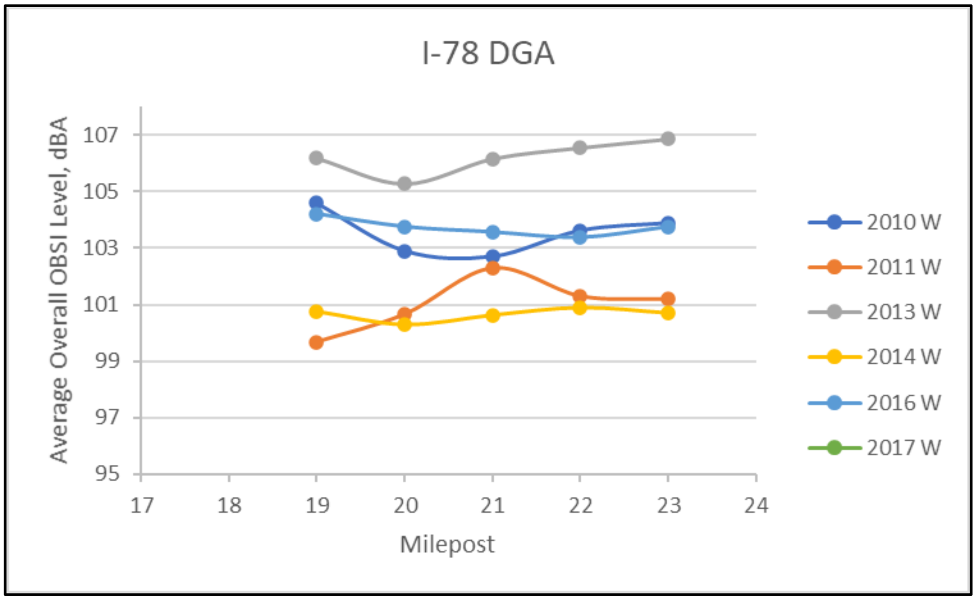

Figure 40 I-78 (West) MM 18-23 noise levels from 2010-2017

The Figure 39 shows the noise levels for I-78 East section from milepost 18 to 23. The noise levels for this DGA section is observed to decrease and increase over the years. It is similar to the GSP sections presented above. For the year 2016 and 2017, the noise levels decrease with a drop of approx. 2 dBA. The pavement could have undergone treatments for maintenance. The overall pavement noise from 2010 to 2017 decreased from an average of 104 dBA to an average of 100 dBA respectively.

The figure above of I-78 west section as shown in Figure 40 is observed to follow the same trend as the east section of the same pavement. However, the western section of the I-78 route is louder than its east section. This could be due to high AADT on the west section. The pavement was loudest at 107 dBA in 2013 and quietest below 100 dBA. Similar to the eastern section, the western side also could have undergone maintenance in 2017 as it shows the lowest levels compared to other years.

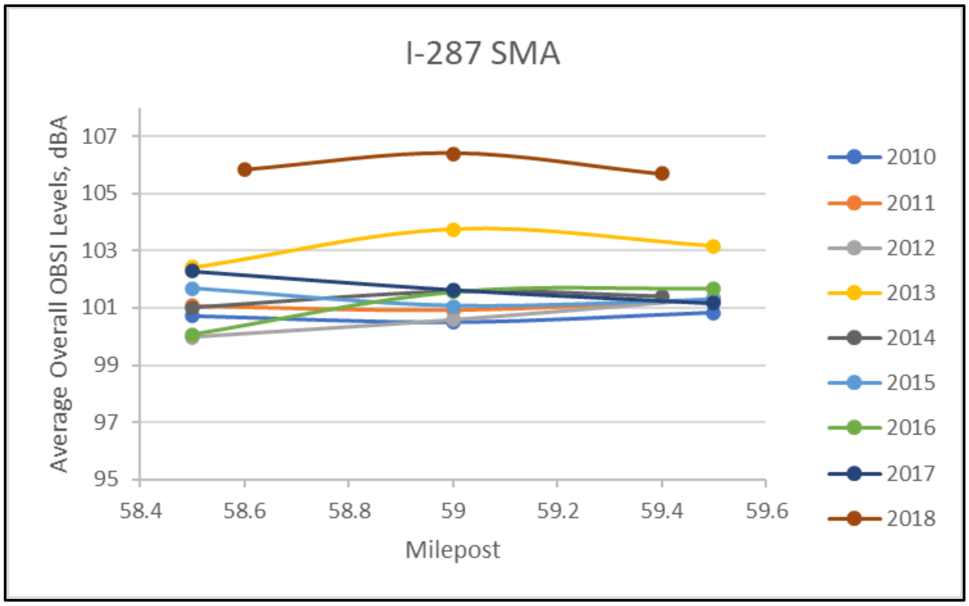

Figure 41 I-287 (North) MM 58-60 noise levels from 2010-2018

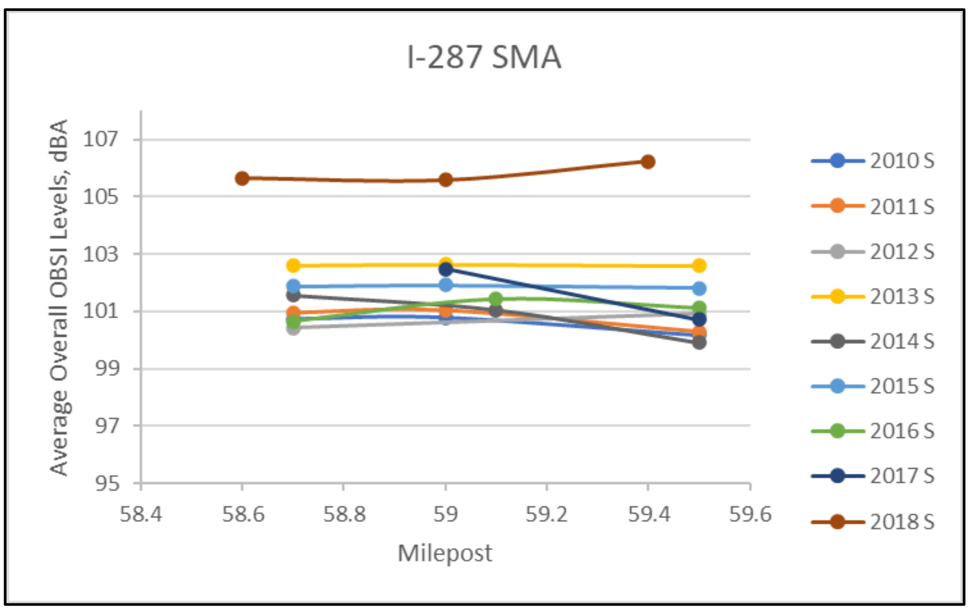

Figure 42 I-287 (South) MM 58-60 noise levels from 2010-2018

The OBSI noise levels for I-287 North section (Figure 41) was observed to be between 100 dBA to 102 dBA over the testing period (2010-2018) for almost all the years. However, the pavement was the loudest in 2018 and 2013 at approx. 106 dBA and 104 dBA respectively. This could have been the effects of surface distresses and reduction of porosity of the pavement. The overall SMA section has been consistent in the noise levels.

Route I-287 Southern section is quieter than the northern section as shown in Figure 42. The overall noise levels remain in the range 100 dBA to 102 dBA from the year 2010 -2017. The years 2013 and 2018 have recorded the highest noise at approximately 102.8 dBA and 106 dBA respectively.

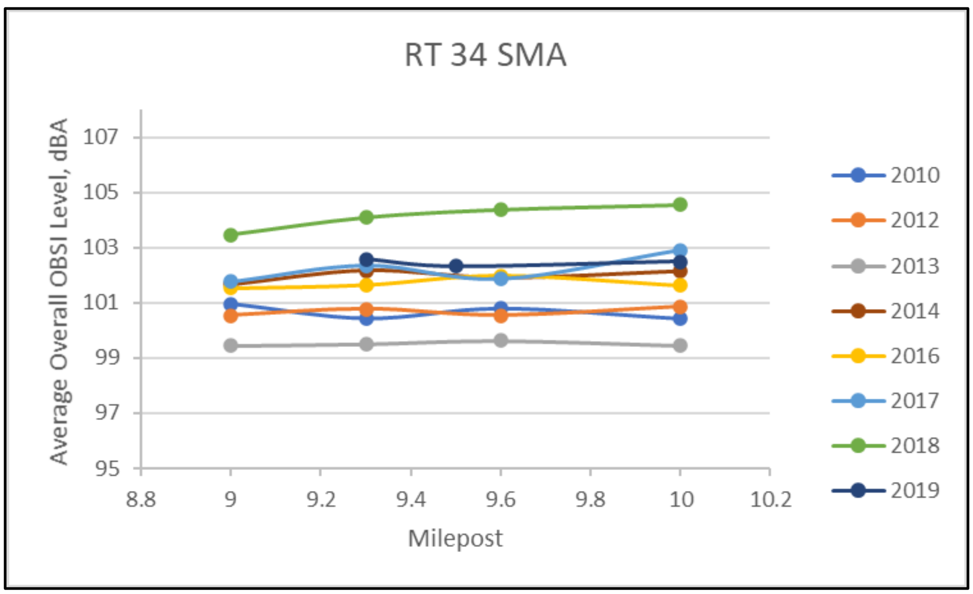

Figure 43 Rt 34 (North) MM 9-10 noise levels from 2010-2019

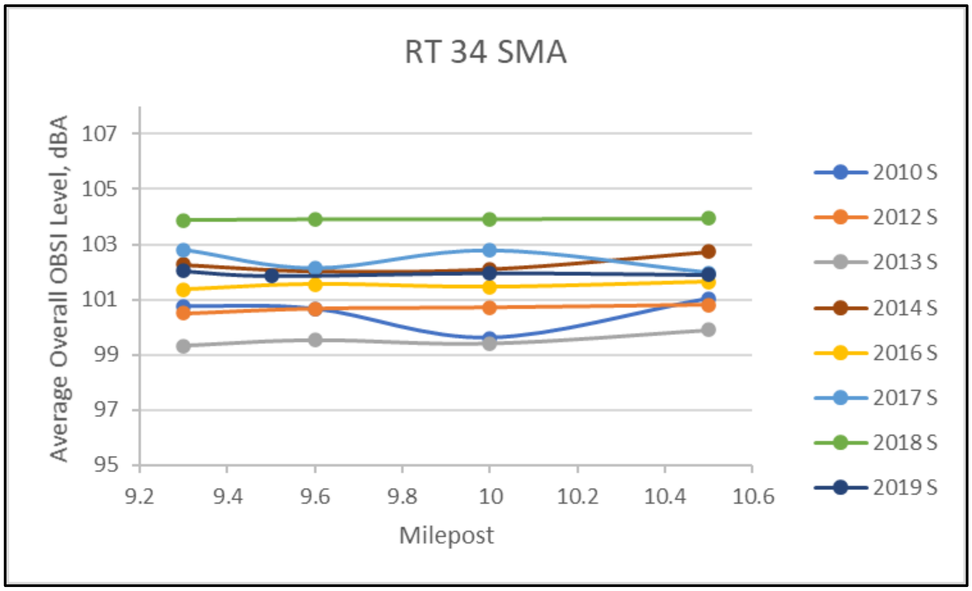

Figure 44 Rt 34 (South) MM 9-10 noise levels from 2010-2019

The Figure 43 shows Route 34 North SMA section from milepost 9 to 10. The years 2013 and 2019 recorded decrease in the measurements when compared with the previous years. The decline of 2 to 3 dBA could be due to pavement surface treatment. The overall noise levels were observed to be between 100 dBA to 103 dBA.

The results for the Southern section as shown in Figure 44 were observed to be the same as that of the Northern section. However, the Southern section was little quieter than the Northern. This could have resulted in low AADT in the southern direction.

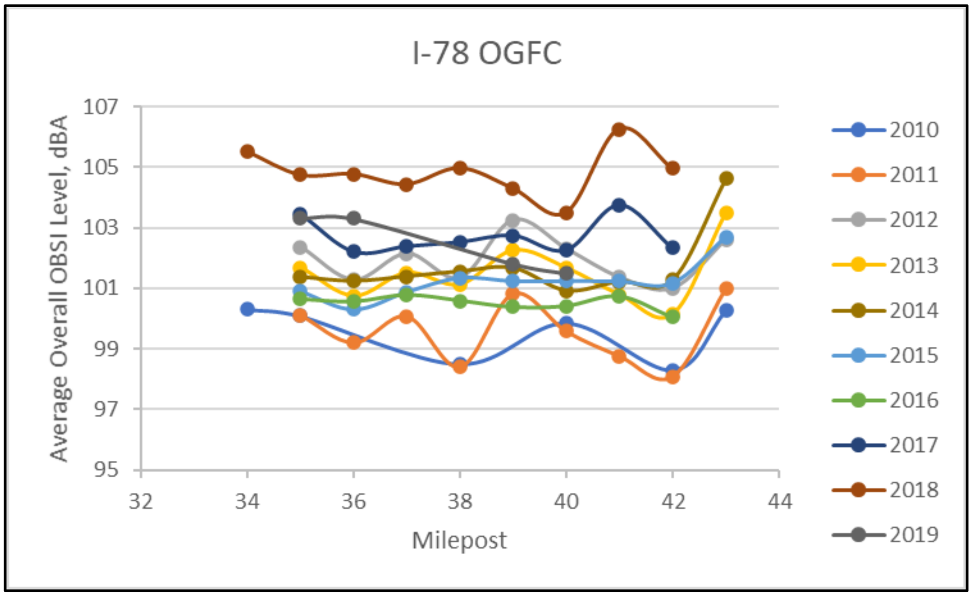

Figure 45 I-78 (East) MM 34-43 noise levels from 2010-2019

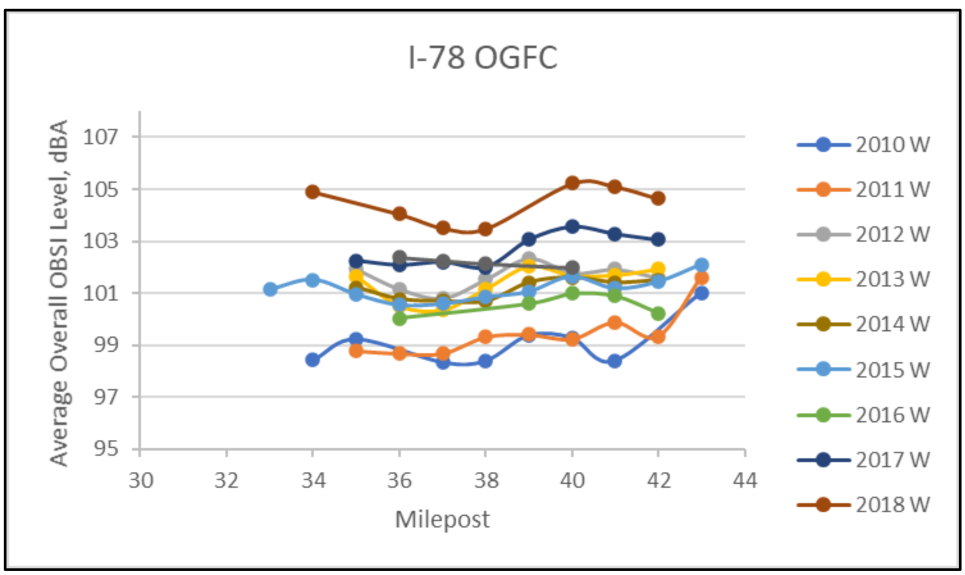

Figure 46 I-78 (West) MM 34-43 noise levels from 2010-2019

The noise levels from 2010-2019 in I-78 OGFC East section as shown in Figure 45 were observed to increase. There was significant growth from 99 dBA in 2011 to 102 dBA in 2012. In addition, the noise levels increased from 100 dBA to 105 dBA from 2016 to 2018 respectively. During these years, the pavement must have undergone severe surface distresses due to environmental conditions and heavy traffic.

The West section (see Figure 46) follows similar trend like the east section. Both the sections have undergone surface treatments between the year 2018 to 2019 as the noise level drops by approx. 2 to 3 dBA.

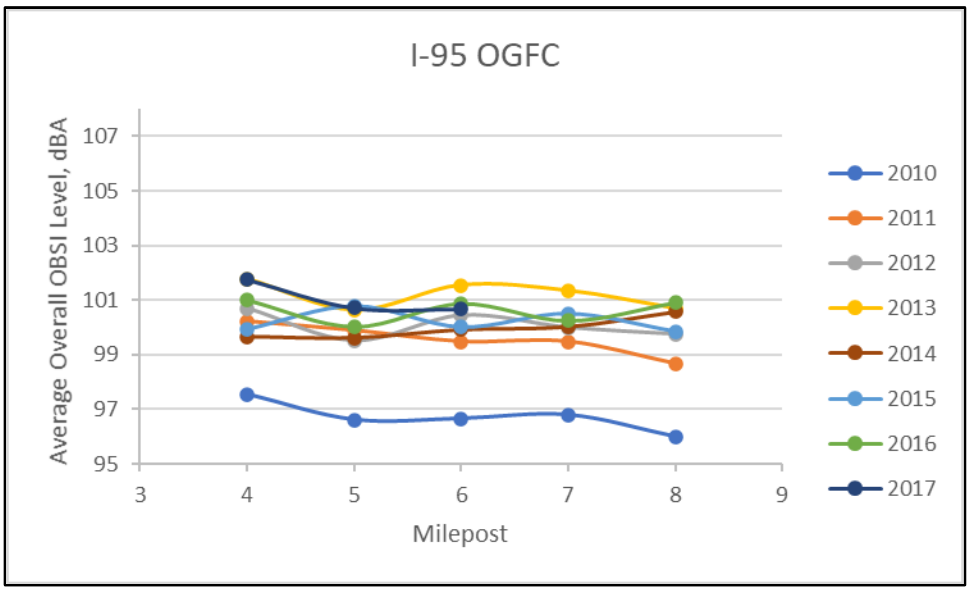

Figure 47 I-95 (North) MM 4-8 noise levels from 2010-2017

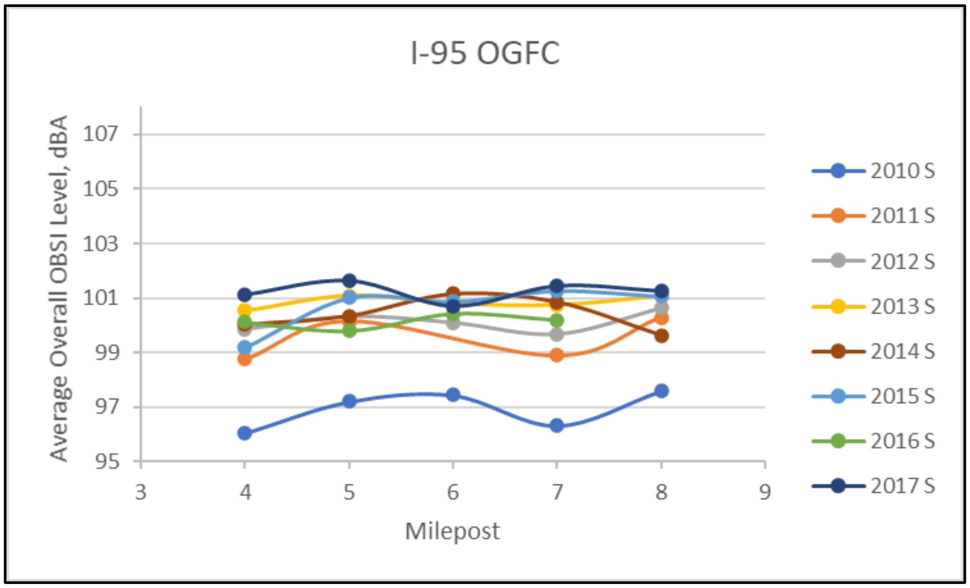

Figure 48 I-95 (South) MM 4-8 noise levels from 2010-2017

The Figures 47 and 48 represent I-95 North and South OGFC sections, respectively. From the graphs, it was observed that for both the sections the noise levels increased by 2.5 dBA from the year 2010 to 2011. This could have been due to changes in the surface texture of the pavement or effects of temperature and wind. However, the noise levels were observed to increase at slow rate from 2011 to 2017 with an overall increase of 2 dBA.

4.2.3 Preservation Treatments

Preservation treatments improve the serviceability of pavement by reducing the rate of deterioration. It is used before the pavement undergoes any significant damage. These treatments are cost-effective and make the pavement structurally sound. Since several preservation treatments are an integral part of pavement surface, it is essential to consider it as one of the factors that affects the tire-pavement noise. The data used in the analysis of effects of preservation treatments on tire-pavement noise was collected in 2018 using OBSI method. The preservation treatments selected for the analysis were Micro-surfacing (2 sections), HFST (2 sections), Slurry Seal (2sections), HPTO (3 sections) and Chip Seal (4 sections) are shown in Figure 49

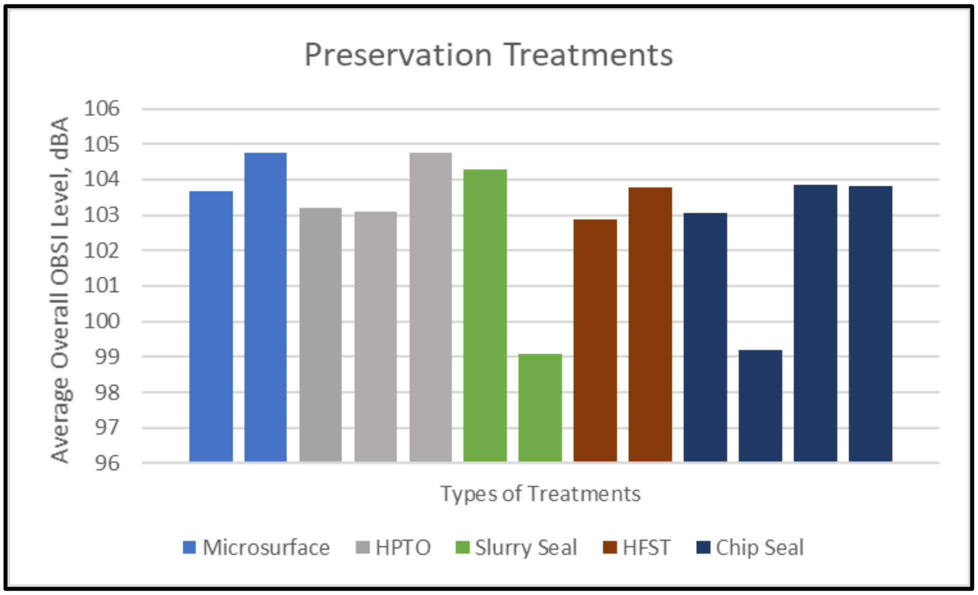

Figure 49 Preservation treatment- Noise Levels 2018

4.2.4 Surface Distress

Multiple studies have proven that surface distresses have an impact on the tire-pavement noise. Transverse cracking and rutting were considered to obtain correlation between distress and tire/pavement noise. The change in the tire – pavement noise over 1 year was correlated with the change in the distress condition for the years 2016 -17, 2017-18, and 2018-19. Table 13 shows the results obtained from the analysis. Rutting shows moderate to weak correlation with noise. The better correlation for rutting was observed for OGFC pavement followed by SMA. Since the DGA section does not have enough data available, the results cannot be concluded. The correlation between noise and transverse cracking was even weaker than rutting. Overall correlation for both the distresses with Tire-pavement noise was found to be better for OGFC.

Table 13 Correlation between change in the tire-pavement noise and change in Surface Distress

Route	Pavement Type	Correlation Coefficient					
		Change from 2016 - 2017		Change from 2017 - 2018		Change from 2018 - 2019	
		Noise and Rutting	Noise and Transverse cracking	Noise and Rutting	Noise and Transverse cracking	Noise and Rutting	Noise and Transverse cracking
I-78 E	DGA	-0.11	-0.06	-	-	-	-
Rt 34 N	SMA	0.255	0.34	0.4	-0.9	-0.49	0.98
Rt 34 S	SMA	0.46	0.99	-0.67	-0.93	-0.95	-0.97
I-287 N	SMA	0.58	-0.765	-0.93	-0.49	-	-
I-78 E	OGFC	0.2	0.6	0.66	0.23	0.87	0.71
I-95 N	OGFC	-0.98	0	-	-	-	-

4.3 Cost Analysis OGFC and Sound Barrier Wall

OGFC is recorded to be the quietest pavement (Brown, 2006). However, it costs 42% ($/m^3) more than the traditional dense mix overlays (Chen et. al, 2016). In order to determine cost effectiveness of the noise mitigation techniques, it is essential to compare the cost of OGFC pavement with sound barrier walls.

The cost of building and maintaining noise walls is anywhere between $1 to $2 million per mile. (Brown, 2008). These walls are built up to 25 feet (8 meters) in height. Dense materials (at least 20 kg/sq. m, or 36.9 lbs/sq. ft) are selected to effectively reduce the sound transmission. Based on State DOT Noise Personnel Survey, the estimated average service life of barriers was between 25 years to 50 years depending on the materials (Morgan, 2001). The Initial Construction Cost (ICC), discounted future cost and Life Cycle Cost

(LCC) for different Barrier materials ($/m^2) are given in Table 14 (Morgan, 2001) . Table 15 shows the cost required to construct and maintain the noise barrier walls for the year 2004 in the United States. One of the studies showed that a 2m wall reduced the noise by 4 dBA when another barrier is present on the opposite side of the road. The noise reduces and is observed to be in the range of 1 to 5 dBA when absorptive materials are applied to the barrier walls.

Another study analyzed the cost estimates for OGFC and DGHMA (Dense Graded Hot Mix Asphalt) (Watson et al., 2018). The 2 lane sections were a mile long, 24 ft wide and 0.75 inch thick. The service life of OGFC in Nevada is usually 7 years and that of DGHMA is 10 years. The Table 16 shows the pavement cost analysis for 4 sections. The Elko OGFC section (urban highway) shows higher Net Present Value (NPV) than the Las Vegas OGFC (rural highway). The NPV of cost per lane mile for Elko OGFC section was $30466. From this, it can be interpretated that the OGFC pavement sections are more cost-effective than sound barrier walls.

Table 14 Illinois Noise Barriers Sorted by Estimated LCC (Morgan, 2001)

Barrier	Estimated ICC [dollars/m^2 (dollars/ft^2)]	Discounted future costs [dollars/m^2 (dollars/ft^2)]	Estimated LCC [dollars/m^2 (dollars/ft^2)]
Earth berm	111 (10.33)	39 (3.60)	150 (13.93)
Precast/prestressed concrete stacked panels, steel posts	212 (19.67)	43 (4.03)	255 (23.70)
Precast/prestressed concrete stacked panels, concrete posts	262 (24.33)	28 (2.62)	290 (26.95)
Timber post-and-panel (hardwood or softwood)	180 (16.70)	122 (11.35)	302 (28.05)
Precast/restressed cantile-ver	291 (27.00)	30 (2.80)	321 (29.80)
Carsonite	273 (25.33)	50 (4.65)	323 (29.98)
Precast concrete, full-height panels, monolithic posts	305 (28.33)	28 (2.62)	333 (30.95)
Glue-laminated wood	197 (18.33)	145 (13.48)	342 (31.81)
Durisol	212 (19.67)	152 (14.14)	364 (33.81)
Noishield steel	298 (27.67)	131 (12.19)	429 (39.86)
Noishield aluminum	377 (35.00)	163 (15.15)	540 (50.15)

Table 15 Noise Barrier Data for United States (Brown, 2008)

State	Square Feet (Thousands)	State	Linear Miles
California	30,644	California	482.8
Virginia	11,227	Arizona	155.1
Arizona	11,226	Virginia	127.5
New Jersey	9,440	Ohio	112.4
Ohio	8,675	New Jersey	96.9
Maryland	8,422	Colorado	92.5
Minnesota	7,187	New York	90.7
New York	7,011	Pennsylvania	87.0
Florida	6,700	Minnesota	83.7
Pennsylvania	6,415	Maryland	81.8
10 State Total	**106,946**		**1,410.4**
	Actual Cost (Millions)		2004 Dollars Millions
California	$399.6	California	$592.8
Arizona	258.7	Arizona	284.6
New Jersey	202.4	New Jersey	277.5
Maryland	200.9	Maryland	253.6
Virginia	169.6	Virginia	225.3
New York	165.9	New York	207.3
Pennsylvania	159.6	Pennsylvania	197.8
Florida	150.7	Florida	175.9
Ohio	117.2	Ohio	139.0
Colorado	80.0	Minnesota	107.7
10 State Total	**$1,904.5**		**$2,461.4**

Table 16 Life cycle cost of OGFC and DGHMA sections (Watson et al., 2018)

Monetary Item	Elko Sections		Las Vegas Sections	
	OGFC	DGHMA	OGFC	DGHMA
Initial construction cost ($)	66,906	39,553	43,471	38,518
Maintenance cost ($/year)	469	375	0	0
Salvage value ($)	0	11,866	0	11,555
Safety benefits ($)	-1,886	0	2,084	0
Noise benefits ($)	20,110	0	12,057	0
NPV of life cycle costs ($)	60,933	32,790	18,905	29,737
NPV of costs per lane mile ($/mile)	30,466	16,395	9,453	14,868

A comparison was made between Life Cycle Cost (LCC) of OGFC and Sound Barrier Wall to determine which of them is a cost-effective sound mitigation technique. The LCC of OGFC increases with increase in the number of lanes. However, the cost for barrier wall remains the same.

Table 17 Life cycle cost of OGFC, DGHMA and Sound Barrier Wall

Monetary Item	OGFC	DGHMA	Increased cost by OGFC	Sound Barrier Wall	Sound Barrier Wall
Life Cycle Cost per lane ($/mile)	30466	16395	14071	1 million	2 million
Service life (years)	7	7	7	25-50	25-50
Cost per year per lane ($/mile)	4353	2342	2011	20000 to 40000	40000 to 80000
Cost per year for 4 lane roadway ($/mile)	17412	9368	8044	20000 to 40000	40000 to 80000

4.4 Summary

Some of the factors that affect pavement noise are temperature, aging of the pavement, mixture type etc. Pavement testing is conducted to reduce noise generation of existing pavement and to counter the resulting adverse effects on human health. There are several testing methods used to collect noise data which are broadly classified into Field and Laboratory Measurements. Field measurements include Close Proximity Method (CPX), Statistical Passby (SPB), On-Board Sound Intensity (OBSI) etc. On the other hand, Laboratory measurements include Impedance Tube Absorption Testing and Tire - Pavement Test Apparatus. In this study, the OBSI test was conducted since it is convenient to use and requires less time to collect considerable amount of data. Firstly, 3 flexible pavement types were selected which were Open Graded Friction Course (OGFC), Stone Mastic Asphalt (SMA) and Dense Graded Hot Mix Asphalt (DGA). The tire pavement noise data was temperature corrected at 68°F. This data was further analyzed with factors affecting tire pavement noise. OGFC was determined to be the quietest pavement amongst the three mentioned types. Lastly, a comparative cost analysis was conducted between OGFC and the sound barrier wall.

Chapter 5 Conclusion and Recommendations

5.1 Findings and Conclusions

5.1.1 Comparison Between TSD and FWD Deflections

After conducting multiple analyses to compare TSD and FWD data, the results can be interpreted as follows:

- The multiple regression model was able to predict the FWD from TSD and other parameters with R square ranging between 0.9 to 0.96 for all the offsets. However, the R square value decreases between the range 0.6 to 0.05 if only TSD deflection and layer thickness are considered for the analyses. Therefore, all the given parameters are required to predict better FWD data.
- In the Limit of Agreement (LOA) method, the data showed positive results as most of the data points remained in the 95% LOA. This means that the difference in the data is due to the measurement error and there is no significant reason for the change in the data.
- In the backcalculation analysis, the data did not show good correlation as measured FWD and predicted FWD were considered. The highest correlation of 0.67 was observed for the first and second layer. Since there is difference in the performance of tests between the two devices, it affects the applied load in some ways. Hence, the correlation will always be moderate.
- While analyzing the pavement deflections with surface conditions, it was observed that the deflection had moderate linear relation with pattern cracking with highest R value 0.55 (FWD) and 0.6 (TSD) for US 9 NB. Rutting, transverse and longitudinal cracking showed very weak relation with the deflection data.

5.1.2 Tire-pavement noise

The above analysis was conducted for six pavement sections. Two sections of the same pavement type (DGA, SMA and OGFC) were selected for better comparison. From the results, it can be interpreted that the OFGC sections produce the lowest noise (approx. 96 dBA), followed by DGA and SMA. However, the noise levels for DGA sections increases with an average of 1 dBA each year. The noise levels for OGFC and SMA pavement types do not show significant increase under normal conditions. Furthermore, when five preservation treatment sections were analyzed, Slurry seal was the quietest with the lowest noise produced is 99.19 dBA and Micro-surfacing was the loudest with noise level at 104.7 dBA (see Table 12). However, when the average of the data for different sections of same treatment is considered, the preservation treatments do not show any significant difference in the noise levels. When surface distress were correlated with the noise levels, I-78 E (OGFC) noise levels showed moderate correlation with rutting and transverse cracking. The Life Cycle Cost of OGFC pavement was estimated to be $30466 per lane mile and the cost of sound barrier walls was estimated to be between $1 to $2 million per mile. After comparing the cost per year per mile, it was concluded that the LCC of OGFC increased per lane and the LCC of sound barrier wall did not change. Therefore, factors like service life and number of lanes should be taken into consideration while determining the noise mitigation techniques to be used.

5.2 Recommendations for Future Research

To achieve better comparison, the measurements from both the devices (TSD and FWD) should be recorded at the same time and under similar weather conditions. The cause of bias between the two devices should be addressed by evaluating the effects of different type of loading and effect of speed on TSD measurements. The backcalculation analysis software should be improved to incorporate TSD deflection without the need for conversion. Deflection Slope Index (DSI) should be considered as a parameter to correlate with surface distress. The monitoring of the TSD deflections over time with the increase in distress would prove to effective in future research.

The tire-pavement noise should be included as one of the impact categories in Life Cycle Analysis (LCA) as pavement noise is considered as major health risk to human (Ongel 2016). Furthermore, an in-depth research is needed to understand the behavior of materials. A systematic research program is required to develop new preservation techniques that will maintain noise benefits over time.

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Appendix A:

FWD And TSD Deflections at D0

FWD and TSD Deflections at 0 mm (D0) for Route 9 (NB)

Routes	Milepost (miles)	FWD D0(mm)	TSD D0(mm)
9 NB	32.47	0.363878	0.41794345
9 NB	32.55	0.416417	0.7473177
9 NB	32.62	0.475766	0.58815674
9 NB	32.67	0.526359	0.39868508
9 NB	32.71	0.486468	0.32990714
9 NB	32.76	0.34442	0.2769009
9 NB	32.81	0.339555	0.28387656
9 NB	32.86	0.260844	0.32065617
9 NB	32.9	0.272325	0.34066283
9 NB	32.95	0.198966	0.33015488
9 NB	33	0.220565	0.34227079
9 NB	33.05	0.248099	0.36465796
9 NB	33.1	0.29013	0.28303368
9 NB	33.14	0.225819	0.11301769
9 NB	33.19	0.150903	0.03914975
9 NB	33.25	0.152751	0.20405014
9 NB	33.29	0.086008	0.39018892
9 NB	33.33	0.098364	0.46873225
9 NB	33.38	0.48355	0.47811303
9 NB	33.43	0.401823	0.48598905
9 NB	33.48	0.511765	0.46176093
9 NB	33.51	0.439768	0.47888479
9 NB	33.57	0.476739	0.48170134
9 NB	33.62	0.45728	0.47379352
9 NB	33.67	0.484523	0.49569071
9 NB	33.72	0.570141	0.49658106
9 NB	33.76	0.47382	0.46056411
9 NB	33.81	0.529278	0.4804016
9 NB	33.86	0.411552	0.43561226
9 NB	33.9	0.580843	0.36175657
9 NB	33.97	0.36096	0.41692361
9 NB	34	0.363878	0.43966089
9 NB	34.05	0.485496	0.47746223
9 NB	34.09	0.416417	0.40226524
9 NB	34.15	0.355122	0.28856972
9 NB	34.19	0.281276	0.27635966
9 NB	34.23	0.232824	0.26337295
9 NB	42.82	0.082019	0.17276867

9 NB	42.91	0.124633	0.29240138
9 NB	42.96	0.195658	0.32326913
9 NB	43	0.262888	0.316765
9 NB	43.06	0.263179	0.23250597
9 NB	43.1	0.261136	0.15414573
9 NB	43.15	0.353176	0.11232137
9 NB	43.2	0.142924	0.20137579
9 NB	43.24	0.121812	0.29880456
9 NB	43.29	0.21716	0.33418108
9 NB	43.34	0.251699	0.31516272
9 NB	43.39	0.185442	0.3058026
9 NB	43.43	0.237299	0.29617361
9 NB	43.48	0.209571	0.2890706
9 NB	43.52	0.207917	0.27589179
9 NB	43.57	0.252769	0.2437277
9 NB	43.62	0.198479	0.2480863
9 NB	43.71	0.198771	0.22443955
9 NB	43.76	0.190793	0.29479904
9 NB	43.81	0.206652	0.29705933

FWD and TSD Deflections at 0 mm (D0) for Route 40 (EB)

Routes	**Milepost (miles)**	**FWD D0(mm)**	**TSD D0(mm)**
40 EB	50.44	0.281081	0.16887256
40 EB	50.47	0.143605	0.2425802
40 EB	50.51	0.328853	0.32564429
40 EB	50.54	0.36096	0.3841242
40 EB	50.58	0.370689	0.37770649
40 EB	51.04	0.254909	0.20517562
40 EB	51.09	0.149735	0.18172288
40 EB	51.12	0.080462	0.13003232
40 EB	51.53	0.236716	0.28764405
40 EB	51.58	0.415444	0.36151648
40 EB	51.62	0.317177	0.41035127

FWD and TSD Deflections at 0 mm (D0) for Route 17 (NB)

Routes	Milepost (miles)	FWD D0(mm)	TSD D0(mm)
17 NB	4.56	0.171619	0.1860184
17 NB	4.7	0.128475	0.1524838
17 NB	4.77	0.160828	0.21966597
17 NB	4.84	0.179198	0.28536028
17 NB	4.91	0.158483	0.20996333
17 NB	4.96	0.097567	0.14865372
17 NB	5.02	0.143508	0.1796008
17 NB	5.09	0.14617	0.15673803
17 NB	5.13	0.138941	0.21100812
17 NB	5.22	0.134634	0.22518705
17 NB	5.27	0.127474	0.18767755
17 NB	5.35	0.144887	0.3102572
17 NB	5.41	0.325472	0.39472732
17 NB	5.48	0.201214	0.31510347
17 NB	5.55	0.335351	0.31556182
17 NB	5.61	0.148389	0.25080425
17 NB	5.67	0.203806	0.23764699
17 NB	5.81	0.14614	0.19149061
17 NB	7.5	0.080725	0.08529142
17 NB	7.54	0.070679	0.07354859
17 NB	7.65	0.134235	0.10197686
17 NB	7.68	0.119582	0.12053861
17 NB	7.73	0.154441	0.12268577
17 NB	7.77	0.119872	0.10929432
17 NB	7.9	0.126299	0.14291819
17 NB	7.95	0.138692	0.13402723
17 NB	7.99	0.143899	0.13371577
17 NB	8.02	0.209175	0.13775005
17 NB	8.07	0.175189	0.15404009
17 NB	8.12	0.153111	0.22368241
17 NB	8.17	0.116304	0.24979641
17 NB	8.32	0.19315	0.1843744

FWD and TSD Deflections at 0 mm (D0) for Route I-80 (EB)

Routes	Milepost (miles)	FWD D0(mm)	TSD D0(mm)
I80 EB	67.14	0.054811	0.07843846
I80 EB	67.21	0.056657	0.06061093
I80 EB	67.25	0.078691	0.06592579
I80 EB	67.30	0.076042	0.06120672
I80 EB	67.35	0.07211	0.07441887
I80 EB	67.40	0.05917	0.05776705
I80 EB	67.45	0.062376	0.08990685
I80 EB	67.50	0.066152	0.07660274
I80 EB	67.55	0.053594	0.04533685
I80 EB	67.59	0.03181	0.03745439
I80 EB	67.65	0.056155	0.041534
I80 EB	67.70	0.066723	0.06058449
I80 EB	67.75	0.073101	0.05319689
I80 EB	67.81	0.14665	0.07657755
I80 EB	67.85	0.165008	0.04161516
I80 EB	67.91	0.158558	0.08070848
I80 EB	67.96	0.145389	0.0697524
I80 EB	68.00	0.288402	0.21206017
I80 EB	68.05	0.424764	0.1938468
I80 EB	68.10	0.384886	0.16568479
I80 EB	68.15	0.198627	0.17061568
I80 EB	68.21	0.136119	0.12803255
I80 EB	68.26	0.054016	0.13672022
I80 EB	68.31	0.078593	0.15531096
I80 EB	68.36	0.093919	0.15602231
I80 EB	68.41	0.071184	0.16275493
I80 EB	68.46	0.059168	0.16367701
I80 EB	68.50	0.065676	0.1412467

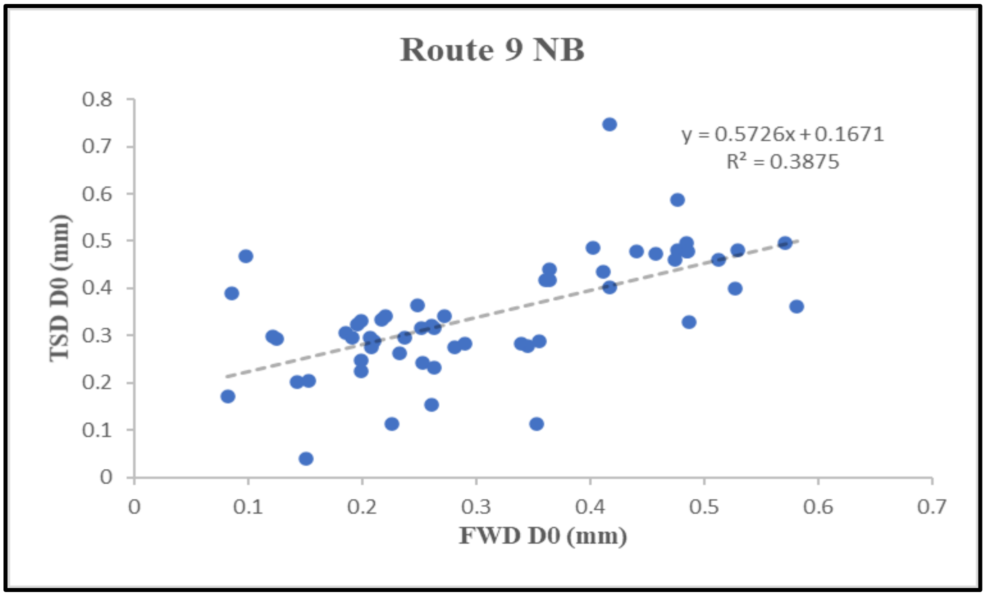
FWD and TSD Deflections at 0 mm (D0) for Route 35 (SB)

Routes	Milepost (miles)	FWD D0(mm)	TSD D0(mm)
35 SB	50.682	0.055457	0.18704707
35 SB	50.71	0.102158	0.15940059
35 SB	50.732	0.151778	0.19179848
35 SB	50.759	0.131346	0.23491272
35 SB	50.845	0.081727	0.26404083
35 SB	50.9	0.087564	0.21143001
35 SB	*52.37*	0.283125	0.43544883
35 SB	52.39	0.084646	0.40063183
35 SB	52.436	0.169291	0.32136749
35 SB	52.477	0.22183	0.31991181
35 SB	52.567	0.215992	0.32217639
35 SB	52.639	0.192642	0.33193401
35 SB	52.731	0.143022	0.38886443
35 SB	52.825	0.075889	0.18245383
35 SB	*52.891*	0.070051	0.12154078
35 SB	52.955	0.07297	0.16153281
35 SB	53.008	0.102158	0.15272475
35 SB	53.048	0.055457	0.12396914
35 SB	53.103	0.055457	0.10932579
35 SB	*53.143*	0.067133	0.13164341
35 SB	53.187	0.078808	0.12611381
35 SB	53.234	0.075889	0.13055049
35 SB	53.296	0.084646	0.08297746
35 SB	53.326	0.078808	0.0812711
35 SB	53.401	0.078808	0.081084
35 SB	53.508	0.052539	0.11406804
35 SB	53.573	0.075889	0.11389592
35 SB	53.63	0.058376	0.12609271
35 SB	53.702	0.070051	0.10661339
35 SB	53.767	0.07297	0.08423706
35 SB	53.853	0.061295	0.11669519
35 SB	*53.93*	0.067133	0.15377717
35 SB	54	0.067133	0.12503956
35 SB	54.081	0.078808	0.15268467
35 SB	54.155	0.078808	0.09611839
35 SB	54.229	0.052539	0.16225608
35 SB	54.453	0.070051	0.25575746
35 SB	54.49	0.067133	0.14326138
35 SB	54.533	0.061295	0.15324369

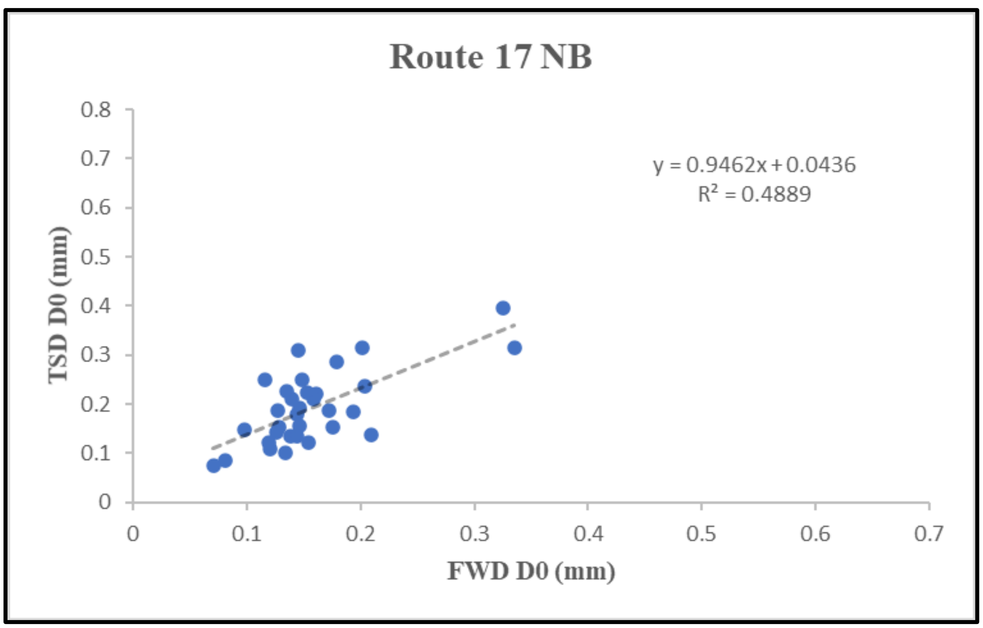
35 SB	54.611	0.070051	0.15205232
35 SB	54.662	0.07297	0.11718587
35 SB	54.69	0.046701	0.0704746
35 SB	54.77	0.040863	0.15456432
35 SB	54.784	0.102158	0.15903945
35 SB	54.848	0.055457	0.15832709
35 SB	54.911	0.084646	0.13428598
35 SB	54.934	0.093402	0.12490767
35 SB	54.944	0.064214	0.11814179
35 SB	54.962	0.064214	0.12102269
35 SB	54.995	0.078808	0.1232126
35 SB	55.049	0.064214	0.12806197
35 SB	55.065	0.055457	0.15022978
35 SB	55.1	0.046701	0.17235304
35 SB	55.155	0.131346	0.19561693
35 SB	55.197	0.113834	0.16783672
35 SB	55.301	0.075889	0.18610201
35 SB	55.374	0.078808	0.15760063
35 SB	55.397	0.087564	0.13902861
35 SB	55.448	0.145941	0.18869772
35 SB	55.501	0.140103	0.18000585
35 SB	55.58	0.093402	0.14801938
35 SB	55.655	0.078808	0.1438393
35 SB	55.691	0.07297	0.19183265
35 SB	55.73	0.087564	0.25255019
35 SB	55.747	0.09924	0.29053619
35 SB	56.33	0.058376	0.18947918
35 SB	56.363	0.061295	0.13184493
35 SB	56.405	0.067133	0.11413291
35 SB	56.431	0.064214	0.1123517
35 SB	56.481	0.046701	0.12374686
35 SB	56.59	0.070051	0.11927489
35 SB	56.635	0.061295	0.12007981
35 SB	56.659	0.067133	0.14952301
35 SB	56.692	0.148859	0.22268503
35 SB	56.995	0.040863	0.3032363
35 SB	57.077	0.046701	0.31832371
35 SB	57.165	0.107996	0.3591718
35 SB	57.755	0.040863	0.17129804
35 SB	57.767	0.058376	0.15445257
35 SB	57.833	0.04962	0.13489721
35 SB	57.92	0.110915	0.19269964
35 SB	57.989	0.052539	0.12465285

Appendix B:

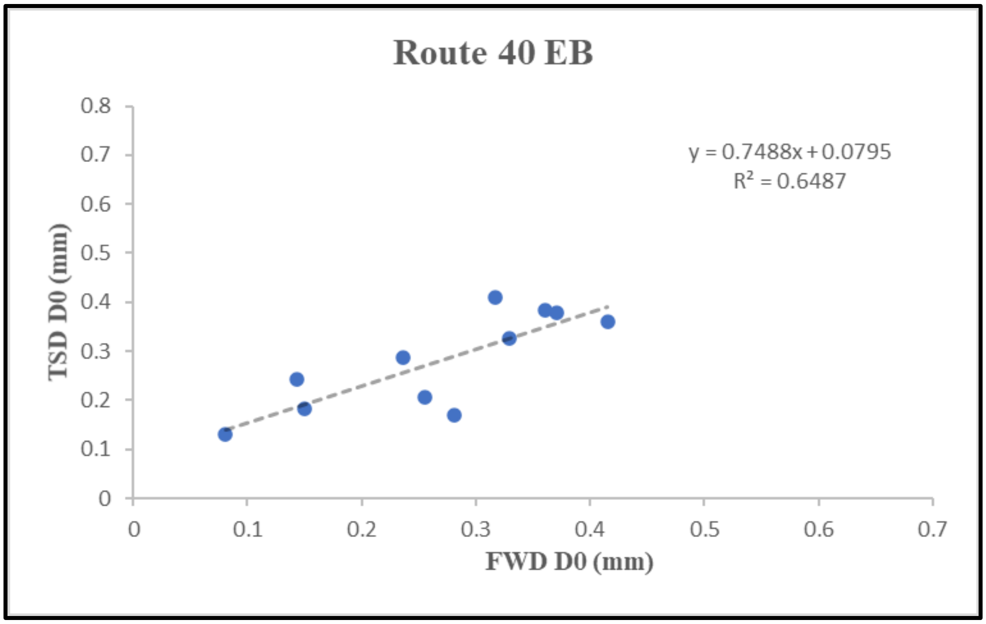
Scatter Plots of FWD D0 Versus TSD D0



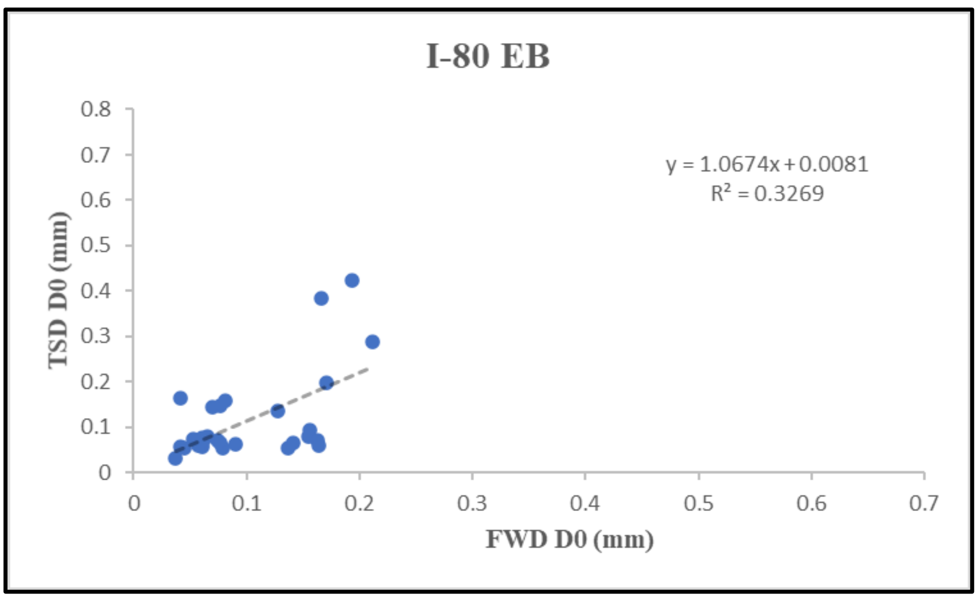
Scatter plot of FWD D0 versus TSD D0 for Route 9 NB



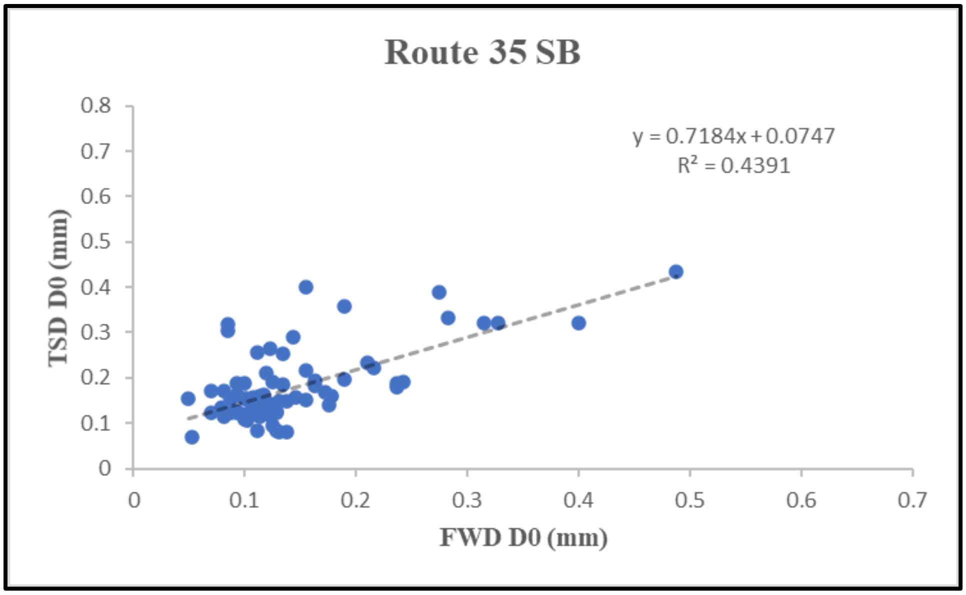
Scatter plot of FWD D0 versus TSD D0 for Route 17 NB



Scatter plot of FWD D0 versus TSD D0 for Route 40 EB



Scatter plot of FWD D0 versus TSD D0 for I-80 EB



Scatter plot of FWD D0 versus TSD D0 for Route 35 SB

Appendix C:

Temperature Correction Factors

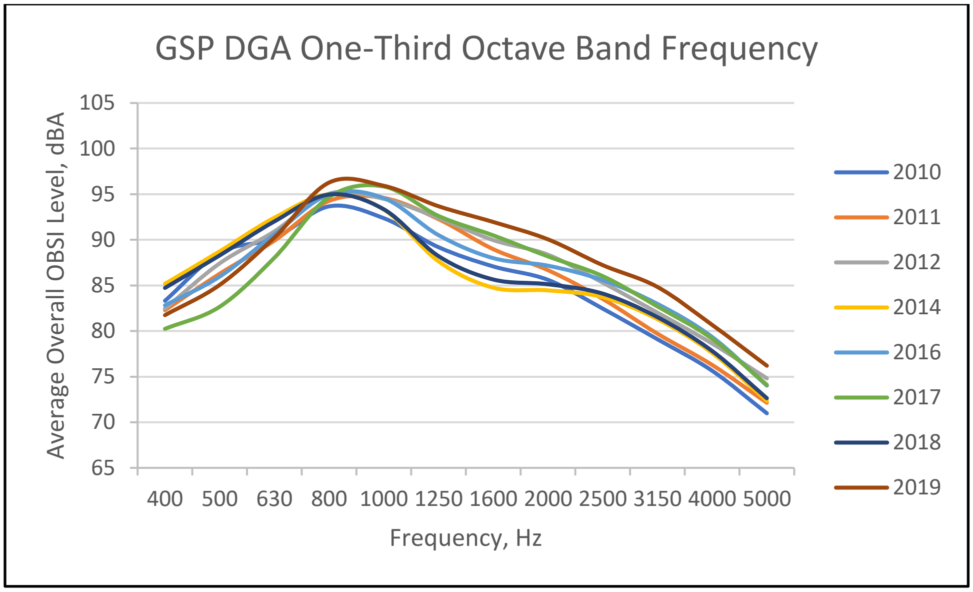
Recorded Kestral temperatures and calculated correction factors

Test Date	Kestral Temperature	Correction Factor	Pavement Type
GSP MP 97-102			
6/24/2010	95.6	1.104	DGA
6/15/2011	82.4	0.576	DGA
4/24/2012	62.8	-0.208	DGA
9/14/2012	62.8	-0.208	DGA
10/12/2012	62.8	-0.208	DGA
11/4/2014	71.8	0.152	DGA
12/1/2016	53.6	-0.576	DGA
8/17/2017	79.1	0.444	DGA
5/10/2018	67.9	0.004	DGA
10/16/2019	68.3	0.012	DGA
I-78 MP 18-26			
5/19/2010	60.5	-0.3	DGA
6/7/2011	88	0.8	DGA
3/13/2013	49.3	-0.748	DGA
10/7/2014	73.1	0.204	DGA
7/21/2016	90.5	0.9	DGA
11/18/2016	74.1	0.244	DGA
8/24/2017	82.76	0.5904	DGA
Rt 34 MP 9-10			
8/26/2010	84	0.64	SMA
4/13/2012	64.5	-0.14	SMA
8/15/2013	74.9	0.276	SMA
5/20/2014	78.5	0.42	SMA
6/22/2016	82.94	0.5976	SMA
11/24/2016	47	-0.84	SMA
7/26/2017	75.02	0.2808	SMA
9/12/2017	80.96	0.5184	SMA
10/19/2018	64.5	-0.0556	SMA
8/19/2019	94.1	1.044	SMA
I-287 MP 58-60			
5/10/2010	53	-0.6	SMA
9/22/2010	79.5	0.46	SMA
9/27/2011	80.8	0.512	SMA
4/27/2012	57.8	-0.408	SMA
9/9/2013	75.5	0.3	SMA
8/28/2014	77	0.36	SMA
8/18/2015	90.3	0.892	SMA

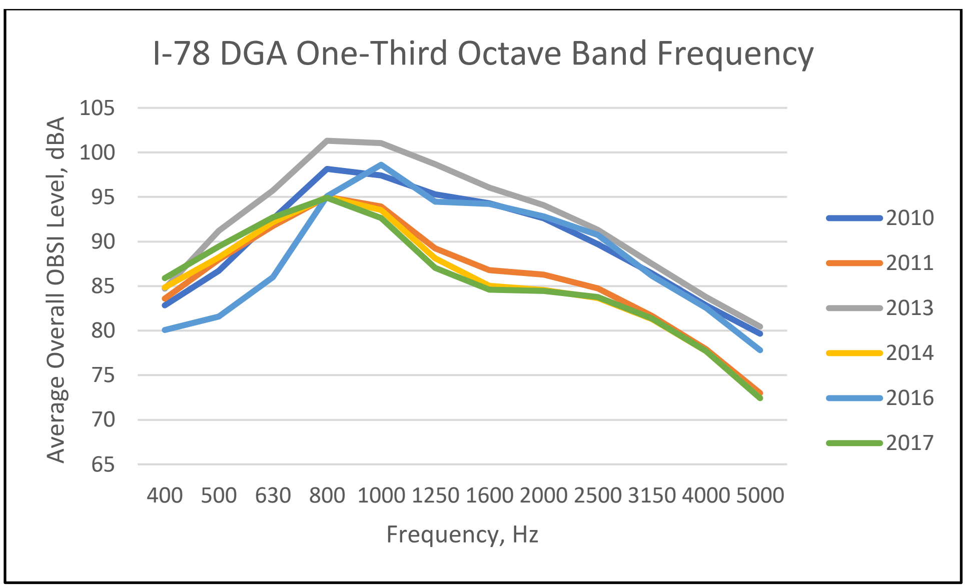
Test Date	Kestral Temperature	Correction Factor	Pavement Type
6/23/2016	82.22	0.5688	SMA
11/21/2016	40.3	-1.108	SMA
7/21/2017	96.62	1.1448	SMA
10/24/2018	53.6	-0.1244	SMA
I-78 MP 34-43			
4/10/2010	62	-0.24	OFGC
10/11/2011	72	0.16	OGFC
10/22/2012	75.2	0.288	OGFC
2/26/2013	45.6	-0.896	OGFC
7/18/2014	78.3	0.412	OGFC
10/21/2014	66.7	-0.052	OGFC
5/11/2015	85.1	0.684	OGFC
6/27/2016	88.34	0.8136	OGFC
11/28/2016	56.4	-0.464	OGFC
10/2/2017	72.32	0.1728	OGFC
10/12/2018	63.7	-0.172	OGFC
7/2/2019	86.6	0.744	OGFC
I-95 MP 2-8			
3/27/2010	46.5	-0.86	OGFC
10/4/2011	75.1	0.284	OGFC
5/5/2011	74	0.24	OGFC
11/19/2012	53.4	-0.584	OGFC
5/17/2012	73.3	0.212	OGFC
5/17/2013	69.5	0.06	OGFC
6/27/2013	87.1	0.924	OGFC
5/19/2014	69.2	0.048	OGFC
4/6/2015	73.8	0.232	OGFC
6/24/2016	82.4	0.576	OGFC
11/16/2016	61.5	-0.26	OGFC
7/19/2017	94.46	1.0584	OGFC

Appendix D:

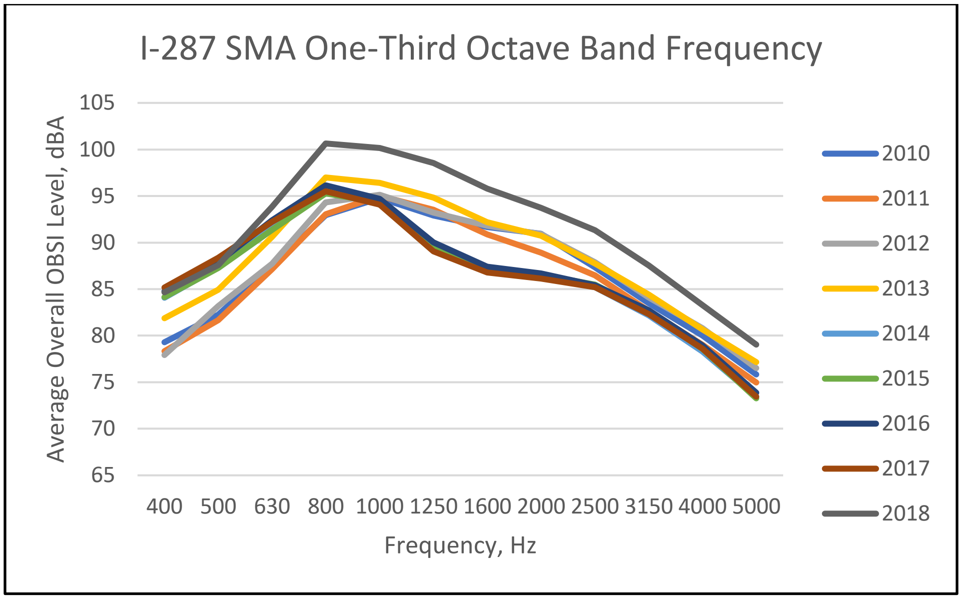
One-Third Octave Band of Noise



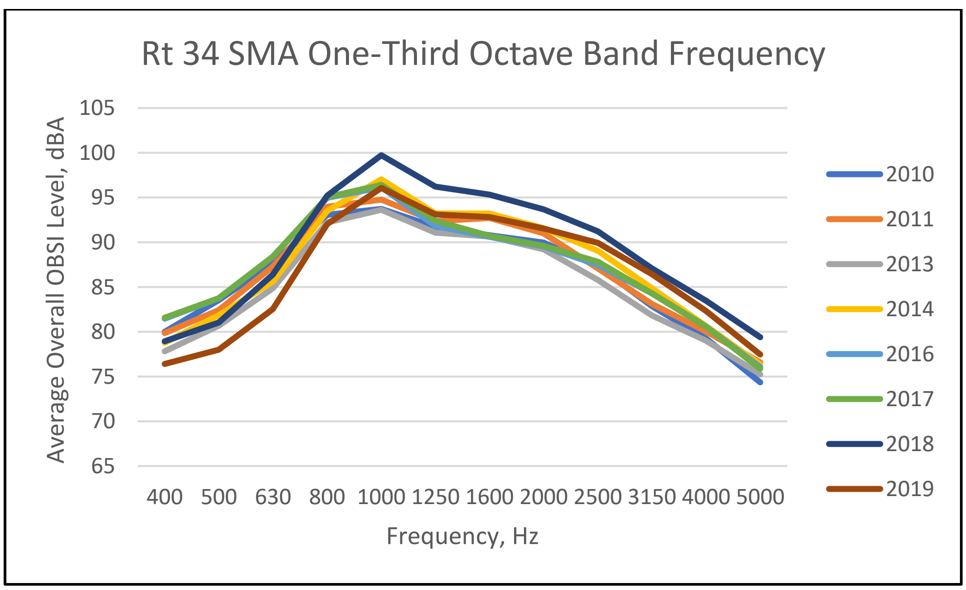
GSP MM 97-102 one-third octave band, from 2010-2019



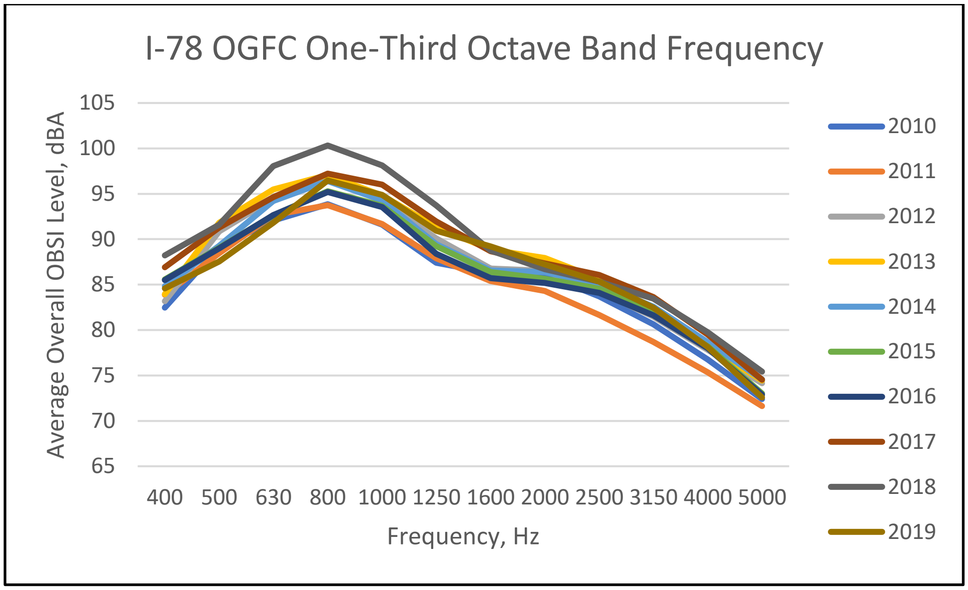
I-78 MM 18-26 one-third octave band, from 2010-2017



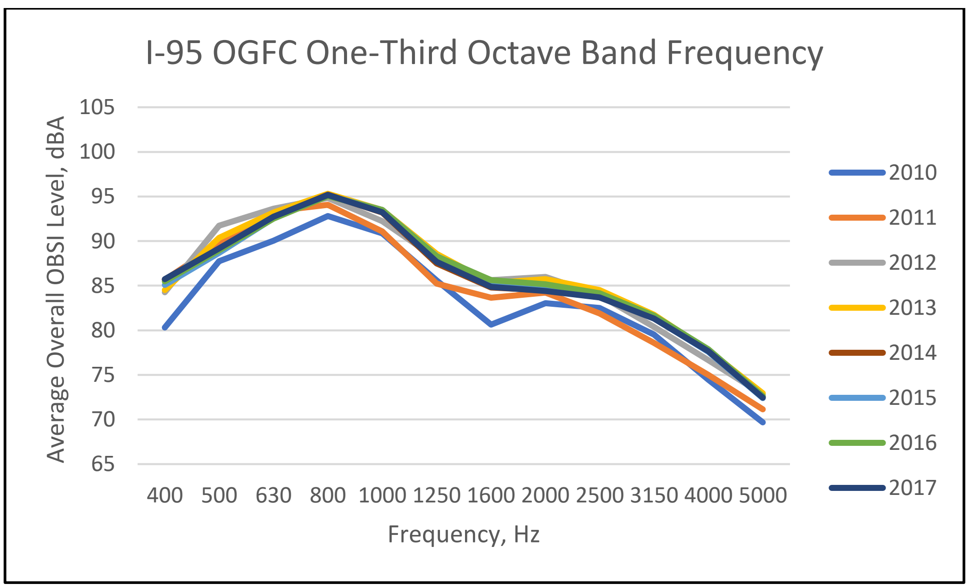
I-287 MM 58-60 one-third octave band, from 2010-2018



Rt 34 MM 9-10 one-third octave band, from 2010-2019



I-78 (East) MM 34-43 one-third octave band, from 2010-2019



I-95 MM 4-8 one-third octave band, from 2010-2017