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EVALUATION OF THE MAIN FACTORS AFFECTING TIRE-PAVEMENT INTERACTION NOISE

BY

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ABSTRACT

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Title: Evaluation of the Main Factors Affecting Tire-Pavement Interaction Noise

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Traffic noise is an environmental pollution that affects many people in today's modernized world. It disrupts the quality of life and causes annoyance, stress, sleep deprivation, and several health problems. When vehicles travel at 'highway speed' in expressways, tire-pavement interaction is considered to be the leading source of traffic noise. Researchers and transportation agencies around the world have focused on designing quieter pavement surfaces as a cost-effective solution to reduce tire-pavement interaction noise and overall traffic noise. Nevertheless, many developing countries are still behindhand in this area. In this study, On-Board Sound Intensity (OBSI) experiments were conducted to identify and quantify the main factors affecting tire-pavement interaction noise. The study found that that tire-pavement interaction noise is increasing 13.4 *ln* [dB(A) per km/h] due to the effect of driving speed and 0.362 [dB(A) per year] due to the effect of aging in dense graded asphalt concrete (DGAC). Furthermore, an ambient temperature adjustment factor of -0.04 [dB(A)/°C] was recommended for Qatar's environmental conditions. Moreover, NMAS was found to be the governing factor for tire-pavement interaction noise on dense graded asphalt Concrete (DGAC) surfaces. Finally, a prediction model for tire-pavement interaction noise was developed based on the pavement characteristics. This model can be used to design and construct quieter pavements in the state of Qatar as it accounts the environmental conditions and local construction materials.

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CHAPTER 1: INTRODUCTION

1.1 Background

Traffic noise is a growing environmental issue that affects communities in today's modernized world. Traffic noise pollution is considered the dominant source of pollution that affects more people than any other types of pollution in the modern industrialized world (Neithlath et al., 2005). It also reduces the quality of life by causing annoyance and stress (Bernhard and Wayson 2005, Donavan 2009). Furthermore, traffic noise has been associated with multiple health issues such as hearing loss, sleep disturbances, sleep deprivation, speech difficulties, and some cardiovascular diseases (Monrad, et al. 2016, Miljković and Radenberg 2012, Bernhard and Wayson 2005, WHO 2009, Vaitkus, et al. 2017). Moreover, traffic noise is also affecting the economy by creating public resistance to highways capacity expansions; decreasing real estate values; and the cost of constructing noise barriers (Bernhard and Wayson 2005).

Traffic noise is a term that is used to describe the distinct noises generated by the traffic. It's mainly partitioned into power unit noise, aerodynamic noise, and tire-pavement interaction noise (Sandberg and Ejsmont 2002, Bernhard and Wayson 2005, Sirin 2016). Tire-pavement interaction noise, also called rolling noise, is the dominating source of traffic noise especially for vehicles moving at medium to high speed.

Nowadays, the continuous developments in automobile industries have led to reducing power unit and aerodynamics noise (Li, Burdisso and Sandu 2018, Mak and Hung 2015). Additionally, tires manufacturers have also produced quieter tires to meet the noise requirements in developed countries. Therefore, there is a growing attention to design and construct quiet pavements by researchers and transportation authorities around the world. Numerous research studies have been conducted to evaluate different pavement surfaces and to identify the affecting factors on tire-pavement interaction noise (Sirin 2016). Moreover, there are many established guidelines and policies in Europe and USA for reducing tire pavement-noise and traffic noise in general (Ohiduzzaman, et al. 2016).

In the State of Qatar, more than 400 km of expressways are being constructed currently in preparation of the FIFA 2022 World Cup (The Expressway Programme 2018). Most of these expressways are located near residential areas as shown in *Figure 1*. Therefore, quieter pavements should be considered to reduce tire-pavement noise. Nonetheless, there are no established policies or guidelines to reduce noise pollution in the State of Qatar. Qatar Highway Design Manual (2015) highlighted briefly tire-pavement interaction noise without stating guidelines and recommendations due to lack of research in this field. This research aims to examine the existing tire-pavement noise levels and to establish the correlations with the main affecting factors.

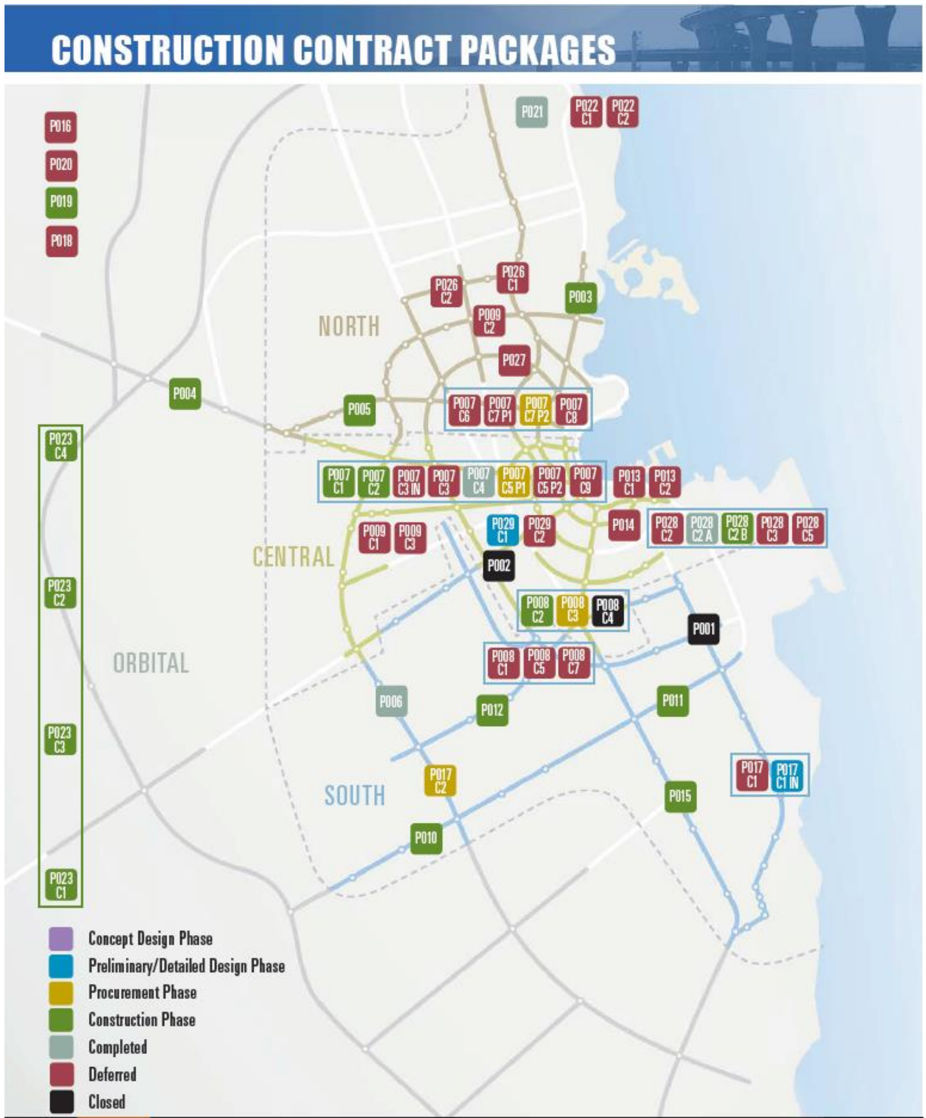


Figure 1. Locations and status of ongoing expressway projects (Source: The Expressway Programme, 2018)

1.2 Research Objective

This research aims to evaluate the effects of the main factors on tire-pavement interaction noise by conducting noise field measurements. The established correlations and prediction models in this research will be of interest to pavement researchers and engineers, in addition to the local and international public authorities concerned with quiet pavement and traffic noise abatement regulations. In particular, local authorities in Qatar will be of interest in this research since the study is considering the environmental conditions and construction materials in Qatar.

1.3 Thesis Report Organization

The research is divided into seven chapters as follows:

- Chapter one provides an introduction to the topic.
- Chapter two presents some acoustical fundamentals and summarize the reviewed literature. The literature review is emphasizing the main factors affecting tire-pavement interaction noise to identify areas where contributions can be added to the current state of knowledge.
- Chapter three describes the data collection process and noise testing procedures.
- Chapter four to Chapter six examine the impact of the main factors affecting tire-pavement interaction noise by conducting field noise experiments and performing statistical analysis to obtain correlation and prediction models.
- Chapter seven concludes the research findings and provide recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

This chapter starts by introducing some essential acoustical fundamentals related to tire-pavement interaction noise. Then, it presents a literature review of traffic noise components, noise measurement methods, and the main factors affecting tire-pavement interaction noise. The chapter will also identify areas where contributions can be added to the current state of knowledge.

2.1 Acoustic Fundamentals

Sounds occur from pressure variations in a transmission medium, such as air (Rasmussen, Bernhard, et al. 2007). The pressure variations are caused by vibrations in the medium molecules due to the movement or vibration of the sound source. Noise can be defined as undesirable or unwanted sound. As the definition may indicate, noise may be considered qualitative; some sounds can be considered desirable by some recipients while others may consider it undesirable. In tire-pavement interaction noise, the tire's tread contact with road surface causes vibrations in the tire tread blocks and carcass that result in noise (Bernhard and Wayson 2005).

Humans hearing system can perceive a very wide range of pressure variation. However, human's auditory system is not linearly correlated to pressure. For example, a sound of 2 [Pa] does not sound twice more than another sound of 1 [Pa] magnitude. Furthermore, sensing something that has changed from 0.1 to 1 [Pa] sounds quite similar to something that has changed from 1 to 10 [Pa]. Thus, a ratio called sound pressure level, or Decibels [dB], was introduced to better represent the human perception of sound loudness (Rasmussen, Bernhard, et al. 2007).

2.1.1 Decibels

A decibel [dB] is a logarithmic ratio of sound pressure levels to a standard reference level that exemplifies human perception of sound loudness. The standard reference level for humans hearing in the air is equal to 0.00002 [Pa], and it's assumed to be the lowest sound pressure that an average person can hear (Rasmussen, Bernhard, et al. 2007). The sound pressure level can be expressed mathematically as follows:

$$Sound\ Level\ [dB] = 20 \times \log_{10}\left(\frac{Pressure\ [Pa]}{0.00002\ \ [Pa]}\right) \tag{1}$$

For traffic noise measurements, decibels are measured along a span of time and then averaged to obtain the average noise. A comparison of sound pressure and sound level for different sounds is shown in *Figure 2*.

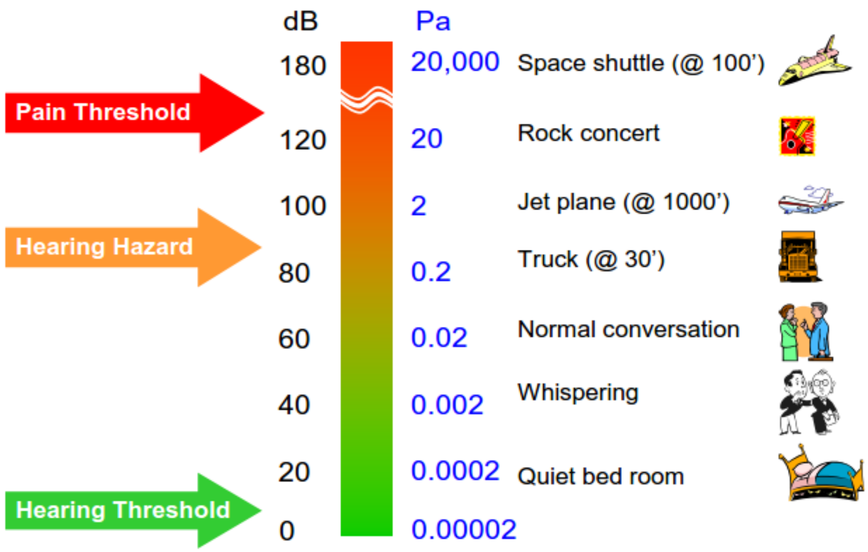


Figure 2. Comparison between decibel and pressure (Rasmussen et al., 2007)

Since sound pressure level is a logarithmic ratio; it can't be added arithmetically. Table 1 provides rule of thumb to add decibels as provided in the Federal Highway Administration (FHWA) guideline for analysis and abatement of traffic noise (FHWA 2011).

Table 1

Rule of thumb for decibels addition (source: FHWA-HEP-10-025, 2011)

When two decibel values differ by	Add the following amount to the higher value
0 or 1 dB	3 dB
2 or 3 dB	2 dB
4 or 9 dB	1 dB
10 dB or more	0 dB

2.1.2 Frequency

Sound comes in different frequencies depending on the source. The frequency of a sound, also referred to as pitch or note, is the rate of change of sound pressure variations. In other words, the number of sound wave oscillations per second is represented in Hertz (1/sec). Humans can perceive sounds between 20 to 20,000 [Hz], the noise outside this range are not heard by humans and intentionally omitted in sound meters. Although a higher sound frequency doesn't mean a louder sound, higher frequencies sounds are perceived as more annoying than lower frequencies (Carroll 1930). On the other hand, lower frequencies tend to propagate more distances comparing to higher frequencies

(Hanson and James 2004). Hence, representing noise level in terms of frequency with conjunction to of overall noise helps in better representation and understating of noise.

Moreover, human’s auditory system perceives successive doubling of frequency as equal steps in pitch. Therefore, the frequency is represented in spans of octave bands or one-third octave bands (Bernhard and Wayson 2005). Octave is a frequency band that the successive frequency is double the preceding frequency. Weighting Circuits are added to sound level meters to exemplify human’s sensitivity to sounds within the audible frequency range. This is because humans have varying sensitivity for frequencies. For traffic noise measurements, the A-weighting scale is generally used (FHWA 2011). The A-weighting scale amplifies the sound levels in frequencies between 400 and 5000 Hz where most people can hear. When the weighing scale is used in noise measurement, decibels are represented as dB(A).

2.2 Traffic Noise Components

Traffic noise is mainly a blend of the following noises: the power unit noise, the aerodynamic noise, and tire-pavement interaction noise (Sandberg and Ejsmont 2002, Bernhard and Wayson 2005, Sirin 2016). When the vehicle speed of a passenger vehicle exceeds a certain crossover speed, around 40 [km/h] for passenger cars and 70 [km/h] for trucks, tire-pavement noise becomes the dominant source (Sandberg 2001, Bernhard and Wayson 2005, Rasmussen, Bernhard, et al. 2007, Li, Burdisso and Sandu 2018). Consequently, tire-pavement interaction noise is considered the dominant source of traffic noise in expressways as generally vehicles driving speed are above the crossover speed. *Figure 3* illustrates the crossover and the contributions of each traffic noise components (Rasmussen, Bernhard, et al. 2007).

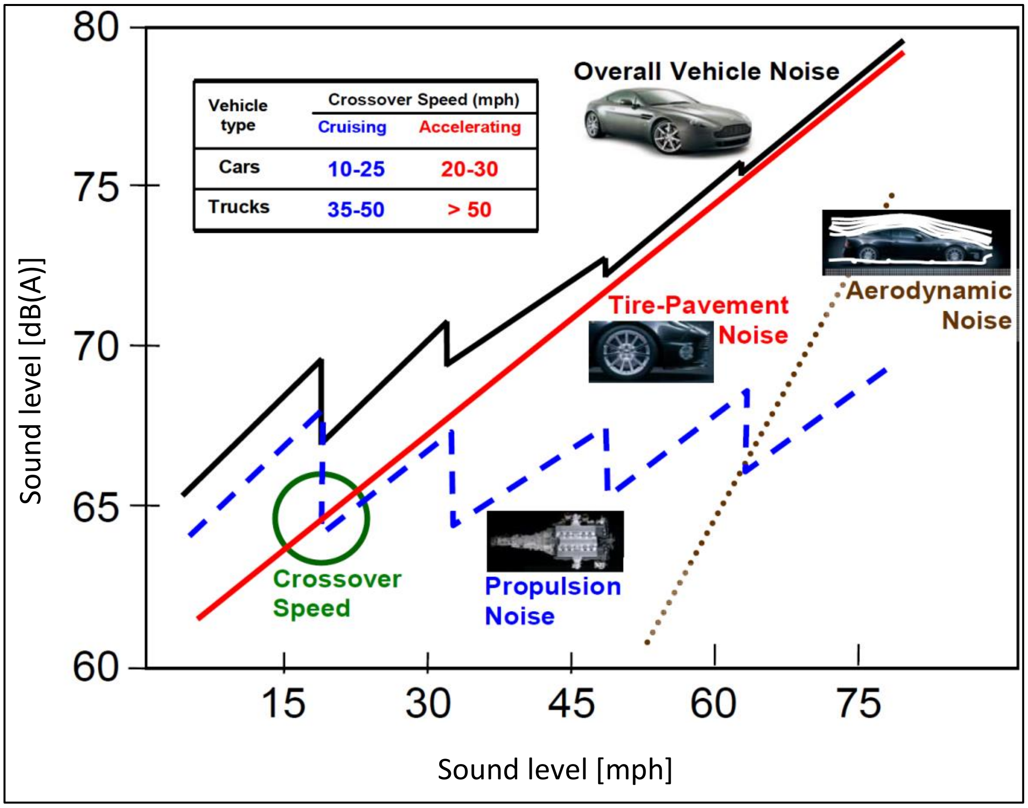


Figure 3. Contribution of different noises in overall noise (Bernhard & Wayson, 2005)

2.3 Noise Measurement Methods

Several traffic noise measurement techniques were utilized in literature to investigate traffic noise and evaluate its dependency on relevant factors. This section compares those methods and highlights the advantages and disadvantages of each method to nominate suitable method for this research. Noise measurement methods can be categorized as wayside and source methods based on the location of the apparatus as shown in Table 2.

Table 2

Summary of noise measurement methods

Category	Method	Standard
Wayside Noise Measurement	Statistical Pass-by (SPB)	(ISO 11819-1 1997)
	Statistical Isolated Pass-by (SIP)	(AASHTO TP 98-13 2013)
	Controlled Pass-by (CPB)	(NF S S1 119-2)
	Continuous Flow Traffic Time Integrated (CTIM)	(AASHTO TP 99-13 2015)
Source Noise Measurement	Close Proximity (CPX)	(ISO 11819-2 2017)
	On-Board Sound Intensity (OBSI)	(AASHTO T 360-16 2016)

2.3.1 Wayside Noise Measurement

This type of noise measurement is conducted by using sound level meters positioned beside the carriageway at standard distances or designated distances. There are generally four recognized and widely used wayside noise measurement methods to conduct noise measurement: Statistical pass-by (SPB), Statistical Isolated Pass-by method (SIP), Controlled pass-by (CPB), and Continuous flow traffic time-integrated model (CTIM). Wayside noise measurement methods are efficient to calculate the overall traffic noise which is affecting the neighboring communities. Therefore, it is recommended for noise measurement in noise abatement policies, urban noise planning, and for investigating and reporting the noise environmental effects on adjacent communities (FHWA 2011). These mentioned techniques are generally similar but differ in test setups and data analysis.

2.3.1.1 Statistical Pass-by Method (SPB)

The Statistical Pass-by Method (SPB) is a well-established method by the International Standardization Organization (ISO 11819-1 1997). The method is primarily used for investigating traffic noise impact on adjacent communities. It is also utilized for investigating tire-pavement noise by computing a Statistical Pass-by Index (SPBI) to compare different pavements (Lédée and Pichaud 2007). The maximum sound pressure level is measured for each vehicle by placing a sound level meter 7.5 meters (25 ft) away from the center of the observed lane, in a height of 1.2 meters (4 ft). The speed and class of each vehicle are needed to be registered. The measurement duration should be sufficient to capture clean noise measurements for 100 passenger cars and 80 trucks according to ISO standard. Thus, SPB is a time consuming technique.

In the USA, statistical pass-by noise measurements are conducted according to FHWA guidelines to measure highway noise (Lee and Fleming 1996). Unlike ISO SPB, the sound level meter, referred to as microphone, is placed in a horizontal distance of 50 ft (15 m) and a vertical distance of 5 ft (1.5 m) from the center of the observed lane. FHWA procedures don’t specify a sample size, instead, it provides a minimum number of vehicles according to the travel speed (Hanson, James and NeSmith 2004).

2.3.1.2 Statistical Isolated Pass-by method (SIP)

The Statistical Isolated Pass-by method (SIP) was established by AASHTO to evaluate traffic noise generated by different road surfaces (AASHTO TP 98-13 2013). It utilizes elements in Statistical Pass-by Method (ISO 11819-1 1997) and FHWA guidelines to measure highway noise (Lee and Fleming 1996) to allow comparisons of noise measurements of varying pavements in different research studies through a reference noise curve. SIP method recommends using two sound level meters; one is placed at the position specified in ISO SPB and the other placed according to FHWA guidelines to measure highway noise as described in section 2.3.1.1. However, it can be conducted using one microphone only if site conditions don't allow for two microphones.

2.3.1.3 Controlled Pass-by Method (CPB)

The Controlled Pass-by Method (CPB) is an enhanced version of SPB. It was introduced by the French National Standard (no. NF S S1 119-2) to reduce the testing duration and to capture traffic noise (Wang, et al. 2011). The main difference between the two techniques is that CPB is performed in controlled pavement sections using selected test vehicles. Therefore, it can't be used on regular highways with high traffic volume, which will be difficult to control. This method was used in several studies to compare noise levels on different pavements (Kuemmel, et al. 2000, Lédée and Pichaud 2007).

2.3.1.4 Continuous Flow Traffic Time Integrated Method (CTIM)

FHWA and AASHTO established the Continuous Flow Traffic Time Integrated Method (CTIM) to allow for investigating the effect of pavement surfaces on road noise in high traffic volume highways with continuous flow (AASHTO TP 99-13 2015). In this method, the sound level meter is positioned 15 meters (50 ft) horizontally and 3.7 meters (12 ft) vertically from the center of the examined lane with a minimum height of 1.5 m (5 ft) from the ground. Unlike the previous wayside methods in which individual vehicle type and speed were recorded, the traffic volume and traffic flow speed of the examined lane is documented to provide an average sound pressure level. CIMT has been adopted in several studies to assess the effects of pavement surface on vehicle noise in highways with continuously flowing traffic in California and Arizona (Rochat, et al. 2012, Illingworth & Rodkin, Inc 2012). The noise data captured by CTIM include the noise levels generated by all vehicles on all lanes with the propagation effects. Hence, CTIM is not recommended for investigating pavement noise unless a single vehicle SPL can't be measured due to heavy continues traffic flow (AASHTO TP 99-13 2015).

2.3.2 Noise Measurement at Source

Unlike wayside methods that measure all components of traffic noise, Close Proximity method (CPX) and On-Board Sound Intensity method (OBSI) are two methods that measure tire-pavement interaction noise at the source of interaction. This section is describing and comparing the two methods.

2.3.2.1 Close Proximity Method (CPX)

The Close Proximity Method (CPX) is a well-established method by ISO to quantify tire-pavement noise (ISO 11819-2 2017). The sound pressure level is measured by using microphones attached to testing tire within an isolated trailer that is hauled by a regular vehicle. The trailer acts like an isolation chamber for tire-pavement interaction noise. This technique was adopted in many studies especially in Europe (Bennert, et al. 2005, Punnamee and Dai 2007, Cho and Mun 2008). The literature shows also that the usage of free field CPX system comes without enclosure around the microphones but is not common (Trevino and Dossey 2009). *Figure 4* and *Figure 5* shows the CPX hauled trailer and the configuration of microphones within the trailer, respectively.

Figure 4. CPX trailer manufactured by M+P (Source: www.mplusp.eu)

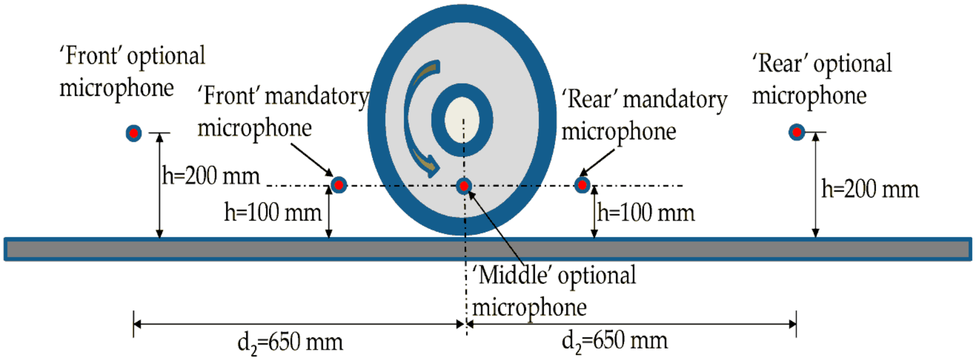


Figure 5. Configuration of microphones in CPX (Ohiduzzaman, et al. 2016)

Despite all of the advantages of CPX, reflections within the enclosed isolation compartment may affect the measurement results (Trevino and Dossey 2009). In addition, it cannot be performed in normal traffic condition as noise from other vehicles can contaminate the measured noise. Moreover, constructing and maintaining CPX trailer is expensive.

2.3.2.2 On-Board Sound Intensity Method (OBSI)

The OBSI method was introduced in the 1970's when the acoustic science was advanced by the capability to physically quantify sound intensity (Oswald and Donavan 1980). Sound intensity is a vector quantity that represents the power carried by a sound wave per unit area (W/m^2), which can be simplified as the power that is causing the sound pressure. Unlike CPX, the OBSI method captures sound intensity, not sound pressure, and then is converted analytically to sound pressure. This allows researchers to measure tire-pavement interaction noise at source during regular traffic conditions; since sound intensity is a vector quantity that can be quantified at a certain source and distinguished from other noise sources (Hanson, James and NeSmith 2004, Ohiduzzaman, et al. 2016). Therefore, this system can be mounted on any passenger car tire without the need for isolation chamber or specific traffic condition.

OBSI is standardized under AASHTO and it's considered much accurate in measuring tire-pavement noise than other methods (AASHTO T 360-16 2016). The OBSI system includes sound intensity probe consists of two microphones that are connected to preamplifiers and 4-channel analyzer. It also requires a laptop equipped with OBSI software to run the measurement in real time. The OBSI system apparatus is shown in *Figure 6*.

Figure 6. OBSI testing equipment

2.4 Factors Affecting Tire-Pavement Noise

Many research studies have been conducted to study the varied factors that influence the generation and propagation of tire-pavement interaction noise. There are more than 2000 studies related to tire-pavement interaction noise (Li, Burdisso and Sandu 2018). Sirin (2016) summarized more than 13 factors that were correlated with tire-pavement interaction noise. This section is discussing the conducted research efforts on the relevant main factors only. The section is also focusing on the related studies to DGAC since it's the most widely used asphalt mix type in the region.

2.4.1 Effect of Vehicle Speed

Vehicle driving speed is considered to be one of the governing factors that influence the overall traffic noise and tire-pavement interaction noise particularly. As mentioned earlier in section 2.2, when the speed of a passenger vehicle exceeds a certain crossover speed (40 [km/h]) tire-pavement interaction noise becomes the dominant source of traffic noise. Therefore, several studies were conducted to investigate the impact of driving speed on tire-pavement interaction noise. Bennert et al. (2005) found that the measured noise level increases linearly by 0.12 [dB(A)/kmph] (0.18 [dB(A)/mph]). The study was conducted on multiple hot mix asphalt (HMA) and rigid pavements using CPX Method. The study assumed that the relation between tire-pavement noise level and speed is linear since the gradient was calculated by using two speeds only, 55 and 65 [mph] (Bennert, et al. 2005). Other more recent research studies in HMA pavements, found that the measured noise level using OBSI increases linearly about 0.3 [dB(A)] per one mile increase in driving speed (0.18 [dB(A)/kmph]) (Donavan and Lodico 2009, Wang, et al. 2011).

Haas (2013) investigated the correlation of driving speed on tire-pavement interaction noise by measuring OBSI at seven different speeds (20, 30, 35, 40, 45, and 50 mph) on a DGAC road in New Jersey. The study concluded that the noise intensity level increases by a logarithmic factor of 9.247 *ln* per one km/h increase in driving speed (14.879 *ln* [dB(A)/mph]). This conclusion is similar to another research work conducted by Cho and Mun (2008) using the novel close proximity (NCPX) and SPB methods. The study examined a wide range of speeds (50, 60, 70, 80, 90, 100, 110 and 120 km/h) and using different vehicles (passenger cars, buses, and trucks). The study demonstrated that the correlation between MILs and vehicle speed is logarithmic, not linear. This study also concluded that the measured tire-pavement interaction noise increases with the increase in vehicle speed regardless of vehicle type or surface type.

2.4.2 Effect of Temperature

Many studies have explored the effect of ambient temperature on the generation and propagation of tire-pavement interaction noise (Sirin 2016). It was evident in the studies that tire-pavement interaction noise tends to decrease when the ambient temperature increases. Many researchers have also established similar correlations for tire-pavement interaction noise and the temperatures of pavements and/or the temperature of tires (Sandberg and Ejsmont 2002, Lédée and Pichaud 2007, Donavan and Lodico 2009). The "Tire Road Noise Reference Book" (Sandberg and Ejsmont 2002), summarized previous research work in evaluating the relationship between temperature and tire-pavement interaction noise. It showed that there is a wide variation in the reported linear coefficients, between -0.001 to -0.14 [dB(A)/°C]. The linear coefficient varied depending on the type of pavement surface, tires, and noise measurement method.

The temperature impact on tire-pavement interaction noise varies on different pavement surfaces (Sandberg and Ejsmont 2002, Bendtsen, Lu and Kohler 2010). Le´de´e and Pichaud (2007) examined the variations of tire-pavement interaction noise measured by CPB over a range of temperatures between 0 and 30 °C. The study was repeated on seven different pavement surfaces. The linear noise variation of pass-by noise with temperature was found to be -0.1 d[B(A)/°C] in dense graded asphalt surfaces, -0.06 [dB(A)/°C] in porous pavements, and -0.03 [dB(A)/ °C] in rigid pavements (Lédée and Pichaud 2007). A more recent study conducted by using CPX reported linear temperature coefficients of -0.061, -0.055, and -0.043 [dB(A)/°C] for DGAC, open graded, and concrete surfaces, respectively (Bendtsen, Lu and Kohler 2010). Therefore, tire-pavement interaction noise in DGAC is more susceptible to temperatures effect than other HMA or rigid pavement surfaces.

In a study conducted in DGAC using OBSI method, Mogrovejo et. al. (2014) found a linear temperature correlation factor of -0.05 [dB(A)/°F]. The study investigated the dependency of noise levels on a wide range of ambient temperatures (90, 80, 60, 50, and 40 °F) (Mogrovejo, et al. 2014). Another study that was conducted in semi-dense asphalt surface by using CPX method reported a correlation factor of -0.06 [dB(A)/°C] (Bueno, et al. 2011). AASHTO Standards for OBSI method (AASHTO T 360-16 2016), recommended a linear adjustment coefficient of 0.072 [dB(A)/°C] (0.040 dB(A)/°F) to normalize the varied OBSI noise measurements to a reference ambient air temperature of 20°C (68 °F) using the following equation:

$$IL\left(dB(A)\right) = Measured\ IL\left(dB(A)\right) + 0.072 \times (Air\ Temperature\ ℃ - 20\ ℃) \qquad (2)$$

All of the reviewed research studies examined the behavior of tire-pavement noise within a range of temperatures that don’t exceed 38 °C (100 °F) (Sirin 2016). Additionally, AASHTO procedures for tire-pavement noise measurement using OBSI method (AASHTO T 360-16 2016) has recommended conducting the noise measurements on ambient temperatures range between 4 and 38°C (40 to 100°F) to avoid preamplifiers overheating and overloading. Notwithstanding this, capturing tire-pavement interaction noise in hot temperatures is essential to examine the effect of environmental conditions on tire-pavement noise generation. This is particularly important in the Gulf region where the average temperatures during the summer time usually exceed 38°C (100°F).

2.4.3 Effect of Pavement Aging

Many research studies focused on the effect of pavement aging on tire-pavement interaction noise to ensure the sustainability of quiet pavement designs. In general, tire-pavement interaction noise levels were found to be increasing over time. In a research study conducted on 42 roads with distinct surfaces' characteristics in New Jersey, noise levels were found to be increasing with time irrespective of the type of pavement surface (Bennert, et al. 2005). The rate of increase of pavement noise is depending on the type of pavement surface. Similar trends were also evident in several other studies conducted on various pavement surfaces over varied ranges of years (Hanson and Waller 2006, Yu and Lu 2013, Irali, et al. 2015). Trevino and Dossey (2009) found that porous pavements are more affected by the aging than other types of HMA and rigid pavements due to the combined effect of clogging and compaction of layers. However, no similar studies were conducted to examine the effect of pavement aging in the Middle East or Arabic Gulf countries.

Researchers have also tried to find a correlation factor for aging effect in order to ensure the acoustic sustainability of quiet pavement designs. In a research study conducted in Colorado, noise levels were found to be increasing over time with a rate of change of 0.19 [dB(A) per year] in DGAC surfaces, 0.23 [dB(A) per year] in rigid pavements (PCC), and 0.25 [dB(A) per year] in SMA surfaces (Rasmussen and Sohaney 2012). A similar rate of change of 0.2 [dB(A) per year] was also reported in a recent study in Florida where noise data were collected on four distinct surfaces over five years (Wayson, MacDonald and Martin 2014).

The increase in tire-pavement noise levels over time has been explained by the surface deterioration and distresses that are caused by the effects of traffic and environmental conditions (Khazanovich and Izevbekhai 2008). A twelve-year OBSI study showed that noise levels on an OGAC section in California have increased about 2 [dB(A)] in the first ten years after construction. However, when surface deterioration emerged in the twelfth year, tire-pavement interaction noise increased 2 [dB(A)] in a span of two years (Illingworth & Rodkin, Inc 2012).

2.4.4 Effect of Pavement Surface Characteristics

There are numerous research efforts conducted to investigate the effect of different pavement surface characteristics on tire-pavement noise (Li, Burdisso and Sandu 2018, Sirin 2016, Cong, Swiertz and Bahia 2013). For DGAC, the studies concentrated in aggregate gradation and nominal maximum aggregate sizes (NMAS) to represent the surface texture to evaluate different DGAC. According to Qatar Construction Specification (QCS 2014), NMAS is defined as "The nominal maximum particle size larger than the first sieve to retain more than 10 percent". In a CPX study conducted on multiple surfaces in New Jersey, DGAC surfaces with 12.5 mm NMAS were found to be quieter than the ones with 19 mm NMAS (Bennert, et al. 2005). Similar observations were also found in a laboratory experiment that compared between 19 and 9.5 NMAS dense graded Superpave mixtures (Kowalski 2007). Timm, et al. (2006) compared MILs on nine different DGAC surfaces and concluded that course graded DGAC surfaces are nosier than fine graded DGAC (Timm, et al. 2006). Furthermore, Donavan (2006) reported that DGAC gradation can increase overall noise levels up to 8 [dB(A)]. The study investigated the tire-pavement noise levels on six DGAC pavements with different gradations in Europe. The effect of DGAC gradation on noise levels at 1/3rd octave band frequency and reported that the variation in low frequencies (below 1600 Hz) is larger than higher frequencies. However, this study didn't include the effect of pavement aging (Donavan 2006).

Air void percentage in mix design has always been associated with the design of quiet pavements (Miljković and Radenberg 2012). However, the percentage of air voids in DGAC pavements are usually limited by 4 to 7%. Therefore, air void content in DGAC mix design has insignificant negative correlation with tire-pavement interaction noise (Hanson and Waller 2006, Kocak 2011, Cong, Swiertz and Bahia 2013).

In a laboratory study conducted by using several Superpave mix designs, binder content was found to have a minor negative correlation with tire-pavement interaction noise (Kocak 2011). This trend was explained by increasing pavement surface viscosity while increasing the amount of binder. However, the study stated that the results are not conclusive and highlighted that binder content should be optimized to avoid decreasing the voids in the mixture.

Other pavement surface characteristics have been also considered in literature such as aggregate type, layer thicknesses, and maximum or bulk specific gravities. However, no correlation, or no direct correlation at least, was found in the reviewed literature with the respective to these factors (Rasmussen, Bernhard, et al. 2007, Sirin 2016).

CHAPTER 3: DATA COLLECTION AND TESTING PROCEDURES

The accuracy of noise measurements is very important for evaluating tire-pavement interaction noise. In this chapter, tire-pavement interaction noise measurement procedure is discussed. In addition, data collection procedure for pavement as-built mix design is also described.

3.1 Collection of Tire-Pavement Interaction Noise

Several noise measurement methods have been discussed in the literature review chapter, Section 2.3. Nevertheless, On-Board Sound Intensity (OBSI) method is considered the most accurate method if the goal is quantifying and identifying tire-pavement noise. OBSI is also the preferred testing method by AASHTO (AASHTO T 360-16 2016). This section will introduce the different components of OBSI system and the noise testing procedure in this study.

3.1.1 OBSI Hardware Components

The OBSI measurement was conducted using a system developed by Acoustical and Vibrations Engineering Consultants (AVEC). AVEC's system mainly consists of a testing rig, sound intensity probes, and an OBSI software. This section lists the components of OBSI testing system and the function of each component.

3.1.1.1 Sound Intensity Probes

AVEC noise measurement system consists of two sound intensity probes to measure the sound intensity level. Each sound intensity probe consists of two microphones that are connected to a preamplifier. The microphones are polarized free field microphone with a size of ½ inch. The microphones and preamplifier were supplied by G.R.A.S and satisfy the requirements of Class 1 ANSI S1.9. *Figure 7* shows the assembled intensity probes. The sound intensity probes are connected to 4-channel data analyzer and a laptop inside the test vehicle. The sound intensity probe covered with a windscreen to reduce the effects of wind in the measurements as shown in *Figure 8*. The windscreen is a spherical perforated foam that also acts as a protection to the sound intensity probe for damage or dirt.

Figure 7. Intensity probes

Figure 8. Two intensity probe windscreens

3.1.1.2 Microphone Calibrator

A calibrator Type 42 AB manufactured by G.R.A.S was used to calibrate the microphones before the start of testing. The calibrator has a ½ inch microphone opening to fit the microphones and a calibration frequency of 1000 Hz. *Figure 9* shows the intensity probes during calibration.

Figure 9. OBSI probes while calibrating

3.1.1.3 Testing Rig

The OBSI system used a testing rig to mount the sound probes to the body of the testing vehicles. It's made of aluminum and stainless steel and configured in a way that eliminates aerodynamic noises. *Figure 10* shows a mounted testing rig and *Figure 11* illustrates the microphone position on the testing rig.

Figure 10. Mounted OBSI testing rig

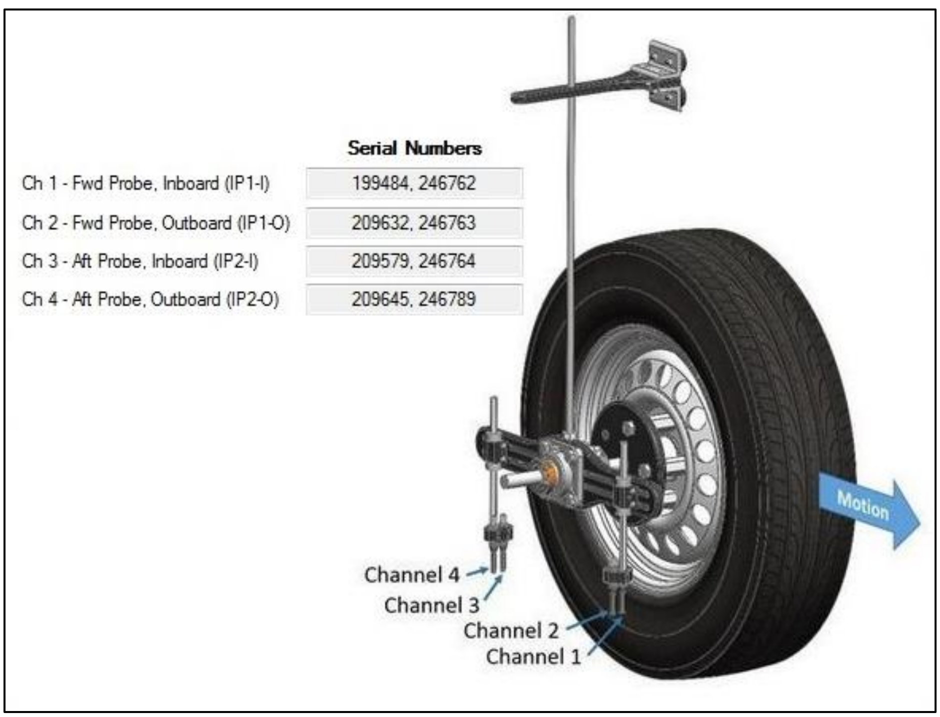


Figure 11. A diagram for the testing rig with microphones serial numbers

3.1.1.4 *Test Vehicle and Test Tire*

A normal passenger car, Honda Accord model 2012, was used for all the OBSI testing. The car specifications met the requirements of AASHTO standards (AASHTO T 360-16 2016) and fit the Universal Standard Reference Testing Tire (SRTT). The total weight of the vehicle and onboard passengers was kept below 360 ± 45 kg in accordance to AASHTO standards.

A new (SRTT) size P225/60 R16 was mobilized for testing purposes. The SRTT tire is designed to mount the OBSI testing rig along with the intensity probes in accordance with ASTM standard (ASTM F2493 - 18 2018). The tire was only used during testing to keep the accumulated mileage below 17,700 km as specified in section A2 in AASHTO standard (AASHTO T 360-16 2016). Additionally, the SRTT tire was fixed on a 16.50 ± 0.5-inch wide rim. The sound intensity probe was placed at leading and trailing edge of the SRTT tire. Tire pressure was kept around 30±2 psi. *Figure 12* shows the SRTT tires. The final OBSI testing setup is shown in *Figure 13*.

Figure 12. SRTT tires

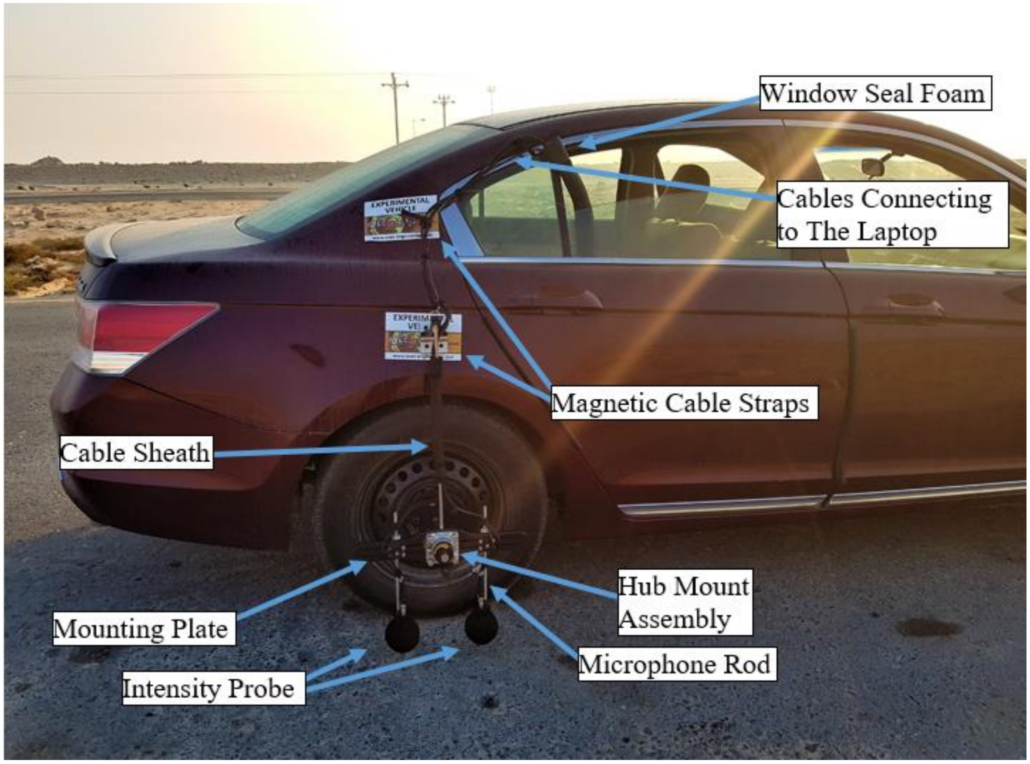


Figure 13. OBSI setup components

3.1.1.5 4-Chanel Data Analyzer

AVEC OBSI system includes a USB-based 4-channel data analyzer (NI USB-9234) that is connected to the intensity probes. It's used for noise data analyzing and recording. The 4-channel analyzer was manufactured by National Instruments, Texas, USA, and complies with the requirements of the Type I Specification of American National Standards Institute (ANSI). The 4-channel analyzer has a dynamic range of 102 dBA and simultaneously digitize signals at rates up to 51.2 kHz per channel. The USB-based 4-channel analyzer used in this research is shown in *Figure 14*.

Figure 14. The 4-Channel data analyzer

3.1.1.6 Semi-rugged Laptop

The AVEC OBSI system comes also with a semi-rugged Panasonic Laptop PC to control and analyze the noise measurements. The laptop has a preinstalled copy of OBSI software and is connected to the 4-channel analyzer. The laptop is shown in *Figure 15*.

Figure 15. Testing Laptop

3.1.1.7 Other Equipment and Accessories

AVEC's OBSI testing system included also some other accessories such as DC/AC converter; laptop car mount; USB trigger (4-button keypad); magnetic stabilizer attachment; cables for intensity probes; and a cable management system. Moreover, the following list includes other equipment that was necessary for conducting the noise measurements:

- Global position system (GPS) to locate testing sections and driving speed.
- Weather station to collect atmospheric pressure, humidity, wind pressure, and direction.
- Digital thermometer and A Fluke Infrared temperature gun to measure the ambient temperature pavement surface temperature, respectively.

3.1.2 OBSI Software

The AVEC's OBSI software was used for data measuring and processing in accordance with AASHTO standards (AASHTO T 360-16 2016). The software is the principal part of OBSI system as it controls the on-board noise measurement. It also provides real time results representation and run validation. Additionally, the software allows to process data and generate automatic tables, graphs, and reports in a very user-friendly interface as shown in *Figure 16*.

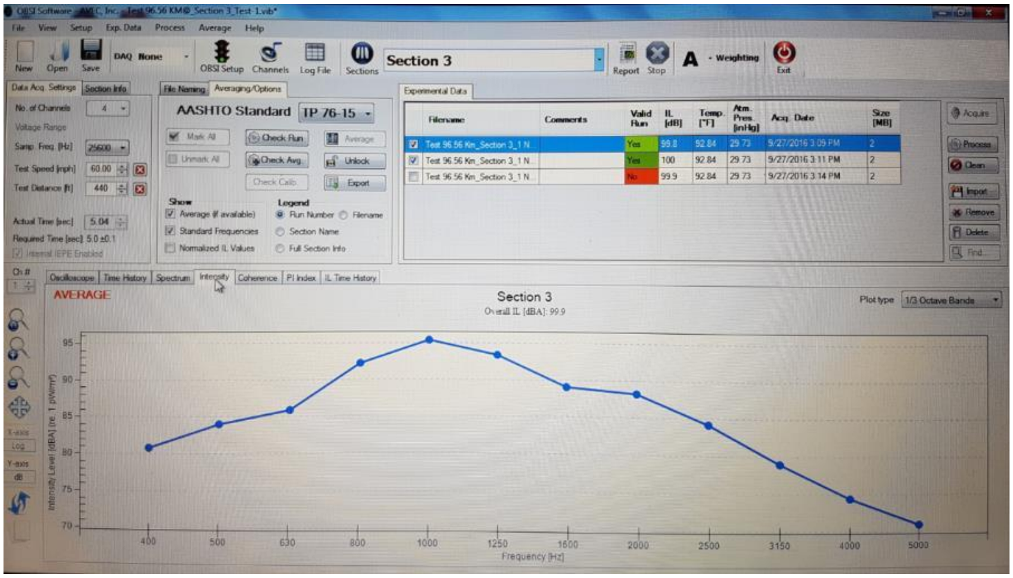


Figure 16. AVEC's OBSI software User Interface

3.2 OBSI Testing Procedure

OBSI noise measurements were conducted following the AASHTO standard test procedure T 360-16 (AASHTO T 360-16 2016). Prior to performing any noise test, a field visit was conducted to the road section to select the testing sections. The length of each section was 134±3 m (440 ft±10). The test section shall be a straight segment of the roadway, and any horizontal curves shall be avoided. Any obstruction that could affect the noise (i.e. overpass, noise barrier, pavement failure, pavement transition, grade transition, and dust) was either avoided or recorded in the field notes. The beginning of each test sections was identified by a mile marker or a street furniture and identified in the GPS. In addition, AASHTO standard advised that test sections should be dry and clean of any debris.

The OBSI test requires a driver and an operator. The driver is mainly responsible for maintaining the test speed limit as instructed by the operator. The driver is also required to watch the testing equipment while driving and to keep test vehicle in the center of the examined lane. If not mentioned otherwise, all the noise measurements were conducted in the right lane of the pavement at 96 [km/h] (60 [mph]). The test operator is the key person in OBSI testing procedure. The operator is responsible for fixing the different components of OBSI system, perform quality control activities, calibrate the microphones, operate and control the test using the preinstalled OBSI software on the laptop. In addition, the operator is also responsible to collect noise measurements at the specified sections and to validate each measurement in real time.

Prior to starting the actual testing on public roads, in-house training for OBSI system assembly was performed. Furthermore, several trial tests were conducted in Qatar University campus for practice purposes. The trial tests were performed to confirm the stability of the different testing components while driving at various speeds. These tests also aimed to verify the repeatability of the measured noise data. All standard settings with quality control activities were also conducted.

The measurement run was taken as an average of five seconds noise recording. A minimum of three valid runs was conducted in each section. The average of the multiple runs in each section is then taken to represent the measured intensity level (MIL) and normalized intensity level (NIL). Table 3 and Table 4 show the MILs and the NILs in a trial section, respectively.

Table 3

Sample results of MILs from a trial section

MIL	**IL [dB(A)]**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**	**1250 Hz**	**1600 Hz**	**2000 Hz**	**2500 Hz**	**3150 Hz**	**4000 Hz**	**5000 Hz**
Run 0001	81.3	68.5	71.3	71.1	74.1	75.9	72.9	68.4	68.1	63.2	58.4	54.0	49.8
Run 0002	81.3	68.5	71.2	70.8	74.1	75.9	73.2	68.6	68.1	63.1	58.6	54.3	50.2
Run 0003	81.4	68.5	71.4	71.2	74.2	76.0	73.2	68.9	68.6	63.6	59.1	55.0	51.0
Average [dBA]	**81.3**	**68.5**	**71.3**	**71.0**	**74.1**	**75.9**	**73.1**	**68.6**	**68.2**	**63.3**	**58.7**	**54.4**	**50.3**
IL Range	0.2	0.1	0.2	0.3	0.1	0.1	0.3	0.4	0.5	0.5	0.7	1.0	1.2
Avg. Coherence		1.00	1.00	1.00	1.00	0.99	0.99	0.94	0.92	0.95	0.92	0.86	0.78
Avg. PI Index [dB]		1.6	1.9	1.3	1.0	1.1	1.2	1.9	2.1	2.0	2.2	2.3	3.1

Table 4

Sample results of NILs from a trial section

NIL	**IL [dB(A)]**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**	**1250 Hz**	**1600 Hz**	**2000 Hz**	**2500 Hz**	**3150 Hz**	**4000 Hz**	**5000 Hz**
Run 0001	82.4	69.6	72.5	72.2	75.3	77.0	74.1	69.6	69.2	64.3	59.6	55.2	50.9
Run 0002	82.5	69.7	72.4	72.0	75.3	77.1	74.4	69.8	69.3	64.3	59.7	55.5	51.4
Run 0003	82.6	69.7	72.5	72.3	75.3	77.1	74.4	70.0	69.7	64.8	60.3	56.1	52.2
Average [dBA]	**82.5**	**69.7**	**72.5**	**72.2**	**75.3**	**77.1**	**74.3**	**69.8**	**69.4**	**64.5**	**59.9**	**55.6**	**51.5**

According to AASHTO procedure T 360-16, the following conditions must be satisfied in any OBSI noise measurement to be considered a valid run:

- The difference between sound intensity and pressure at any given frequency must be less than AASHTO standard specified value.
- The coherence between two microphones must be greater than 0.8 for the frequency range 400 Hz to 4000 Hz.
- Run-to-run variability among three runs shall be less than 1 [dB(A)] for overall MILs and less than 2 [dB(A)] for MILs at 1/3rd octave band frequency levels.

Figure 17 and *Figure 18* illustrate the validation process by OBSI software. The software also provides frequency response plots and measurement time history for both MILs and NILs as an average of the multiple runs as shown in *Figure 19* to *Figure 22*.

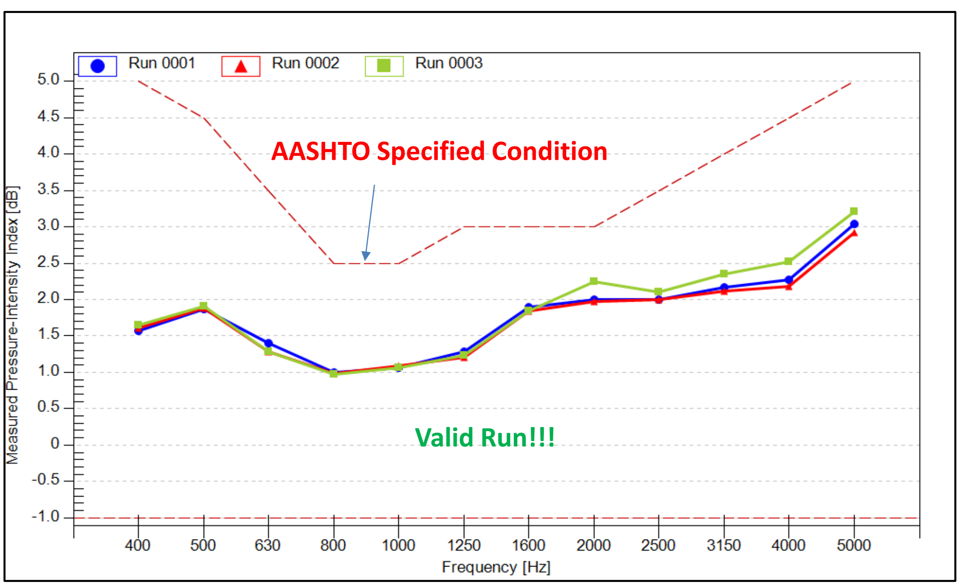


Figure 17. Measured pressure-intensity index in a trial section

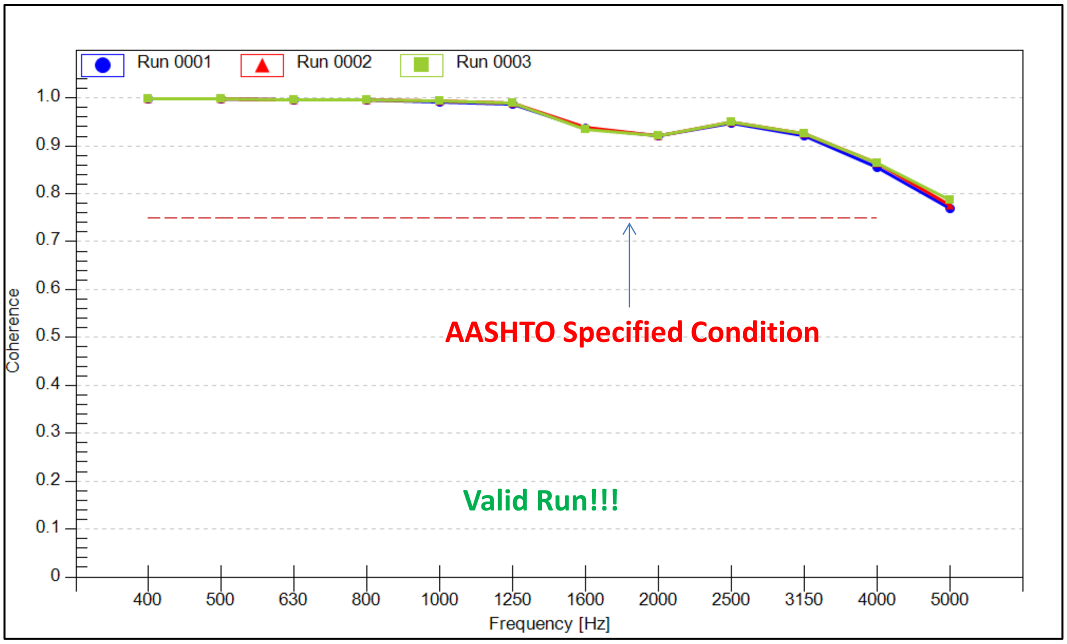


Figure 18. Coherence in a trial section

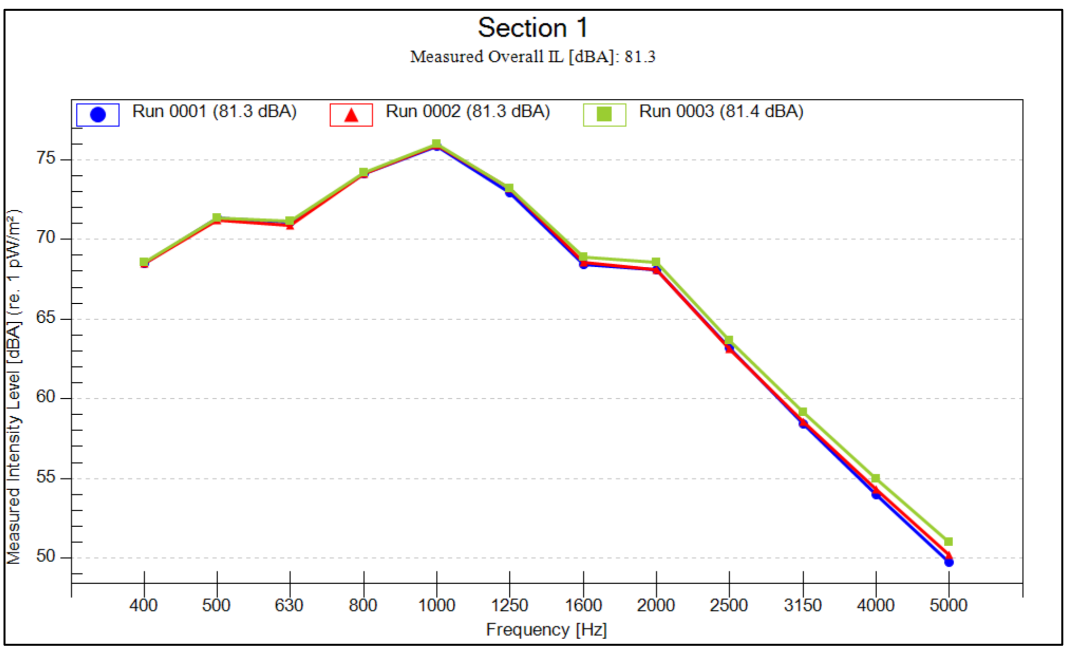


Figure 19. Frequency response of MILs for trial runs used in average

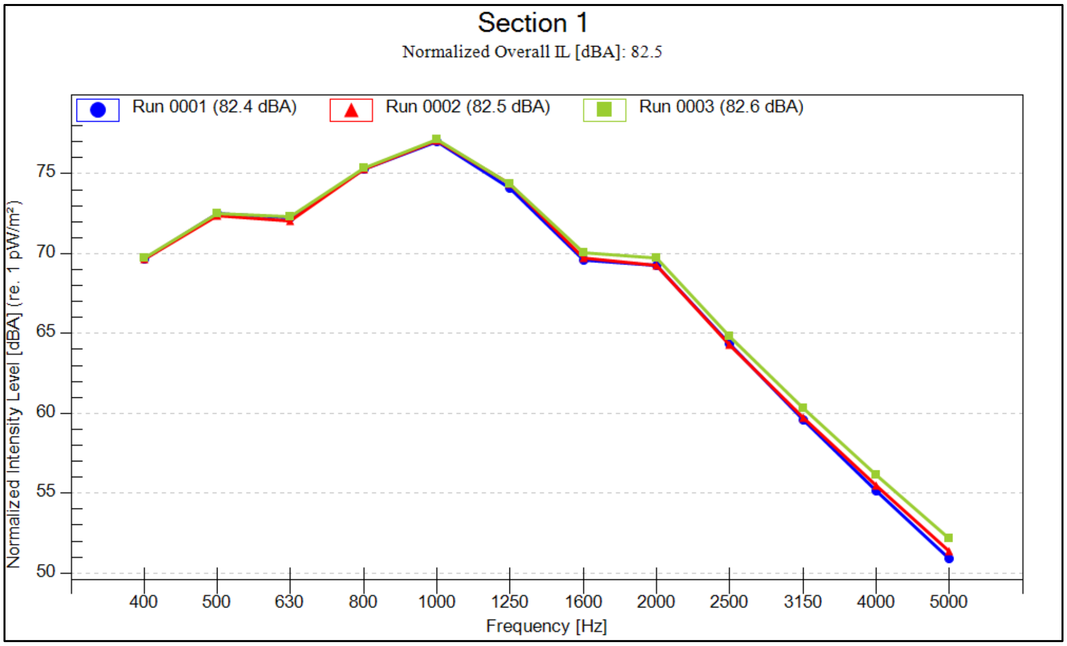


Figure 20. Frequency response of NILs for trial runs used in average

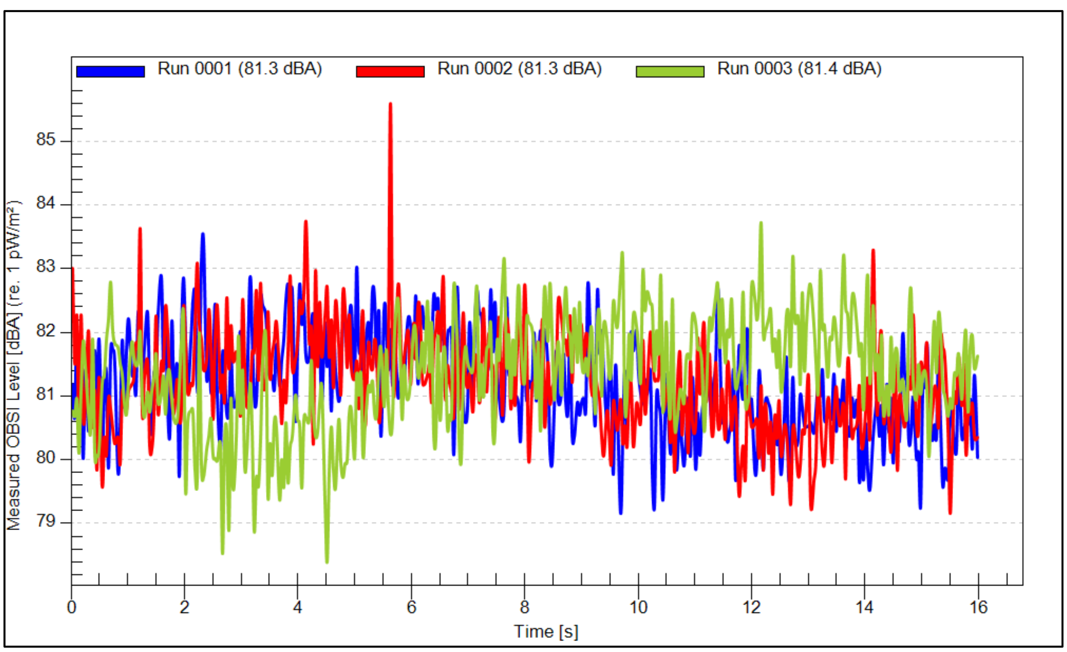


Figure 21. MILs time history in a trial section

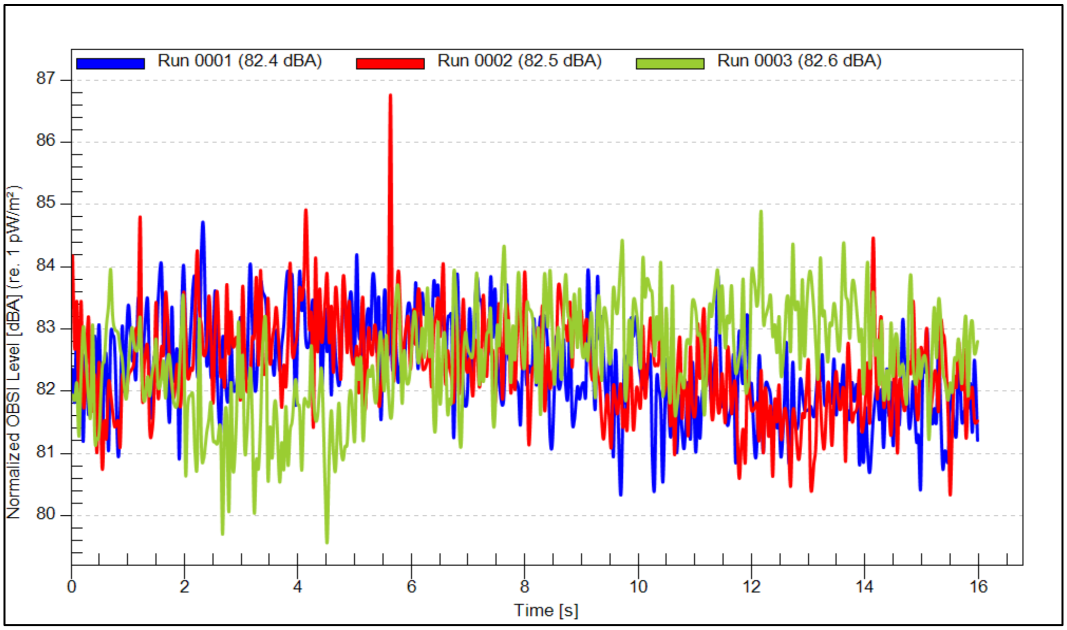


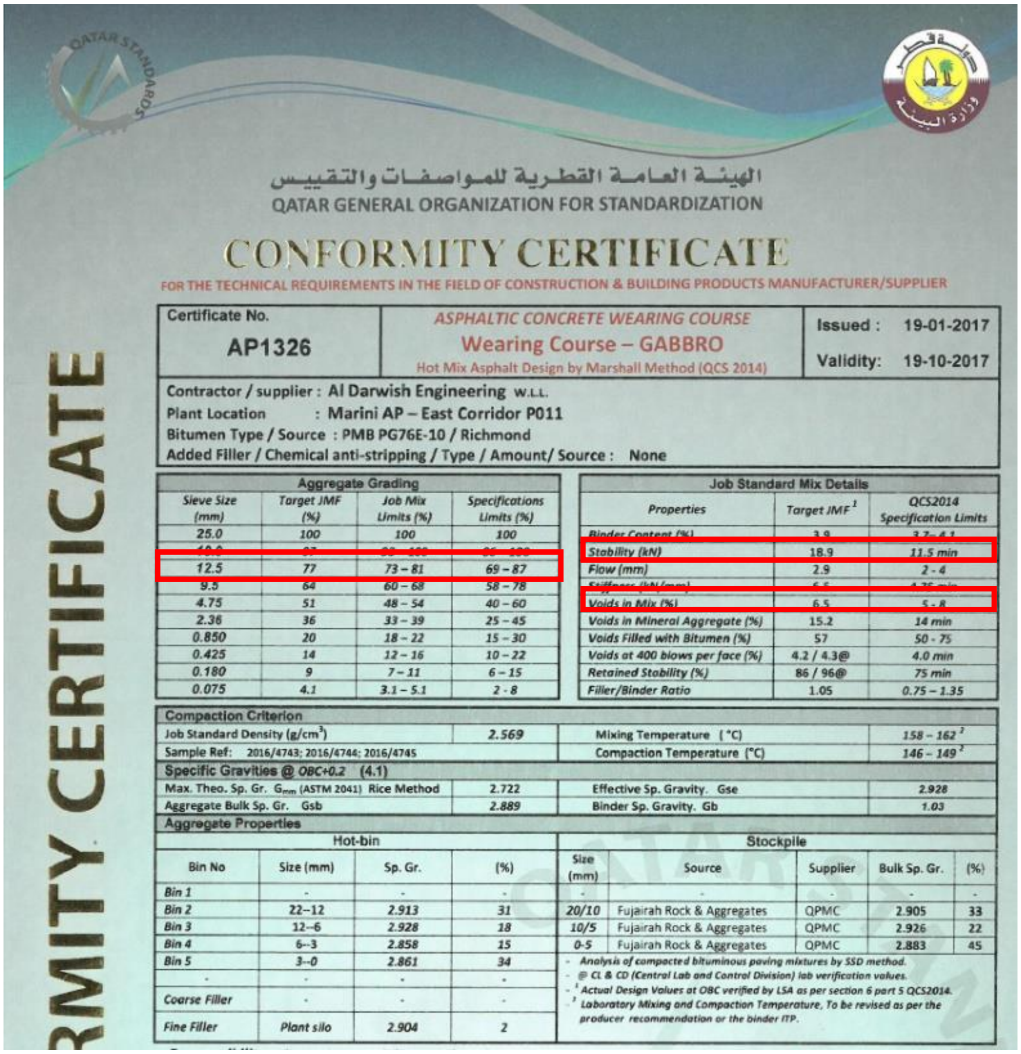
Figure 22. NILs time history in a trial section

3.3 Collection of Pavements As-Built Mix Design Data

One of the objectives of this study is to investigate the effect of pavement characteristics related to the pavement mix design on the tire-pavement interaction noise. The as-built pavement mix design data were obtained from Public Works Authority (PWA) in Qatar. The availability of pavement mix design was one of the main criteria to select expressways for noise measurements. The data were provided in the form of Conformity Certificate. The Conformity Certificate is a document that is issued for the contractors to authorize the use of a certain asphalt Job Mix Formula (JMF). It specifies the job standard mix details, the source of materials, and acceptable gradation limits as per the latest issue of Qatar Construction Specifications (QCS). In case that there was more than one JMF issued in the construction of a certain road, the pavement as-built drawings were used to specify the used JMF in the required sections. Also, interviews with the relevant engineers in PWA, consultants, or contractors were also conducted to confirm the used JMF in the construction. The Conformity Certificate for the surface wearing course in the G Ring road is shown in *Figure 23*. The values of (NMAS), air void, and binder content are highlighted in *Figure 23*. Furthermore, the age of selected pavements, at the time of measurement, was obtained from PWA through road opening press release. The relevant engineers in PWA, consultants, or contractors were also communicated to verify the dates of road opening.

3.4 Summary

OBSI noise method was selected for quantifying tire-pavement interaction noise in this study. The adopted noise testing procedure was in accordance with AASHTO standard (AASHTO T 360-16 2016). At first, repeatability and validity of the data were examined by performing trial runs in the campus of Qatar University. Once, it was proved that assembled testing setup producing data with excellent repeatability and validity, then OBSI test was performed on various pavement sections in the State of Qatar. The pavement age and as-built pavement mix design have been collected from the records of Qatar' PWA.



الهيئـة العامـة القطـرية للمـواصفـات والتقييـس

QATAR GENERAL ORGANIZATION FOR STANDARDIZATION

CONFORMITY CERTIFICATE

FOR THE TECHNICAL REQUIREMENTS IN THE FIELD OF CONSTRUCTION & BUILDING PRODUCTS MANUFACTURER/SUPPLIER

Certificate No.	ASPHALTIC CONCRETE WEARING COURSE	Issued : 19-01-2017
AP1326	Wearing Course – GABBRO Hot Mix Asphalt Design by Marshall Method (QCS 2014)	Validity: 19-10-2017

Contractor / supplier : Al Darwish Engineering W.L.L.
Plant Location : Marini AP – East Corridor P011
Bitumen Type / Source : PMB PG76E-10 / Richmond
Added Filler / Chemical anti-stripping / Type / Amount/ Source : None

Aggregate Grading

Sieve Size (mm)	Target JMF (%)	Job Mix Limits (%)	Specifications Limits (%)
25.0	100	100	100
19.0	97	90 – 100	[illegible]
12.5	77	73 – 81	69 – 87
9.5	64	60 – 68	58 – 78
4.75	51	48 – 54	40 – 60
2.36	36	33 – 39	25 – 45
0.850	20	18 – 22	15 – 30
0.425	14	12 – 16	10 – 22
0.180	9	7 – 11	6 – 15
0.075	4.1	3.1 – 5.1	2 - 8

Job Standard Mix Details

Properties	Target JMF [1]	QCS2014 Specification Limits
Binder Content (%)	3.9	3.7 – 4.1
Stability (kN)	18.9	11.5 min
Flow (mm)	2.9	2 - 4
Stiffness (kN/mm)	6.5	4.75 min
Voids in Mix (%)	6.5	5 - 8
Voids in Mineral Aggregate (%)	15.2	14 min
Voids Filled with Bitumen (%)	57	50 - 75
Voids at 400 blows per face (%)	4.2 / 4.3@	4.0 min
Retained Stability (%)	86 / 96@	75 min
Filler/Binder Ratio	1.05	0.75 – 1.35

Compaction Criterion

Job Standard Density (g/cm^3)	2.569	Mixing Temperature (°C)	158 – 162 [2]
Sample Ref: 2016/4743; 2016/4744; 2016/4745		Compaction Temperature (°C)	146 – 149 [2]

Specific Gravities @ OBC+0.2 (4.1)

Max. Theo. Sp. Gr. G_{mm} (ASTM 2041) Rice Method	2.722	Effective Sp. Gravity. Gse	2.928
Aggregate Bulk Sp. Gr. Gsb	2.889	Binder Sp. Gravity. Gb	1.03

Aggregate Properties

Hot-bin

Bin No	Size (mm)	Sp. Gr.	(%)
Bin 1	-	-	-
Bin 2	22--12	2.913	31
Bin 3	12--6	2.928	18
Bin 4	6--3	2.858	15
Bin 5	3--0	2.861	34
-	-	-	-
Coarse Filler	-	-	-
Fine Filler	Plant silo	2.904	2

Stockpile

Size (mm)	Source	Supplier	Bulk Sp. Gr.	(%)
-	-	-	-	-
20/10	Fujairah Rock & Aggregates	QPMC	2.905	33
10/5	Fujairah Rock & Aggregates	QPMC	2.926	22
0-5	Fujairah Rock & Aggregates	QPMC	2.883	45

- Analysis of compacted bituminous paving mixtures by SSD method.
- @ CL & CD (Central Lab and Control Division) lab verification values.
- [1] Actual Design Values at OBC verified by LSA as per section 6 part 5 QCS2014.
- [2] Laboratory Mixing and Compaction Temperature, To be revised as per the producer recommendation or the binder ITP.

RMITY CERTIFICATE

Figure 23. Conformity certificate of G Ring Road

CHAPTER 4: EFFECT OF VEHICLE SPEED ON TIRE-PAVEMENT INTERACTION NOISE

4.1 Introduction

Vehicle driving speed is considered one of the governing factors that influence tire-pavement interaction noise and traffic noise in general. The previous research efforts conducted on this topic is summarized in the literature (Section 2.4.1). Tire-pavement interaction noise was found to be positively correlated with driving speed. Some researchers stated that tire-pavement noise level is linearly proportional to vehicle speed and the noise intensity level increases in a range of 0.18 to 0.3 [dB(A)/mph] (Bennert, et al. 2005, Donavan and Lodico 2009, Wang, et al. 2011, Mogrovejo, et al. 2014). However, other research studies found that there is a logarithmic correlation between tire-pavement noise and vehicle driving speed (Haas 2013, Cho and Mun 2008, Mak, Hung and Lee, et al. 2012). The logarithmic correlation factor was found to be 9.247 *ln* [dB(A)/kmph] (14.879 *ln* [dB(A)/mph]) (Haas 2013). Generally, the variation in speed correlation coefficients in previous studies was due to the differences of the pavement surfaces and adopted noise measurement methods. Therefore, there is a need to conduct a comprehensive evaluation for speed effect on tire-pavement interaction noise to develop a correlation factor that is valid for Qatar's conditions.

4.2 Objectives

This chapter aims to evaluate the correlation of tire-pavement interaction noise and driving speed in Qatar, through conducting designed OBSI field noise experiments. This chapter also presents a prediction model for tire-pavement interaction noise with respect to driving speed. This model can be used in determining posted speed limits in urban areas to reduce noise pollution.

4.3 Methodology

Two OBSI field noise experiments were designed to examine the effect of driving speed on tire-pavement interaction noise. Both experiments were carried out on two expressways with different pavement characteristics. At first, OBSI testing was performed on multiple sections on Al Shamal expressway. This road was built six years ago with 14 [mm] NMAS as per QCS2007 design criteria. The noise field measurements were carried out using nine different speeds ranged from 40 to 120 [km/h]. The wide range of speed was intended to gain sufficient set of data to establish the correlation. Then, OBSI testing was carried out on multiple sections at Lijmiliya expressway. Lijmiliya expressway was recently constructed (7 months old) using 19 [mm] NMAS as per QCS2014. The noise testing was carried out using AASHTO (2016) recommended testing speeds of 96, 75, 56 [km/h] (60, 45 and 35 [mph]) so that comparison can be made with other noise studies. The details of the two OBSI field noise experiments are summarized in Table 5. The locations of the tested sections are highlighted in *Figure 24* and *Figure 25*.

Table 5

Details of noise field experiments on Al Shamal and Lijmiliya expressways

Name	Al Shamal Expressway	Lijmiliya Expressway
Number of Sections	4	10
Test Date	March 2017	May 2017
Temperature	30.1 °C	38.4 °C
Pavement Age	six years	seven months
Surface Type	DGAC (14 NMAS)	DGAC (19 NMAS)
Speeds (km/h)	40, 50, 60, 70, 80, 90, 100, 110, 120	56, 72, 96

Figure 24. Location of test sections at Al Shamal expressway

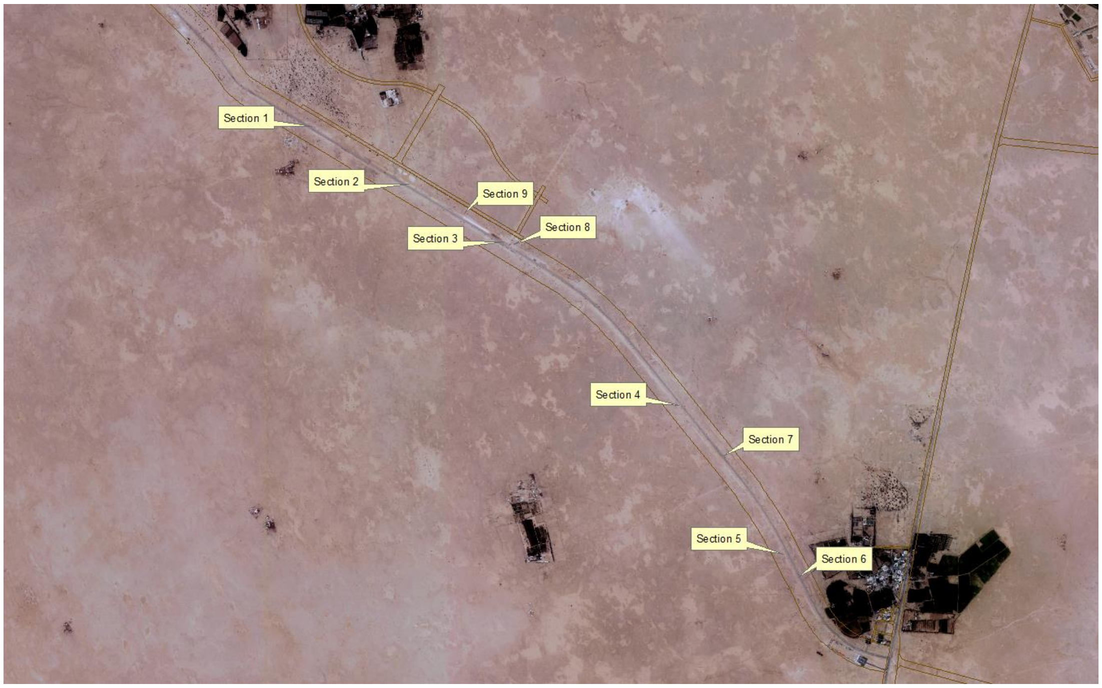


Figure 25. Location of test sections at Lijmiliya expressway

4.4 Noise Test Results

The noise test results of Al Shamal and Lijmiliya experiments are shown in Table 6 and Table 7, respectively. The MILs and NILs on each section within the two expressways are shown in Appendix A. The variation of noise levels between the different sections under the same driving speeds was minimal. Hence, the noise levels were considered in the analysis for comparison purposes.

Table 6

Averaged noise test results on Al Shamal expressway

Speed [km/h]	MIL [dB(A)]	NIL [dB(A)]
40	89.50	89.85
50	91.98	92.33
60	95.03	95.38
70	97.48	97.80
80	99.13	99.45
90	100.8	101.18
100	102.28	102.60
110	103.23	103.53
120	104.08	104.45

Table 7

Averaged noise test results on Lijmiliya expressway

Speed [km/h]	MIL [dB(A)]	NIL [dB(A)]
56.3	93.85	95.24
72.4	97.33	98.64
96.5	100.82	102.16

4.5 Analysis and Discussion

A total of nine driving speeds and the corresponding noise MILs on Al Shamal expressways are shown in *Figure 26*. The bar chart clearly illustrates that noise MILs are increasing when the driving speed increases. The highest MIL was 104.8 [dB(A)], corresponding to the highest tested driving speed (120 [km/h]). Similarly, the lowest MIL was 89.5 [dB(A)], corresponding to the lowest tested speed (40 [km/h]). The difference between the highest and the lowest MIL was 14.58 [dB(A)]. This considerable variation in MILs demonstrates the influence of driving speed on tire-pavement interaction noise.

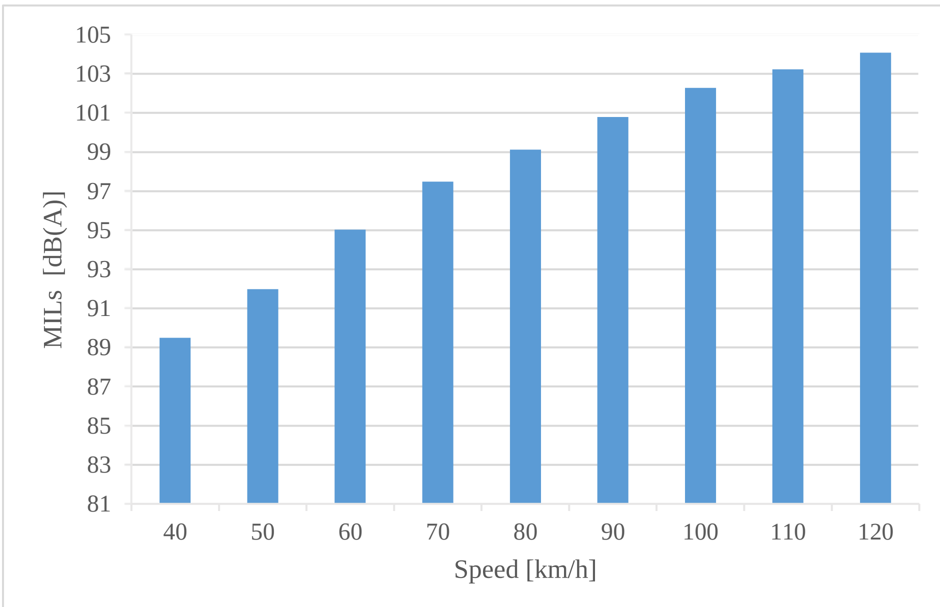


Figure 26. MILs on Al Shamal expressway under various driving speeds

The resulted noise MILs on Lijmiliya expressway are shown in *Figure 27*. The figure also confirms the direct correlation between noise MILs and the driving speed. The averaged MILs were 100.82, 97.33, and 93.85 [dB(A)], corresponding to the three tested standard speeds 56, 72, and 96 [km/h], respectively.

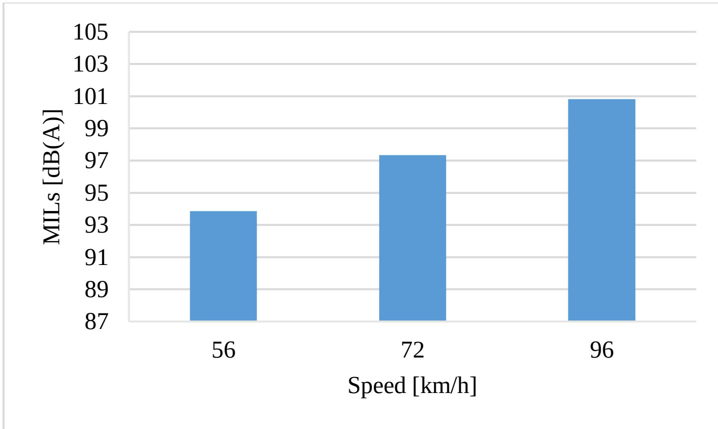


Figure 27. MILs on Lijmiliya expressway under various driving speeds

Assuming a linear relationship between tire-pavement interaction noise and the driving speed, the MILs on both experiments showed a similar rate of change of 0.18 [dB(A) per km/h] as shown in Table 8 and Table 9. This finding indicates that tire-pavement interaction noise increases about 1.8 [dB(A)] when the vehicle driving speed increases by 10 [km/h].

Table 8

MILs rate of change under various driving speeds on Al Shamal Expressway

Speed [km/h]	MIL [dB(A)]	Rate of Change	Average Rate of Change [dB(A) per (km/h)]
40	89.5	-	
50	91.98	0.248	
60	95.03	0.305	
70	97.48	0.245	
80	99.13	0.165	0.182
90	100.8	0.167	
100	102.28	0.148	
110	103.23	0.095	
120	104.08	0.085	

Table 9

MILs rate of change under various driving speeds on Lijmiliya Expressway

Speed [km/h]	**MIL [dB(A)]**	**Rate of Change**	**Average Rate of Change [dB(A) per (km/h)]**
56.3	93.85	-	
72.4	97.33	0.216	0.180
96.5	100.82	0.145	

4.5.1 Effect of Speed in Noise Spectrum

Spectral analysis was conducted on the measured noise data in both experiments to gain additional insight into the correlation of driving speed with tire-pavement noise. The MILs at 1/3rd octave band frequency level for each tested speed on Al Shamal and Lijmiliya expressways are illustrated in *Figure 28* and *Figure 29*, respectively. It can be seen from both figures that the DGAC surfaces maintained similar acoustic signature at different speeds. Additionally, MILs in large frequencies, 1000 to 5000 [Hz], are increasing in magnitude only when the speed increases. However, this is not valid for small frequencies, 400 Hz to 800 Hz, which fluctuate slightly in both magnitude and tonal quality. This fluctuation at low frequencies is probably due to the slight variation of surface texture in the different sections.

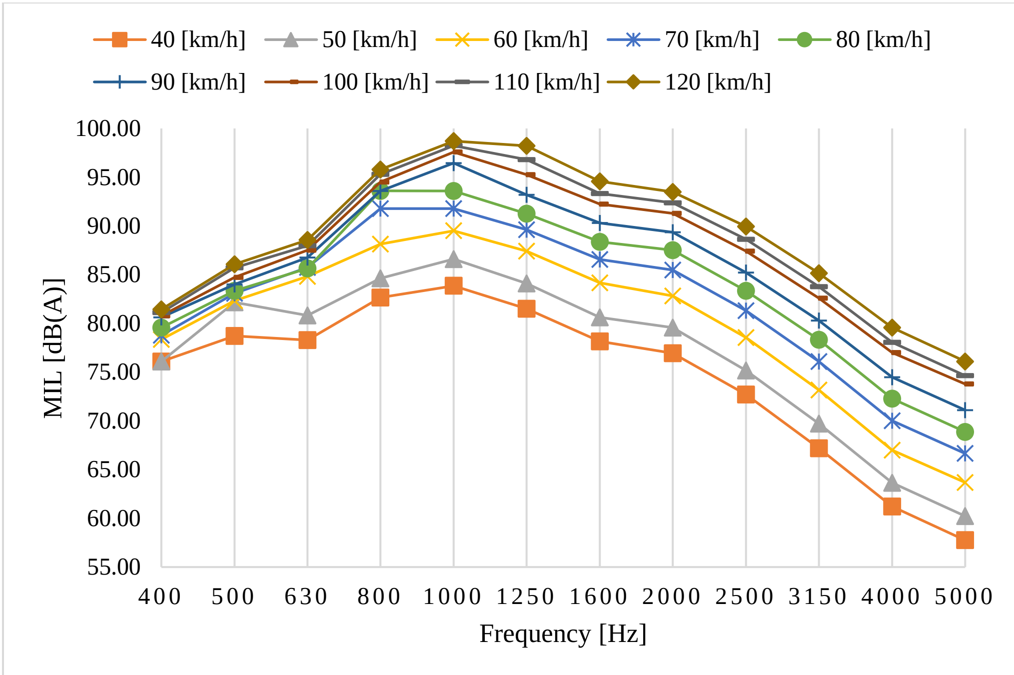


Figure 28. Effect of speed on noise spectrum on Al Shamal expressway

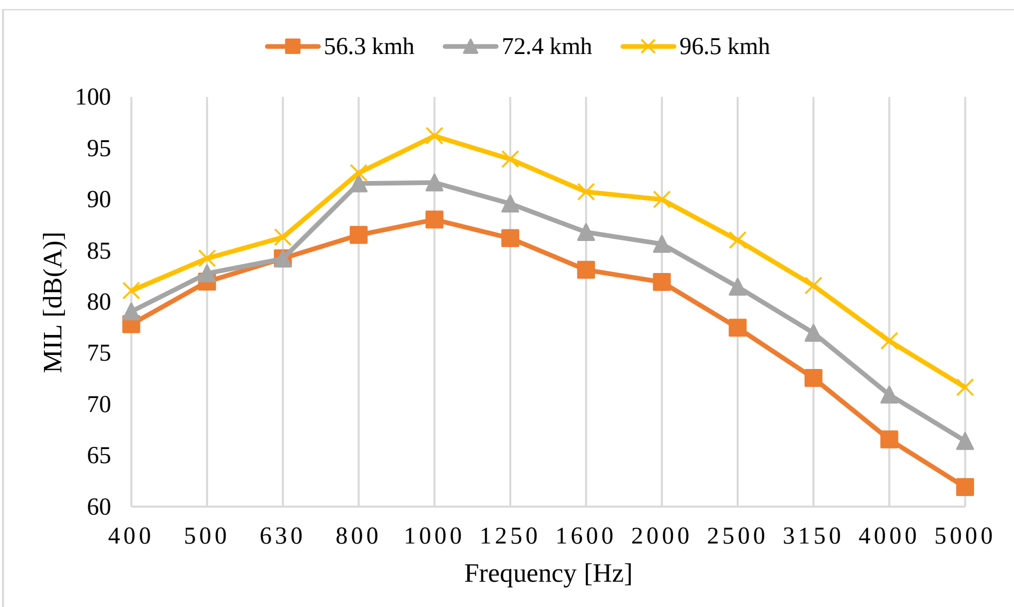


Figure 29. Effect of speed on noise spectrum on Lijmiliya expressway

4.5.2 Regression Analysis of Noise MILs and Speed

A regression analysis was conducted on the data of the two field noise experiments to quantify MIL correlation with driving speed. As shown in *Figure 30*, MILs rate of change with respect to driving speeds was large initially and then gradually decreased at higher speeds. Consequently, a logarithmic trendline gave the best-fit curve to represent the relationship. The logarithmic trendline also gave the best-fit curve for the data of Lijmiliya experiment as shown in *Figure 31*. The obtained speed coefficients in Al Shamal and Lijmiliya experiments were relatively similar, 13.754 *ln* and 12.916 *ln* [dB(A) per 1 km/h], respectively. The slight variation in speed coefficients could be justified by the different range of speeds; Al Shamal regression model examined nine speeds, while the other model included only the three recommended testing speeds in AASHTO standard (AASHTO T 360-16 2016).

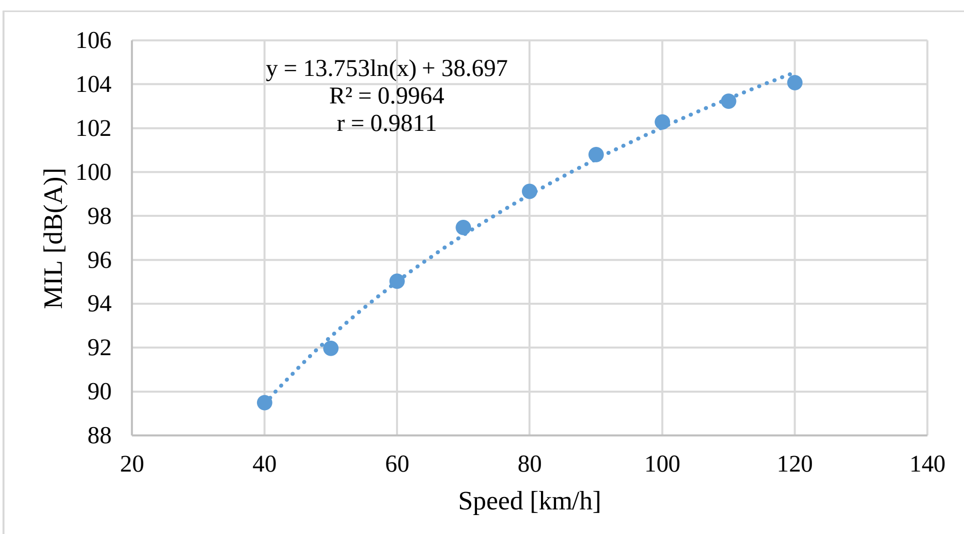


Figure 30. Regression analysis for the noise data on Al Shamal expressway

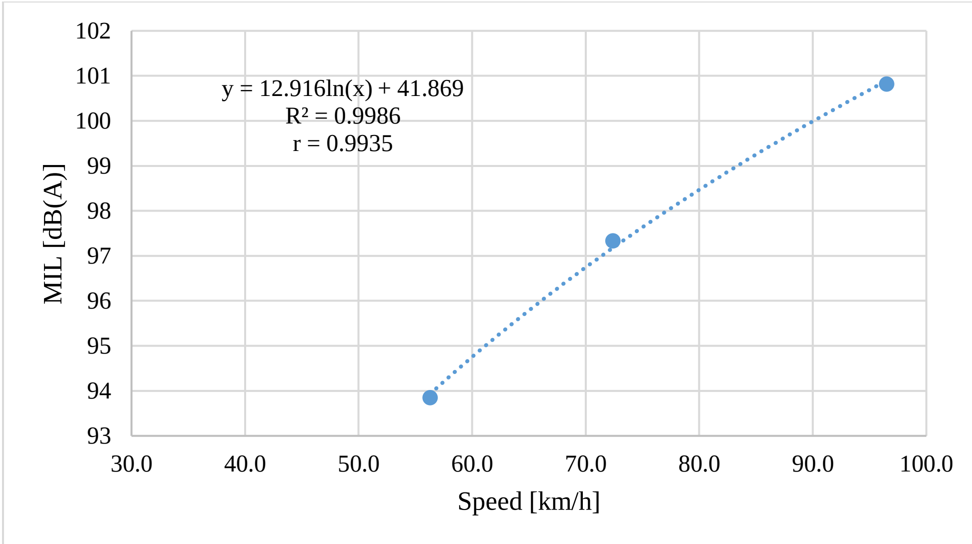


Figure 31. Regression analysis for the noise data on Lijmiliya expressway

Moreover, the coefficients of determination (R square) in both experiments indicated that more than 99% of the total variation in tire-pavement interaction noise was explained by the logarithmic correlation with driving speed.

The correlation of noise MIL with speed was also investigated for each 1/3rd octave band frequency. Table 10 presents the speed coefficients and coefficients of determination. The data shows that the correlation is more prominent in higher frequencies (1000 to 5000 Hz) than lower frequencies (400 to 800 Hz). Nevertheless, the correlation of MIL with speed was significant in all 1/3rd octave band frequencies.

Table 10

Regression Analysis for MIL in each Frequency

Road Name	Al Shamal Expressway		Lijmiliya Expressway	
Number of Sections	4		10	
Speeds [km/h]	40, 50, 60, 70, 80, 90, 100, 110, 120		56, 72, 96	
Frequency [Hz]	**Speed Coefficient**	**R^2**	**Speed Coefficient**	**R^2**
400	5.534ln	0.8699	6.0912ln	0.8626
500	5.3703ln	0.856	4.2892ln	0.8084
630	8.4767ln	0.887	3.9044ln	0.6592
800	12.577ln	0.9294	11.066ln	0.8392
1000	14.468ln	0.9838	15.16ln	0.9737
1250	15.517ln	0.9947	14.363ln	0.9732
1600	15.527ln	0.9952	14.131ln	0.9738
2000	15.759ln	0.9939	14.98ln	0.9631
2500	16.463ln	0.9934	15.867ln	0.9673
3150	17.245ln	0.9916	16.705ln	0.9715
4000	17.786ln	0.9905	17.861ln	0.9763
5000	17.811ln	0.9923	18.116ln	0.969

The minor reduction in the values of coefficients of determination for lower frequencies can be justified by the variation in measurement locations within the section during experiments. It’s hypothesized that at lower frequency surface texture dominates

MIL because of the thread impact mechanism (Bernhard and Wayson 2005)

4.5.3 NIL Prediction Model with respect to Driving Speed

The obtained results from the noise experiments were used to develop a prediction model for tire-pavement interaction noise with regard to vehicle driving speed. Prior to combining the results of the two experiments, MILs were normalized as per AASTHO procedure (AASHTO T 360-16 2016). The NILs were used to develop the model, instead of MILs, to avoid any bias since the two noise experiments were conducted in slightly varying meteorological condition. The NILs under different driving speeds for all sections on Al Shamal and Lijmiliya expressways are shown in Figure 32.

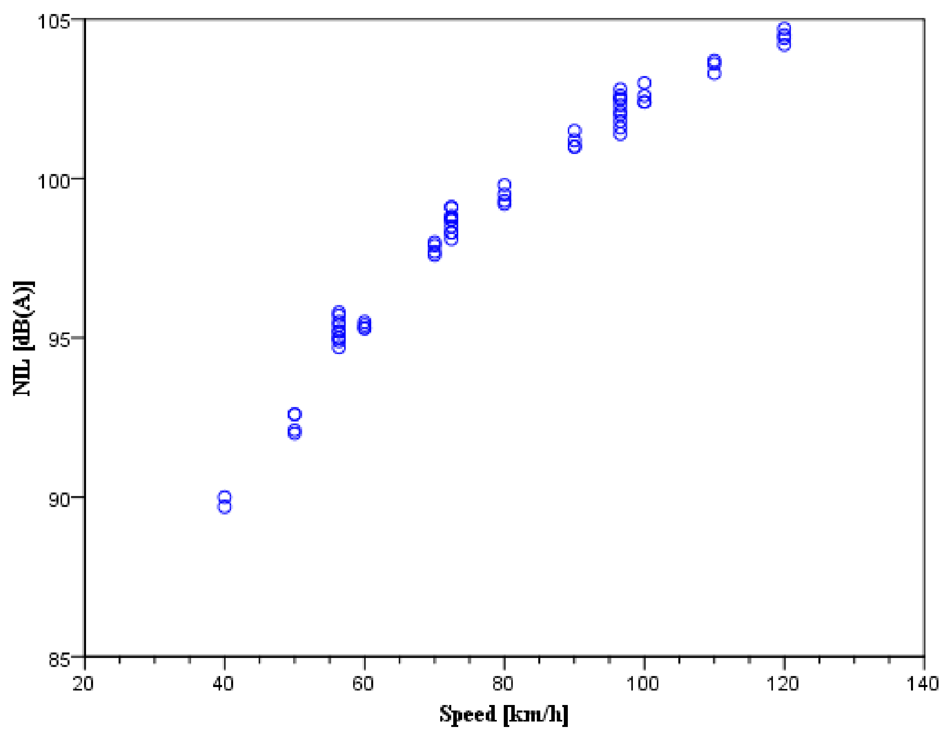


Figure 32. NILs under different driving speeds on both expressways

A simple logarithmic regression model was adopted to predict tire-pavement interaction noise with respect to speed. The model was developed using SPSS statistical software. The SPSS output for the simple regression analysis is shown in *Figure 33*.

Logarithmic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.992	.984	.984	.486

The independent variable is Speed [km/h].

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	886.584	1	886.584	3750.397	.000
Residual	14.420	61	.236		
Total	901.004	62			

The independent variable is Speed [km/h].

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
ln(Speed [km/h])	13.400	.219	.992	61.240	.000
(Constant)	40.838	.948		43.070	.000

Figure 33. Simple regression output in SPSS

It can be seen from the output that the obtained speed coefficient was 13.4(ln) [dB(A) per 1 km/h]. The p-value ($1.7x10^{-56}$) and the standard error (0.219) of the speed coefficient emphasized the significance of the model. Moreover, the logarithmic correlation coefficient (R-value) was 0.984. The coefficient of determination (R square) shows that

98.4% of the total variation in NILs within the model was explained by the logarithmic relationship with driving speed. The prediction model is presented in Equation 3:

$$Predicted\ NIL\ [dB(A)] = 13.4 \ln\left(speed\ \left[\frac{km}{h}\right]\right) + 40.838 \qquad (3)$$

The model is limited to DGAC surfaces with a speed range of 40 to 120 [km/h]. The resulted speed coefficient (13.4 *ln* [dB(A)/kmph]) was relatively large comparing to the reported coefficient (9.247 *ln* [dB(A)/kmph]) by Haas (2013). Nevertheless, this study is more comprehensive since it included a total of 63 noise measurements using 12 different speeds. The measured NILs and the logarithmic regression best-fit curve are shown in *Figure 34*.

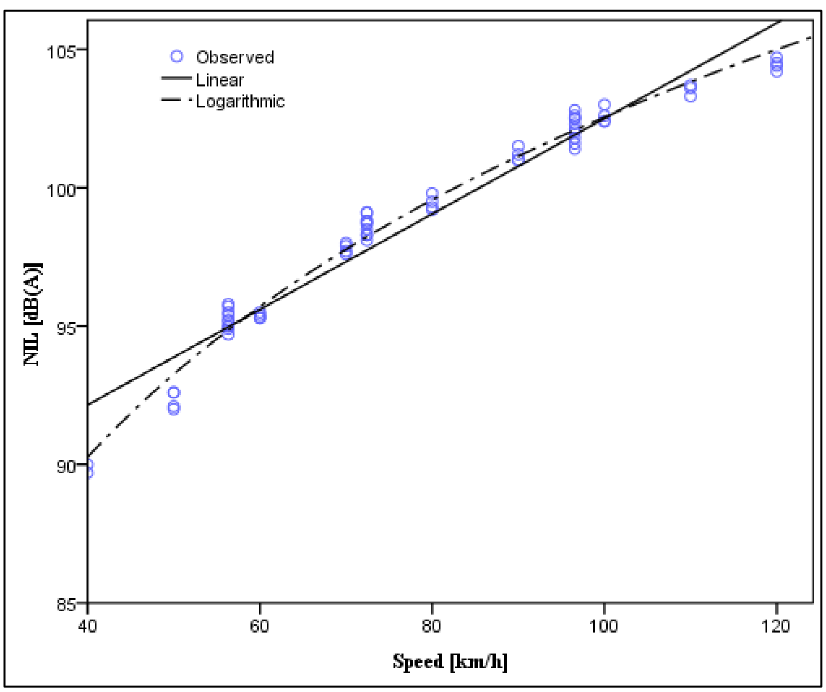


Figure 34. Best-fit curve for NILs prediction model

4.6 Summary and Conclusions

This chapter conducted a comprehensive evaluation of the effect of driving speed on tire-pavement interaction noise. Two designed OBSI field experiments were conducted on two different expressways constructed with DGAC surfaces, Al Shamal and Lijmiliya. A total of 63 OBSI measurements were carried out using twelve different driving speeds.

Tire-pavement noise was found to be positively correlated with driving speed. Assuming a linear relationship between MILs and speed, it can be concluded that that tire-pavement interaction noise increases about 1.8 [dB(A)] when the speed increases 10 [km/h]. However, correlation of tire-pavement noise and driving speed was found to be better represented by a logarithmic curve.

Noise spectral analysis at 1/3rd octave band demonstrated a similar acoustic signature for all DGAC surfaces under speed variation. The MILs frequency response under speed variations was consistent in large frequencies (1000 Hz to 5000 Hz). Nevertheless, there was a slight low variation in frequency response with speed in low frequencies (400 Hz to 800 Hz).

A simple regression analysis was performed using the collected data on each expressway separately to verify MILs correlation with speed. Logarithmic trendlines gave the best-fit curves to represent the measured noise data variation in both expressways. The rate of change of measured noise intensity level was 13.754 *ln* [dB(A) per 1 km/h] in the Al Shamal experiment and 12.916 *ln* [dB(A) per 1 km/h] in Lijmiliya experiment. Nonetheless, this slight variation was considered inconsequential. Regression analysis was also conducted on MILs at each 1/3rd octave band frequency. The results showed that the correlation between tire-pavement interaction noise and speed is more prominent in higher frequencies (1000 to 5000 Hz) than those of lower frequencies (400 to 800 Hz).

The chapter concluded with presenting a simple logarithmic regression model to predict noise NIL with respect to driving speed. The obtained speed coefficient was 13.4 *ln* [dB(A) per 1 km/h]. The model explained 98.4% of the noise variation by the correlation with the speed. The model can be used in determining posted speed limits on expressways, especially in urban areas where expressways are located within residential areas. Moreover, the model will provide researchers with a tool to compare noise measurements taken at different speeds in Qatar.

CHAPTER 5: EFFECT OF TEMPERATURE ON TIRE-PAVEMENT INTERACTION NOISE

5.1 Introduction

Tire-pavement interaction noise varies with the ambient temperature as discussed in section 2.4.2 of the literature review. This inverse correlation was expressed by a linear coefficient that ranged between -0.001 and -0.14 [dB (A)/ °C]; depending on the type of pavement surface, tires, and noise measurement method. The impact of ambient temperature on tire-pavement noise was also found more prominent in DGAC surfaces than that of other types of surfaces such as open-graded, porous, and PCC surfaces. To avoid bias due to varying temperature, AASHTO recommended a linear adjustment coefficient of 0.072 [dB(A)/°C] (0.040 [dB(A)/°F]) to normalize MILs to a reference ambient temperature of 20°C (68 °F) (AASHTO T 360-16 2016).

Previous research studies presented in section 2.4.2 examined the behavior of tire-pavement noise within a range of temperatures that don't exceed 38 °C (100 °F). This may be due the fact that the published studies were conducted mostly in Europe, USA, and Far East countries. Additionally, AASHTO procedure recommends a temperature range between 4 and 38°C (40 to 100°F) to avoid overheating or overloading of preamplifiers (AASHTO T 360-16 2016). However, in the Gulf region, ambient temperatures often exceed 38°C during summer times. Therefore, this chapter will investigate the tire-pavement interaction noise at hot temperatures to properly evaluate the tire-pavement noise in this region.

Furthermore, some studies investigated the temperature effect on tire-pavement interaction noise by conducting noise measurements on different environmental seasons to capture a wide range of temperatures (Lédée and Pichaud 2007). However, such testing methodology increased the possibility of errors as the surface texture may change with time due to the combined effects of environmental conditions and traffic. In the state of Qatar, the temperature variation between the day and at night during the summertime can reach 15°C. This large diurnal temperature variation provided an opportunity to examine the effect of temperature on tire-pavement interaction noise on the same day.

5.2 Objectives

The objective of this chapter is to examine the correlation between tire-pavement interaction noise and ambient temperature through conducing OBSI field noise experiments in the state of Qatar. The adopted testing methodology aims to reduce the effect of other parameters that may influence noise measurements, by taking advantage of the wide diurnal temperature range during summer. The chapter also presents a temperature correlation factor for tire-pavement interaction noise with the hot temperature and pavement construction materials in Qatar.

5.3 Methodology

In order to examine the ambient temperature effect on tire-pavement noise, two OBSI field measurements were carried out on two expressways, Salwa and Dukhan. Multiple sections were selected on each expressway. The sections were selected in between two closest interchanges to reduce testing time and condense variations in temperature during testing. The start point of each section was identified on site by a mile marker to ensure that the test starts at the specified sections in each expressway. The locations of the selected sections on Salwa and Dukhan expressways are shown in *Figure 35* and *Figure 36*, respectively.

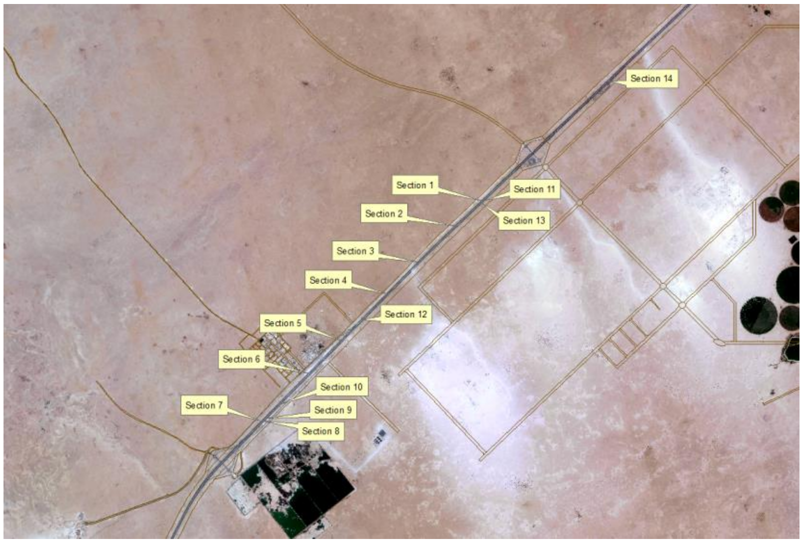


Figure 35. Location of test sections on Salwa expressway

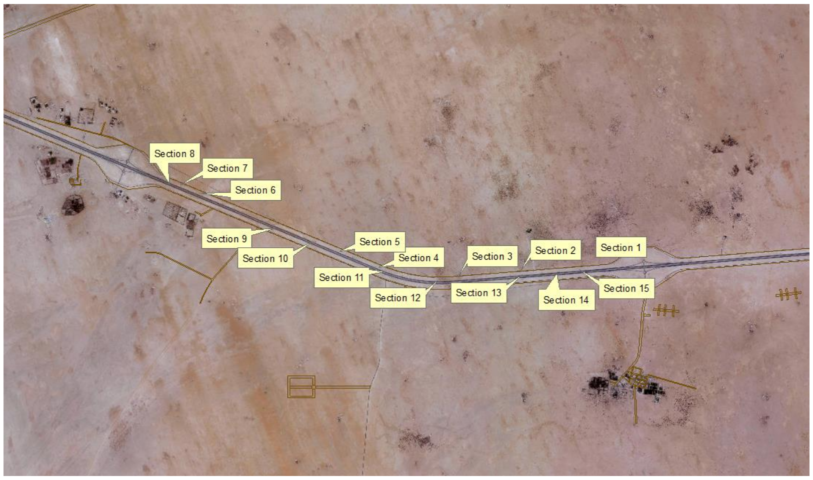


Figure 36. Location of test sections on Dukhan expressway

For each expressway, the first set of measurements were carried out at noon, when the ambient temperature is maximum (12:00 PM) and the second set of measurements were conducted at midnight when the temperature is minimum (12:00 AM). All testing was conducted in accordance with AASHTO standard (AASHTO T 360-16 2016), except for the recommended range of ambient temperatures. The adopted methodology took advantage of diurnal temperature variation in the state of Qatar during the summertime by conducting the noise measurements on the same day. This helped in eliminating the effect of other factors that may influence the noise measurement and ensure that there is only one variable in each field experiment. Hence, the conducted methodology was based on the following:

- Both measurements were conducted using one set of tires. There is no variation due to differences in tire age, inflation, rubber hardness, or wearing and tearing.
- Pavement surface in each section is exactly the same; there is no variation on the measurements due to the combined effect of atmospheric condition and traffic induced stress.
- There is no variation in measured noise level due to a change in OBSI equipment, vehicle, or operators.

The details of the noise measurements conducted on Salwa and Dukhan expressways are shown in Table 11.

Table 11

Details of noise field experiments for effect of temperature

Road Name	Dukhan Expressway	Salwa Expressway
Number of Sections	15	14
Date	April 23, 2017	April 24, 2017
Time of Day Measurement	11:39 AM	12:13 PM
Day Temperature	35.5°C (95.9°F)	39.8°C (103.6°F)
Time of Night Measurement	11:36 PM	11:28 PM
Night Temperature	26.4°C (79.5°F)	25.2°C (77.3°F)
Pavement Surface type	DGAC	DGAC
Pavement Age	7 years	8 years

5.4 Noise Test Results

The results of the two set of noise measurements at noon and midnight on Dukhan expressway experiment are shown in Table 12. The noise MILs and NILs at 1/3rd octave band frequency levels are available in Appendix B. The variation of ambient temperatures between the two set of measurements was about 9.1°C. The MILs ranged between 101.4 and 102.4 [dB(A)] in the 15 sections during the noon measurements. In the night measurements, the MILs ranged between 102.5 and 103.4 [dB(A)].

Table 12

Noise test results on Dukhan expressway

Sections	**Measurements during the Day (35.5°C)**		**Measurements during the Night (26.4°C)**	
	Overall MIL [dB(A)]	**Overall NIL [dB(A)]**	**Overall MIL [dB(A)]**	**Overall NIL [dB(A)]**
Section 1	101.6	102.7	102.8	103.2
Section 2	101.5	102.6	102.5	103
Section 3	102.4	103.5	103.4	103.9
Section 4	101.7	102.8	102.5	102.9
Section 5	101.9	103	103	103.4
Section 6	101.9	103.1	102.8	103.2
Section 7	102.2	103.3	103	103.5
Section 8	102.3	103.4	103.1	103.5
Section 9	101.7	102.8	103	103.5
Section 10	101.5	102.6	102.8	103.3
Section 11	101.8	103	103.1	103.5
Section 12	101.4	102.5	102.6	103.1
Section 13	101.5	102.6	103	103.4
Section 14	101.4	102.8	103	103.5
Section 15	101.5	102.7	102.7	103.2

Similarly, the on Salwa expressway experiment are shown in Table 13. The noise MILs and NILs at frequency level are also available in Appendix B. The variation of temperatures between the two sets of measurements in Dukhan expressway was about 14.7°C. The MILs in Salwa expressway at noon ranged between 102.3 and 104.2 [dB(A)]. At midnight, MILs in the different sections ranged between 103 and 104.8 [dB(A)].

Table 13

Noise test results on Salwa expressway

Sections	**Measurements during the Day (39.8°C)**		**Measurements during the Night (25.1°C)**	
	Overall MIL [dB(A)]	**Overall NIL [dB(A)]**	**Overall MIL [dB(A)]**	**Overall NIL [dB(A)]**
Section 1	103.3	104.7	103.7	104.1
Section 2	102.7	104.1	103	103.3
Section 3	103.7	105.1	104.1	104.5
Section 4	102.7	104.1	103.1	103.5
Section 5	103.2	104.6	103.7	104.1
Section 6	102.3	103.8	103.3	103.6
Section 7	104.2	105.6	104.8	105.2
Section 8	104	105.5	104.8	105.2
Section 9	103	104.4	103.4	103.8
Section 10	102.5	104	103.1	103.5
Section 11	103	104.4	103.6	104
Section 12	103.6	105	103.8	104.2
Section 13	102.9	104.3	103.9	104.2
Section 14	103.1	104.5	103.8	104.2

5.5 Analysis and Discussion

5.5.1 Comparison of MILs under Temperature Variation

The noise test results of the two sets of OBSI field measurements, at noon and midnight, on Dukhan expressway are shown in *Figure 37*. The first set of measurement was conducted at noon at a temperature of 35.5°C (95.9°F), while the second set of measurements were conducted at midnight at a temperature of 26.4°C (79.5°F). It can be observed from the figure that noise MILs increased in all sections when the temperature decreased at night. This finding confirms the negative correlation observed in the previous studies that investigated the relation between tire-pavement interaction noise and air temperature. *Figure 37* also shows that there are some variations in MILs, at the same ambient temperature, from one section to other.

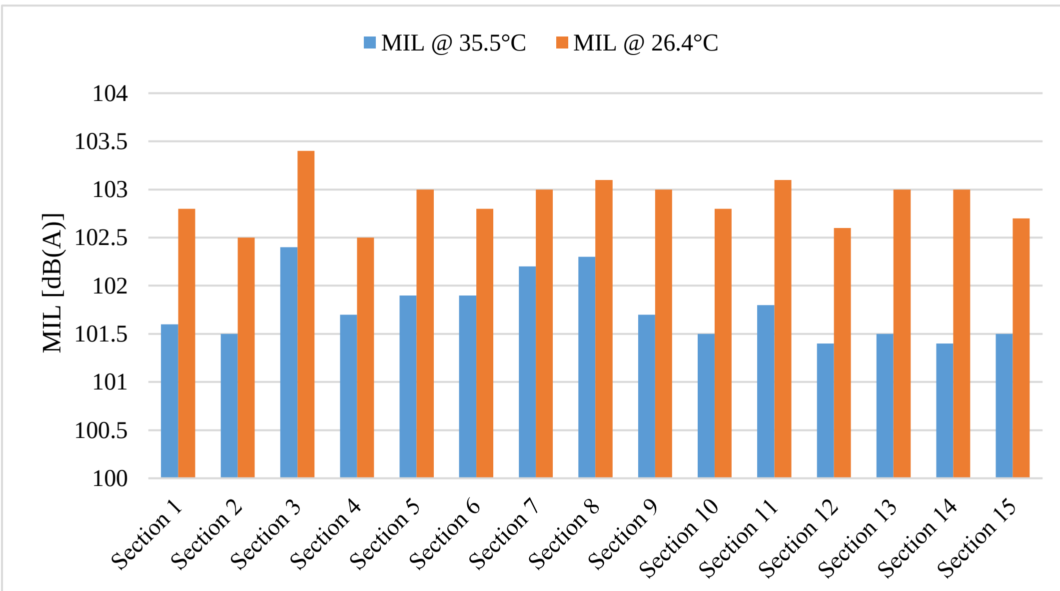


Figure 37. Variation of MILs with temperature on Dukhan expressway

The calculations of MILs rate of change with temperature in all sections within Dukhan expressway are shown in Table 14. The variation of MILs during the day ranged between -0.8 and -1.6 [dB(A)]. The average variation was -1.13 [dB(A)]. The rate of change of MILs with respect to temperature at Dukhan expressway was found to be -0.12 [dB(A)/°C] (-0.07 [dB(A)/°F]). This is significantly higher than that of AASHTO recommended value (-0.072 [dB(A)/°C]).

Table 14

MILs rate of change with temperature on Dukhan expressway

Sections	MIL [dB(A)] at Noon (@35.5°C)	MIL [dB(A)] at Night (@26.4°C)	Difference [dB(A)]	Rate of Change [dB(A)/°C]	Rate of Change [dB(A)/°F]
Section 1	101.6	102.8	-1.2	-0.13	-0.07
Section 2	101.5	102.5	-1	-0.11	-0.06
Section 3	102.4	103.4	-1	-0.11	-0.06
Section 4	101.7	102.5	-0.8	-0.09	-0.05
Section 5	101.9	103	-1.1	-0.12	-0.07
Section 6	101.9	102.8	-0.9	-0.10	-0.05
Section 7	102.2	103	-0.8	-0.09	-0.05
Section 8	102.3	103.1	-0.8	-0.09	-0.05
Section 9	101.7	103	-1.3	-0.14	-0.08
Section 10	101.5	102.8	-1.3	-0.14	-0.08
Section 11	101.8	103.1	-1.3	-0.14	-0.08
Section 12	101.4	102.6	-1.2	-0.13	-0.07
Section 13	101.5	103	-1.5	-0.16	-0.09
Section 14	101.4	103	-1.6	-0.18	-0.10
Section 15	101.5	102.7	-1.2	-0.13	-0.07
Averaged Values			**-1.13**	**-0.12**	**-0.07**

Similarly, the results of the two sets of OBSI field measurements on Salwa expressway experiment are shown in *Figure 38*. The negative correlation between tire-pavement interaction noise and the air temperature was also evident in this experiment. The first set of measurements were conducted at noon on a temperature of 39.8°C (103.6°F), while the second set of measurements were conducted at midnight on a temperature of 25.1°C (77.3°F). However, some of the noise measurements showed invalid results due to overloading of preamplifiers when the temperature exceeds 38°C (100°F). Any measurement which showed overloading signal was discarded from the data set and the test was repeated.

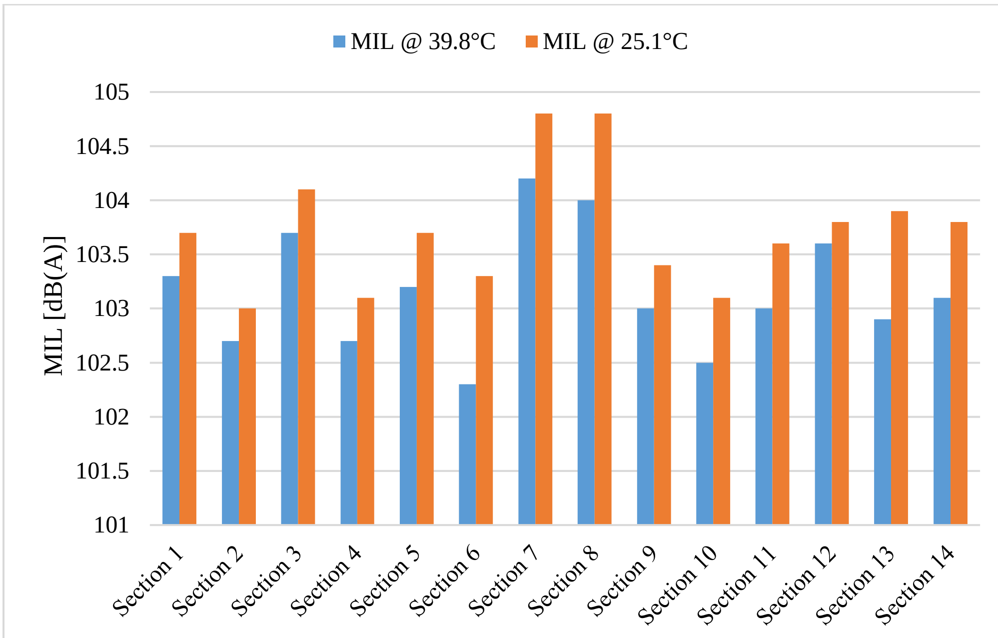


Figure 38. Variation of MILs with temperature on Salwa expressway

The calculations of MILs rate of change with temperature in all section within Salwa expressway OBSI field experiment are shown in Table 15. The variation of MILs between the two measurement sets ranged between -0.3 and -1 [dB(A)]. The average variation of MILs was -0.56 [dB(A)]. The MILs rate of change with respect to temperature was -0.04 [dB(A)/°C] (-0.02 [dB(A)/°F]). The obtained rate of change is slightly lower than AASHTO's linear adjustment coefficient for temperature (0.072 [dB(A)/°C].

Table 15

MILs rate of change with temperature on Salwa expressway

Sections	**MIL [dB(A)] at Noon (@39.8°C)**	**MIL [dB(A)] at Night (@25.1°C)**	**Difference [dB(A)]**	**Rate of Change [dB(A)/°C]**	**Rate of Change [dB(A)/°F]**
Section 1	103.3	103.7	-0.4	-0.03	-0.02
Section 2	102.7	103	-0.3	-0.02	-0.01
Section 3	103.7	104.1	-0.4	-0.03	-0.02
Section 4	102.7	103.1	-0.4	-0.03	-0.02
Section 5	103.2	103.7	-0.5	-0.03	-0.02
Section 6	102.3	103.3	-1	-0.07	-0.04
Section 7	104.2	104.8	-0.6	-0.04	-0.02
Section 8	104	104.8	-0.8	-0.05	-0.03
Section 9	103	103.4	-0.4	-0.03	-0.02
Section 10	102.5	103.1	-0.6	-0.04	-0.02
Section 11	103	103.6	-0.6	-0.04	-0.02
Section 12	103.6	103.8	-0.2	-0.01	-0.01
Section 13	102.9	103.9	-1	-0.07	-0.04
Section 14	103.1	103.8	-0.7	-0.05	-0.03
Average Rate of Change			**-0.56**	**-0.04**	**-0.02**

The resulted MILs rate of change with temperature (-0.04 [dB(A)/°C]) is considerably lower than the obtained rate of change in Dukhan experiment (-0.12 [dB(A)/°C]). This significant variation was not anticipated initially since both expressways are DGAC surfaces that were constructed with similar materials. Moreover, the two field experiments were carried out in two consecutive days using the same equipment and testing procedures.

The difference between the two temperature correlation factors can be explained by the following:

- The two expressways were made of similar DGAC mix design. However, Salwa expressway was constructed in 2008 while Dukhan expressway was constructed in 2009. Therefore, the difference of pavement age and total traffic could have influenced the noise susceptibility to temperature. The effect of aging and other pavement characteristics will be addressed in detail in the following Chapter.
- The difference between the range of diurnal temperature in the two experiments may be contributed to the variance of the obtained rate of change. The diurnal temperature range in Dukhan expressway was 9.1 °C with a noon temperature of 35.5°C (95.9°F), whereas the diurnal temperature range in Salwa expressway was 14.7°C with a noon temperature of 39.8°C (103.6°F). Hence, the correlation factors obtained in Salwa expressway experiment included a larger range of temperature variation. Additionally, Salwa expressway experiment examined the hot temperatures above 38°C (100°F). Therefore, the temperature coefficient on Salwa expressway experiment (0.04 [dB(A)]/°C) may be also considered more illustrative for the typical environmental conditions in Qatar during the summer.

Furthermore, the MILs on Salwa expressway was noticeably louder than the MILs on Dukhan expressway, regardless of testing ambient temperature. Therefore, it was not feasible to combine the resulted MILs in one model to examine the effect of temperature as anticipated initially in this chapter. The comparison of noise MILs on the two expressways are shown in *Figure 39*. It can be observed that the effect of pavement characteristics on MILs is more prominent than the effect of temperature.

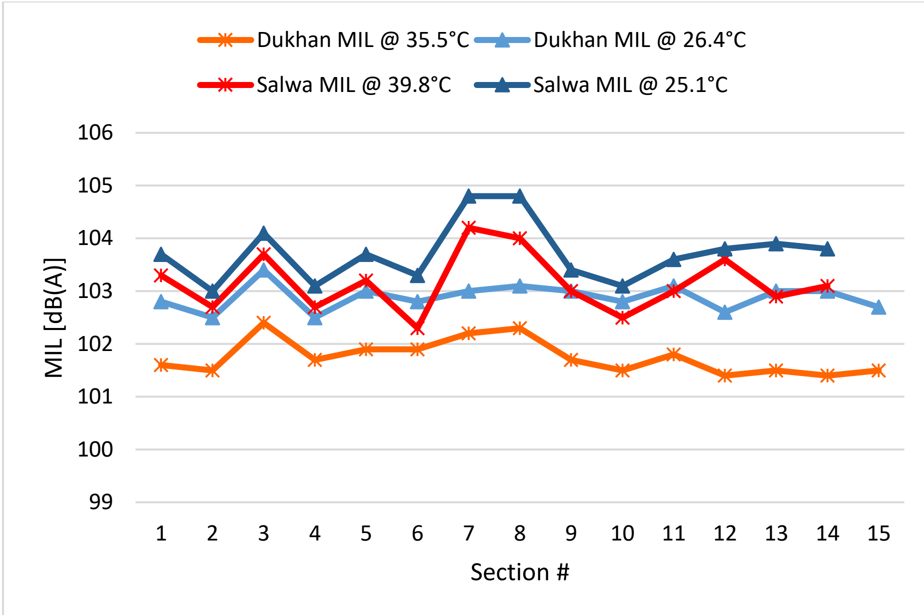


Figure 39. Comparison between MILs on the two noise experiments

Figure 39 also shows that there are wide variations in MILs between different sections on Salwa road. Nevertheless, there was no significant variation in MILs between the different sections on Dukhan expressway. It can be seen also that the effect of temperature was not consistent for all sections. These observations indicate that effect of temperature on MILs is varying in DGAC with the variation of pavement surface characteristics.

5.5.2 Comparison of NILs under Temperature Variation

The comparison between NILs on Dukhan expressway at noon and midnight is shown in Table 16. The average difference between noise levels was reduced to -0.45 [dB(A)]; instead of -1.13 [dB(A)] when MILs were considered. However, this difference shows that variation on MILs due to the effect of ambient temperatures was not fully adjusted when AASHTO linear adjustment coefficient was considered.

Table 16

NILs rate of change with temperature on Dukhan expressway

Sections	NIL at Noon [dB(A)]	NIL at Night [dB(A)]	Difference [dB(A)]
Section 1	102.7	103.2	-0.5
Section 2	102.6	103	-0.4
Section 3	103.5	103.9	-0.4
Section 4	102.8	102.9	-0.1
Section 5	103	103.4	-0.4
Section 6	103.1	103.2	-0.1
Section 7	103.3	103.5	-0.2
Section 8	103.4	103.5	-0.1
Section 9	102.8	103.5	-0.7
Section 10	102.6	103.3	-0.7
Section 11	103	103.5	-0.5
Section 12	102.5	103.1	-0.6
Section 13	102.6	103.4	-0.8
Section 14	102.8	103.5	-0.7
Section 15	102.7	103.2	-0.5
	Average		**-0.45**

The NILs on Salwa expressway at noon and midnight are shown in Table 17. The data shows that the average difference between noise levels was increased to +0.48 [dB(A)]; instead of -0.56 when MILs were considered. The data also indicate that noise levels at night (at low temperatures) were lower than the noise levels at noon (at higher temperatures); it shows a positive correlation. This variation was resulted by the large value of temperature coefficient used in AASHTO normalization procedure (0.072 [dB(A)/°C]) comparing to the actual variation of MILs in this experiment.

Table 17

NILs rate of change with temperature on Salwa expressway

Sections	**NIL at Noon [dB(A)]**	**NIL at Night [dB(A)]**	**Difference [dB(A)]**
Section 1	104.7	104.1	0.6
Section 2	104.1	103.3	0.8
Section 3	105.1	104.5	0.6
Section 4	104.1	103.5	0.6
Section 5	104.6	104.1	0.5
Section 6	103.8	103.6	0.2
Section 7	105.6	105.2	0.4
Section 8	105.5	105.2	0.3
Section 9	104.4	103.8	0.6
Section 10	104	103.5	0.5
Section 11	104.4	104	0.4
Section 12	105	104.2	0.8
Section 13	104.3	104.2	0.1
Section 14	104.5	104.2	0.3
	Average		**0.48**

5.5.3 MILs Spectral Analysis with Temperature Variation

Spectral analysis for MILs under temperature variation was conducted on the result of Dukhan and Salwa experiments are shown in *Figure 40* and *Figure 41*, respectively. It can be seen from the two figures that MILs on each 1/3rd octave band frequency were increased by the decrease of temperature on all tested sections. This may indicate that ambient temperature variation is affecting more than one noise generation mechanism.

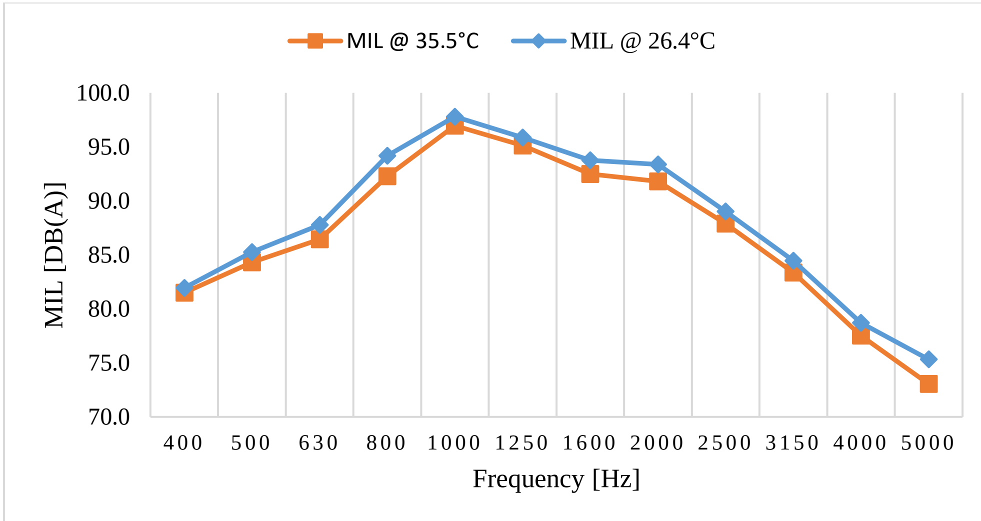


Figure 40. Effect of temperature at 1/3rd octave band frequency on Dukhan expressway

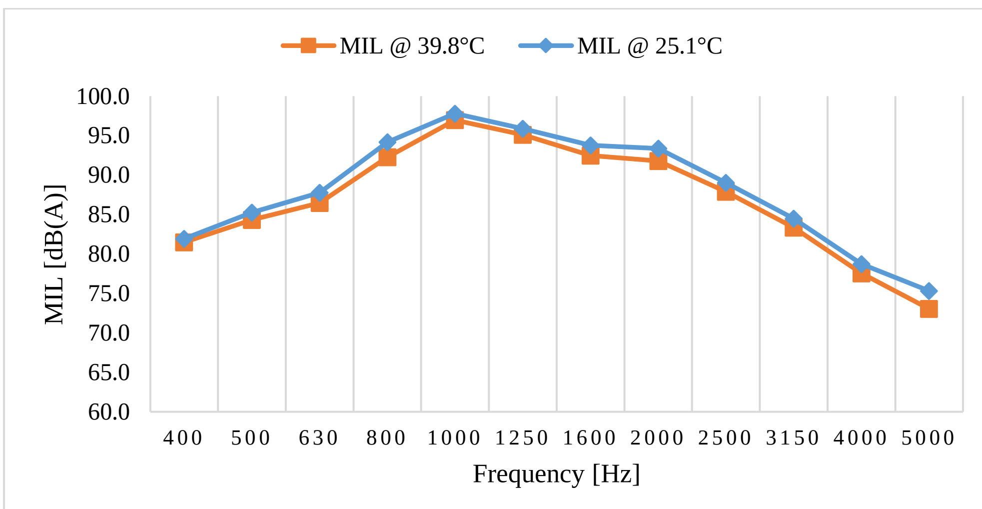


Figure 41. Effect of temperature at 1/3rd octave band frequency on Salwa expressway

5.6 Summary and Conclusions

OBSI field measurements were conducted on 29 sections on two different expressways to examine the effects of ambient temperature on tire-pavement interaction noise. Some of the noise measurements were conducted at hot temperatures, above 38°C (100°F) to properly evaluate tire-pavement interaction noise in this region. The resulted MILs showed that tire-pavement noise levels are inversely correlated with ambient temperatures. This finding is in line with the previous research studies conducted in this area. Furthermore, MILs rate of change with respect to ambient temperature was not consistent in both conducted experiments. The temperature rate of change was also not constant in all sections in each experiment. Therefore, it was concluded that effect of temperature on MILs is varying in DGAC with the variation of pavement surface characteristics. Lastly, a temperature adjustment coefficient of 0.04 [dB(A)/°C] was recommended for future studies in Qatar since AASHT'O's recommended coefficient was found to be overestimating the temperature effect when considering hot temperatures.

CHAPTER 6: EFFECTS OF PAVEMENT SURFACE CHARACTERISTICS ON TIRE-PAVEMENT INTERACTION NOISE

6.1 Introduction

A number of research studies showed that several pavements characteristics can be correlated to tire-pavement noise (Sirin 2016). The age of pavement is one of the important pavement characteristics when evaluating tire-pavement interaction noise. The sustainability of pavement acoustic performance with aging is one of the FHWA's concerns to accept quiet pavements (FHWA 2011). Therefore, studies have focused on the effect of pavement aging on noise to ensure the sustainability of quiet pavement designs. The positive correlation between tire-pavement noise and pavement aging was found to be varying between 0.19 and 0.25 [dB(A) per year] depending on the type of surface (Hanson and Waller 2006, Yu and Lu 2013, Irali, et al. 2015, Rasmussen and Sohaney 2012). Nonetheless, tire-pavement interaction noise generally increases with time in all types of pavement surfaces due to combined effects of environmental conditions and traffic. In DGAC surfaces, researchers have found that tire-pavement interaction noise is increasing about 0.2 [dB(A)] per year (Rasmussen and Sohaney 2012, Wayson, MacDonald and Martin 2014).

Furthermore, several pavement characteristics that are related to pavement mix design, such as gradation of aggregates and air voids have been also been correlated to tire-pavement interaction noise. Several studies showed that DGAC with lower NMAS tends to generate more noise than DGAC with larger NMAS in both Marshall and Superpave mixtures (Bennert, et al. 2005, Kowalski 2007). Additionally, air void percentage was found to have a slight or inconsequential negative correlation with tire-pavement noise in DGAC (Hanson and Waller 2006, Kocak 2011). Furthermore, a negative correlation between tire-pavement noise and binder content in DGAC was also reported in the literature (Kocak 2011). Other pavement characteristics such as aggregate type, layer thicknesses, and maximum or bulk specific gravities have been also considered in the literature. However, there was no significant correlation between these characteristics and tire-pavement noise for DGAC at least (Rasmussen, Bernhard, et al. 2007, Sirin 2016).

6.2 Objectives

The effects of DGAC pavement characteristics on tire-pavement interaction noise are investigated in this chapter by conducting OBSI field noise measurements on pavements having different surface characteristics. The chapter also aims to introduce a prediction model for tire-pavement interaction noise in DGAC with respect to its pavement characteristics. The age of pavement along with some mix design parameters such as NMAS, air void, and binder content has been considered as the predicting pavement characteristics. This model may be used to predict the acoustic performance of different DGAC mix design over the course of time.

6.3 Methodology

In order to investigate the effect of pavement characteristics on tire-pavement noise, multiple OBSI noise measurements were carried out on seven diverse expressways across the State of Qatar. These expressway locations were selected based on the following criteria:

- The as-built records of pavement mix designs are available to examine the effect of different pavement characteristics on noise levels.
- The posted speed limits equal or exceed AASHTO (2016) recommended testing speed 96 [km/h] (60 [mph]). This was also important to ensure traffic safety and adhere to traffic regulations.
- There is no evident surface deterioration or degradation since the objective of the field noise measurement is to evaluate different pavement characteristics on tire-pavement noise.
- The pavement sections are large enough and no sudden variation of surface materials or evident resurfacing to ensure the accuracy of obtained as-built pavement surfaces mix design.
- There is diversity in the age of the selected pavements to include the effect of pavement aging on the analysis.
- The roads are permanent and there is no planned upgrade or developments, to allow for further investigations and future studies for long time pavement noise monitoring.

In each expressway, multiple sections were selected to have sufficient statistical sample of noise data. A total of 59 sections were tested in seven expressways. The locations of the studied expressways are highlighted in *Figure 42*.

Figure 42. Locations of tested sections

Although, the specified temperature coefficient in AASHTO (2016) standard slightly overestimated the noise levels as shown in the previous chapter, NILs were considered in this chapter to avoid any bias due to the variation of testing temperature. This is mainly for comparison purposes and because the results in the previous chapter included only two expressways. The pavement characteristics data were obtained from Qatar Public Works

Authority as described in chapter three. Table 18 summarizes the information of OBSI field noise measurements and the collected pavement characteristics.

Table 18

Details of test sections and pavement characteristics

Expressway	**No. of Sections**	**Speed [Km/h]**	**Temp. [°C]**	**Testing Date**	**Const. Date**	**Age [Y]**	**NMAS [mm]**	**Air Voids (%)**	**Binder Content (%)**
G Ring	8		35.6	02-May-2017	Apr-17	0	19	6.5	3.9
Lijmiliya	10		38.4	09-May-2017	Oct-16	0	19	6.5	4.1
Rawdat Rashed	7		40.3	16-May-2017	Dec-16	0	20	6.2	3.8
F Ring	8	96	36.7	06-Jun-2017	Dec-14	2	20	7	3.9
Al Ruffa	8		31.83	11-Apr-2017	Dec-11	5	14	6.2	3.7
Al Shamal	4		30.1	22-Mar-2017	Jul-10	6	14	6.2	3.7
Dukhan	15		35.5	23-Apr-2017	May-09	7	14	6.6	3.7

6.4 Noise Test Results

The averaged values of MILs and NILs in each expressway are shown in Table 19 along with pavement characteristics. The measured and normalized noise data on all tested sections are presented in Appendix C.

Table 19

Mean MILs and NILs on selected expressways

Expressway	Age [Y]	DMAX [mm]	NMAS [mm]	Air Voids (%)	Binder Content (%)	Binder Type	MILs [dB(A)]	NILs [dB(A)]
G Ring	0	25	19	6.5	3.9	PG76E-10	101.36	102.49
Lijmiliya	0	25	19	6.5	4.1	PG76E-10	100.91	102.24
Rawdat Rashed	0	25	20	6.2	3.8	60-70 Pen	102.18	103.63
F Ring	2	25	20	7.0	3.9	60-70 Pen	102.88	104.08
Al Ruffa	5	20	14	6.2	3.7	60-70 Pen	101.30	102.16
Al Shamal	6	20	14	6.2	3.7	60-70 Pen	102.28	102.60
Dukhan	7	20	14	6.6	3.7	60-70 Pen	101.75	102.89

6.5 Analysis and Discussion

The variation of overall NILs on the seven distinct expressways is illustrated in *Figure 43*. It can be seen from the figure that the NILs ranged about 2 [dB(A)] between 102.16 [dB(A)] and 104.08 [dB(A)]. The loudest DGAC surface was the F Ring road, which is a two years old section with 19 mm NMAS in accordance to QCS2010. The quietest DGAC surface was Al Ruffa expressway, which is 5 years old section constructed with 14 mm NMAS in accordance to QCS2007. This finding indicates that the effect of NMAS on tire-pavement interaction noise is larger than the effect of aging for DGAC surfaces.

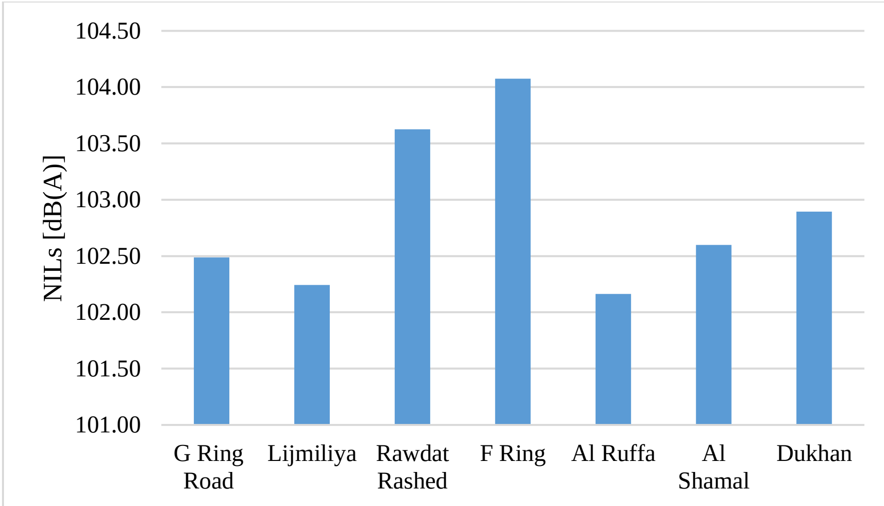


Figure 43. Averaged NILs on selected expressways

Tire-pavement interaction noise at frequency level was investigated by plotting MILs at 1/3[rd] octave band frequency spectra as shown in Figure 44.

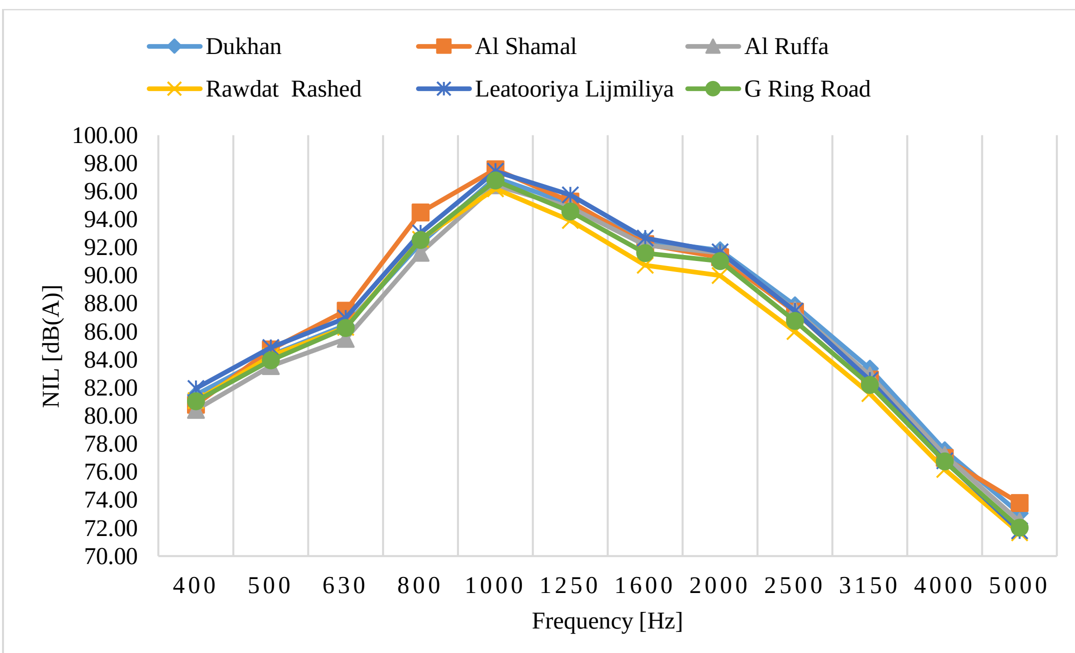


Figure 44: Frequency spectrum for the averaged NILs on selected expressways

Although, the selected DGAC surfaces varied in age and pavement mix design parameters, the frequency spectrum shows that all DGAC had similar noise signature with a maximum at 1000 [Hz]. Therefore, the spectral analysis demonstrated that tire-pavement noise in the different DGAC has a similar acoustic tone.

6.5.1 Bivariate Correlation in Data

As an initial step, SPSS statistical analysis software was used to conduct bivariate Pearson correlation analysis. Table 20 presents Pearson correlation coefficients along with the 2-tailed p-value.

Table 20

Pearson Correlation Coefficient values for 2-tailed correlation of data

		NIL	**Age**	**NMAX**	**Air Void**	**Binder Content**
NIL	Pearson Correlation	1	-.100	.402**	.490**	-.065
	Sig. (2-tailed)		.451	.002	.000	.626
	N	59	59	59	59	59
Age	Pearson Correlation	-.100	1	-.930**	-.002	-.806**
	Sig. (2-tailed)	.451		.000	.990	.000
	N	59	59	59	59	59
NMAX	Pearson Correlation	.402**	-.930**	1	.289*	.760**
	Sig. (2-tailed)	.002	.000		.026	.000
	N	59	59	59	59	59
Air Void	Pearson Correlation	.490**	-.002	.289*	1	.286*
	Sig. (2-tailed)	.000	.990	.026		.028
	N	59	59	59	59	59
Binder Content	Pearson Correlation	-.065	-.806**	.760**	.286*	1
	Sig. (2-tailed)	.626	.000	.000	.028	
	N	59	59	59	59	59

The analysis presented the correlation between NILs (the response) and the different pavement characteristics (the predictors). The p-value showed the statistical significance of each correlation comparing to the significant level (0.01 or 0.05). Additionally, Table 20 also demonstrated some multicollinearities on the data set.

It can be seen from the table that NIL was positively correlated with NMAS and negatively correlated with binder content which is consistent with the published literature. However, NIL was found negatively correlated with pavement age and positively correlated with air void. These findings are not consistent with the current state of knowledge as noise levels generally increase with aging and decrease when the air void percentage increase. The opposite sign of Pearson correlation coefficients for aging and NMAS are explained by the multicollinearity between pavement age, air void, and NMAS.

The multicollinearities in pavement characteristics data were expected due to the differences in Marshall's mix design criteria adopted by the different QCS versions over the course of time. Therefore, a separate simple linear regression analysis was conducted to examine the effect of pavement aging on tire-pavement interaction noise.

6.5.2 Prediction Model for NILs with aging

A separate simple linear regression analysis was conducted to examine the effect of pavement aging on tire-pavement interaction noise. The analysis considered only the noise data on three similar DGAC expressways, Al Shamal, Al Ruffa, and Dukhan expressways. Theses expressways were constructed in 2009, 2010, and 2011, respectively. Moreover, the surfaces of those three expressways were constructed using similar DGAC Marshall mix design criteria as per QCS2007. Al Shamal and Al Ruffa expressways were also constructed by the same contractor using the same asphalt mix plant. Consequently, it is presumed that pavement age is the only independent variable on theses tested sections at the three expressways. The simple linear regression model was performed on using the captured NILs in 27 sections. The regression best fit line is shown in *Figure 45*.

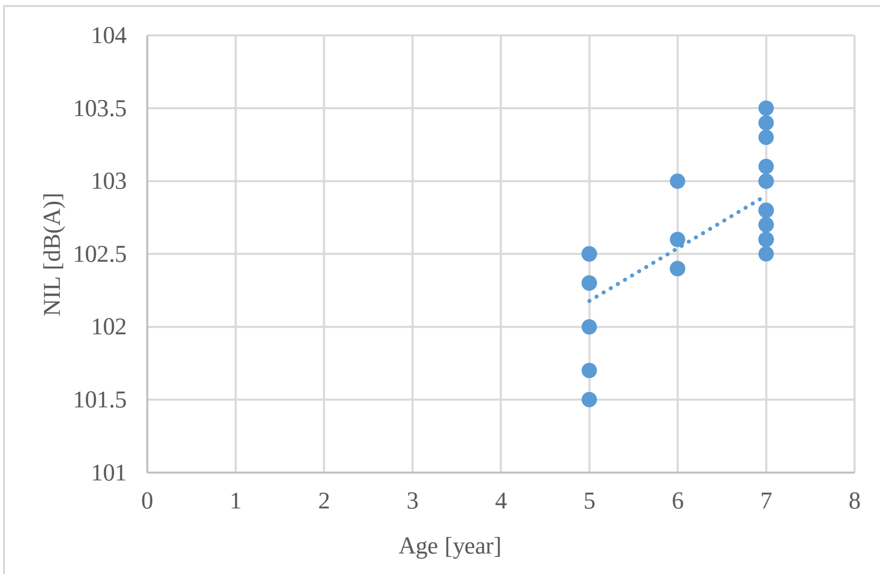


Figure 45. Best fit line for pavement aging regression analysis

The summary of the regression analysis and ANOVA are tabulated in *Figure 46*. The correlation coefficient (R) was 0.713. Nonetheless, the coefficient of determination shows that only 50.08% of NILs variation is explained by the simple regression model. However, it can be seen from *Figure 46* that there is a clear upward trend of sound intensity with pavement age. This can be due to the limited data set (only 3 expressways) used in the regression model. Additionally, there were other variations in NILs, between sections on each expressway, which was not explained by the regression model.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.713[a]	.508	.488	.3278

a. Predictors: (Constant), Age

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2.774	1	2.774	25.828	.000[b]
	Residual	2.686	25	.107		
	Total	5.460	26			

a. Dependent Variable: NIL

b. Predictors: (Constant), Age

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	100.368	.450		222.966	.000
	Age	.362	.071	.713	5.082	.000

a. Dependent Variable: NIL

Figure 46. Simple linear regression output in SPSS

The obtained aging coefficient was 0.362 [dB(A) per year]. This finding is slightly larger than the average correlation coefficient (0.2 dB(A) per year) reported in the literature. The P-values (denoted "Sig.") of the coefficient highlights the significance of pavement aging effect on NILs (less than 0.01). The measured and predicted NILs are shown in *Figure 47*.

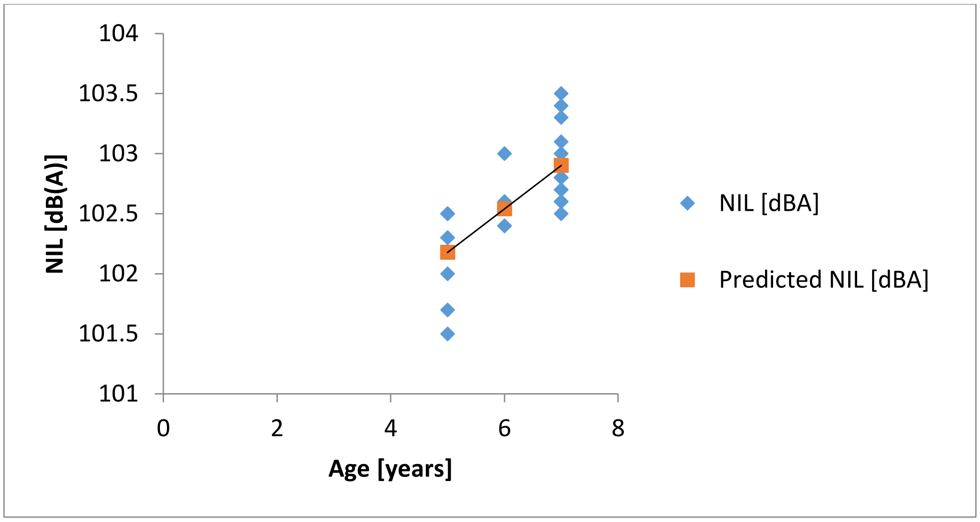


Figure 47. Measured versus predicted NILs fit plot

6.5.3 NIL Prediction Model with respect to Pavement Characteristics

A multivariate regression analysis was carried out to predict NILs in DGAC with respect to pavement characteristics. The multivariate regression model was developed using SPSS software and included NILs of all 59 sections within the seven selected expressways. The values of NMAS, pavement age, air void, and binder content were defined as independent variables. *Figure 48* presents the multivariate regression output in SPSS.

It can be seen from *Figure 48* that the multiple correlation coefficients (R) was 0.903. The coefficient of determination (R square) indicates that 81.5% of NILs variation was explained by the multivariate regression model. The ANOVA's p-value (denoted by "Sig.") for the F-statistic was less than 0.05 (the significant level), which confirms that at least one of the parameters is linearly correlated to NILs. The ANOVA's F-statistic represents the ratio of the regression mean square to residual mean square.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.903[a]	.815	.802	.3208

a. Predictors: (Constant), BinderContent, AirVoid, NMAS, Age

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	24.551	4	6.138	59.641	.000[b]
	Residual	5.557	54	.103		
	Total	30.109	58			

a. Dependent Variable: NIL

b. Predictors: (Constant), BinderContent, AirVoid, NMAS, Age

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	98.681	2.319		42.545	.000
	Age	.553	.092	2.322	5.978	.000
	NMAS	.743	.085	2.858	8.778	.000
	AirVoid	-.693	.380	-.248	-1.824	.074
	BinderContent	-1.475	.715	-.294	-2.063	.044

a. Dependent Variable: NIL

Figure 48. SPSS output for NILs prediction model

The obtained regression coefficients for age, NMAS, air void, and binder content were 0.553, 0.743, -0.693, and -1.475, respectively. The coefficients' p-value (denoted by "Sig.") shows that relation of NILs with age and NMAS are statistically significant ("Sig." less than 0.05). The coefficient of air void and binder content were slightly higher than that of the significant level (0.05). The obtained multivariate regression model for predicting noise levels of DGAC is expressed in Equation (4):

$$NIL\ [dB(A)] = 98.681 + 0.533(Pavement\ Age\ [years]) + 0.743(NMAS\ [mm]) - 0.693(Air\ Void\ [\%]) - 1.475(BinderContent\ [\%]) \quad (4)$$

It must be noted that the model is limited to AASHTO (2016) specified testing conditions; ambient temperature of 20°C, driving speed of 96 [km/h] (60 [mph]), and using SRTT testing tire. The presented coefficients in chapter 4 and 5 can be used to derive the predicted noise levels to the desired speed and ambient temperature.

As can be seen from equation 4, NILs are increasing 0.553 and 0.743 [dB(A)] per unit change in pavement age and NMAS, respectively. On the other hand, NILs are decreasing 0.693 and 1.475 [dB(A)] with the increase of the percentage of air void and binder content in the mix, respectively.

6.6 Summary and Conclusions

In this chapter, OBSI field measurements were conducted on 59 sections in seven different expressways to examine the effects of pavement surface characteristics on tire-pavement interaction noise. The selected DGAC sections varied significantly on pavement age and mix design parameters and the average NILs ranged almost 2 [dB(A)]. Furthermore, the spectral analysis of NILs on the different DGAC surfaces suggests that tire-pavement noise in DGAC is varying in magnitude only and share similar acoustic tone. Furthermore, the averaged NILs also showed that the effect of aggregate gradation on tire-pavement interaction noise is larger than that of the effect of aging for DGAC surfaces.

A separate simple linear regression analysis was performed on 27 similar sections to examine the effects of pavement aging on tire-pavement interaction noise. The analysis was conducted to avoid the multicollinearity between pavement age, NMAS, and binder content. NILs in DGAC were found to be increasing 0.362 [dB(A)] per year due to the effect of aging.

The chapter was concluded by introducing a multivariate regression model to predict tire-pavement interaction noise on DGAC with respect to pavement characteristics. The model was developed by using SPSS statistical analysis software and included a total of 59 noise measurements. The model considered the age of pavement along with some mix design parameters such as NMAS, air void, and binder content as the predicting pavement characteristics. The prediction model explained 81.5% of the variation of tire-pavement noise variation. The t-statics and p-values of the four coefficients emphasized the significance of their relationship with tire-pavement noise, especially for the coefficients of pavement age and NMAS. The introduced model may be used to evaluate the acoustic properties of different pavement mix designs over the course of time. Such model will be also beneficial to researchers and authorities interested in designing quiet pavements and noise abatement policies, especially in Qatar where the use of DGAC surface is recommended due to the environmental conditions.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In this study, OBSI noise measurements were performed on a number of expressways in the State of Qatar. The main factors affecting tire-pavement interaction noise was also investigated by conducting controlled experiments. Based on the experimental program, the main findings can be summarized as follows:

- A regression model was presented to predict tire-pavement interaction noise with respect to driving speed. The speed coefficient was 13.4 *ln* [dB(A) per km/h]. This model can be used in determining posted speed limits and to compare noise measurements taken at different speeds worldwide.
- Tire-pavement interaction noise was inversely correlated with ambient temperatures in all examined sections. However, the noise rate of change with temperature was not constant in all tested sections and varied depending on pavement characteristics.
- The adopted temperature coefficient by AASHTO's normalization procedure was found to be overestimating the temperature effect when considering hot temperatures. Therefore, a temperature coefficient of -0.04 ([dB(A)/°C]) was recommended for future studies in the State of Qatar.
- The effect of aggregate gradation, represented by NMAS, on tire-pavement interaction noise was larger than that of pavement aging on DGAC surfaces.
- Tire-pavement interaction noise was found to be increasing by a rate of 0.362 [dB(A)/year] on DGAC surfaces due to the effect of aging.
- DGAC surfaces that is constructed in Qatar by using Marshall mix design criteria in

QCS 2007 was quieter than the surfaces constructed under later QCS versions.

- A multivariate regression model was developed to predict tire-pavement interaction noise on DGAC with respect to pavement age, NMAS, air void and binder content in the State of Qatar. The derived statistical model can be used to evaluate the acoustic properties of different pavement mix designs over the course of time.

7.2 Recommendations

7.2.1 Future Research Recommendations

In this study, the main factors affecting tire-pavement interaction noise were studied and a number of correlations have been established. However, there are still some issues that can be studied in the future. The following list highlights some recommendations for future studies in this area.

1) The established correlations could be adopted in future research studies to design quieter DGAC surfaces in hot climates.
2) The effect of Polymer and Crumb rubber modified bitumen on tire-pavement interaction noise could be evaluated in Qatar once there is a sufficient number of sections.
3) A validation study for the recommended temperature adjustment coefficient can be conducted in the future by considering a larger set of data.

7.2.2 Practical Recommendations in Qatar

The following points are highlighting some of the practical recommendations that can be adapted by relevant authorities in Qatar:

1) The results are suggesting that relevant authorities in Qatar shall consider using smaller sizes of NMAS while designing DGAC surfaces. The NMAS should be equal or less than 14 mm to design quitter DGAC.
2) The tire-pavement interaction noise level shall be considered in determining the posted speed limit in residential areas. The noise prediction model given below can be used to measure the effect of speed on the generated tire-pavement interaction noise level.

$$NIL\ [dB(A)] = 13.4 \ln\left(speed\ \left[\frac{km}{h}\right]\right) + 40.838 \qquad (3)$$

3) The noise prediction model given below could be included in Qatar Highway Design Manual (QHDM) to evaluate the acoustic properties of different DGAC mix designs over the course of time.

$$NIL\ [dB(A)] = 98.681 + 0.533(Pavement\ Age\ [years]) + 0.743\ (NMAS\ [mm]) - 0.693(Air\ Void\ [\%]) - 1.475(BinderContent\ [\%]) \qquad (4)$$

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Appendix A: Resulted MILs and NILs in Speed Experiments

Table A1: MILs on Al Shamal expressway

Speed (Km/h)	MIL [dB(A)]	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
40	89.6	76.1	78.8	78.4	82.8	84.1	81.7	78.1	76.8	72.6	67	61	57.6
40	89.4	76.1	78.6	78.2	82.5	83.6	81.3	78.2	77.1	72.8	67.4	61.4	57.9
50	91.6	76.2	81.8	80.7	84.4	86.3	83.6	80	78.8	74.4	68.9	62.9	59.6
50	92.3	75.9	82.5	80.8	84.7	86.9	84.5	81.2	80.3	75.9	70.5	64.4	60.9
50	91.7	76.1	81.9	80.7	84.6	86.3	83.8	80.1	79	74.6	69	63	59.6
50	92.3	76.2	82.4	81	84.8	86.9	84.5	81.2	80.1	75.8	70.5	64.3	60.8
60	95.1	78.3	82.5	84.9	88.2	89.7	87.5	84.2	82.6	78.3	72.8	66.6	63.4
60	94.9	77.9	81.8	84.7	88	89.2	87.4	84.3	83.1	78.8	73.6	67.4	64
60	95	78	82.3	84.8	88.1	89.6	87.4	84.1	82.7	78.4	72.8	66.7	63.4
60	95.1	79.2	82.7	84.9	88.3	89.5	87.4	84.1	82.8	78.7	73.4	67.3	63.9
70	97.7	78.9	83.2	85.6	92.1	92	89.8	86.6	85.5	81.3	75.9	69.8	66.5
70	97.2	78.8	83.1	86.1	91.3	91.6	89.4	86.4	85.2	81.1	76.1	69.9	66.5
70	97.6	78.7	83.2	85.5	92.2	91.9	89.7	86.5	85.6	81.3	75.9	69.9	66.6
70	97.4	78.7	82.8	85.7	91.5	91.6	89.5	86.7	85.6	81.5	76.4	70.4	67
80	99.2	79.4	83.3	85.7	93.8	93.7	91.3	88.3	87.4	83.2	78	72	68.8

Speed (Km/h)	MIL [dB(A)]	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
80	98.9	79.4	83.1	85.4	93.4	93.3	91.1	88.3	87.5	83.4	78.5	72.5	68.9
80	99.5	80.7	84.2	86.5	93.9	94.1	91.6	88.5	87.3	83.2	78	71.9	68.7
80	98.9	78.8	82.8	85	93.3	93.2	91	88.4	87.8	83.5	78.8	72.7	69.1
90	100.7	80.6	83.8	86.4	93.3	96.5	92.9	90.2	89.3	85.1	80	74.3	71.1
90	100.6	80.1	83.5	86.5	93.2	96.2	93.1	90.3	89.4	85.4	80.6	74.8	71.2
90	101.1	81	84.6	87.2	94.2	96.8	93.4	90.4	89.3	85.1	80.1	74.2	71
90	100.8	80.7	84.1	86.9	93.7	96.3	93.3	90.3	89.4	85.3	80.5	74.6	71.1
100	102.2	81.1	84.9	87.9	94.7	97.8	94.9	92.1	90.9	86.9	82	76.4	73.5
100	102.1	80.2	84.3	87	94	97.3	95.3	92.2	91.5	87.7	83	77.4	73.8
100	102.7	81.8	85.8	88.8	95.7	98.1	95.3	92.3	91	86.9	82	76.3	73.5
100	102.1	80	83.9	86.3	93.6	97.1	95.6	92.3	91.8	88.2	83.3	77.9	74.3
110	103.3	80.9	86.2	88.2	95.5	98.3	96.8	93.4	92.4	88.6	83.7	78	74.6
110	103	81.3	84.7	87.5	94.8	98	96.6	93.1	92.2	88.7	83.9	78.2	74.7
110	103.4	81.1	86.2	88.2	95.6	98.4	97	93.5	92.5	88.6	83.7	78	74.6
120	104.1	83.1	87.1	88.9	95.8	98.7	98.2	94.5	93.4	89.8	84.9	79.4	76.1
120	103.9	81	85.4	88.2	95.5	98.4	98	94.4	93.4	89.9	85.2	79.5	76
120	104.3	81.7	86.2	88.9	96.1	99	98.5	94.8	93.7	90	85.2	79.6	76.1
120	104	80	85.6	88.2	95.8	98.7	98.1	94.6	93.4	90	85.3	79.7	76.2

Table A2: NIL on Al Shamal expressway

Speed (km/h)	NIL [dBA]	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
40	90	76.5	79.2	78.8	83.1	84.4	82.1	78.4	77.1	73	67.3	61.3	57.9
40	89.7	76.4	78.9	78.6	82.8	83.9	81.7	78.5	77.5	73.1	67.8	61.7	58.2
50	92	76.6	82.1	81.1	84.8	86.6	84	80.4	79.1	74.8	69.2	63.2	59.9
50	92.6	76.2	82.8	81.2	85	87.2	84.8	81.6	80.6	76.2	70.9	64.7	61.2
50	92.1	76.4	82.3	81	84.9	86.7	84.1	80.5	79.3	75	69.3	63.3	60
50	92.6	76.5	82.7	81.4	85.1	87.2	84.9	81.6	80.4	76.1	70.9	64.6	61.1
60	95.5	78.7	82.9	85.2	88.5	90.1	87.9	84.5	83	78.7	73.1	67	63.7
60	95.3	78.3	82.1	85	88.3	89.6	87.7	84.7	83.4	79.2	74	67.7	64.3
60	95.3	78.3	82.6	85.2	88.4	89.9	87.8	84.4	83	78.7	73.2	67.1	63.7
60	95.4	79.5	83	85.2	88.7	89.8	87.8	84.4	83.2	79	73.8	67.7	64.3
70	98	79.2	83.6	86	92.5	92.4	90.1	86.9	85.9	81.6	76.2	70.2	66.9
70	97.6	79.1	83.4	86.5	91.6	91.9	89.7	86.8	85.5	81.5	76.4	70.2	66.8
70	97.9	79	83.5	85.8	92.5	92.2	90	86.8	85.9	81.6	76.3	70.2	67
70	97.7	79	83.2	86	91.9	92	89.8	87	86	81.9	76.8	70.7	67.4
80	99.5	79.7	83.6	86	94.1	94.1	91.6	88.6	87.7	83.5	78.3	72.3	69.1
80	99.3	79.7	83.5	85.7	93.7	93.7	91.4	88.7	87.9	83.7	78.8	72.8	69.3
80	99.8	81.1	84.5	86.9	94.3	94.5	91.9	88.8	87.7	83.5	78.4	72.2	69
80	99.2	79.2	83.1	85.3	93.7	93.5	91.3	88.7	88.1	83.8	79.1	73.1	69.4
90	101	81	84.1	86.8	93.6	96.8	93.2	90.6	89.7	85.4	80.3	74.6	71.5

90	101	80.4	83.9	86.8	93.5	96.6	93.4	90.6	89.8	85.7	80.9	75.1	71.5
90	101.5	81.4	84.9	87.6	94.6	97.1	93.8	90.8	89.6	85.4	80.4	74.5	71.3
90	101.2	81	84.4	87.3	94	96.7	93.7	90.7	89.7	85.6	80.9	74.9	71.4
100	102.6	81.4	85.2	88.3	95.1	98.1	95.2	92.4	91.2	87.2	82.3	76.7	73.9
100	102.4	80.5	84.6	87.3	94.3	97.7	95.7	92.5	91.8	88	83.3	77.8	74.2
100	103	82.1	86.2	89.1	96.1	98.4	95.6	92.6	91.4	87.2	82.3	76.7	73.8
100	102.4	80.4	84.2	86.6	93.9	97.5	95.9	92.6	92.2	88.6	83.7	78.3	74.6
110	103.6	81.2	86.6	88.5	95.8	98.6	97.1	93.7	92.8	88.9	84	78.3	74.9
110	103.3	81.6	85	87.8	95.2	98.3	97	93.4	92.6	89	84.2	78.6	75
110	103.7	81.4	86.5	88.6	96	98.7	97.3	93.8	92.9	88.9	84	78.4	74.9
120	104.5	83.5	87.5	89.2	96.1	99.1	98.5	94.9	93.7	90.2	85.3	79.8	76.4
120	104.2	81.3	85.8	88.5	95.9	98.7	98.3	94.8	93.7	90.2	85.5	79.9	76.4
120	104.7	82	86.5	89.2	96.4	99.3	98.8	95.1	94	90.3	85.5	79.9	76.4
120	104.4	80.4	85.9	88.6	96.1	99	98.5	94.9	93.8	90.3	85.7	80.1	76.6

Table A3: MIL on Lijmiliya expressway

Speed (mph)	**Speed (km/h)**	**MIL [dB(A)]**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**	**1250 Hz**	**1600 Hz**	**2000 Hz**	**2500 Hz**	**3150 Hz**	**4000 Hz**	**5000 Hz**
56	56.3	93.5	78.1	82.3	84.3	86.7	87.4	85.6	82.5	80.9	76.5	71.7	65.8	61.2
56	56.3	93.8	77.9	81.9	84.3	86.7	87.9	86.1	83.1	81.9	77.4	72.6	66.7	62.1
56	56.3	94.4	77.9	81.9	84.3	86.5	88.8	86.9	84	83.1	78.8	73.9	67.9	63.4
56	56.3	94.1	77.9	82	84.2	86.5	88.3	86.4	83.6	82.7	78.4	73.7	67.8	63.4
56	56.3	94.3	78	82.3	84.2	86.7	88.8	86.8	83.8	82.8	78.3	73.3	67.3	62.8
56	56.3	94	78.1	81.9	83.9	86.4	88.5	86.6	83.2	81.7	77.3	72.1	65.9	61.2
56	56.3	93.7	77.5	81.8	84.1	86.5	87.9	86	82.8	81.5	76.8	71.8	65.8	61
56	56.3	93.8	77.5	81.7	84.2	86.4	88.1	86.3	83	81.8	77.2	72	66	61.1
56	56.3	93.6	77.2	81.7	84.4	86.4	87.6	86	82.8	81.6	77.2	72.3	66.2	61.4
56	56.3	93.3	77.9	82	84.5	86.4	87	85.3	82.3	81.2	76.7	72.2	66.1	61.3
72	72.4	97	79.5	83.4	84.6	91.9	90.9	88.8	86	84.6	80.5	76.3	70.3	66
72	72.4	97.4	79.3	83.3	84.6	91.9	91.5	89.5	86.7	85.5	81.3	76.9	71	66.6
72	72.4	97.8	79.3	82.8	84.5	91.6	92.2	90.3	87.4	86.3	82.2	77.8	71.6	67.1
72	72.4	97.5	79.2	83.1	84.5	91.5	91.9	89.8	87	86	82	77.5	71.4	67
72	72.4	97.8	79.4	83.3	84.6	91.5	92.5	90.2	87.2	86.2	82	77.2	71.1	66.7
72	72.4	97.5	78.5	82.1	83.6	91.1	92.1	90.1	87.2	86.3	82	77.3	71.2	66.5
72	72.4	97.2	78.6	82.1	83.7	91.4	91.6	89.5	86.7	85.7	81.3	76.6	70.8	66.1
72	72.4	97.4	78.6	82.4	84.1	91.4	91.9	89.9	87.1	85.9	81.6	76.9	70.9	66.3
72	72.4	96.9	78.4	82.2	83.9	91.4	91.2	89.2	86.5	85.2	81	76.7	70.7	66.1

Speed (mph)	**Speed (km/h)**	**MIL [dB(A)]**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**	**1250 Hz**	**1600 Hz**	**2000 Hz**	**2500 Hz**	**3150 Hz**	**4000 Hz**	**5000 Hz**
72	72.4	96.8	79.7	83	84	91.7	90.6	88.6	86.1	84.7	80.6	76.4	70.4	65.7
96	96.5	100.3	81.1	85	87	92.9	95.4	93.3	89.8	88.7	84.9	80.7	75.5	71
96	96.5	101.2	81.4	84.8	87.1	93.3	96.5	94.1	91.1	90.3	86.2	81.8	76.5	72
96	96.5	101.5	82.4	84.7	86.8	93	96.8	94.7	91.5	90.8	86.8	82.6	77.2	73
96	96.5	101.2	81.5	84.6	86.8	92.7	96.6	94.3	91.2	90.5	86.6	82.4	77	72.5
96	96.5	101.1	82	84.6	86.4	92.7	96.5	94.3	91.2	90.5	86.6	82.2	76.7	72.3
96	96.5	100.9	80.8	83.6	85.7	92.1	96.5	94.2	90.9	90.4	86.3	81.5	76	71.5
96	96.5	100.7	80.6	83.6	85.8	92.4	96.1	93.8	90.5	89.8	85.7	81.1	75.6	71
96	96.5	100.8	80.7	83.6	85.7	92.3	96.3	94.1	90.8	90.2	86.1	81.3	75.8	71.2
96	96.5	100.5	80	83.6	85.5	92.2	95.9	93.6	90.4	89.7	85.7	81.2	75.8	71.1
96	96.5	100	80.2	84.4	86.2	92.2	95.3	92.9	89.9	89	85.2	80.9	75.6	70.9

Table A4: NILs on Lijmiliya expressway

Speed (km/h)	Sections	NIL [dBA]	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
56	1	94.9	79.5	83.7	85.6	88.1	88.8	87	83.9	82.3	77.9	73.1	67.2	62.6
56	2	95.2	79.3	83.3	85.7	88	89.2	87.5	84.4	83.2	78.8	74	68.1	63.5
56	3	95.8	79.3	83.3	85.7	87.9	90.1	88.3	85.4	84.5	80.1	75.3	69.3	64.8
56	4	95.5	79.3	83.4	85.6	87.8	89.7	87.8	84.9	84.1	79.8	75	69.2	64.8
56	5	95.7	79.4	83.6	85.6	88	90.1	88.2	85.2	84.1	79.7	74.7	68.6	64.2
56	6	95.4	79.5	83.3	85.3	87.8	89.9	88	84.5	83.1	78.7	73.4	67.3	62.6
56	7	95	78.9	83.1	85.5	87.9	89.3	87.4	84.1	82.8	78.2	73.1	67.2	62.4
56	8	95.2	78.9	83.1	85.5	87.8	89.5	87.7	84.4	83.2	78.6	73.4	67.3	62.5
56	9	95	78.6	83.1	85.8	87.8	89	87.3	84.2	83	78.5	73.7	67.6	62.8
56	10	94.7	79.3	83.4	85.9	87.8	88.4	86.7	83.6	82.5	78.1	73.6	67.5	62.7
72	1	98.3	80.8	84.7	85.9	93.2	92.2	90.1	87.4	85.9	81.8	77.6	71.7	67.3
72	2	98.7	80.7	84.7	85.9	93.2	92.8	90.8	88.1	86.8	82.7	78.3	72.3	67.9
72	3	99.1	80.6	84.1	85.8	92.9	93.6	91.6	88.7	87.6	83.6	79.1	73	68.4
72	4	98.8	80.6	84.4	85.8	92.8	93.2	91.1	88.3	87.4	83.3	78.8	72.7	68.3
72	5	99.1	80.6	84.7	85.9	92.8	93.8	91.5	88.5	87.5	83.3	78.5	72.4	68
72	6	98.8	80.6	83.4	84.9	92.4	93.4	91.4	88.5	87.6	83.3	78.6	72.6	67.9
72	7	98.5	80.6	83.5	85	92.7	92.9	90.8	88	87	82.7	77.9	72.1	67.4
72	8	98.7	80.6	83.8	85.4	92.7	93.2	91.2	88.4	87.2	82.9	78.2	72.2	67.6
72	9	98.3	80.6	83.5	85.2	92.7	92.5	90.5	87.8	86.5	82.3	78	72	67.4

Speed (km/h)	Sections	NIL [dBA]	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
72	10	98.1	80.6	84.3	85.4	93	92	89.9	87.4	86	81.9	77.7	71.8	67
96	1	101.6	80.6	86.4	88.4	94.2	96.7	94.7	91.1	90	86.2	82	76.9	72.3
96	2	102.5	80.6	86.2	88.4	94.6	97.8	95.4	92.4	91.6	87.5	83.1	77.8	73.4
96	3	102.8	80.6	86.1	88.1	94.3	98.1	96	92.9	92.1	88.2	83.9	78.5	74.3
96	4	102.6	80.6	85.9	88.2	94.1	97.9	95.7	92.6	91.9	88	83.7	78.3	73.8
96	5	102.5	80.6	85.9	87.7	94	97.8	95.6	92.6	91.8	87.9	83.5	78	73.6
96	6	102.3	80.6	84.9	87.1	93.4	97.9	95.5	92.2	91.7	87.6	82.8	77.3	72.8
96	7	102	80.6	84.9	87.1	93.7	97.5	95.2	91.9	91.1	87	82.4	76.9	72.3
96	8	102.1	80.6	84.9	87	93.7	97.6	95.4	92.1	91.5	87.4	82.7	77.2	72.6
96	9	101.8	80.6	84.9	86.8	93.5	97.2	94.9	91.7	91	87	82.5	77.1	72.4
96	10	101.4	80.6	85.7	87.5	93.6	96.6	94.2	91.2	90.3	86.5	82.2	76.9	72.2

Appendix B: Resulted MILs and NILs in Temperature Experiments

Table B1: MILs and NILs on Dukhan expressway at 35.5°C

Section	MIL [dBA]	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz	NIL [dBA]	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
Section 1	101.6	81.7	84.5	86.5	92.1	96.7	94.8	92.4	91.9	87.8	83.3	77.4	72.9	102.7	82.9	85.6	87.6	93.2	97.8	95.9	93.6	93	89	84.4	78.5	74.1
Section 2	101.5	80.9	83.9	86.2	91.9	96.6	94.7	92.4	92	88.1	83.6	77.8	73.2	102.6	82.1	85	87.3	93	97.7	95.8	93.5	93.2	89.2	84.7	78.9	74.3
Section 3	102.4	81.8	85.1	87.2	93.2	97.6	95.8	93.3	92.2	88.4	83.9	77.9	73.5	103.5	82.9	86.2	88.3	94.3	98.7	96.9	94.4	93.3	89.5	85	79	74.6
Section 4	101.7	82.3	84.9	86.7	92.2	96.8	94.8	92.7	92	88	83.5	77.7	73	102.8	83.4	86	87.8	93.3	97.9	95.9	93.8	93.1	89.2	84.6	78.8	74.2
Section 5	101.9	81.9	84.6	87	92.4	97	95	92.6	92.1	88.2	83.7	78	73.5	103	83	85.7	88.1	93.5	98.1	96.1	93.8	93.2	89.3	84.8	79.1	74.6
Section 6	101.9	82.2	84.9	87.2	92.8	97.1	95.3	92.7	91.7	87.9	83.4	77.4	73	103.1	83.3	86.1	88.3	93.9	98.2	96.4	93.8	92.8	89	84.6	78.5	74.1
Section 7	102.2	82.9	85.5	87.5	93.1	97.3	95.4	93	91.7	87.9	83.4	77.4	73	103.3	84	86.6	88.7	94.2	98.4	96.5	94.1	92.8	89.1	84.5	78.5	74.2
Section 8	102.3	82	85.5	87.8	93.4	97.7	95.8	92.7	91.3	87.3	82.5	76.4	72.2	103.4	83.2	86.6	88.9	94.5	98.8	96.9	93.8	92.4	88.4	83.6	77.5	73.3
Section 9	101.7	80.8	84	86.2	92.2	97.1	95.2	92.3	91.6	87.6	82.9	77	72.5	102.8	81.9	85.1	87.3	93.3	98.2	96.3	93.4	92.7	88.8	84	78.1	73.6
Section 10	101.5	80.6	83.5	85.5	91.7	96.8	95	92	91.6	87.6	83	77.3	72.7	102.6	81.7	84.6	86.7	92.8	97.9	96.1	93.2	92.7	88.7	84.1	78.4	73.9
Section 11	101.8	82	85	86.2	92.7	97.1	95.1	92.2	92	88	83.5	77.9	73.4	103	83.2	86.1	87.3	93.8	98.2	96.2	93.3	93.1	89.1	84.6	79	74.5
Section 12	101.4	80.5	82.7	85.1	91.3	96.6	94.9	92	91.8	88	83.5	77.9	73.5	102.5	81.6	83.8	86.2	92.4	97.7	96	93.1	92.9	89.1	84.6	79	74.6
Section 13	101.5	80.7	83.5	85.8	91.7	96.7	95	92.3	91.8	87.9	83.5	77.8	73.2	102.6	81.8	84.6	86.9	92.8	97.8	96.1	93.4	92.9	89	84.6	78.9	74.3
Section 14	101.4	81	83.5	85.9	91.7	96.5	94.8	92.3	91.6	87.9	83.4	77.7	73.2	102.8	83	84.6	87.4	93.1	98.1	96.1	93.5	92.7	89	84.5	79	74.6
Section 15	101.5	80.9	83.6	86	91.8	96.8	95	92.2	91.6	87.7	83.2	77.4	72.9	102.7	82	84.7	87.1	93	97.9	96.2	93.4	92.7	88.8	84.3	78.5	74

Table B2: MILs and NILs on Dukhan expressway at 26.4°C

Section	MIL [dBA]	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz	NIL [dBA]	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
Section 1	102.8	82.5	85.3	87.7	94.2	97.5	95.8	93.7	93.3	89	84.4	78.8	75.5	103.2	83	85.8	88.1	94.6	98	96.3	94.1	93.8	89.4	84.9	79.2	76
Section 2	102.5	81.5	84.6	87.2	93.6	97.3	95.3	93.4	93.5	89.1	84.6	79	75.6	103	82	85.1	87.7	94.1	97.8	95.8	93.9	94	89.6	85.1	79.5	76.1
Section 3	103.4	82.4	85.7	88.5	94.9	98.2	96.4	94.4	93.8	89.6	85	79.3	76	103.9	82.9	86.2	88.9	95.3	98.7	96.8	94.9	94.2	90	85.5	79.8	76.4
Section 4	102.5	81.5	85	87.3	93.6	97.3	95.3	93.5	93.3	89	84.6	78.8	75.1	102.9	81.9	85.4	87.8	94	97.8	95.8	94	93.7	89.4	85.1	79.3	75.6
Section 5	103	82.1	85.6	87.9	94.2	97.8	96	93.9	93.7	89.4	84.9	79.2	75.8	103.4	82.6	86	88.3	94.7	98.3	96.5	94.4	94.2	89.8	85.4	79.6	76.2
Section 6	102.8	81.7	85	87.8	94.2	97.6	95.8	93.8	93.1	88.9	84.4	78.5	75	103.2	82.2	85.4	88.2	94.7	98.1	96.3	94.3	93.5	89.3	84.9	78.9	75.4
Section 7	103	82.7	85.9	88.5	94.7	97.9	96.1	93.9	92.9	88.7	84.3	78.3	74.8	103.5	83.2	86.4	89	95.1	98.3	96.5	94.4	93.4	89.2	84.8	78.8	75.3
Section 8	103.1	82.1	85.9	88.4	94.6	98	96.3	93.9	93	88.4	83.6	77.6	74.2	103.5	82.5	86.3	88.9	95.1	98.5	96.7	94.3	93.5	88.9	84.1	78	74.6
Section 9	103	81.9	85.4	87.8	94.4	98.1	96	93.8	93.2	88.8	84	78.2	74.9	103.5	82.4	85.9	88.3	94.8	98.6	96.4	94.2	93.7	89.2	84.5	78.7	75.4
Section 10	102.8	81.5	84.9	87.5	93.9	97.9	95.8	93.6	93.4	88.9	84.2	78.4	75.1	103.3	82	85.3	88	94.4	98.3	96.3	94	93.9	89.4	84.7	78.9	75.6
Section 11	103.1	83.4	86.2	88.2	94.6	98.1	95.8	93.5	93.9	89.2	84.7	79.3	75.9	103.5	83.8	86.7	88.7	95	98.5	96.3	93.9	94.3	89.7	85.2	79.7	76.4
Section 12	102.6	81.3	84	86.7	93.4	97.8	95.6	93.4	93.5	89.1	84.6	79.1	75.8	103.1	81.7	84.5	87.1	93.9	98.2	96.1	93.9	94	89.5	85	79.6	76.3
Section 13	103	81.3	85.1	87.7	94.2	97.9	96	93.9	93.6	89.2	84.7	78.9	75.6	103.4	81.8	85.6	88.2	94.7	98.4	96.5	94.3	94	89.7	85.2	79.4	76
Section 14	103	82.1	85.6	88.1	94.4	97.9	96	94	93.3	89.1	84.5	78.7	75.3	103.5	82.5	86.1	88.6	94.9	98.4	96.5	94.4	93.8	89.5	85	79.2	75.8
Section 15	102.7	81.2	84.7	87.3	93.9	97.7	95.7	93.6	93.2	88.9	84.5	78.7	75.2	103.2	81.6	85.2	87.8	94.4	98.1	96.2	94	93.7	89.3	84.9	79.1	75.7

Table B3: MILs and NILs on Salwa expressway at 39.8°C

Section	MIL [dBA]	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz	NIL [dBA]	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
Section 1	103.3	83.5	87.7	89.8	95.5	98.8	96.6	93	90.7	86.8	81.9	75.5	71.2	104.7	84.9	89.1	91.3	96.9	100.2	98	94.4	92.2	88.2	83.4	76.9	72.7
Section 2	102.7	82.1	85.8	87.9	94	98.2	96.2	92.8	91.1	87.1	82.3	76	71.4	104.1	83.5	87.2	89.4	95.4	99.6	97.6	94.2	92.5	88.6	83.7	77.4	72.8
Section 3	103.7	83.4	87.8	90.4	95.9	99.2	97	93.4	91.1	87.3	82.4	76	71.8	105.1	84.8	89.2	91.8	97.3	100.6	98.4	94.8	92.6	88.7	83.8	77.4	73.2
Section 4	102.7	82.5	86.3	88.4	94.6	98.2	96	92.6	90.8	87	82.2	75.9	71.6	104.1	83.9	87.8	89.8	96.1	99.6	97.4	94	92.2	88.4	83.7	77.3	73
Section 5	103.2	84.2	88.5	90.4	95.5	98.7	96.4	92.4	90	86.6	82	75.2	71	104.6	85.6	90	91.8	97	100.1	97.8	93.9	91.4	88	83.4	76.6	72.4
Section 6	102.3	82.5	86.6	88.7	94.7	98	95.5	91.7	89.7	86.2	81.8	75.1	70.9	103.8	84	88.1	90.2	96.1	99.4	96.9	93.1	91.1	87.6	83.2	76.6	72.3
Section 7	104.2	87.5	92.2	94	99.3	99.1	93.7	90.4	88.7	85	81.1	74.2	70.2	105.6	88.9	93.7	95.4	100.7	100.6	95.2	91.8	90.1	86.4	82.6	75.7	71.7
Section 8	104	88	92.9	94.1	98.7	98.8	94.4	90.8	88.8	85.2	81.2	74.4	70.3	105.5	89.5	94.3	95.5	100.1	100.2	95.8	92.2	90.3	86.6	82.7	75.8	71.8
Section 9	103	84.1	88.7	90.4	96.4	98.9	95.2	90.9	88.9	85.3	80.9	73.8	70	104.4	85.5	90.2	91.8	97.8	100.3	96.6	92.3	90.3	86.7	82.3	75.2	71.4
Section 10	102.5	82.9	87.7	89.5	95.6	98.3	95.3	91	88.9	85.4	81	74	70.1	104	84.4	89.1	90.9	97	99.7	96.7	92.4	90.4	86.8	82.4	75.4	71.5
Section 11	103	84.8	89.5	91.3	97	98.7	94.5	90.3	88.5	84.7	80.5	73.6	69.8	104.4	86.2	90.9	92.7	98.4	100.1	95.9	91.7	89.9	86.2	81.9	75	71.3
Section 12	103.6	84	88.4	90.6	96.3	99.3	96.5	92.5	90	86.3	81.6	74.7	70.5	105	85.4	89.8	92	97.7	100.8	97.9	93.9	91.4	87.7	83.1	76.1	71.9
Section 13	102.9	83.1	87.4	89.6	95.4	98.7	96	92	89.6	86	81.3	74.5	70.4	104.3	84.5	88.8	91	96.8	100.1	97.4	93.5	91	87.4	82.7	75.9	71.8
Section 14	103.1	83.2	87.9	90.1	95.7	98.8	96.2	92.3	89.7	86.1	81.3	74.4	70.3	104.5	84.6	89.3	91.5	97.1	100.2	97.6	93.7	91.2	87.5	82.7	75.9	71.7

Table B4: MILs and NILs on Salwa expressway at 25.1°C

Section	**MIL [dBA]**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**	**1250 Hz**	**1600 Hz**	**2000 Hz**	**2500 Hz**	**3150 Hz**	**4000 Hz**	**5000 Hz**	**NIL [dBA]**	**400 Hz**	**500 Hz**	**630 Hz**	**800 Hz**	**1000 Hz**	**1250 Hz**	**1600 Hz**	**2000 Hz**	**2500 Hz**	**3150 Hz**	**4000 Hz**	**5000 Hz**
Section 1	103.7	83.1	87.8	90.5	96.7	98.9	96.7	93.6	91.7	87.4	82.4	76.3	73.1	104.1	83.5	88.1	90.8	97.1	99.3	97.1	94	92.1	87.8	82.8	76.7	73.4
Section 2	103	81.6	85.3	88.3	95	98.3	96	93.4	92.2	87.8	83.1	77.1	73.6	103.3	82	85.6	88.7	95.4	98.6	96.4	93.7	92.6	88.2	83.5	77.4	74
Section 3	104.1	83.4	88	90.7	96.9	99.3	97.1	94.2	92.3	87.9	83.1	76.9	73.8	104.5	83.8	88.4	91.1	97.3	99.6	97.5	94.5	92.6	88.3	83.4	77.3	74.1
Section 4	103.1	82.5	86.3	89	95.6	98.3	96.1	93.3	91.9	87.6	82.8	77	73.7	103.5	82.8	86.6	89.4	96	98.6	96.4	93.7	92.3	88	83.2	77.4	74
Section 5	103.7	84.4	88.8	90.7	96.8	98.8	96.7	93.5	91	87.1	82.7	76.4	73.2	104.1	84.8	89.1	91.1	97.1	99.1	97	93.8	91.4	87.5	83.1	76.7	73.6
Section 6	103.3	82.9	87.6	90.1	96.3	98.5	96.2	92.9	90.8	87	82.6	76	73	103.6	83.3	88	90.4	96.7	98.8	96.6	93.3	91.1	87.3	83	76.4	73.3
Section 7	104.8	87.4	92.4	94.1	100	99.8	94.6	91.4	89.7	85.9	82.4	75.3	72.2	105.2	87.7	92.7	94.4	100.4	100.2	95	91.7	90	86.3	82.7	75.7	72.6
Section 8	104.8	88.1	93.4	94.6	99.9	99.4	95.2	91.9	89.8	86	82.3	75.5	72.3	105.2	88.5	93.7	95	100.3	99.7	95.6	92.3	90.1	86.3	82.7	75.9	72.6
Section 9	103.4	83.7	88.4	90.7	96.8	99	95.7	92.3	89.8	86.1	81.9	75.2	72.4	103.8	84.1	88.7	91	97.2	99.3	96.1	92.6	90.2	86.5	82.3	75.6	72.8
Section 10	103.1	83.3	88.1	90.2	96.6	98.5	95.6	92.2	89.9	86.2	81.9	75.2	72.2	103.5	83.6	88.4	90.6	97	98.8	96	92.6	90.3	86.5	82.3	75.6	72.6
Section 11	103.6	84.9	89.7	91.9	98.2	98.9	95.1	91.5	89.4	85.7	81.8	75	72.1	104	85.2	90.1	92.3	98.6	99.2	95.4	91.8	89.8	86	82.2	75.3	72.5
Section 12	103.8	83.6	88.4	90.8	97	99.1	96.6	93.5	91.1	87.1	82.6	75.9	72.8	104.2	84	88.7	91.2	97.4	99.5	96.9	93.9	91.5	87.5	83	76.3	73.2
Section 13	103.9	84	88.6	91	97.4	99	96.5	93.3	90.9	86.9	82.4	75.9	72.8	104.2	84.4	89	91.4	97.8	99.4	96.9	93.7	91.3	87.3	82.8	76.2	73.2
Section 14	103.8	84.2	88.7	91.3	97.2	99	96.6	93.4	90.9	87	82.5	75.9	72.8	104.2	84.6	89	91.6	97.6	99.4	96.9	93.8	91.2	87.4	82.8	76.3	73.2

Appendix C: Resulted MILs and NILs in the Seven Expressways

Table C1: Resulted MILs and NILs in the Seven Expressways

Road Name	Date	Speed	Temp. [°C]	Section	Overall IL [dBA]	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz	Overall IL [dBA]	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
G Ring	02-May-17	60	35.6	1	101.4	80.2	83.7	86.3	92.6	96.7	94.6	91.6	91.3	86.7	82.3	76.9	72.6	102.5	81.4	84.8	87.4	93.8	97.8	95.7	92.7	92.4	87.8	83.4	78	73.7
				2	100.9	81.8	84.8	87.2	93.1	96.3	93.5	91	90.4	85.6	81.2	75.8	71.2	102.1	83	85.9	88.3	94.2	97.4	94.6	92.1	91.5	86.7	82.3	77	72.4
				3	101.2	81.1	84	86.5	92.9	96.6	94.2	91.3	90.4	86.5	82.2	76.8	72.1	102.3	82.2	85.2	87.6	94	97.7	95.4	92.4	91.6	87.6	83.3	77.9	73.3
				4	101.4	80.5	83.4	85.6	92.3	96.9	94.8	91.7	91	86.8	82.1	76.7	71.9	102.5	81.6	84.6	86.7	93.4	98	95.9	92.8	92.2	87.9	83.2	77.8	73
				5	101.4	81.1	84.5	86.7	92.6	96.8	94.8	91.6	90.7	86.4	81.5	75.8	71.1	102.5	82.2	85.6	87.8	93.8	98	95.9	92.7	91.9	87.5	82.6	76.9	72.2
				6	101.5	81.7	84	85.7	92.1	96.9	95	92	91.4	87.5	82.9	77.4	72.6	102.7	82.8	85.1	86.8	93.3	98	96.1	93.1	92.5	88.6	84	78.6	73.8
				7	101.7	80.7	83.7	86.3	92.8	97.1	95.1	91.9	91.2	87.2	82.6	77	72.1	102.8	81.9	84.9	87.4	93.9	98.2	96.2	93	92.4	88.3	83.7	78.1	73.3
				8	101.4	81.1	83.5	85.7	91.9	96.8	94.5	91.7	91.8	87.4	82.8	77.5	72.6	102.5	82.2	84.7	86.8	93	97.9	95.6	92.8	92.9	88.5	83.9	78.6	73.7
Ljmiliya	09-May-17	60	38.4	1	100.3	81.1	85	87	92.9	95.4	93.3	89.8	88.7	84.9	80.7	75.5	71	101.6	82.5	86.4	88.4	94.2	96.7	94.7	91.1	90	86.2	82	76.9	72.3
				2	101.2	81.4	84.8	87.1	93.3	96.5	94.1	91.1	90.3	86.2	81.8	76.5	72	102.5	82.8	86.2	88.4	94.6	97.8	95.4	92.4	91.6	87.5	83.1	77.8	73.4
				3	101.5	82.4	84.7	86.8	93	96.8	94.7	91.5	90.8	86.8	82.6	77.2	73	102.8	83.7	86.1	88.1	94.3	98.1	96	92.9	92.1	88.2	83.9	78.5	74.3
				4	101.2	81.5	84.6	86.8	92.7	96.6	94.3	91.2	90.5	86.6	82.4	77	72.5	102.6	82.9	85.9	88.2	94.1	97.9	95.7	92.6	91.9	88	83.7	78.3	73.8
				5	101.1	82	84.6	86.4	92.7	96.5	94.3	91.2	90.5	86.6	82.2	76.7	72.3	102.5	83.4	85.9	87.7	94	97.8	95.6	92.6	91.8	87.9	83.5	78	73.6
				6	100.9	80.8	83.6	85.7	92.1	96.5	94.2	90.9	90.4	86.3	81.5	76	71.5	102.3	82.1	84.9	87.1	93.4	97.9	95.5	92.2	91.7	87.6	82.8	77.3	72.8
				7	100.7	80.6	83.6	85.8	92.4	96.1	93.8	90.5	89.8	85.7	81.1	75.6	71	102	81.9	84.9	87.1	93.7	97.5	95.2	91.9	91.1	87	82.4	76.9	72.3
				8	100.8	80.7	83.6	85.7	92.3	96.3	94.1	90.8	90.2	86.1	81.3	75.8	71.2	102.1	82	84.9	87	93.7	97.6	95.4	92.1	91.5	87.4	82.7	77.2	72.6
				9	100.5	80	83.6	85.5	92.2	95.9	93.6	90.4	89.7	85.7	81.2	75.8	71.1	101.8	81.3	84.9	86.8	93.5	97.2	94.9	91.7	91	87	82.5	77.1	72.4
Rawdat Rashed	16-May-17	60	40.3	1	102.1	82.4	85	87.3	93.1	97.3	95.7	92.8	91.6	87.3	82.4	76.8	71.9	103.6	83.8	86.5	88.7	94.5	98.7	97.2	94.2	93	88.7	83.9	78.3	73.4
				2	102.7	81.9	85.4	87.4	93.5	98.2	96.4	92.9	91.7	87.3	82.2	76.2	71.4	104.1	83.4	86.8	88.9	95	99.7	97.9	94.4	93.2	88.8	83.6	77.6	72.9
				3	102.3	82.7	85.9	88	93.8	97.5	95.8	92.5	91.3	87.3	82.3	76.6	71.9	103.8	84.2	87.4	89.5	95.3	99	97.3	94	92.7	88.7	83.8	78.1	73.4
				4	102.6	82.8	85.9	88	93.8	97.8	96.3	92.8	91.4	87.4	82.6	76.8	72	104	84.3	87.3	89.5	95.3	99.3	97.7	94.3	92.8	88.8	84.1	78.3	73.4
				5	102	81.4	84.3	86.3	92.6	97.3	95.5	92.7	91.9	87.7	82.7	77	71.7	103.5	82.9	85.8	87.8	94	98.8	97	94.2	93.4	89.2	84.2	78.4	73.2
				6	101.6	81.1	83.5	85.3	91.5	96.9	95	92.3	92	87.7	82.7	77.1	71.8	103	82.5	84.9	86.8	93	98.4	96.5	93.8	93.5	89.1	84.2	78.5	73.2
				7	102.1	81.5	84.4	86.7	93.2	97.3	95.7	92.7	91.8	87.5	82.8	77.1	72	103.6	83	85.9	88.2	94.6	98.8	97.2	94.2	93.3	89	84.3	78.5	73.4
				8	102	81.7	84.6	86.8	92.7	97.1	95.5	92.7	91.8	87.6	82.6	76.8	71.7	103.4	83.2	86	88.3	94.1	98.6	97	94.2	93.3	89	84	78.3	73.1
F Ring	6-Jun-17	60	36.7	1	102.8	81.3	83.3	85.9	92.7	98.6	95.6	93.2	94.2	88.8	83.1	78.1	74.7	104	82.5	84.5	87.1	93.9	99.8	96.8	94.4	95.4	90	84.3	79.3	75.9
				2	103	81.5	83.9	86.1	92.9	98.6	95.7	93.6	94.3	89.1	83.8	78.5	74.6	104.2	82.7	85.1	87.3	94.1	99.8	96.9	94.8	95.5	90.3	85	79.7	75.8
				3	102.8	81.5	83.9	86.1	92.7	98.4	95.6	93.4	93.8	88.6	83.5	78.1	74.1	104	82.7	85.1	87.3	93.9	99.6	96.8	94.6	95	89.8	84.7	79.3	75.3

				4	102.4	81.3	83.3	85.7	92.4	98	95.4	93	93.1	88.2	83.2	77.7	73.7	103.6	82.5	84.5	86.9	93.6	99.2	96.6	94.2	94.4	89.4	84.4	78.9	74.9
				5	102.9	82	84.1	86.8	92.9	98.4	96	93.5	93.7	88.8	83.8	78.3	74.3	104.1	83.2	85.3	88	94.1	99.6	97.2	94.7	94.9	90	85	79.5	75.5
				6	102.9	82.6	84.7	87.1	93.2	98.4	95.9	93.4	93.4	88.6	83.4	78	74.1	104.1	83.8	85.9	88.3	94.4	99.6	97.1	94.6	94.6	89.8	84.6	79.2	75.3
				7	103.1	82	84.5	87.4	93.5	98.5	96.2	93.8	94	88.8	83.4	78	74.2	104.3	83.2	85.7	88.6	94.7	99.7	97.4	95	95.2	90	84.6	79.2	75.4
				8	103.1	82.9	84.7	87.4	93.4	98.4	96.1	93.7	94.1	88.8	83.6	78.1	74.4	104.3	84.1	85.9	88.6	94.6	99.6	97.3	94.9	95.3	90	84.8	79.3	75.6
Al Ruffa	11-April-17	60	31.83	1	101.6	79.8	83.8	86.1	92.4	96.8	95.2	92.5	91.5	87.4	82.7	76.8	72.1	102.5	80.6	84.7	86.9	93.2	97.7	96	93.3	92.3	88.2	83.6	77.6	73
				2	100.7	80	82.8	84.4	90.4	95.8	94.1	91.7	91.3	87.2	82.6	77.2	72.4	101.5	80.8	83.6	85.3	91.3	96.7	95	92.6	92.1	88	83.5	78.1	73.2
				3	101.4	80.9	83.7	85.9	92	96.5	94.9	92.3	91.5	87.6	83.1	77.2	72.8	102.3	81.7	84.5	86.8	92.8	97.4	95.8	93.1	92.4	88.4	83.9	78.1	73.7
				4	100.8	80.9	83.6	85.5	91.7	95.8	94.3	91.6	91.1	87	82.5	77	72.3	101.7	81.7	84.4	86.3	92.6	96.6	95.1	92.5	91.9	87.8	83.4	77.8	73.2
				5	101.6	79.8	83.5	85.5	91.7	96.8	95.2	92.5	92.2	88	83.2	77.5	72.7	102.5	80.7	84.3	86.4	92.6	97.6	96.1	93.4	93.1	88.8	84	78.4	73.5
				6	101.7	80.4	83.9	86	92	96.9	95.4	92.4	91.7	87.7	83	77.1	72.3	102.5	81.3	84.7	86.8	92.8	97.7	96.3	93.3	92.6	88.6	83.8	78	73.1
				7	101.2	80.3	83.1	84.9	91.1	96.3	94.8	92	91.7	87.6	82.9	77.4	72.5	102	81.2	84	85.7	92	97.1	95.6	92.9	92.5	88.5	83.8	78.2	73.4
				8	101.4	81.2	84	85.6	91.6	96.5	95	92.3	91.9	87.8	83	77.4	72.7	102.3	82	84.8	86.5	92.5	97.3	95.8	93.1	92.7	88.6	83.9	78.3	73.5
Al Shamal	22-March-17	60	30.1	1	102.2	81.1	84.9	87.9	94.7	97.8	94.9	92.1	90.9	86.9	82	76.4	73.5	102.6	81.4	85.2	88.3	95.1	98.1	95.2	92.4	91.2	87.2	82.3	76.7	73.9
				2	102.1	80.2	84.3	87	94	97.3	95.3	92.2	91.5	87.7	83	77.4	73.8	102.4	80.5	84.6	87.3	94.3	97.7	95.7	92.5	91.8	88	83.3	77.8	74.2
				3	102.7	81.8	85.8	88.8	95.7	98.1	95.3	92.3	91	86.9	82	76.3	73.5	103	82.1	86.2	89.1	96.1	98.4	95.6	92.6	91.4	87.2	82.3	76.7	73.8
				4	102.1	80	83.9	86.3	93.6	97.1	95.6	92.3	91.8	88.2	83.3	77.9	74.3	102.4	80.4	84.2	86.6	93.9	97.5	95.9	92.6	92.2	88.6	83.7	78.3	74.6
Dukhan	23-April -17	60	35.5	1	101.6	81.7	84.5	86.5	92.1	96.7	94.8	92.4	91.9	87.8	83.3	77.4	72.9	102.7	82.9	85.6	87.6	93.2	97.8	95.9	93.6	93	89	84.4	78.5	74.1
				2	101.5	80.9	83.9	86.2	91.9	96.6	94.7	92.4	92	88.1	83.6	77.8	73.2	102.6	82.1	85	87.3	93	97.7	95.8	93.5	93.2	89.2	84.7	78.9	74.3
				3	102.4	81.8	85.1	87.2	93.2	97.6	95.8	93.3	92.2	88.4	83.9	77.9	73.5	103.5	82.9	86.2	88.3	94.3	98.7	96.9	94.4	93.3	89.5	85	79	74.6
				4	101.7	82.3	84.9	86.7	92.2	96.8	94.8	92.7	92	88	83.5	77.7	73	102.8	83.4	86	87.8	93.3	97.9	95.9	93.8	93.1	89.2	84.6	78.8	74.2
				5	101.9	81.9	84.6	87	92.4	97	95	92.6	92.1	88.2	83.7	78	73.5	103	83	85.7	88.1	93.5	98.1	96.1	93.8	93.2	89.3	84.8	79.1	74.6
				6	101.9	82.2	84.9	87.2	92.8	97.1	95.3	92.7	91.7	87.9	83.4	77.4	73	103.1	83.3	86.1	88.3	93.9	98.2	96.4	93.8	92.8	89	84.6	78.5	74.1
				7	102.2	82.9	85.5	87.5	93.1	97.3	95.4	93	91.7	87.9	83.4	77.4	73	103.3	84	86.6	88.7	94.2	98.4	96.5	94.1	92.8	89.1	84.5	78.5	74.2
				8	102.3	82	85.5	87.8	93.4	97.7	95.8	92.7	91.3	87.3	82.5	76.4	72.2	103.4	83.2	86.6	88.9	94.5	98.8	96.9	93.8	92.4	88.4	83.6	77.5	73.3
				9	101.7	80.8	84	86.2	92.2	97.1	95.2	92.3	91.6	87.6	82.9	77	72.5	102.8	81.9	85.1	87.3	93.3	98.2	96.3	93.4	92.7	88.8	84	78.1	73.6
				10	101.5	80.6	83.5	85.5	91.7	96.8	95	92	91.6	87.6	83	77.3	72.7	102.6	81.7	84.6	86.7	92.8	97.9	96.1	93.2	92.7	88.7	84.1	78.4	73.9
				11	101.8	82	85	86.2	92.7	97.1	95.1	92.2	92	88	83.5	77.9	73.4	103	83.2	86.1	87.3	93.8	98.2	96.2	93.3	93.1	89.1	84.6	79	74.5
				12	101.4	80.5	82.7	85.1	91.3	96.6	94.9	92	91.8	88	83.5	77.9	73.5	102.5	81.6	83.8	86.2	92.4	97.7	96	93.1	92.9	89.1	84.6	79	74.6
				13	101.5	80.7	83.5	85.8	91.7	96.7	95	92.3	91.8	87.9	83.5	77.8	73.2	102.6	81.8	84.6	86.9	92.8	97.8	96.1	93.4	92.9	89	84.6	78.9	74.3
				14	101.4	81	83.5	85.9	91.7	96.5	94.8	92.3	91.6	87.9	83.4	77.7	73.2	102.8	83	84.6	87.4	93.1	98.1	96.1	93.5	92.7	89	84.5	79	74.6
				15	101.5	80.9	83.6	86	91.8	96.8	95	92.2	91.6	87.7	83.2	77.4	72.9	102.7	82	84.7	87.1	93	97.9	96.2	93.4	92.7	88.8	84.3	78.5	74