ASSESSMENT OF THE EFFECTS OF VEHICULAR SPEEDS ON NOISE LEVELS GENERATED FROM VEHICLES AS PERCEIVED BY COMMUTERS AND ROADUSERS

Submitted in partial fulfilment of the requirements

for the award of the degree of

Doctor of Philosophy

by

KAMINENI ADITYA

714101

DEPARTMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, WARANGAL

JUNE 2020

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WARANGAL

CERTIFICATE

This is to certify that the thesis entitled "**ASSESSMENT OF THE EFFECTS OF VEHICULAR SPEEDS ON NOISE LEVELS GENERATED FROM VEHICLES AS PERCEIVED BY COMMUTERS AND ROADUSERS**" being submitted by **Mr. KAMINENI ADITYA** for the award of the degree of **DOCTOR OF PHILOSOPHY** to the Department of Civil Engineering of **NATIONAL INSTITUTE OF TECHNOLOGY, WARANGAL** is a record of bonafide research work carried out by him under my supervision and it has not been submitted elsewhere for award of any degree.

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APPROVAL SHEET

This Thesis entitled **"ASSESSMENT OF THE EFFECTS OF VEHICULAR SPEEDS ON NOISE LEVELS GENERATED FROM VEHICLES AS PERCEIVED BY COMMUTERS AND ROADUSERS"** by Mr. **KAMINENI ADITYA** is approved for the degree of **Doctor of Philosophy**.

Examiners

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DECLARATION

This is to certify that the work presented in the thesis entitled **"ASSESSMENT OF THE EFFECTS OF VEHICULAR SPEEDS ON NOISE LEVELS GENERATED FROM VEHICLES AS PERCEIVED BY COMMUTERS AND ROADUSERS"**, is a bonafide work done by me under the supervision of **Dr. Venkaiah Chowdary**, AssociateProfessor, Department of Civil Engineering, NIT, Warangal, Telangana, India and was not submitted elsewhere for the award of any degree. I declare that this written submission represents my ideas in my own words. I have adequately cited and referenced the original sources where others ideas or words have been included. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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MY PARENTS AND TEACHERS

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KAMINENI ADITYA

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LAeq	A-Weighted equivalent continuous sound pressure level
LA10	Noise level exceeded for 10% of the measurement period
LAmax	Maximum A - weighted sound pressure level
LAFmax	The maximum Sound Level with 'A' frequency weighting and Fast time weighting
h	Hour
min	Minute
kmph	kilometre per hour
m	Metre
dB	Decibels

LIST OF ABBREVIATIONS

SLM	Sound Level Meter
CPB	Controlled Pass-By
CB	Coast-By
CPX	Close Proximity
OBSI	On-Board Sound Intensity
PCU	Passenger Car Unit
LV	Light Vehicle
MV	Medium Vehicle
HV	Heavy Vehicle
PCU	Passenger Car Unit
2W	2-Wheeler
3W	3-Wheeler
PCU	Passenger Car Unit

ABSTRACT

With globalization, the exponential rise of vehicle number in different classes has made the nature of heterogeneous traffic into more complex phenomena. Accordingly, with the presence of different vehicle sizes, different engine characteristics, and maneuvering abilities, road traffic movements result in a wide spectrum of speeds and noise levels. Thus, with road speed being the prime fluctuating agent, researchers determined road traffic noise from vehicle fleet as a combination of aerodynamic noise, propulsion noise and tire-pavement interaction noise. Aerodynamic noise is the source emitted along the geometrical structure of the vehicle in motion, and its effect is very low compared to other noise sources on the road. This is due to the fact that, it is experienced only by the person sitting in the vehicle and the major aerodynamic drag at the tire-pavement interface is considered within the tire-pavement noise itself. Moreover, dependence of aerodynamic noise on vehicle speed is a complex phenomenon as it varies with temporal changes in the field. Tire-pavement interaction noise is defined as the noise generated due to tire-pavement interaction caused by the movement of vehicle tires over the pavement surface. As the vehicle moves at a high speed, high tire-pavement interaction can occur. Thus, tire-pavement interaction outstrips other noise sources at higher vehicle speeds exceeding 40 kmph. On the contrary, propulsion noise is a dominant noise source at vehicle speeds falling below 40 kmph, as it is noise generated from the engine, gear transmission and the exhaust system.

At lower vehicle speeds in mixed traffic conditions, one more major noise source known as honking (number of honks in the time interval) defines noise levels. This is due to the fact that, accelerating vehicles generate more noise than vehicles travelling at constant speed, where the driving pattern of a vehicle is likely to change frequently at intersections and rotaries or roundabouts. Even though the primary objective of improving traffic flow by reducing conflict points from safety point of view is achieved with rotaries or roundabouts, the noise level due to honking will severely affect people residing nearby. Thus, apart from high speed midblock sections of a highway passing through urban area, there is a need to initiate the study on evaluating traffic noise pollution near urban units such as intersections, rotaries or roundabouts, where traffic volumes are high, and vehicle speeds are comparatively low. Thus, prior to the individual source level noise quantification, the current study focused on identifying major parameters responsible for overall traffic noise on both midblock

sections and rotaries. Standardized Control Pass-By (CPB) method was used for measuring the far field noise experienced by the roaduser on both highways and rotaries. The noise levels measured for all selected highways showed that, both LAeq (dB) and LA10 (dB) exceed noise limits prescribed by Central Pollution Control Board (2000). Overall, two and three wheelers are dominating the volume proportion in most of the highways selected, showing the need for improved public transportation facilities. The results also revealed that, a combination of volume proportion and vehicle speeds would play a significant role in highway noise level generation. Similar approach of far field measurement at the rotaries revealed that, heavy vehicles and their corresponding honking were majorly affecting the LAeq (dB) compared to other vehicular proportion. It was observed that, an equivalent noise level [LAeq (dB)] rise of 2 to 6 dB was solely caused by heavy vehicles. These results revealed that, each vehicle class moving at different speeds in mixed traffic flow is certainly responsible for the rise in traffic noise level in its own way. This shows the need for source level noise measures to be taken for reduction of noise levels.

Thus, the current study further attempts to study the effect of both tire-pavement interaction and propulsion noise on overall noise levels with the objective of identifying the major factors affecting them. Accordingly, passenger cars of varying engine types were selected as test vehicles for assessing the effect of propulsion noise. To assess the impact of tire-pavement interaction, two asphalt and two cement concrete pavements were selected as test sections in the Warangal city, and Controlled Pass-By (CPB) and Coast-By (CB) measurements were conducted on these test sections at mid-night using a Sound Level Meter (SLM). Accordingly, capturing the vehicle noise level requires a clear distinction on assessing the effect of propulsion, and tire-pavement interaction. Thus, an approach for assessing the pass-by propulsion noise levels is used with logarithmic subtraction of relative energies of the sound pressure levels captured from CPB and CB methods. Further, an added advent to pass-by methods using the vehicle jack was developed and the respective tire-pavement noise levels were measured in this case study. In comparison, tire-pavement noise levels quantified using the developed method showed a good correlation with standard CB noise levels, with an R^2 value of 0.965. On an average, petrol vehicles are producing 4 dB to 5 dB less propulsion noise levels compared to diesel powered vehicles. Moreover, tire-pavement noise levels are hugely affected by pavement types, and showed considerable increase of 3 dB to 9 dB on cement concrete pavements in comparison with asphalt pavements. Tire-pavement and

vehicle noise levels were reaching similar edge on overall fine-tuned A-weighed noise levels, at speeds exceeding 60 kmph for all selected test vehicles. This shows the dominance of tire-pavement interaction on roadusers (people outside the vehicle including pedestrians). Thus, the study attempts to measure the effect of tire-pavement interaction on commuters (driver and passengers), who are under continuous noise exposure throughout the travel, unlike momentary exposure by roadusers. To avoid the effect of vehicle vibrations on SLM inside the vehicle, a new method is proposed using a handheld SLM and a 3-axis stabilizer mounted SLM. The noise levels captured using both sound level meters were compared at different vehicle speeds ranging from 40kmph to 70 kmph. The stabilizer mounted SLM had shown 1 to 2 dB lower noise levels compared to handheld SLM. Average variation of 3 to 5 dB was observed between asphalt and cement concrete pavements, with the highest noise being produced by cement concrete pavements. Even though several researches in the past had measured the in-vehicle noise as perceived by commuters, the method adopted in this study is first of its kind in tire-pavement noise research where the noise levels due to reduced effect of tremor vibrations experienced by the driver at the ear level were captured. Overall, the dominance of tire-pavement interaction on overall noise at most speeds was clearly observed, which is hugely influenced by the change in pavement type. This shows the immediate need for constructing low noise pavements to mitigate the tire-pavement noise at the source level.

Keywords - Heterogeneous traffic, noise levels, tire-pavement interaction, propulsion noise, Controlled Pass-By, Coast-By, roadusers, commuters.

CHAPTER 1

INTRODUCTION

1.1 General

With the vehicle fleet expanding day by day, road traffic noise has increased considerably, from being an annoyance to chronic health affecting agents in the environment. The health hazards associated with the noise pollution are dreadful, with both physiological and psychological effects on human beings. Annoyance, irritability, sleeplessness, interference with communication, reduction in work performance, heartburn, indigestion, ulcers, changes in blood pressure, permanent hearing loss and cardiovascular diseases are the common side effects. With a contribution of 55% to total urban noise and with the exponential growth of vehicles at present, road traffic noise may lead to extreme noise pollution in the future (Zannin et al. 2003). This situation proves the severity and necessity of mitigating traffic noise wherever possible. This inevitable requirement has led to the need for taking up traffic noise studies by researchers globally, including India, to study the core factors contributing to road noise levels. As the drastic increase in different vehicle classes hitting the Indian roads is dreadful, as the Compound Annual Growth Rate (CAGR) is 10.5% between 2002 and 2012 (Guite, 2017). This rise in different classes of vehicles in the traffic stream transformed the heterogeneity of Indian traffic highly complex phenomena. Accordingly, even a sensitive factor-like honking (number of horns in a specified interval) proves to be a significant source of noise pollution in heterogeneous traffic. Thus, compared to most countries across the world, the unique phenomena that worry road planners and traffic engineers in India is the heterogeneity in traffic flow on most of the roads. With the presence of different vehicle sizes, different engine characteristics, and maneuvering abilities, speeds vary more often in heterogenic traffic and result in a vast spectrum of noise levels. Thus, vehicle speeds will have a significant effect on vehicular noise sources. Therefore, it is the prime objective of planners and engineers to understand noise pollution origin to develop noise regulations for roads. As rapid/slow movement of traffic will promptly generate different noise levels from various noise sources, measuring noise levels caused solely from each source at varying speeds can be a principal prerequisite for the anticipated achievement of low noise levels.

1.2 Vehicle Noise Sources and their Importance

With road speed being the prime agent prone to fluctuation, researchers have defined road traffic noise from the vehicle fleet as a combination of aerodynamic noise, propulsion noise, and tire-pavement interaction noise. Along with the three noise sources, one critical source of noise leading to an incidental rise in heterogenic traffic noise levels is honking. Defining these noise sources along with their actual effect on the overall vehicle noise is essential to measure, understand, and reduce prevalent traffic noise through suitable measures.

Aerodynamic noise is the source emitted throughout the geometrical structure of the vehicle in motion. It depends on the frontal area, and speed of the vehicle whose mitigation on a common objective is not possible. It is because the aerodynamic noise effect is very low on overall noise emission, and is experienced only by the person sitting in the vehicle. Moreover, significant aerodynamic drag at the tire-pavement interface included within the tire-pavement interaction noise itself. Across the globe, aerodynamic noise is neither being separately prioritized in the quantification of far-field noise experienced by the roadusers (pass-by) nor in noise measurements close to the field.

Tire-pavement noise is the noise generated due to tire-pavement interaction caused by the movement of vehicle tires over the pavement surface. As the vehicle moves with high speed, high tire-pavement interaction can occur. Thus, tire-pavement interaction noise is the most dominant source for vehicles exceeding 40-50 kmph speed. The speed domain of 40-50 kmph is most common in an urban agglomeration and will have a prominent effect on both roadusers (pass-by) and commuters (in-vehicle).

As both the noise sources (aerodynamic and tire-pavement interaction noise) vary directly with vehicle speed, an inference cannot be drawn by stating that, reduction in vehicle noise levels can be achieved at lower vehicle speeds. This is because vehicular noise will not gradually decrease with a decrease in vehicle speeds, as propulsion noise of vehicle dominates at lower road speeds, usually below 50 kmph. Unlike the tire-pavement interaction noise source, propulsion noise will not hold a direct relation with vehicle speed, and its dependence on the logarithmic relationship is characterized by engine speed (RPM) and gear selection. Even the variance in engine type of the vehicle can result in a considerable change in noise level generation. Accordingly, the high propulsion noise levels can usually be encountered in a heterogenic traffic stream of most urban structures, where vehicle speeds decline more often.

Overall, aerodynamic noise effect is very low on overall vehicle noise emission and is experienced only by the person sitting in the vehicle (commuter). It is the concentration of noise levels due to tire-pavement interaction, and propulsion noise sources are mainly considered in pass-by (roaduser) traffic noise quantification. Accordingly, different methods have been developed for quantifying the dominant noise sources experienced by the roaduser (pass-by) and commuter (in-vehicle).

1.3 Research Background – Noise Measurement Methods

Field measurement methods for the road noise can be divided into far-field and near field measurement methods. The quantification of noise levels near the interactive surface between the tire and the road. Two such methods are the close proximity (CPX) method and the on-board sound intensity (OBSI) method.

1.3.1 Close Proximity Method

The close proximity method is used to measure the sound pressure level near the tire-pavement interface. A set of 2 to 11 microphones are installed on a test tire, and the sound pressures measured from all the microphones are averaged over a short pavement section to estimate the average sound pressure level (SPL). The tested tire can be either one of the tires of running vehicles or separately mounted under a trailer (trailer close proximity test), which is towed by the test vehicle. Trailer close proximity test has the advantage of eliminating the propulsion noise during measurement. On the other hand, due to the geometrics of many urban streets, and the safety of the test vehicle, trailer speed cannot exceed 50 kmph, which is a severe limitation when quantifying tire-pavement interaction noise. Thus, the running vehicle tire itself is used as the test tire in the CPX method across the world. On the other hand, this method possesses the limitation of slight inclusion of propulsion noise, along with the quantified tire-pavement interaction noise level.

1.3.2 On-Board Sound Intensity Method

The on-board sound intensity method includes two synchronized, directional sound intensity probes on the passenger car wheel close to the pavement for quantifying the tire-pavement interaction noise levels. In this method, the vehicle can be driven at any speed, and on any pavement. Moreover, the system is attached to the test vehicle itself. Similar to the CPX method, the OBSI method has the disadvantage of inclusion of propulsion noise with the quantified tire-pavement interaction noise. To overcome this problem, recently electric vehicle was used in place of petrol/diesel vehicle in OBSI method, which could incorporate the advantage of avoiding propulsion noise while measuring tire-pavement interaction noise (Zofka et al. 2017).

Overall, near field techniques have their advantages and disadvantages. Both CPX and OBSI methods require a series of microphones where noise levels captured do not resemble the actual noise levels experienced by the roadusers. This is because noise levels are compressed and altered during the propagation over the road surface. Consequently, far-field (or) pass-by noise methodologies have gained a lot of attention from researchers due to their compatibility, and the advent of simulating the actual audible spectrum of roadusers. The statistical pass-by (SPB) method, coast-by (CB) method, and controlled pass-by (CPB) method are classified under pass-by methods of road noise measurements.

1.3.3 Statistical Pass-By Method

The effect of pavement surface on noise levels generated due to tire-pavement interaction at constant vehicle speed can be estimated by the SPB method. Free flow traffic streams with rapid vehicle movements involving a minimum of 100 cars and 80 trucks are selected in this method (Li, 2013). A sound level meter is placed on the roadside at a distance of 7.5 meters from the centerline of the outer lane, at the height of 1.2 to 1.5 m on the ground. This method is limited to free-flow traffic involving isolated vehicle classifications, and the respective A-weighted sound pressure level of specific vehicle stream at the reference speeds are drawn from the data and expressed as Statistical Pass-By Index (SPBI). Even though this method represents the actual pass-by traffic noise from the vehicle flow, it has some limitations. Uninterrupted traffic flow conditions and limitations of shorter geometrics of urban streets are not covered in this method, which is most common in urban roads.

Moreover, this method requires a huge vehicle noise data, which is time-consuming. These limitations can be overcome with the help of CPB and CB methods.

1.3.4 Controlled Pass-By Method

The controlled pass-by method is quite similar to the SPB method. One noticeable difference is the estimation of the road noise on a limited number of vehicles. A single or several vehicles with different modal characteristics (passenger car, bus, truck) are independently run over a test site at pre-defined speeds, and the respective sound pressure level is captured at the wayside. The actual pavement/tire effect on the road noise level can be quantified in this study due to the control over the selection of vehicles and their speeds. The limitations being the traffic closure requirement to avoid the inclusion of other vehicle noise while conducting the study on roads instead of the constructed test track. Similar to the SPB method, propulsion noise will be included in the captured tire-pavement noise levels in the CPB method. For adding the advantage of the trailer in the CPX method to the CPB method, a new method known as the coast-by method is developed.

1.3.5 Coast-By Method

The coast-by method is similar to the CPB method in estimating the noise level from a single vehicle on a selected test track. Tire-pavement interaction noise levels are measured by a vehicle driven with inertia force by switching off the engine/disengaging the gear transmission at the desired vehicle speed in the CB method. Sound level meters are kept at 3.5 to 7.5 m from the centerline of the vehicle movement, at the height of 1.2 m on the ground to capture the maximum A-weighted sound pressure level [LAmax (dB)], at each pass of the vehicle, and at a known speed. Pre-defined distance and height combination is preferred to analyze the realistic listening situation of the roaduser standing at the roadside. Different pavement and tire combinations give different tire-pavement interactions leading to variation in noise levels. Since the vehicle has to run in coast-by condition, control on the vehicle is limited at higher speeds, which demands separate test tracks, straight road stretches, and experienced drivers for using this method. Among all the methods available, capturing the pass-by tire-pavement interaction noise level with complete elimination of propulsion noise is possible with this method.

Subsequently, simple observation can be drawn among all these methodologies. The near field methods measure noise levels at the source of generation, and far-field methods measure noise levels perceived by the roadusers in the outer environment of the vehicle. It can be clearly observed that none of these methods measures the noise levels experienced by the passenger/driver (commuter) sitting in the vehicle, who is exposed to noise continuously when the vehicle is in motion. This is because the acoustic environment in the vehicle is complex, and noise measurement is prone to massive vibrations from the vehicle. Accordingly, it is essential to note that reflections and vibrations will severely affect the noise levels measured. Moreover, unlike the far filed noise assessment where the sturdy tripod holds the sound level meter [SLM] at a preferred height (usually 1.2 to 1.5 meters for simulating the human ear height from ground), SLM cannot be placed steadily on the tripod inside the vehicle during the travel. Thus, techniques of fixing the sound level meters and microphones to the vehicle body near the driver's ear height and use of in-ear microphones were employed for assessing in-vehicle noise levels in different parts of the world.

As field measurement techniques possess their advantages and disadvantages, selection of the method purely relies on the noise source to be quantified. It is necessary to identify the effect of dominant noise sources on overall noise levels by selecting an appropriate methodology to identify the measures for reducing noise levels at the source.

1.4 Need for the Study

In general, traffic in developing countries such as India is heterogeneous in nature where the vehicle classes vary from slow-moving non-motorized vehicles such as bicycles and tricycles to fast-moving motorized vehicles including Light Vehicles (LV) [motorized two-wheeler], Medium Vehicles (MV) [auto-rickshaw, car/jeep, and light commercial vehicle] and Heavy Vehicles (HV) [bus, regular truck, dumper truck, and tractor-trailer]. As the modal mix includes both slow-moving and fast-moving vehicles with different sizes and maneuvering abilities, speeds fluctuate more often in heterogenic traffic and result in a spectrum of noise levels. Accordingly, even a sensitive factor such as honking would add high noise levels in mixed traffic conditions compared to homogeneous traffic. Thus, there will be a significant effect of modal mix flows and speeds on the generation of traffic noise levels.

Most studies across the globe developed traffic noise prediction models under homogeneous traffic conditions. However, heterogenic traffic noise assessment requires the consideration of the independent proportion of vehicles and factors affecting them. Moreover, the rapid/slow movement of vehicles promptly generate different noise levels due to noise originating from various noise sources. Indeed, measuring the noise levels solely by each source can be a principal prerequisite for the anticipated achievement of the low noise levels in the society. Thus, measuring the noise levels requires clear assessment on the effect of principal noise sources. As tire-pavement interaction and propulsion noise levels contribute to the major part of the noise levels from the vehicle, measuring these noise sources with respect to vehicle speed is needed. Thus, a method which can assess the noise level distinction between the principal noise sources need to be developed. Moreover, noise sources generated from the vehicle is different at outside and inside the vehicle. Thus, measurement procedures adopted for source level noise measurement requires different techniques. Unlike the sturdy tripod holding the noise measurement equipment placed on the ground outside the vehicle, noise measurement equipment inside the vehicle is subjected to movements and vibrations from the vehicle when it is fixed to the vehicle body. Thus, placement of the noise measurement equipment inside the vehicle is a need to be addressed. This enables the planners and engineers to identify the measures to minimize the noise at the source level for creating a healthy environment on the road.

1.5 Objectives of the Study

The Objectives of the research work are listed as follows:

1. To investigate the effect of vehicular movement on the generation of road traffic noise.
2. To quantify the noise levels generated due to honks from different vehicle types at urban rotaries.
3. To identify vehicular sources generating the road noise levels at different speeds.
4. To develop a process to quantify pass-by noise levels due to engine and tire-pavement interaction of vehicles.
5. To develop a process to quantify in-vehicle noise levels due to tire-pavement interaction.
6. To investigate the overall variation of tire-pavement interaction noise at different speeds.

1.6 Scope of the Current Study

The present work is confined only to mid-block sections on highways and urban arterials. The study is restricted to plain terrain, with heterogenic traffic flow. Further, the study considers rotaries passing through residential and commercial areas.

1.7 Organization of the Thesis

The thesis is presented in six chapters, and the contents of the report are organized as follows:

Chapter 1 includes an overview of the traffic noise pollution and its significance in the Indian context, with a detailed explanation of vehicle noise sources and respective measurement methods. Overall, this chapter deals with the rationale, objectives, and scope of the work.

Chapter 2 includes a review of earlier research work related to traffic noise pollution. Work-related to factors affecting traffic noise levels on midblock sections and rotaries are discussed. Further, studies on the principal noise sources responsible for the high noise levels and studies on methods available for the measurement of the noise sources on the road are reviewed separately at the source and receiver ends. In conclusion, inference from the literature review is presented with an emphasis on the gaps observed in the literature.

Chapter 3 includes the methodology of the current study with the help of a flow chart. A detailed explanation of the methods used for noise measurements is presented in this chapter.

Chapter 4 presents the details of procedures adopted for noise data collection in each study location and the analysis of field data with the help of noise tools software. Heterogeneous traffic noise data collection procedures on highway sections and rotaries are presented. Further, the effect of tire-pavement interaction noise sources on pass-by noise levels and in-vehicle noise levels are thoroughly discussed.

Chapter 5 includes the details of the noise prediction model developed in this study, including the validation process. Further, statistical significance checks for the developed models are included in this chapter.

Chapter 6 includes a summary of current research work, along with conclusions and limitations. Further, the scope for future work is also presented.

CHAPTER 2
LITERATURE REVIEW

2.1 General

Over the past few decades, the majority of researchers across the world focused on studying the effect of principal noise sources responsible for noise generation on roads having homogeneous traffic conditions. Accordingly, substantial work carried out with the intent of reducing the negative upshot of an unhealthy environment on roadusers and commuters due to traffic noise exposure. Subsequently, speed restrictions, noise barriers, and noise abatement measures have been enforced in many countries to reduce the noise. However, the heterogenic traffic composition in India is leading the spectrum of noise levels due to the fluctuating speeds. The complexity of fluctuating speeds with ever-increasing vehicle growth is challenging the traffic engineers in creating a healthy environment.

Thus, noise level variation in mixed traffic conditions needs a thorough study in identifying the principal noise sources responsible for noise levels at fluctuating speeds. Both highway midblock sections and the roundabouts/rotaries situated along the road will experience different speeds and different noise levels. Thus, a thorough study is essential for identifying the dominant noise sources responsible for higher noise levels at both places. As each vehicular noise source needs to be captured separately with the suitable methodologies, studies on current methods available for the measurement of noise levels need to be analyzed. This chapter presents a comprehensive review of research work covering the studies related to various factors affecting the traffic noise levels, principal noise sources responsible for higher noise levels, and the methods available for the measurement of noise levels experienced by roadusers and commuters.

2.2 Studies on Factors Affecting the Traffic Noise Levels on Roads

Most of the researchers in the past conducted traffic noise studies for homogenous traffic conditions. However, the unique phenomenon that bothers the road planners and the traffic engineers in India is the heterogeneity in traffic flow on most of the roads. With the presence of different vehicle sizes, different engine characteristics, and maneuvering abilities, the heterogenic traffic movements result in the spectrum of noise levels. To understand the unique factors affecting the noise levels in both the homogeneous and heterogeneous research works carried out across the world are reviewed and presented below.

Nelson and Piner (1977) examined the noise levels generated by the vehicles in free - flow and non- free-flow conditions. Accordingly, congested traffic moving at 20 kmph to free flow traffic moving at 100 kmph are considered for the study. Further, vehicles are classified into light vehicles (unladen weight < 3000kg), medium heavy vehicles (2 axles) and heavy vehicles (3 or more axles). Range of traffic conditions for each set of these vehicle categories are varied in the computer program in the range of 200, 1000 and 2000 vehicles per hour. With the vehicle speed exceeding 50 kmph, vehicle noise increases at approximately 9 dB per doubling of the speed in free-flow conditions. Whereas, noise levels from the noisiest vehicle exceeding the quietest vehicle by a massive margin of 17 dB in non- free-flow conditions. In conclusion, vehicle classes in both the flow conditions were exceeding the safe noise limits at most speeds.

Gupta et al. (1984) developed a relationship between vehicular noise and traffic stream flow parameters. The highway passing through Roorkee city, India, was selected as the study area near Polaris intersection. Motorized vehicle count and percentage of heavy vehicles in the mixed traffic stream were considered to evaluate the traffic noise situation. Both peak and off-peak hour are considered for the study to analyze the effect of variation in traffic flow on the noise generation. The considered sixty-minute volume count had the dominant vehicle volume of light vehicles followed by the heavy vehicles. Thus, the researchers developed a prediction equation for the noise level LA10, based on the volume monitored for a time interval of sixty minutes. Overall, compared to other modal classes, heavy vehicles are generating more noise levels.

Raghavachari and Narsimhamurthy (1986) attempted to relate highway noise levels to traffic factors such as speed, volume, and pedestrian density. Hyderabad city in the current Telangana state, India, was selected as the study area with the intent of analyzing the highway noise levels. Both light and heavy vehicle combination in the traffic stream are considered in the study for the time interval of sixty minutes. Most of the roads selected for the study had the dominant proportion of light vehicles over heavy vehicles. It was also observed that, the combination of vehicle volumes and the respective traffic speeds in the heterogeneous traffic are responsible for change in the noise levels. Accordingly, traffic noise in terms of sound pressure level was expressed in decibels (dB), as shown in the following equations (2.1 to 2.3).

$$dB = 66.8+0.0037(Q)+0.145(V)+0.0022(P) \quad (2.1)$$

$$dB = 75.58+0.000099(QV) \quad (2.2)$$

$$dB = 74.41+0.0026(Q+P) \quad (2.3)$$

Where, Q is the Volume (vph), V is the Speed (kmph), and P is the pedestrian density.

Skarlatos and Drakatos (1988) studied the scenario of noise pollution in Greek towns with the intent of developing a probabilistic model for environmental noise prediction. By consideration of the assessed environment noise as the stochastic signal, the proposed model neglects the noise source identity. Accordingly, to fit the varying noise levels to a trigonometric series, methods of regression are used. The study also assumes that the use of power spectral densities helps the noise capturing mechanism and helps the process of regression in opting for the optimum model. A descriptor named day-night noise level (L_{dn}) considered for the developed model, which was prominent in understanding noise exposure over the community. The measured noise level (Leq) used with the day-night noise level (L_{dn}) appears to be better with an R^2value of 0.9. Further investigation is needed on the proposed noise descriptor to check its adaptability in different cities.

Victoria (1991) documented the quantification and detailed study of noise levels in noise-sensitive areas. The document addressed the placement of the microphone positions on the tripod during noise measurements. The researcher reported that the microphone should be located at a ground height of 1.2 to 1.5 meters away from the reflecting surfaces in outdoor measurements. Whereas, the reflection adjustment is not mandatory for indoor noise measurements. Unwanted vibrations on the sound level meter should be avoided in the field for error-free measurements by using vibration isolation.

Singh and Jain (1995) measured the traffic noise levels in the residential, commercial, and industrial areas of New Delhi city. Commercial areas in the city are experiencing the highest noise level, followed by industrial and residential areas. The equivalent sound pressure level (Leq) of 65 dB observed in the commercial area in the day-time. Whereas day-time Leq of 52.8 dB and 62.1 dB were captured in the residential and industrial areas, respectively, which are below the standards prescribed by the World Health Organization (WHO). The researchers concluded that noise pollution would not pose a severe threat in the industrial and residential areas of Delhi city.

Rao (1997) studied the influence of mixed traffic on the generation of road traffic noise levels near the Vindhyachal project, located in India. Accordingly, the equivalent noise level (Leq) can be quantified for the one-hour interval, as proposed by equation (2.4).

$$Leq=C+K\log_{10}N_x \quad (2.4)$$

Where C and K are the constants, Nx is the equivalent number of vehicles per hour of each class related to the overall heterogeneous traffic density. Further, the environmental noise levels (Leq) for each class proposed in terms of equations (2.5) and (2.6).

$$L_{eq}=40.60+9.5\log10N_l \quad (2.5)$$

$$L_{eq}=40.50+9.5\log10N_h \quad (2.6)$$

Where N_l and N_h represent the equivalent numbers of light and heavy vehicles per hour.

Central Pollution Control Board (2000a) proposed the rules and regulations for controlling noise pollution to control noise emissions at the source level for protecting the receiver from the noise-induced health hazards. Accordingly, the Indian government has legislated noise pollution rules 2000, which listed in table 2.1.

Table 2.1 Central Pollution Control Board (CPCB) noise pollution rules (2000)

Area code	**Category of area/zone**	**Limits (dB)**	
		Day time (6 a.m. to 10 p.m.)	**Nighttime (10 p.m. to 6 a.m.)**
A	Industrial area	75	70
B	Commercial area	65	55
C	Residential area	55	45
D	Silence zone	50	40

Pandya (2001) measured equivalent noise levels for cities, including New Delhi, Jamshedpur, Dehradun, and Nagpur cities in India. The main objective behind the noise measurement was to provide guidelines for the design and planning of different land use classifications in urban areas. The L_{dn} (day-night noise level) of the urban centers was calculated to assess the noise quality of the different regions of land use. It was observed that areas in New Delhi and Jamshedpur fall under the highest noise-induced areas in comparison with the cities of Dehradun and Nagpur. Thus, the study suggested mitigation measures for the noise generation with respect to infrastructural design such as noise barriers for highways, raised or depressed roads, and increasing the absorption effects of landscaping alongside the highways with the trees.

Leong and Laortanakul (2003) evaluated the average noise levels in different traffic regions of the Bangkok Metropolitan Region. It was observed that the variation of noise levels vary between the 72.8–83.0 dB in the day time, and 59.5-74.5 dB during night time. These noise level variations are the result of variation in distance of measurement from the roadside and street configuration. Along with a noise level survey, an audiometric survey was conducted on 4000 persons to establish the relationship between noise levels and hearing loss. Observations have shown that noise exposure conditions in urban proximity were observed to be poor compared to the groups living in suburban sites. Among all the occupants (drivers, street vendors, traffic officers, and dwellers) in monitoring sites, drivers are prone to the maximum risk of hearing loss due to the traffic noise.

Zannin et al. (2003) studied environmental noise pollution and documented its impact on the community in the city of Curitiba, Brazil. It was observed that most dominant noise polluting agents were traffic (73%) and neighbors (38%). Apart from these two principal sources, animals, sirens from the nearby factory units, noise arising from the civil construction, religious places, and the usage of domestic electric appliances were irritating the community to the extent of disturbance. This subjective evaluation of the noise exposure reactions clearly shown that the population in the urban agglomeration of Curitiba city was under threat of psychological and physiological effects on quality of life. It was concluded that legislative norms are to be strictly applied in every sector, in order to control the noise pollution within limits.

Abbate et al. (2005) investigated the effect of noise due to the industries in the locality on the chronic hearing loss for the workers. Accordingly, the study considered 186 male workers subjected to occupational exposure. At the obtained hearing threshold values at the frequencies 500, 1000, 2000, and 4000 Hz, a statistical analysis was performed. Accordingly, the assessment between the threshold values indicated a substantial difference, particularly at the frequency of 4000 Hz, leading to chronic hearing loss. Thus, it was concluded that occupational exposure governed by variation in the environmental factors would significantly affect the acoustic environment of the workers, who are under intermittent noise exposure.

Tokairin and Kitada (2005) evaluated the performance of a porous fence on reducing noise pollution. A two-dimensional numerical model for the pollutant concentration and an analytical model for traffic noise pollution were used for the study. It was observed that traffic noise was hugely affected by the change in the porosity of the fence with a concentration of about 20%. Overall, reduction of noise pollution was achieved with a porous nature, of about 4-6% on the noise level measured at 10 m away from the roadside at the height of 1 m from the ground.

Jamrah et al. (2006) studied the effect of fast development, expansion of the economy, travel, and tourism on the city of Amman in Jordan. The study aimed at investigating the effect of transportation noise pollution in Amman with the measurement of road traffic noise index L10 (1 h). Noise measurements, along with the traffic volume, speed, and road characteristics, were measured at 28 locations in the city. All the surveys were conducted for a period of one hour during the early morning and early evening peak hours. The Road Traffic Noise (CRTN) prediction model was used to calculate the noise levels for the study. The results showed that noise levels of about 46 dB – 81 dB throughout day-time and 58 dB – 71 dB during evening peak hours were observed. Near the majority of the selected locations, the noise levels crossed the acceptable limit of 62 dB due to the enormous increase in vehicle volume in the past decade. Moreover, the CRTN model predicted the noise levels at chosen locations successfully during morning and evening peak hours. These results show that the immediate need for mitigating noise measures for a better-quality environment for the community in the city of Amman.

Ma et al. (2006) measured the continuous traffic noise data at 142 sites distributed on 52 roads during the years 1989 to 2003 in the city of Lanzhou. Principal traffic noise indices such as L_{eq}, L_{10}, L_{50}, L_{90}, and TNI were calculated for analyzing the noise levels with respect to time. On average, noise levels increased from 0.9 dB to 5.4 dB during the course of fifteen years at most locations. Moreover, it was clearly observed that most of the locations were experiencing noise levels, which exceeded the prescribed noise limits and continue to grow in the last fifteen years. Overall, vehicle volume, vehicle composition, pavement condition, and road traffic management were found to be the four principal entities affecting noise generation at the root level.

Yilmaz and Hocanli (2006) measured the traffic noise level along highways on the Sanliurfa city of Turkey with the intent of developing the noise maps for future environmental approaches. As the vehicles plying on highways result in an inline source of noise, along with conventional point source noise maps, line source maps were also developed in their study. It was observed that noise values were decreasing in point source maps even though there is no change in the intensity of noise value on the roadway. This problem was solved through the inline source noise map with the constituted method, which can be applied to all GIS techniques. Moreover, GIS software allows the periodical data update with the line source noise map, which is most common in environmental noise levels.

Zannin et al. (2006) evaluated the environmental noise scenario in different urban parks situated in the city of Curitiba, Brazil. Equivalent noise levels (Leq) were quantified at 303 points selected in parks. It was observed that both Botanical Garden Park and public walk parks are experiencing huge fluctuation in noise levels (64.8 dB – 67 dB) with the traffic infrastructure nearby. It was concluded that urban parks must be situated away from the main city roads to reduce excessive noise exposure on the community. It was also suggested that speed limits and restrictions on the usage of horns must be implemented at the street signals indicating the proximity to green areas.

Doygun and Gurun (2008) quantified traffic noise pollution in Kahramanmaraş, Turkey. Overall, 114 measurement stations were made in different places, including residential, industrial, and commercial areas. Results indicated that both residential and commercial areas were experiencing excessive noise levels throughout the day, with the minimum and maximum values throughout the afternoon and evening hours. It was suggested that the improvement of public transportation vehicles could reduce the noise at its source level.

Ozer et al. (2008) studied the effect of Pinussylvestris and Populusnigra trees on noise reduction along the E-80 State highway in Erzurum, Turkey. Noise levels were measured at the distance of 0 m (near the noise source), 25, 50, and 75 m from the noise source (with and without the trees). At the distance of 25 m from the noise source, the sound pressure level was 78.5 dB in the zone without trees. The same was reduced to 75.5 dB and 69.2 dB with the presence of Populusnigra and Pinussylvestris. This shows the reduction rates of 24.7 and 31%, respectively, with the vegetation. These results show the need for vegetation along the highways and the urban arterials of the cities for controlling the traffic noise levels.

Pathak et al. (2008) monitored the achieved noise level reduction with different width and height of vegetation belts in Varanasi city, India. The study compared the four plant species named Putranjivaroxburghi, Cestrum nocturnum, Hibiscus rosasinensis, and Murrayapaniculate for noise reduction at different frequencies. It was observed that Hibiscus rosasinensis reduced noise levels to the maximum at both low and high frequencies (100–500 Hz, 22 dB and 2.5–6.3 kHz 26 dB), followed by Murrayapaniculate, Putranjivaroxburghi, and

Cestrum nocturnum. Overall, it was clearly observed that the study area without vegetation was highly polluted in comparison with the area with vegetation due to less fluctuation of traffic load.

Agarwal and Swami (2011) developed an empirical noise prediction model for the evaluation of the equivalent noise level (Leq) in terms of the equivalent traffic density number under heterogeneous traffic flow conditions in Jaipur city, India. The study aimed to evaluate the equivalent noise pollution levels (Leq) in terms of equivalent numbers of heavy [Leq (Lh)] and light vehicles [Leq (Lv)]. Basic study reveals the fact that selected roads are narrow, poorly maintained, overpopulated, and having commercial activities along the roadsides, resulting in interrupting the free flow of vehicular traffic. Traffic density data indicate that almost 72% of the vehicles consisted of two-wheelers, followed by cars/jeep (15%) and three-wheelers (12%), while the remaining 1% consists of buses and trucks. It was observed that light motor vehicles were the main source of noise pollution. A new factor known as the equivalent number of light and heavy vehicles was introduced for the calculation of Leq values, and a comparison was made between the Leq (Lv) and Leq (Hv). It was concluded that the developed model gives significantly higher correlation coefficient values, and can be applied for the calculation of road traffic noise under interrupted traffic flow conditions in Indian cities.

Al-Mutairi et al. (2011) quantified the traffic noise levels during peak and off-peak hours in the urban streets of Kuwait. All the classified street types named collector, arterial, and freeways were included in the study area. It was observed that noise levels on freeways observed to be 66.7 to 94.8 dB and 64.9 to 89.1 dB during off-peak and peak hours, respectively. Whereas, collector and arterial streets experienced the noise ranges between 56.0 to 79.2 dB, 55.3 to 76.4 dB, and 62.3 to 89.2 dB, 59.6 to 78.9 dB during off-peak and peak hours, respectively. It was observed that all these noise levels were higher than the prescribed limits, which may lead to ill effects on health. It was suggested that noise policies have to be defined, and mitigation measures have to be applied immediately in order to improve the quality of life.

Ghotbi et al. (2012) measured the noise levels in the subway system, with the intent of understanding the noise exposure on workers and even the passengers. Noise measurements were conducted at Imam Khomeini Station, which is the most crowded subway station in Tehran, Iran. The equivalent noise level (Leq) for each ten-minute duration was measured throughout the day from 7 A.M to 10 P.M. On average, noise levels varied between 68.35 dB – 79.12 dB among the measured points, which are way beyond the permissible limits. It was suggested that an effective way to minimize the subway noise levels could be optimizing the cross-sectional shape of subway wheels.

Arana et al. (2013) developed strategic noise maps in the autonomous community of Navarre, Spain, for analyzing the city's noise pollution. Six strategic noise maps were developed for120 km of major roads with a population of 280,199 inhabitants. It was observed that 13% of people are exposed to the day-night noise levels (L_{dn}) exceeding 55 dB, and 15% of people are experiencing the day-night noise levels over 65 dB. It was also observed that most of the residential area was experiencing noise levels more than the prescribed limits throughout the day, which is a serious threat to health. It was concluded that the action plans developed with the current strategic mapping system should consider these facts before proposing the noise policies for the roads in the future.

Lam et al. (2013) studied the relationship between road traffic noisescape and urban form in Hong Kong. Overall, 212 residential complexes from 11 contrasting urban forms were sampled, and their noise levels were quantified at dwelling and neighborhood scales by developing noise maps. It was observed that residential complexes with different urban forms have significantly different noisescape attributes. A strong correlation was observed between the noise characteristics and morphological indicators at the dwelling scale, indicating the influence of urban form on the noisescape in the urban acoustic environment. The researchers conclude that thoughtful urban design by considering the influence of noise pollution on the community could be the ideal solution for better quality living.

Singh et al. (2013) made an attempt to examine the role of meteorological parameters affecting the ambient noise levels in New Delhi, India. The noise levels were collected at the roadside, considering the hourly variation during day time. The results showed that the introduction of compressed natural gas vehicles in public transport had made a significant reduction in noise levels. It was also observed that high vegetation and low relative humidity were playing a prominent role in reducing the noise level. The regression models developed by these researchers showed the contribution of meteorological parameters in the noise scenario of the city.

Banerjee et al. (2014) studied the impact of high noise levels on potentially vulnerable sub-populations in India. A designed cross-sectional study was conducted for sociodemographic and health-related characteristics on 533females and 376 males (aged 18–80 years). The time-weighted road traffic noise indicator (L_{dn}) was used as a categorical predictor for the reference group of study. It was observed that odds ratio (OR) for males (OR 1.47 (1.07–2.02)) and female (OR 1.83 (1.27–2.65)) respondents were differed significantly by gender, which indicates the occurrence of coronary heart disease (CHD) in both the groups. Their study results suggested a higher risk for people residing in the same location for more than 15 years. It was concluded that changing the orientation of bedroom windows at the roadside can be a significant modifier for the reduction in noise level exposure.

Heritier et al. (2014) investigated the relationships between road traffic noise and the annoyance caused by various noise sources. A total sample of 1375 adults was selected for the study in the city of Basel, Switzerland. Each individual's noise exposure was modeled with annoyance on a four-point Likert scale. The annoyance category falling under somatic symptoms showed the strongest relations with industry noise and road traffic noise. Their study revealed that noise level exposure causes sleep disturbances, which in turn affects the health-related quality of life in a menacing way.

Prascevic et al. (2014) monitored and analyzed the environmental noise pollution in the city of Nis, Serbia, during the period (2008-2011). Results show that noise levels are higher than the permissible values, and the population exposed to noise levels were way beyond the permissible noise levels at the analyzed locations. Sensitive areas like schools and hospitals were experiencing continuous noise levels on a scale more than the limit in most locations. The major part of the pollution is solely contributed by the traffic-related source, with the maximum share of cars in the city (86.7%). It was concluded that mitigating measures at the source level of noise generation on the roads was the immediate need to be addressed in order to keep the noise pollution in control.

Kumar et al. (2017) developed an approach for monitoring the noise levels in the urban areas using a smartphone-enabled technology with the fuzzy logic-based noise classification. The developed system includes a client application on smartphones that records noise levels, process, communicate, and shares the information as visual data on Google Maps application. As an experiment, all the land use classifications named residential, commercial, and industrial areas of the northern region of India are demonstrated in the current study. In most of the study locations, noise levels were found to be higher than the prescribed standards. It was suggested that user community participation is needed using the developed application in order to check its validity on monitoring noise pollution.

Lokhande et al. (2018) studied the heterogeneous traffic noise levels in the Nagpur city, India by considering the peak and off-peak traffic hours. Measured noise levels are time averaged and the respective Traffic Noise Index (TNI) and NPL (Noise Pollution Level) are calculated to assess the precise traffic noise levels. Further, Federal Highway Administration (FHWA) noise prediction model is used to predict the noise levels in the study locations. Overall, noise levels varied from 71 to 76.3 dB (A) in peak and off-peak hours. It was concluded that, Sound Exposure Levels (LAE) at the selected study area are exceeding the daytime acceptable noise limit of 70 dB(A) recommended by the World Health Organization (WHO).

Paiva et al. (2019) assessed the noise levels in the city of Sao Paulo, Brazil, using the questionnaire to ascertain the perception of the residents regarding the effects of this exposure. It was observed that noise levels at all the measured points were found to exceed the critical level for the area, 55 dB. The majority of the respondents revealed that traffic-related noise is the dominant agent for annoyance. These findings suggest the importance of reviewing and updating Brazilian public policies regarding environmental noise.

2.3 Studies on Factors Affecting the Traffic Noise Levels near Rotaries and Roundabouts

Apart from high-speed midblock sections of highways passing through urban areas, vehicle speeds are comparatively less at roundabouts/rotaries. Thus, several research works across the world focused on identifying the responsible sources for possible noise level generation at these urban units. A comprehensive review of these research works is presented below.

Chevallier et al. (2009) compared the traffic noise levels obtained by the static, analytic, and micro-simulation noise models at signalized intersections and roundabouts. It was observed that static noise models only consider the free-flow constant-speed traffic with uniformly distributed vehicles, and analytic noise models consider the mean kinematic profile over the whole road network. Whereas micro-simulation noise models fully capture the traffic flow dynamic effects, including queue evolution. Thus, a comparison of the results shown that the micro-simulation model outperformed the other two approaches. At the signalized intersections and roundabouts, it was able to capture the effects of queues in under-saturated and oversaturated conditions. It was also observed that a roundabout is found to induce a 2.5 dB noise reduction compared to a signalized intersection with the acoustic contributions.

Hyden and Svensson (2009) studied the influence of traffic calming strategies on noise and air pollution in urban areas. It was observed that a decrease in traffic speeds with the calming measures on roads, noise pollution reduced to a greater extent. That is, with the traffic speed reduction from 50 to 30 km/h, traffic noise levels reduced by 4-5 decibels. It was concluded that with the modal mix of two-wheelers, three-wheelers, and non-motorized traffic flows, traffic calming is a vital measure to be applied on Indian roads.

Oyedepo and Saadu (2009) evaluated the noise pollution levels in the Ilorin metropolis, Nigeria, to determine the effect of traffic noise pollution on the community. Noise measurements were conducted throughout the day near commercial centers, road junctions/busy roads, passenger loading parks, and high-density and low-density residential areas. It was observed that the road junctions had the highest noise pollution levels, followed by commercial centers. The results also showed that the noise levels in the city exceeded prescribed limits at 30 of 42 measurement points. Moreover, a significant difference ($P < 0.05$) in the noise pollution levels and traffic noise index was observed at all the measurement locations. It was concluded that mitigating measures at the source level of noise generation on the roads was the immediate need to be addressed in order to keep the noise pollution in control.

Guarnaccia (2010) analyzed the acoustical noise produced by vehicular traffic at an intersection in the proximity of Salerno University, Italy, using the experimental measurements and software simulations, especially during peak hours. It was observed that geometry and the general features of the road and variation in traffic volume were principally affecting the noise levels at the presence of conflicting points near the intersection. Shortcomings of a simulation strategy for not considering the traffic dynamics were analyzed using the experimental data related to free-flow traffic conditions. It was concluded that the approach needed a further inclusion of driver behavior with the help of the neural network approach for the better acoustic study on noise level generation.

Covaciu et al. (2015) studied the traffic noise levels at a signalized cross intersection and a roundabout. The traffic flow speeds were measured using a moving observer in real conditions for passenger cars at near and inside the intersection. Results showed that at the low vehicle speeds near intersections, acceleration plays a major role in generating the noise levels. Moreover, noise emission on a roundabout differs from the straight driving by including more accelerating phases, with a higher contribution from the powertrain noise source and the lower influence of the tire-road interaction.

Estevez-Mauriz and Forssen (2018) developed a model based on individual-vehicle characteristics as a function of time. It was observed that the acceleration of the simulated traffic has a substantial effect on the source strength. The developed model incorporated the state-of-art microscopic traffic simulation software combined with the recent noise emission model. Further, both electric and combustion engines are considered for model development with different traffic flows. In conclusion, researchers presented the outcomes through graphs and maps explaining acceleration effects, vehicle configurations, and traffic flows.

Fedorko et al. (2019) studied the effect of noise exposure on roads using infrared technology. Measurements are carried out in the vicinity of the urban roads to demonstrate the need for the design of anti-noise measures. Researchers classified the possible solutions for excessive noise into proper landscape planning, noise barriers, and traffic calming measures. Further, the mathematical model of traffic noise prediction was exclusively processed by using the Lima software, which found to be effective.

2.4 Studies on the Principal Noise Sources Responsible for High Noise Levels on the Road

Vehicle movement on the road will generate noise due to the combination of noise sources originated from the vehicle and the road. Accordingly, several research works across the world focused on the responsible noise sources for high road noise levels. A comprehensive review of these research works is presented below.

Meiarashi et al. (1995) analyzed the noise reduction capability of the drainage asphalt pavement on overall road noise. Results indicated an overall noise reduction of 3 – 5 dB in comparison with the conventional asphalt pavements. It was observed that the reduction of noise levels was mainly due to the higher absorption coefficient of the asphalt surface and the reduction in airflow through the tread mechanism of the vehicle tire. The quantitative comparison of all the major noise reduction factors shown that the higher absorption coefficient of new asphalt pavement was the main reason for the reduction in tire/road interaction noise, which intern is responsible for overall noise reduction.

Kuemmel et al. (1996) assessed the effect of pavement surface texture on the noise and safety on the twelve Portland Cement Concrete Pavement (PCCP) test sections. The noise levels measured on the PCCP sections were compared with asphaltic concrete pavements (ACP). A preliminary investigation showed that a notable dependency exists between the pavement textures and their noise characteristics. Measurements indicated that uniformly transverse tined PCCP generated dominant noise frequencies that were audible to pass-by and in-vehicle roadusers. On the other side, no significant acoustical advantages of open-graded asphalts were observed over the standard dense asphalt. It was concluded that careful design and construction of transversely tined PCCP could reduce tire-road noise.

McNerney et al. (1998) carried out studies to measure and analyze the sound spectra and sound levels of individual passes of a test vehicle on different pavement types. Vehicle speed, vehicle type, pavement condition, and tire pressure were considered in order to study the root cause for noise levels. On average, the pavements tested in Texas, the USA, and South Africa showed significant differences of 7 dB – 12 dB on different pavement types. It was concluded that the noise characteristics of pavement surface types must be considered prior to a selection of highway surfacing in order to mitigate the road noise levels.

Watts et al. (1999) studied the noise prediction capacity of the porous asphalt (PA) surfacing with the presence of roadside barriers on highways using the Boundary Element Method (BEM). It was observed that for the barriers placed on the far side edge of 2 m height was shown to reduce the noise levels by an amount of 0.6 dB. The same porous asphalt road with barriers coated with absorptive materials shown to reduce the noise levels by 0.8 dB only. Whereas, 4m parallel barriers shown the reduction capability of about 1– 1.9 dB. This is mainly due to the significant decrease in the angle of incidence of reflected waves traveling to the receivers over the nearside barrier.

Sandberg and Ejsmont (2002) identified a new approach for traffic noise prediction and suggested noise reduction possibilities for different pavement types. The study identified that traffic noise spectra composed of contributions from a large number of vehicles having variations in tire properties. Thus, the variation of tire/pavement interaction at each vehicle speed with different tire/road combinations resulted in a prominent peak of 1000 Hz, which can be attributed within the range of 630 to 2000 Hz. It was also observed that the peak would be more pronounced in cases where the road surface has a smooth texture. Accordingly, the sound absorption showed a sharp frequency dependence in the mid-frequency range of 800 to 1600 Hz and reduced to 600 to 1000 Hz in pavements with high porous layers.

Hanson et al. (2005) studied the nature of noise emission on hot mix asphalt roads with the intent of developing safe, quiet, and durable asphalt pavement surfaces. The study highlighted that the use of hot mix asphalt could reduce noise levels, which could save millions of dollars by minimizing the number or height of noise wall barriers along highways. Their study revealed that the smaller nominal maximum size mixes (Stone Mastic Asphalt (SMA) or Open Graded Friction Course (OGFC) mixes) reduced the noise levels. It is also concluded that for OGFC mixes, the higher the air voids, the lower is the noise level.

Eisenblaetter et al. (2006) carried out experimental investigations on aerodynamically related mechanisms of the tire/road noise. It was observed that the combination of tire vibrations and aerodynamical effects in or around the tire were the dominant forces responsible for noise generation. The study also highlighted the fact that more emphasis has to be given to aerodynamical mechanisms of tire noise generation along with noise generated by tire vibrations. As the automotive industry has done a great deal of research and development in recent decades for minimizing the powertrain noise, the dominant contributor to tire/road noise has to be studied in order to reduce the traffic noise pollution.

Cho and Mun (2008) studied the effect of types of vehicle and pavement on the traffic noise generation along the southbound side of the Jungbu Inland Expressway, South Korea. Overall, eleven vehicle classes on nine surface sections of asphalt concrete and portland cement concrete pavements were used for the study. Using the combined noise ratings for the quantified sound power levels (PWLs), noise levels of various vehicles were calculated based on the novel close proximity (NCPX) and Pass-By methods. The results showed that PWLs of vehicles are significantly affected by the combination of vehicle speed and the condition of the road surfaces. In comparison, PCC surfaces shown more noise curve patterns than the asphalt concrete surfaces at most speeds.

Bilova and Lumnitzer (2012) studied the influence of road surface on the emitted traffic noise. Especially, the structure and porosity of the road surface will affect the tire/pavement interaction component of the road noise. Further, this effect resulted in differences in sound pressure levels related to the flow of traffic by 15 dB. It was also observed that noise emission, which is generated higher above the road surface than tire/road-noise, observed during the propagation, was influenced by the porosity of the road surface. Thus, it was concluded that a thorough study aiming at road surface parameters is very much essential to the construction of new roads.

Ho et al. (2013) quantified the effects of road and tire deterioration on tire/road noise generation. The durability and persistence of low noise road surfaces and tires are of great concern. The study revealed that the tire/road noise measured on low noise surface material increased by 1.2–1.5 dB per year. Further, the tire rubber hardness increased by 0.6 shore-A value per month. Accordingly, the tire/road noise level increased by 0.08–0.48 dB, depending on the road surface material. Overall, the minimum effect of the test tire aging on tire/road noise measurement is about 0.6 dB per year.

Donavan (2014) quantified the noise reduction provided by a newly applied open-graded asphalt concrete (OGAC) overlay on an eight-lane portion of US Highway 101 in San Rafael, California. Wayside and on-board sound intensity (OBSI) levels were measured at two selected locations on the highway. Results showed a reduction of 7.8 dB of OBSI tire-pavement noise and 7.8 dB to 8.4 dB of wayside traffic noise at the overall speed spectrum. The application of OGAC has shown a reduction capability of 10.5 dB and 11.3 dB. This difference was attributed to the sound absorption provided by the porous pavement.

Mogrovejo (2014) assessed the noise reduction performance of "quiet" pavement surfaces over the typical asphalt and cement concrete surfaces in Virginia State, USA. Three asphalt surfaces (Porous Friction Course (PFC) mixes) and two cement concrete surfaces (Conventional Diamond Grind (CDG) surfaces and Next Generation Concrete Surfaces (NGCS)) were constructed for the noise measurements. On-Board Sound Intensity (OBSI) methodology was used to assess the change in noise levels of the selected pavement surfaces over time. The results showed that the "quiet" concrete surfaces shown better noise reduction capability of about 5 dB in comparison with the original transverse tined Portland cement concrete pavement. Similarly, porous asphalt surfaces also shown a noise reduction capability of about 3 dB in comparison with the Stone Matrix Asphalt (SMA) pavements.

Narayan (2015) investigated the combustion noise produced in diesel engine vehicles with the intent of reducing the exhaust emissions. Accordingly, the noise was investigated by the mean of the data obtained from cylinder pressure measurements using piezoelectric transducers. The engine was run under different operating conditions by varying injection parameters to understand the effects of noise emissions. Results showed that, increase in pre-injection causes an increase in combustion noise levels. The researcher observed a fair correlation for optimizing combustion noise to keep the pollution emissions at minimum levels.

Knabben et al. (2016) evaluated the sound absorption capacity of different asphalt mixtures on roads. Dense-graded asphalt mixture, dense-graded rubberized asphalt mixture, rubberized porous coat, and rubberized open-graded friction course were selected for the study with the intent of studying the effect of granulometry and void volume of each mixture on the sound absorption coefficient. The preliminary study showed that noise generated by the tire/road interaction is the result of aerodynamic noise related to the coating porosity and the mechanical noise related to the coating texture. Further, mixture slabs were molded in a slab compactor, and the specimens were extracted for investigating the sound absorption capacity. Results revealed that sound absorption is strongly influenced by void percentage, interconnected void percentage, and layer thickness.

Li et al. (2016) studied the impact of different pavement types on in-vehicle noise levels and the associated adverse health effects. An old concrete pavement and a pavement with a thin asphalt overlay were chosen as the test sections. Accordingly, the in-vehicle noise, as well as the drivers' corresponding heart rates, were reported. The overall in-vehicle noise levels are higher than 70 dB even at midnight. Moreover, the newly overlaid asphalt pavement reduced in-vehicle noise at a driving speed of 96.5 km/h by approximately 6 dB. Further, on the concrete pavement with higher roughness, driver heart rates were significantly higher than on the asphalt pavement. It was concluded that in-vehicle noise was strongly associated with pavement type and roughness. Moreover, driver heart rate patterns resulted in statistically significant differences in different types of pavement with different roughness.

Pallas et al. (2016) attempted to extend the applicability of the CNOSSOS-EU emission model for light electric vehicles. In regards to road traffic, correction terms to the propulsion noise component for the emission model were investigated on different vehicle engines. As the internal combustion vehicles were responsible for generating the noise levels at lower speeds, differences between the noise emission from conventional vehicles and electric vehicles are studied for several road surfaces. Results indicated that no correction is required for the rolling noise component.

Winroth et al. (2017) studied the influence of air-pumping noise sources on the generation of tire/road noise. Accordingly, the speed dependency of tire/road noise was analyzed. The findings show that a major part of the tire/road noise was generated by the high-speed exponent traditionally connected with the air-pumping mechanism. Moreover, wind noise is shown to have a major influence on the overall pass-by noise. It was concluded that separating the noise caused by the tire vibrations from air pumping noise was not feasible due to overlap in speed exponents, which require further analysis at the root level.

Staiano (2018) studied the influence of pavement texture on the tire–pavement noise generation with respect to resonant response. The tire-pavement noise levels measured using the On-Board Sound Intensity (OBSI) method shown that pavement wavelength spectra are transformed into the frequency domain with the firm contribution from the pavement texture. It was observed that the use of probe mounted on a vehicle operating in traffic permitted efficient and rigorous measurement with the OBSI method. It was concluded that quantitative functional relationships on each pavement parameter variation with the tire/road noise generation need to be studied for the development of low noise roads.

Freitas et al. (2019) analyzed the tire-pavement noise levels measured in different types of road pavements through acoustic and psychoacoustic indicators. The CPX method was used to measure noise at three-speed levels (30km/h, 50 km/h, and 65 km/h) over the two different types of pavements. It was confirmed that the pathologies have a relevant contribution to the tire-pavement noise. It was observed that psychoacoustic indicators are more sensitive to the testing conditions.

2.5 Studies on the Methods Available for the Measurement of Noise Levels on the Road

The reviewed literature above shown that roadusers (people outside the vehicle, including pedestrians) and the commuters (driver and passengers) will experience the major noise levels due to the vehicular movement on roads. Accordingly, different methods available to quantify the source-level noise and the noise levels experienced by the roadusers and commuters are presented below.

2.5.1 Noise levels at the Source

Bennert et al. (2005) conducted pavement noise evaluation on 42 pavement surfaces in New Jersey, USA using the close Proximity Method (CPX) with the intent of studying the influence of pavement surface on traffic noise. The surfaces comprised of both hot mix asphalt (HMA)and Portland cement concrete (PCC) surfaces. The HMA surfaces consisted of dense-graded asphalt mixes (DGA), an open-graded friction course (OGFC) with and without crumb rubber. The PCC surfaces had varying surface treatments consisting of transverse tining, saw-cut tining, diamond grinding, and broom finish. Results of the testing indicated that the asphalt-based surfaces provided the lowest tire-pavement noise levels. Especially, OGFC mixes modified with crumb rubber provided the lowest noise levels (96.5 dB at 60 mph (96.5 km/h)). PCC surfaces generated the loudest noise levels (106.1 dB at 60 mph (96.5 km/h)). Moreover, the CPX method was found to be repeatable, with an average standard deviation of approximately 0.13 dB. This due to the sensitivity of the method being influenced by the ability to track the identical wheel-path in successive test runs.

Ramussen et al. (2011) briefly described the On-Board Sound Intensity (OBSI) test methodology with a clear emphasis on test setup and important factors to be considered during the test procedure. OBSI measures tire/road noise at the source using microphones in a sound intensity probe mounted outside of a vehicle, close to the tire/road interface. All the measurements were performed while the test vehicle drives across the pavement of interest.

Boodihal et al. (2014) developed a methodology to evaluate tire/ road noise of various road types in Bengaluru, India. The study performed the noise measurements using a CPX noise trailer on the selected asphalt concrete (AC) and Portland cement concrete (PCC) pavements in Bengaluru city at 30 kmph to 40 kmph. It was observed that AC pavements had an average difference of about 1–2 dB in comparison with the PCC mix types. Overall, the study identified an increase of about 0.5–0.7 dB noise levels due to the tire/pavement interaction with every year increment, for the AC pavements selected.

Koike and Ito (2014) conducted tire/road noise measurements on public roads of Japan in order to investigate the effect of pavement surface conditions. Due to the domestic regulations and safety issues, a quasi-CPX method was employed in the study in place of the standard CPX method. Three different types of road surfaces, including Dense Asphalt Concrete (DAC), Porous Asphalt Concrete (PAC), and Double Layer Porous Asphalt Concrete (DLPAC) surfaces were selected for the study. It was observed that the tire/road noise of each pavement surface type spreads to the range of 4 to 9 dB, with the spread of DLPAC pavement appears to be wider than the other surface types.

Zofka et al. (2017) investigated the feasibility of the On-Board Sound Intensity (OBSI) system to measure the tire/road noise in Poland. The study used an OBSI system, having a noise intensity probe installed in the interface close to the pavement surface. All the measurements were performed on stone mastic asphalt (SMA) surface and Portland Cement Concrete (PCC) surface. Accordingly, parameters influencing the OBSI measurement conditions such as testing speed, air temperature, tire pressure, and tire type were selected. Results revealed that the OBSI system is a viable tool that can be used for the quality evaluation of the new/old asphalt pavements.

Ohiduzzaman et al. (2018) evaluated the acoustic performance of asphalt pavements in Qatar using the on-board sound intensity (OBSI) method. The researchers measured the noise at the source level and studied the applicability of the method from the acquired data. The results revealed that the method is capable of measuring the sound intensity with excellent repeatability. It was observed that tire-pavement noise is significantly affected by pavement age, vehicle speed, and tire type. In comparison, pavements in Qatar, generating higher noise levels than dense-graded asphalt pavements in Europe and the USA.

Buhlmann (2019) investigated the uncertainties associated with speed, ambient temperature, and rubber hardness corrections for the close-proximity method. The researcher evaluated the repeatability of the method by measuring the noise levels on the same road surface at different times. Further, the relationship between the CPX and statistical pass-by methods were analyzed within the same time frame. The results show that the CPX method shows a significant improvement with the new standards, while some uncertainties associated with the properties of the test tires remains the same.

2.5.2 Noise Levels Experienced by the Roadusers

Jonasson (1999) examined the difference between vehicle noise and tire/road noise obtained from Controlled Pass-By [CPB] and Coast-By [CB] methods for assessing the effect of change in microphone position on captured noise levels at 70 kmph speed. The results revealed that the microphone located at 0.5 m shown the linear difference of 8 dB between CB and CPB methods. The difference in noise levels was less than 2 dB when measured at a distance of 5.65 m from the middle of the vehicle movement exhibiting the effect of propulsion noise.

Watts (2005) performed noise level measurements using CPB and CB methods. The effect of vehicle size on the difference between the CPB and CB noise levels was examined at 80 kmph vehicle speed. Accordingly, light vehicles, four-wheel-drive vehicles, and two-axle trucks were selected as the test vehicles. The microphone was positioned at 7.5 m from the center-line of the vehicle at 1.2 m height to simulate the field acoustics. The results revealed that the difference in noise levels between CPB and CB methods increased with the increase in vehicle size. The study concluded that an accurate estimation of propulsion noise levels is possible with the subtraction method.

Morgan (2008) used the CPB method to estimate the road noise of a limited number of vehicles. Vehicles with different modal characteristics (passenger car, bus, and truck) were selected and were independently-run over a test site at pre-defined speeds, and the respective sound pressure level was captured at the wayside. Sound Level Meter [SLM] was placed at a distance of 7.5 m from the centerline of the pavement at a ground height of 1.2 m for noise measurement. It was observed that the actual tire/road effect on noise level could be quantified due to the control over the selection of vehicles and their respective speeds. The limitations being the traffic closure requirement to avoid the other vehicle noise inclusion while conducting the study on the city roads instead of the constructed test track. Similar to Statistical Pass-By [SPB] method, propulsion noise will be included in the captured tire/road noise levels in the CPB method.

Braun et al. (2013) presented an extensive literature survey of noise source characteristics in the ISO 362 vehicle pass-by noise test in Europe. As a result of more recent investigations of urban traffic, a revision to the ISO362 standard has been proposed. The revision included a constant-speed test in addition to the traditional, accelerated test for determining the pass-by noise value. Literature also revealed that, in order to ensure compliance with the pass-by noise test, vehicles must quantify the noise source characteristics during the design stage. Further, measured pass-by noise was analyzed in the time and frequency domains by stating the ranking of the noise source contributions with the available predictive tools.

Campillo-Davo et al. (2013) presented a methodology based on the sound pressure measurements of tire/road interaction to obtain the sound power level in the Coast-By condition of the vehicle. This is because the standardized methods (Close-Proximity method and Coast-By method) establish procedures to measure the sound pressure level but not the sound power level of the noise source. Thus, the mathematical simulation was used, and the methodology was further validated through a field study. The results obtained were correlated with the standard methods, which shows the adaptability of technique in Coast-By condition resulted in the measurement of sound power level.

Li (2013) used the SPB method to assess the effect of pavement surface on the tire/road noise generation at constant vehicle speed. Free flow traffic stream with high-speed vehicle movements involving 100 cars and 80 trucks were selected for the noise measurements. A sound level meter was placed on the roadside at a distance of 7.5 m from the centerline of the pavement at a ground height of 1.2 m to 5 m for noise measurement. It was observed that the SPB method is limited to free-flow traffic involving isolated vehicle classifications. It was concluded that uninterrupted traffic flow conditions and limitations of shorter geometrics of urban streets are not covered in this method, which is most common in urban roads.

Ballesteros et al. (2015) studied the application of beamforming for pass-by measurements with the use of near-field holography (NAH). This technique locates the main noise sources during the pass-by of a car along with the characterization in terms of source strength. The technique applied has proven to be adequate with the consideration of frequent gear change patterns and corresponding speeds, which is very useful for pass-by noise measurements.

Morel et al. (2016) discussed the drawbacks of noise mapping with the intent of overcoming the flaws in laboratory experiments. As the energy-based indices only account for one acoustical factor that may give rise to annoyance, the study aimed at an experiment that studies the vehicle pass-by from the annoyance point of view. Accordingly, perceptual and cognitive categories of various urban road vehicle pass-by noises, including two-wheeled vehicle pass-by noises, are included. Further, as the combined exposure situations are left unframed in noise mapping in most cases, vehicle interactions are attributed to the temporal evolution of combined noises. Both of these approaches highlight the necessity to continue efforts to improve the characterization of annoyance due to noise in isolation.

Cesbron and Klein (2017) observed the relationships between tire/road noise levels measured by the CB and the CPX methods. Accordingly, tire/road noise was measured for a passenger car rolling on a set of 15 impervious road surfaces. Both CPX and CB methods were used simultaneously at vehicle speeds ranging between 50 km/h and 110 km/h. It was observed that a very good correlation between overall CPX and CB noise levels recomposed between 400 Hz and 4000 Hz. Overall, a fairly good correlation between CPX and CB spectral noise levels was observed at most frequencies. It was concluded that the perspective of the comparison is useful to compare the different tire/road noise prediction models, which were calibrated or validated with either of the testing methods (pass-by or close-proximity).

Yuan et al. (2019) carried out the road noise measurements to verify the influence of temperature on the road traffic noise. Researchers used both CPX and SPB methods on light vehicles to track and test road noise levels generated at the same time. Both road temperature and air temperature are recorded during the noise measurements. The experimental results show that the vehicle pass-by noise decreases with the increase of temperature. Moreover, the noise level of porous asphalt pavement changes little with temperature compared to dense-graded pavement.

2.5.3 Noise Levels Experienced by the Commuters

Tempest and Bryan (1972) developed a technique to extend the accurate octave band measurements of about 2 Hz. It was observed that sound pressure levels in cars traveling at motorway speeds observed to be very high in relation to the octave band levels. This is because most of the sound energy falls in the low frequency and infrasonic regions. The technique developed in the study incorporates a calibrated sound level meter feeding a frequency modulation tape-recorder to record noise below 64 Hz. It was observed that sound pressure levels of about 120 dB were found in the octave bands of 2 to 16 Hz.

Morrison and Clarke (1975) analyzed two sets of test data that were collected to determine the interior noise levels of trucks. All the interior noise measurements were conducted under controlled stationary test conditions in an effort to correlate the results with those obtained during the dynamic tests conducted on a similar vehicle type at the same time. Moreover, sound level exposure on roadusers, including passengers, was determined for various over-the-road operating conditions and correlated them with the static test results. In most cases, both dynamic and static test results surpassed the safe noise limits prescribed for the roads at most speeds.

Bryan (1976) attempted to develop a criterion for acceptable noise levels inside the passenger or goods vehicles. Accordingly, interior noise measurements were made for the passenger vehicles over the frequency range of 2 Hz–16 kHz with an attempt to develop a measure of subjective response. It was observed that existing subjective rating procedures of dB and Noise Rating (NR) consists of severe limitations for predicting the response for interior noise. It was suggested that criteria based upon noise levels measured on the dB scale are acceptable with further work to produce a satisfactory measure of subjective acceptability for all vehicle types.

Ali and Sarna (1978) measured the in-vehicle noise level of five different makes of cars in the city of Mosul, Iraq. Both vibration and noise levels were discussed from the point of view of the source and the transmission. All the noise readings were taken by placing the sound level meter on the back seat. All the sound pressure levels were averaged for a time duration of 60 seconds. On average, the in-vehicle noise level varied between 60 dB to 92 dB at different vehicle speeds.

Tsuge et al. (1985) analyzed the in-vehicle noise generated during the acceleration of the vehicle by simulating with electrically synthesized noise. It was observed that the discomfort during the exposure of the noise level in the passenger compartment depends upon the phase, frequency, and magnitude of each frequency component. It was concluded that the summing of these magnitudes reveals a good correlation with an auditory rating of the noise inside the passenger compartment.

Kobiki et al. (1990) investigated the mechanism of generating the vehicle interior booming noise through experimentation and numerical analysis. Both rotating torsional excitation and speckle interferometry were used to analyze the vibration mode of a tire under actual rolling conditions. It was observed from the measurements that the dominant factor producing the booming noise was the coupled vibration between the tires and the powertrain–suspension system. It was concluded that booming noise could be effectively reduced by tuning the vibration characteristics of the components related to both tires and the powertrain–suspension system.

Stoker et al. (1996) developed a method for separating the interior wind tunnel background noise from the interior noise to estimate the actual interior wind noise experienced by the commuters in the vehicle. For achieving this, wind tunnel measurements were performed by giving more emphasis on interior acoustics. Aeroacoustics of the measurement unit were considered along the vehicle body to quantify the actual wind tunnel background noise. Results showed that aerodynamics along the vehicle body was showing a significant effect on observed interior noise levels during wind tunnel measurements. It was concluded that more emphasis should be given on aerodynamic noise along with rolling and propulsion noise levels during the noise measurements, as it can have an effect on both commuter and roadusers.

Kim et al. (1997) attempted to identify the transmission path of tire noise into a vehicle. It was observed that the dominant noise generation of a tire below 1 kHz is the tire wall vibration. It was caused by the collisions between the tread blocks and the road, which requires a reciprocity technique to measure the transfer functions. The transmission of sound on a tire wall to a point inside a vehicle was assessed through the measurements involving the separation of airborne noise from the structure-borne noise. It was observed that the reciprocating technique was proven to be sound enough to identify the radiation characteristics and resonance of interior noise in an effective way.

Constant et al. (2001) conducted a study for identifying the methods to reduce the structure-borne interior noise in a vehicle driving on rough road surfaces. Two passenger car makes named BMW and Goodyear were selected for the study with the intent of performing vibrio-acoustic characterization of each car by using a transfer path analysis. Transfer path analysis was purposely used to identify the main suspension parts affecting the interior noise at target frequencies. Accordingly, all the vibration transmissibility characteristics of the tire were measured and simulated by using the finite element method in 1 – 200Hz frequency range. Results showed a 3 dB of interior noise improvement with the new tires at target frequencies for both the cars.

Tsujiuchi (2001) presented the stiffness optimization of rubber mounts that reduces road noise and improves riding comfort. It was observed that mount stiffness is barely changed to avoid the aggravations of riding comfort. This is because the noise generated by the vibration transmitted from the tire and suspension is transmitted through the complex paths involving airborne and structure-borne components. The Road Noise Contribution Analysis (RNCA) was applied to the vehicle for specifying the major factor of road noise generation. Investigation of measured data for identifying an optimal stiffness combination of rubber mounts has resulted in the optimum combination of two mounts to reduce the road noise and resulted in an improvement in riding comfort.

Mukherjee et al. (2003) studied the noise exposure of drivers and conductors of special state buses in Kolkata, India. Equivalent noise exposures of drivers at work and in-bus noise were evaluated using a sound level meter. Thermal conditions like wet and dry bulb temperature and relative humidity were measured while traveling through different traffic routes. It was observed that the driver's exposure to the noise varied with respect to the number of trips performed per day, which was observed to be way beyond the safe limit.

Higaki et al. (2005) documented the noise spectra measured in the interior of a large number of automobiles on the public roads around Atlanta, Georgia, USA. Sound spectra were analyzed over a frequency range of 0 – 20 kHz with an intent of understanding the vehicle interior acoustic amplitudes in the infrasound region and the audible region. It was observed that, on average, the noise from tire and engine reduced by 15 dB and 20 dB, respectively. This is due to the fact that the first hump is related to the vehicle wakes, and the second hump is related to Helmholtz resonance. It was concluded that, in spite of large improvements in the audible region in the automobile industry, infrasound hump has remained unchanged.

Kim et al. (2007) measured the surface velocity of the tire at a number of discrete points in order to assess the effect of tire on airborne or structure-borne sound. Coherence function analysis was used to identify transmission paths with the use of the principle of acoustic reciprocity. Accordingly, the acoustic transfer functions between each point on the tire and a receiver point were measured reciprocally. Results revealed that information on the relative contributions of various regions of the tire wall to the resultant noise could be clearly observed with the coherence function analysis. Further, the sound radiation characteristics, the horn effect, and resonance can be conveniently identified through the reciprocal measurement.

Saguchi et al. (2007) studied the mechanism of structure-borne and air-borne paths in transmitting the vehicle interior noise. It was observed that vehicle interior noise is mainly generated by the combination of tire tread pattern irregularity and road asperity. Accordingly, a study on each path of transmission and the respective noise in each frequency domain resulted in the development of a prediction method for vehicle interior noise affected by variation in given tire characteristics. Results showed that airborne components at higher frequency range and structure-borne components at the low-frequency domain were dominant in response to vehicle interior noise.

Bekke et al. (2010) reviewed the model approaches on the exterior and interior tire-road noise with an intent to identify the promising noise model for varying conditions in the outer environment. It was observed that exterior tire-road noise is bounded by the UN-ECE R117 regulations, and interior tire-road noise, on the other hand, is determined by the market requirements. Accordingly, the current study attempts to identify the most efficient model for evaluating the source level noise in the environment. Among all the available approaches, interior tire-road noise consisting of the exterior tire-road noise model combined with measured structure-borne and air-borne transfer paths was proven to be the most effective model approach.

Kumar et al. (2010) quantified the tire/road noise to assess the structural contribution of a tire to the interior noise of a vehicle with the development of suitable measurement methodology. The comparison was made between the interior noise of a vehicle and near-field tire noise. It was observed that vehicle tire is proven to be the major contributor for interior and exterior noise at higher road speeds. Thus, by conducting the experimental model testing of the tire at all possible freeway speeds, dominant frequencies contributing to the vehicle interior noise were determined. Overall, the sound intensity mapping of the tire noise radiation has been presented for understanding the variation in the noise generation mechanism.

Sottek and Philippen (2010) presented a new approach developed using Operational Path Analysis (OPA) for estimating the tire/road interaction contributions during road noise measurements. The researchers are of the opinion that the tire-pavement noise has become increasingly important due to overall acoustic comfort in luxury sedans with pleasant low-noise engine sounds. Thus, the study intends to estimate the uncorrelated wind noise as the signal between the interior noise and synthesized tire-road noise. This approach has proven to be effective in evaluating the multiple coherence between the excitation signals and the simultaneous recording. Accordingly, the overall sound and the contributions of the different sources, including the airborne and the structure-borne contributions were measured effectively with the developed approach.

He et al. (2011) analyzed the path of tire pattern impact on interior noise and vibration. For investigating the path of tire pattern impact on interior noise, the same type of tires with six kinds of different tread patterns were selected. Accordingly, the interior measuring point's vibration and noise signals of different tires were measured under full load conditions. Both Wavelet Transform (WT) and 1/3 octave wavelet were used for analyzing the sound signal. Further, a comparison in the time domain and frequency domain was made for the distribution features of vibration and noise signals of six tires with different tread patterns. Time-frequency analysis used with the WT for analyzing the aspect for the time-domain signal was proven to be effective, among others.

Alessandrini et al. (2012) developed a methodology to calculate the energy and environmental impact of spark ignition and diesel vehicles. The driving style and its influence on consumption and emissions and their real-world environmental impact were assessed using onboard instrumentation to be used as input for power and consumption models. All the sensor data (rpm, vehicle speed, engine load, intake airflow, pressure, and temperature) was collected using onboard instrumentation. Accordingly, a calibration procedure was developed with the usage of dynamometer chassis. For spark-ignition engines, an additional test was conducted to calibrate a coefficient that takes the accelerator pedal gradients. It was observed that the measured values on all the test vehicles resulted in a difference within 4% with the model measurements, which is an accepted value. Thus, it can be concluded that the developed methodology can be used to calculate the power and consumption of vehicles during their real use.

Buchheim et al. (2014) conducted the vehicle interior noise measurements in the wind tunnel and on-road to understand the influence of aerodynamic noise on perceived noise levels. It was observed that the interior noise experienced by the commuters in the vehicles due to aerodynamic drag was majorly caused by the external flow around the car. Further, pass-by noise measurements were conducted to compare the noise fluctuations due to the aerodynamic noise inside and outside the car. Accordingly, correlations between the pressure fluctuations at the outside body surface of a car and the interior noise were established. It was concluded that aerodynamic noise was significantly influential on both interior and exterior noise levels of the car at most road speeds.

Donavan (2014) investigated the contribution of aerodynamic noise on lower frequency passenger car interior and exterior cruise noise levels. Wind tunnel measurements were used to isolate the impact of aerodynamic drag on rolling and propulsion noises. Results revealed that aerodynamic noise contribution is lesser compared to the tire-pavement noise in generating cruise noise between 50 to 400 Hz at a speed of 80 km/h. Whereas, the exterior pass-by noise levels were hugely affected by the aerodynamic noise levels in the frequency range from 50 to 400 Hz at 97 km/h. Further investigations proved that aerodynamic noise was a partial contributor to the pass-by noise levels at vehicle speeds below 56 km/h. This concludes that serious consideration to be made for the influence of the aerodynamic noise in both predicting and reducing interior and exterior noise.

Palanivelu and Ramarathnam (2015) described the implementation of Transfer Path Analysis (TPA) to analyze structure-borne vehicle interior noise due to tire/road interaction. Accordingly, both the airborne component at mid and high frequencies and structure-borne components at low frequency were studied on a sedan class passenger car. By hitting at the spindle interface, the hammer impact test was repeated with and without tire/wheel assembly for measuring the operational acceleration responses for both engines on and off conditions. The results showed that the current procedure observed to be useful to address the influence of tire design in contributing to structure-borne vehicle interior noise.

Nopiah et al. (2015) proposed a model to evaluate the sound experienced by the passengers in the vehicle using the clustering and classification method. In general, vehicle vibration and acoustical comfort are crucial parameters that attract customers when purchasing a vehicle. Moreover, acoustics impact the performance of the drivers and also distract their vision, which can be stressful for both the driver and passengers. The work focuses on the generation of propulsion noise and the tire/road contact at the root level by performing data analysis towards the factor of sound and vibration. Results revealed that the exposed vibration influences the generation of noise related to the level of acoustical comfort in the cabin.

Abouel-Seoud (2016) analyzed the application of Active Noise Control (ANC) technology to minimize the tire/road noise in a vehicle enclosure. In general, the ANC system is a possible solution for reducing the overall vehicle interior noise levels and the noise annoyance experienced by the driver and passengers. In order to adapt the road noise to the customer preferences and expectations, both cost/weight requirements and increasing comfort demands the application of ANC based on vibration measurement (reference) at the driver's legs region and sound pressure level at the driver's head position. Accordingly, results indicated an excellent noise reduction performance at the driver's head position over frequencies up to 400 Hz.

Cao et al. (2016) analyzed the vehicle interior noise generation by experimental measurements and synthesis approach using noise path analysis. As the noise path varies between electric vehicles and conventional vehicles due to their distinct propulsion system architecture, both types were considered for the study. The comparison between these two types of vehicles revealed that the structure-borne noise from the tire-road excitation acts as a significant contributor to the overall interior noise level compared to structure-borne noise from the power plant system in conventional vehicles. It was reported that the contributions from the electric motor and tire are insignificant at most road speeds.

Konbattulwar (2016) developed in-vehicle noise prediction models for assessing the noise levels experienced by the commuters in the Mumbai metropolitan region, India. The data pertaining to the vehicle speed, traffic volume, and road characteristics was collected by conducting road trips over the total length of 403.80 km via different modes of transport. The vehicle classes were selected in a heterogeneous modal mix and were classified into air-conditioned (A/C) car, non-A/C car, bus, and intermediate public transport. Results showed that noise levels were maximum in the vicinity of intersections and signalized junctions. The models revealed that maximum differences between observed and estimated values were within the range of ±7.8% of the observed values. It was concluded that the models developed in this study could be used for predicting the noise levels from the heterogeneous traffic mix.

Sottek and Philippen (2016) described a new method to evaluate the aerodynamic, tire-pavement, and engine noise in a dynamic driving condition based on Cross-Talk Cancellation (CTC). In CTC, Operational Transfer Path Analysis (OTPA) was used to assess the effect of the tire/road interaction on the interior noise during the coast-down condition. The coast-down condition was used for avoiding the engine noise after attaining the acceleration to the desired maximum speed. As the coast-down with the engine switched off does not comply with customers' driving experience, the analysis was extended to the dynamic driving conditions with the engine running. Accordingly, the developed method based on CTC technology was applied in analyzing the interior tire-pavement noise by eliminating the unwanted crosstalk of the engine to the signals measured near the tires.

Adnadjevic et al. (2018) developed a methodology for using a virtual microphone for sensing of the in-ear noise level. Modified microphone position for in-vehicle noise measurement was proposed by taking into consideration of the general head movements of 20 and 45 degrees. The study also summarized the advantages of moving from one microphone to the array of microphones with a simple, robust filter. In comparison with conventional screening methods, the method utterly dependent on experimental data with the simple and fast operation, which is useful in machine prototyping.

Aladdin et al. (2019) evaluated the comfort level of commuters in a vehicle by considering both separate and combined modality. The noise levels were analyzed on a selected highway section at different vehicle speeds. Measured A-weighted sound pressure levels and the vibration results identified the apparent dominance of vertical vibration on seat pan and backrest. Relative Discomfort Indicator (RDI) calculated at vehicle speeds of 90 km/h and 110 km/h revealed that vehicle B has a higher discomfort level compared to vehicle A. The RDI value is expected to be useful for automotive noise and vibration improvement.

2.6 Inference from the Literature Review

From the literature, it is observed that vehicle noise levels strongly depend upon the vehicle speeds. Moreover, different vehicle types would generate different noise levels at the same speeds. As the noise levels are majorly affected by the vehicle characteristics, mixed traffic conditions would create higher noise levels compared to the homogeneous traffic. As the speed fluctuation being drastic in heterogeneous traffic conditions, consideration of the independent proportion of vehicles in quantifying the noise levels is necessary. Moreover, each vehicle class will have a different maneuvering ability, and their movements vary for each type of road, as the driving pattern involves a sudden change in acceleration and deceleration depending upon the geometrics of the streets. Thus, developing a comprehensive noise prediction model for heterogeneous highway traffic covering the whole possible spectrum of speeds by including the selection of governing parameters affecting the noise levels, such as the individual proportion of modal mix, is necessary.

It is observed from the literature that the majority of the works highlighted the honking effect on noise levels due to the heterogenic traffic flows on mid-block sections of highways. The honking proved to be a significant parameter for the rise in noise levels with the frequent variation of speeds due to the presence of different modes. However, the negative upshot of the honking on the noise levels was not addressed in studies pertaining to the heterogenic traffic noise pollution at the rotaries/roundabouts. Even though the primary objective of improving the traffic flow by reducing the conflict points from a safety point of view is achieved with rotaries/roundabouts, high noise levels are possible due to the honking in mixed traffic conditions. Thus, apart from the high-speed midblock sections on the highways, there is a need to initiate the study on evaluating the traffic noise pollution near urban units such as rotaries or roundabouts in mixed traffic conditions.

With speed being the significant parameter, the type of vehicle and their size will play a vital role in the generation of noise levels due to the propulsion and tire-pavement interaction. Most of the studies revealed that pass-by tire-pavement noise levels overtop the other noise sources in the homogeneous traffic spectrum at speeds exceeding 50 kmph. Accordingly, most of the works across the globe focused, studied, and developed methods for quantifying the tire-pavement noise. With regard to the above conclusion, an inference cannot be drawn by stating that reduction in vehicle noise levels can be achieved at low vehicle speeds by attributing to low tire-pavement noise. This is because the noise level from the vehicle will not gradually decrease with the reduction in vehicle speeds, as propulsion noise of vehicle dominates at lower road speeds. This situation can usually be encountered in a heterogenic traffic stream of most urban structures, where vehicle speeds decline more often, and propulsion noise dominates the tire-pavement interaction below the cross-over speeds. Thus, a clear distinction on the noise sources is needed in estimating the effect of propulsion noise on pass-by levels. As the subtraction method between the CPB and CB measurements was limited to a single entity of speed in literature, the same can be extended for the possible speed spectrum in mixed traffic conditions by considering the characteristics affecting the propulsion and tire-pavement noise sources. However, major problem in assessing tire-pavement interaction noise levels using CB method at the higher speeds on roads is safety. Majority of the researches in the literature used separate test tracks constructed for measuring the tire-pavement noise levels using coast-by method. However, noise measurements on roads is difficult. This is because switching off the engine/disengaging transmission at higher vehicle speeds is very dangerous if the test site consists of any close curve after the selected section. As most of the urban streets are connected by surrounding sub-arterials, any vehicle can intrude onto the test vehicle, which can lead to chaos. Thus, along with the clear distinction of noise sources from the vehicle, a method for the measurement of tire-pavement interaction noise levels needs to be developed.

The other principal receiver of the road noise levels is the passenger/driver (commuter) sitting in the vehicle, who is under continuous noise exposure when the vehicle is in motion. Even though extensive literature is available on the predominance of tire-pavement noise on pass-by noise levels at the roadside, minimal research studies were carried out on the effect of tire-pavement noise levels on passenger/driver (commuter) sitting in the vehicle. Moreover, aerodynamics along the vehicle body significantly affects the observed in-vehicle noise levels when the vehicle is in motion. Thus, a thorough study is essential to capture the noise levels experienced by the drivers due to the effect of both tire-pavement and aerodynamic sources as most of the drivers spend their maximum amount of time in the vehicle than the outside environment. However, the first challenge for the measurement of in-vehicle noise is the methodology to be adopted in assessing the noise levels. This is because, unlike the far-field noise assessment where the sturdy tripod holds the sound level meter at a preferred height (usually 1.2 to 1.5 m for simulating the human ear height from ground), the sound level meter cannot be placed steadily on the tripod inside the vehicle during the travel. Thus, fixing the sound level meters and microphones to the vehicle body and in-ear microphones were the techniques used so far for assessing the in-vehicle noise levels. However, literature also proved that vibrations of the noise measuring equipment would majorly affect the measured noise levels. Accordingly, the method of fixing or placing the microphone to the passenger seat/ the vehicle body will affect the noise levels measured using the sound level meter. At the same time, the handheld sound level meter would also be subjected to the vibrations due to the roughness of the pavement and hand movements of the person. Thus, the placement of sound level meter inside the vehicle by minimizing the effect of vibrations and the movements on the in-vehicle noise experienced by the driver can lead to a new methodology in quantifying the in-vehicle noise levels.

Overall, a review of the literature revealed that it is very much essential to assess the significant effect of noise sources at different road speeds. This is due to the fact that minimizing the noise at the source level is beneficial compared to the other noise mitigating measures for creating a healthy environment for roadusers and commuters.

CHAPTER 3
METHODOLOGY

3.1 General

Due to heterogeneous traffic flow, different vehicle classes that vary in size, engine characteristics, and maneuvering abilities will tend to ply on the same road section leading to fluctuations in traffic speed. These speed fluctuations with the variation of vehicular proportion may lead to different noise levels from various noise sources. Thus, heterogeneous traffic noise quantification needs to be thoroughly investigated at the source level at different vehicle speeds. Accordingly, a thorough literature review was conducted, and the corresponding inference has been used for the current research work discussed in subsequent sections of this chapter.

3.2 Flow Chart of the Methodology

The methodology adopted for the present study is represented in the flowchart shown in Figure 3.1.

3.2.1 Data Collection

From the literature, it is observed that mixed traffic will affect noise levels of both corners of vehicle volume and speeds, which in turn is also affected by pavement characteristics. As each type of vehicle can generate different noise levels at the same speeds, consideration of the independent proportion of vehicles in quantifying noise levels is necessary while considering the broad range of speed variations on highways. Accordingly, eight critical roads in the states of Andhra Pradesh and Telangana in India were selected for assessing the effect of traffic volume and vehicle speeds on noise generation. All the measurements were carried out from 10 am to 5 pm continuously. Further, to identify the significant parameters and the noise sources affecting each vehicle class at different speeds, the study classified the vehicle speeds into lower (<40 kmph) and higher (≥40 mph) depending upon the inference drawn from the literature review.

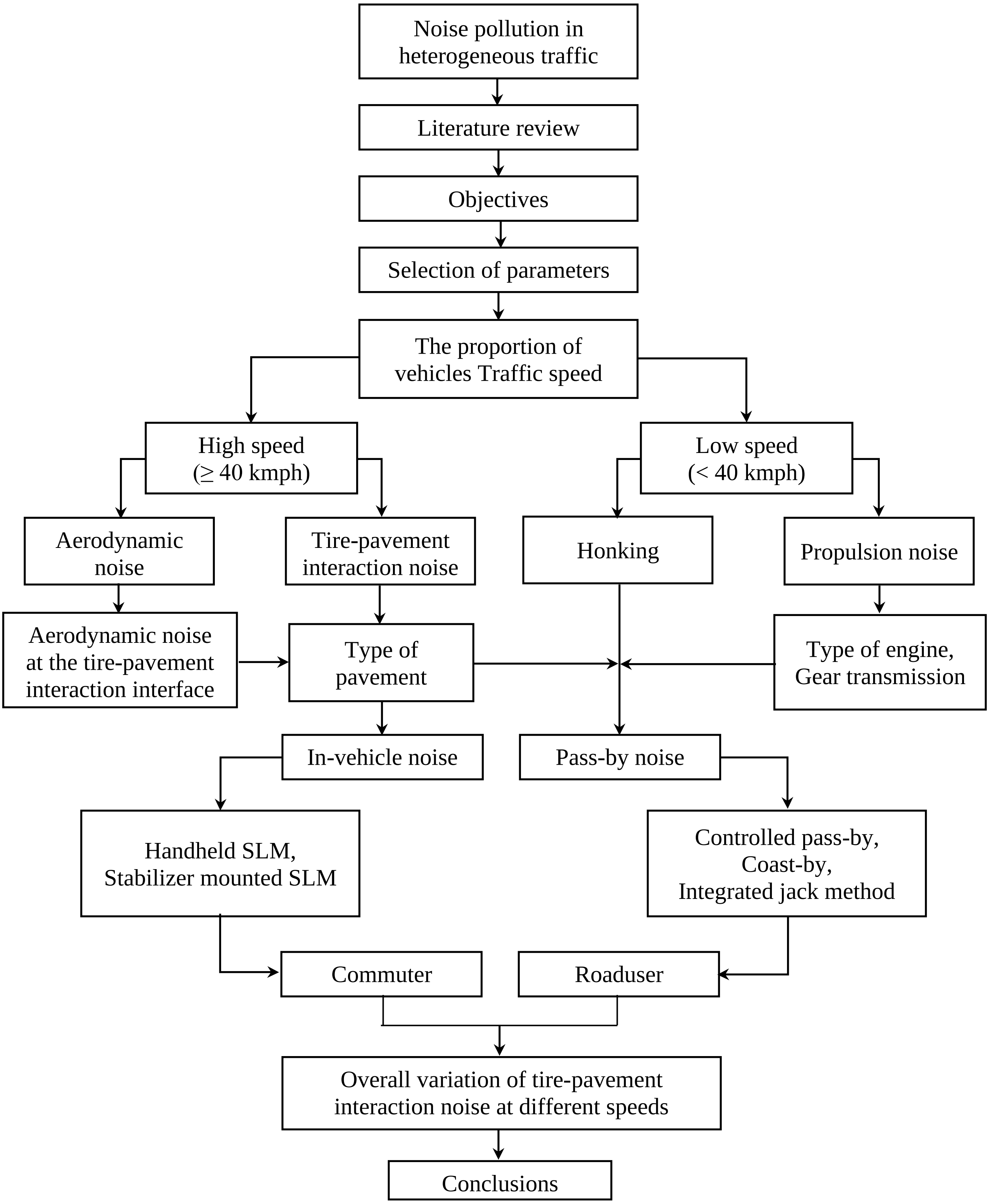

Figure 3.1 Flow chart of the methodology

Accordingly, the study was initiated on evaluating traffic noise pollution near urban units such as intersections, rotaries, or roundabouts, where traffic volumes are high, and vehicle speeds are comparatively less. Thus, along with the traffic volume and noise levels, honking was measured at two 3-legged major rotariesin Karimnagar, a small-sized city in Telangana state, India. Further, to identify the effect of principal noise sources (tire-pavement interaction and propulsion) on the pass-by noise levels at different speeds, Coast-By [CB], and Controlled Pass-By [CPB] methodologies were used in accordance with field acoustics. Petrol and diesel variants of cars were used for the noise measurements on two different asphalt and cement concrete pavements selected in Warangal city, India, to know the effect of type of vehicle and pavement on noise levels. A new integrated technique was developed to measure the propulsion noise levels at higher speeds. On a similar note, an attempt has been made to assess the effect of tire-pavement interaction noise (TPIN) on the commuters with the development of suitable methodology. Test runs were conducted at midnight to avoid fluctuations in background noise and traffic intrusion disturbances.

3.2.2 Effect of Vehicle Noise Sources

Major noise sources affecting vehicle noise levels are classified into tire-pavement interaction noise, propulsion noise, and aerodynamic noise. Thus, an attempt has been made in the current study to capture noise levels due to dominant sources with a suitable methodology. Accordingly, Cirrus Class-1 Optimus sound level meters with facilities for capturing decibel levels ranging from 20 dB to 140 dB were used to measure the noise levels.

3.2.3 Pass-By Noise Levels due to the Tire-Pavement Interaction

Even though the tire-pavement interaction noise was proved to be a significant parameter above 40 kmph speeds from the literature review, the current study attempts to measure tire-pavement interaction noise level from 10 kmph to 70 kmph using the coast-by method. Accordingly, the vehicle was driven at the required target speed, and the engine is switched off on the selected stretch, and maximum sound pressure level (LAmax (dB)) was captured by Sound Level Meters (SLMs) positioned 3.5 m from the center of the lane at a ground height of 1.2 m as shown in the Figure 3.2.

Even if the difference between the noise levels captured by the SLMs varied by 1 dB, the respective test run was repeated. Wind cap was mounted on the microphone of SLMs to evade the effect of wind direction and wind speed. A significant part of aerodynamic noise generated at the tire-pavement interaction interface was included within the tire-pavement interaction noise. Moreover, the aerodynamic noisewas neither separately prioritized in the quantification of far-field noise nor in the noise measurements close to the field. It is due to the fact that aerodynamic noise effect is very less on overall noise emission, and is experienced only by the person sitting in the vehicle.

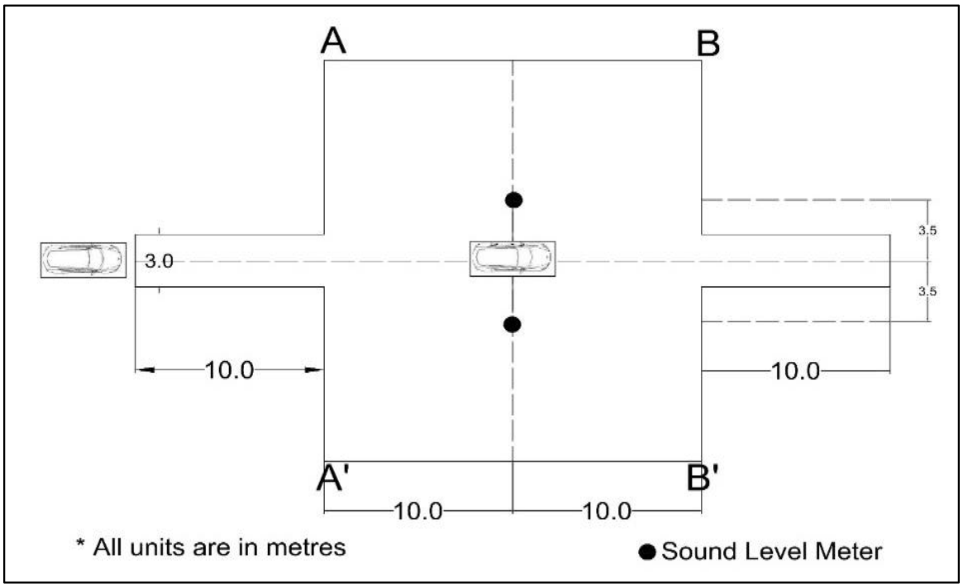

Figure 3.2 The diagram showing the measurement procedure in the coast-by method

3.2.4 Pass-By Noise Levels due to the Propulsion Noise

It is evident that propulsion noise levels vary in accordance with the change in driver characteristics. One considerable effect of driver perception in mixed traffic conditions can be frequent gear change, which differs from an amateur driver to a professional driver. Accordingly, consideration has been made to assess the roadside propulsion noise levels with frequent gear transmission. Thus, to simulate the propulsion noise variation in mixed traffic conditions, gear transmission is constantly varied for different speed runs in the current study. Along with the measurement of noise levels in the CB method, noise levels were also measured in the CPB method to assess the overall vehicle noise levels. As the sound pressure levels cannot be subtracted directly, logarithmic subtraction of relative energies of the sound pressure levels was adopted using the subtraction method to estimate the corresponding propulsion noise levels.

At the same vehicle speed, test vehicles can be driven at different gear transmissions in mixed traffic, which can lead to different engine propulsion noise. However, the principal variation of tire-pavement interaction noise levels measured in the Coast-By method is independent of the characteristics exhibiting propulsion noise levels and is strictly dependent on vehicle speed and pavement characteristics only. Accordingly, subtracting the tire-pavement interaction noise levels at a particular vehicle speed from the single entity of gear transmission is not justifiable in simulating the mixed traffic variation. Subsequently, at each vehicle speed variation of 10 kmph to 70 kmph, the test vehicle was driven at all possible gear transmissions, and the respective propulsion noise levels are considered in overall vehicle noise, which was used in subtracting the tire-pavement interaction noise levels. This can be a guiding tool for assessing pass-by noise levels considering the worst possible vehicle noise sources, which can imitate the real-time mixed traffic conditions.

3.2.5 Development of an Integrated Method for Measuring the Pass-By Noise Levels due to Propulsion

It was observed from the current study that, even after the selection of the test site on urban streets according to the guidelines on acoustic obstructions such as buildings and trees, the major problem in assessing tire-pavement interaction noise level using Coast-By method is safety. This is due to the fact that switching off the engine/disengaging transmission at higher road speeds is very dangerous if the test site consists of any close curve after the selected section. As most of the urban streets are connected by surrounding sub-arterials, any vehicle can intrude onto the test vehicle, which can lead to chaos. However, comparing the effect of different pavements on tire-pavement interaction noise generation at the roadside is not possible without the Coast-By condition of the vehicle at higher speeds. This situation can be tamed by developing an approach for assessing roadside propulsion noise levels and subtracting them from the vehicle noise measured in the Controlled Pass-By method. Thus, a new method known as the integrated jack method has been developed for quantifying the propulsion noise levels in the current study. Passenger cars of different engine variants (petrol and diesel) were selected as test vehicles, and their respective jacks were used for the measurement of propulsion noise. Test vehicles were kept at the same test spot on the measurement section, where the pass-by study was conducted. The vehicle front wheel was raised from the ground level by about three centimeters with the help of a jack. To avoid the effect of the height difference of tripod on noise levels between Controlled Pass-By and Integrated Jack methods, sound level meters were kept at the height of 1.23 m from the ground positioned at 3.5 m from the center of the vehicle, as shown in Figure 3.3.

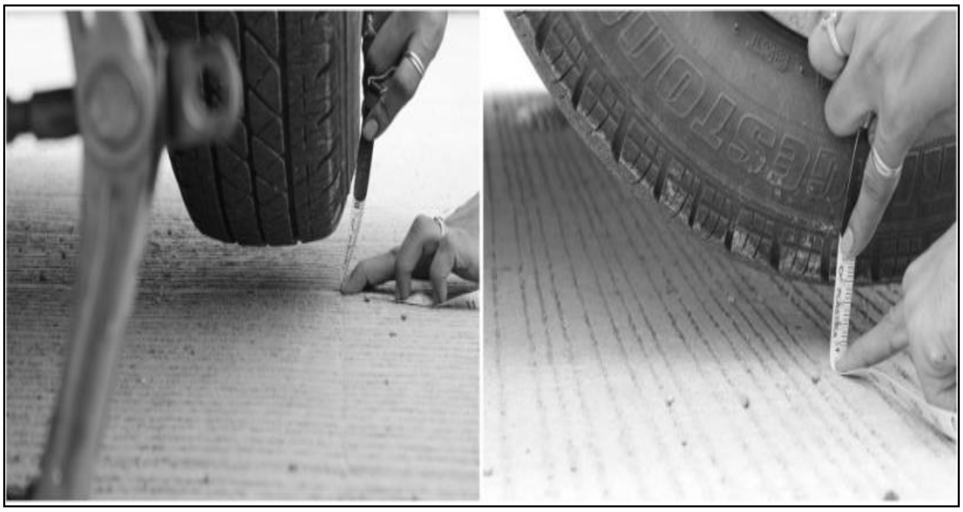

Figure 3.3 The integrated jack method used for measuring propulsion noise levels

Accordingly, the vehicle was driven at all gears, and the respective propulsion noise levels were measured in LAmax (dB). Vehicle speeds varied from 10 kmph to 70 kmph, and the noise levels were recorded for each speed increment of 10 kmph covering the worst and the best possible propulsion transmissions in the real-time traffic situation. Data was collected soon after the measurement of tire-pavement interaction noise levels on the test section between time interval 1:30 am to 4:00 am to avoid changes in background noise and atmospheric conditions on propulsion noise. The distance between the test vehicle and the SLM was kept constant to avoid the effect of distance propagation in both the methods. On a decisive note, propulsion noise levels measured using the method developed in this study can be subtracted from the vehicle noise levels captured in the Controlled Pass-By method, which can result in the respective tire-pavement interaction noise levels. These tire-pavement interaction noise levels were compared with standard Coast-By measurements to check the validity of the method developed in the study.

3.2.6 Development of a Method for Measuring the In-Vehicle Noise Levels due to Tire-Pavement Interaction

The first challenge for the measurement of noise levels inside the vehicle is the methodology to be adopted in assessing noise levels. Unlike far-field noise assessment in the

CB method, where a sturdy tripod holds the SLM at a preferred height (usually 1.2 to 1.5 m for simulating the standing human ear height above the ground level), SLM cannot be placed steadily on the tripod inside the vehicle during travel. This results in reflections and vibrations on the noise measuring equipment, which in turn can significantly affect the noise levels measured. Thus, fixing the sound level meters and microphones to the vehicle body and measurement by artificial head were techniques used so far for assessing the in-vehicle noise levels due to the tire-road interaction. However, reducing the vibrations from the vehicle body is a complex phenomenon, as it involves the effect of both vehicle condition and speed. Moreover, vibration on the vehicle body is quite different from vibrations on the passenger. Thus, noise levels can be different at both these locations. Further, measuring the noise levels by fixing the microphone on the driver's seat or on the vehicle body can give different noise readings in comparison with actual noise levels perceived by the commuter. Thus, the current study aims at the best placement mechanism of SLM inside the vehicle such that the vibrations and the movements caused to SLM are minimized, which in turn can lead to a new methodology for quantification of in-vehicle noise levels due to tire-pavement interaction.

As the vibrations on the sturdy vehicle body are quite different from vibrations on the commuter, SLM is subjected to various movements when it is handheld. In comparison with the fixing of sound level meter to the vehicle body, instability of the handheld sound level meter occurs due to hand movements and vibrations from the human body. It is important to note that vibrations from the human body are the result of the movements about the three-axis (pitch, roll, and yaw) for the commuter sitting inside the vehicle resulting in a phenomenon called tremor. Tremor is an automatic vibration of human body parts during muscle contractions while in action. In general, tremor is the most common phenomenon in every healthy human being. The human parts resulting in the tremor are primarily due to hands and the lower arms. These tremors are perceptible when a human holds the limb (usually arm) against gravity, known as action postural tremor. On realizing the effects of the tremor, to avoid shaky movements during the motion picture shoot, handheld stabilizers are developed for holding the camera, which can reduce tremor vibrations about the three-axis (pitch, roll, and yaw) and enable the use of hand shake-free videos. This principle, which is followed in capturing non-shaky videos for motion pictures, has been applied in the current study for capturing human hand vibration-free noise measurements, by mounting the sound level meter on a handheld stabilizer. That is, the camera is replaced with the sound level meter. The driver of the vehicle is subjected to the same postural tremor with the arms holding the drive wheel/steering against gravity. In similar lines to that of the camera, the driving wheel held by the driver and the sound level meter held by the passenger is also subjected to tremor vibrations during driving. In order to take into account the above phenomenon in the current study, the person sitting next to the driver in the front seat held both the sound level meters (free handheld and with handheld stabilizer) against gravity for capturing in-vehicle noise measurements near the driver's ear. As the stabilizer uses counterweights to balance the movements about three axes, the resulting noise levels captured at the driver's ear by both sound level meters could be compared.

As most of the studies throughout the world have focused on quantifying the tire-pavement interaction noise levels at the roadside using the coast-by method, the same approach has been adopted in the current study for quantifying in-vehicle noise levels, as shown in Figure 3.4.

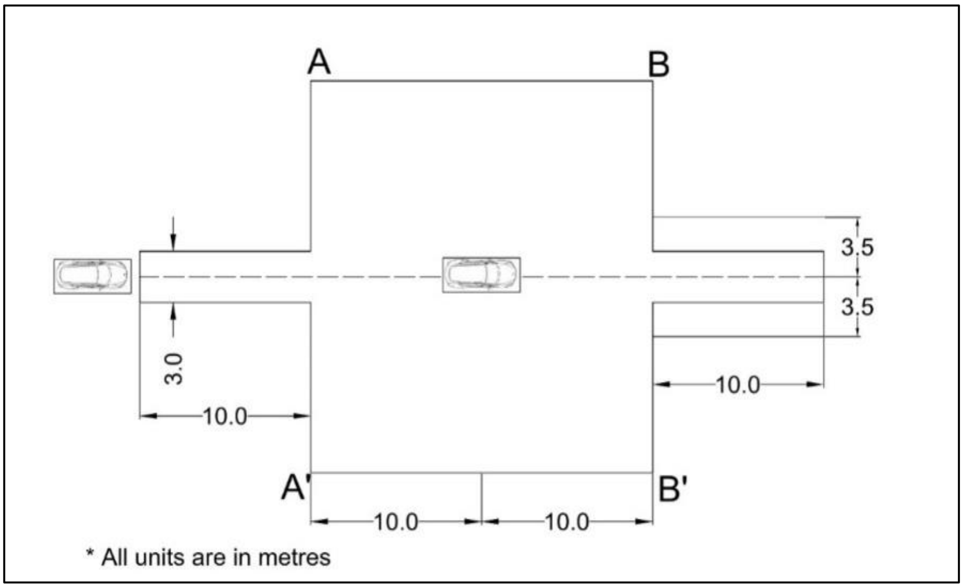

Figure 3.4 Schematic diagram showing the in-vehicle measurement procedure adopted using the coast-by method

For each vehicle run, two Sound Level Meters [SLM-1 and SLM-2] were used to estimate the equivalent sound pressure level LAeq (dB), which represents the logarithmic average of the noise levels observed over the stretch. SLM-1 was handheld, and SLM-2 was mounted on the handheld stabilizer during noise measurements. Both sound level meters were held at the driver's left ear at a distance of 0.2 m away from the reflecting surfaces of the front cabin. It is important to note here that the driver seat is located on the right side of the vehicle in India, where left-side driving is followed. SLM-1 was handheld by the passenger sitting in the front seat at the exact height of the driver's left ear. To avoid the effect of vibrations and hand movements on the noise measurements, SLM-2 mounted on the handheld stabilizer was held by the same passenger sitting in the front seat, as shown in Figure 3.5.

By stabilizing the setup using counterweights, SLM-2 was firmly mounted on top of the stabilizer using adjustable screws. Accordingly, the mounted SLM-2 was stabilized about the three axes (row axis, pitch axis, and yaw axis) such that no vibrations or heavy movements would affect the noise readings. Moreover, the stabilizer has a carbon fiber body that can provide an adjustable length from 38.5 cm to 60 cm. Such a setup is beneficial while measuring noise levels in limited spaces such as cabins of cars or other automobiles. After fixing the SLM on the mount, in-vehicle noise levels due to the tire-pavement interaction were simultaneously captured by both handheld and stabilizer mounted SLMs using the standard CB methodology. Overall, the measured tire-pavement interaction noise levels in pass-by and in-vehicle noise measurements were further analyzed to assess the variation at speeds ranging from 10 kmph to 70 kmph.

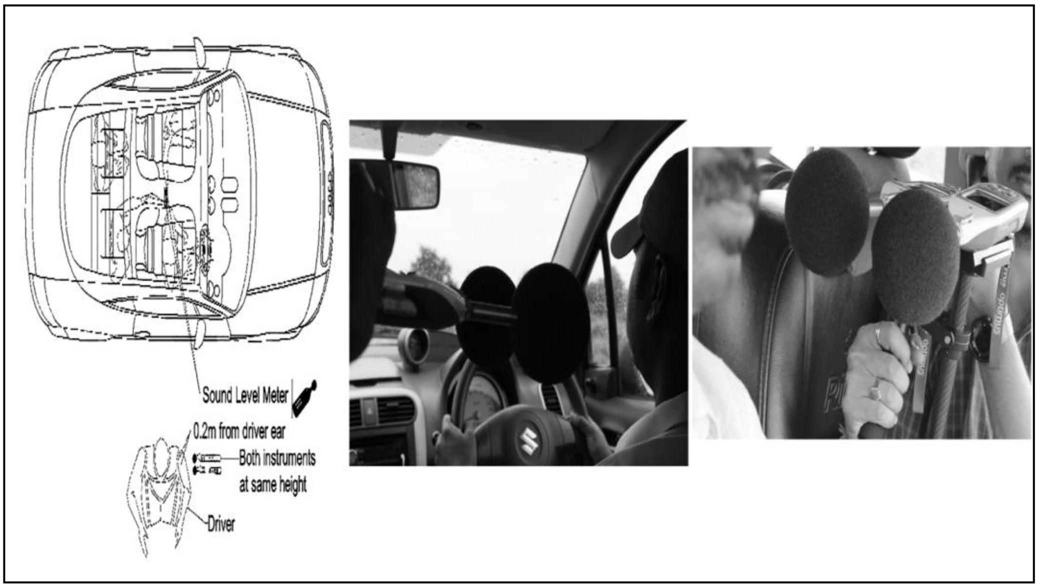

Figure 3.5 Schematic diagram and photographs showing the measurement procedure developed for in-vehicle noise levels

Comparison can be made between the integrated jack and in-vehicle noise measuring methods developed in the current study with the standard methods used so far. Integrated jack method can capture the propulsion noise levels which can be subtracted from the standard CPB noise levels to measure the tire-pavement noise levels. Thus, the developed method is useful in estimating the noise levels due to both principal noise sources from the vehicle. This possesses the advantage of measuring the tire-pavement noise levels without switching-off/disengaging the transmission. This enables the usage of the integrated jack method in streets having the closure curvature which is not safe with the usage of standard CB method.

Further, fixing the sound level meters and microphones to the vehicle body and measurement by artificial head were techniques used so far for assessing the in-vehicle noise levels due to the tire-pavement interaction. However, vibration on the vehicle body is quite different from the vibrations on the commuter and hence the corresponding noise levels can be different at both these locations. Thus, the current methodology in the study uses the handheld stabilizer for mounting the sound level meter which can stabilize the movements about the three-axis (pitch, roll, and yaw) and can capture the noise levels experienced by the person inside the vehicle. This possesses the advantage of using the stabilized sound level meter in any vehicle class.

Finally, the effect of TPIN on both roadusers and commuters at different road speeds was analyzed to identify the need for low noise pavements to mitigate the noise at the source.

3.3 Summary

This chapter provides the methodology adopted for the current study covering the selected test sections for measuring traffic noise levels with a significant focus on the methodological development and the measurement techniques of noise levels. Data collection and analysis of the current work are discussed in the next chapters.

CHAPTER 4
DATA COLLECTION AND ANALYSIS

4.1 General

This chapter includes the process adopted for the data collection on the selected test sections and the techniques used for the extraction of the field data for subsequent analysis. Data consists of the continuous pass-by noise levels measured over the eight different highways and the two 3-legged intersections with a clear emphasis on the traffic parameters at the test sections. Further, measured vehicle volume and speeds were considered in generating the heterogenic traffic noise prediction models. Moreover, pass-by and in-vehicle noise level data collected over the asphalt and cement concrete pavements with the developed methodologies were included in the chapter. Finally, the effect of principal noise sources on the measured noise levels was carefully analyzed with respect to speeds on the selected sections to know the impact on commuters and roadusers. The techniques used for the extraction of the collected data on the test sections and the detailed analysis are discussed in the current chapter.

4.2 Heterogeneous Traffic Noise Data Collection on Highway Sections

To develop a comprehensive noise prediction model for the heterogeneous highway traffic covering the possible spectrum of speeds, Parameters affecting the noise levels such as traffic speed and traffic volume are considered. Usually, noise levels are measured through the near field and far-field measurements. Placing the microphones on the roadside and capturing the noise levels from the moving traffic is classified under far-field methodology and is adopted in the current study. Accordingly, a class 1 sound level meter was placed at a predefined distance of 1.5 m from the adjacent traffic lane, at the height of 1.5 m above the ground, and the continuous noise levels were measured with a data logging of the 1-second interval using the time averaging method. Accordingly, SVAN 945A pocket sound level meter (SLM) was used to measure the noise levels and are analyzed using the SVAN PC suite by transferring the data to the computer. The measured noise indices in the current study include equivalent A-Weighed continuous sound level [LAeq (dB)], Sound Pressure Level [SPL], Sound Exposure Level [SEL] and the A-Weighed noise level exceeded for 10% of the measurement time [LA10]. Along with these noise level measurements, traffic volume and spot speed studies were carried out simultaneously on eight highways in the states of Andhra Pradesh, and Telangana in India were selected under the study area, which listed in Table 4. 1.

Table 4.1 List of survey locations

S. No.	Road Stretch	Survey Location
1	Vijayawada- Kolkata Highway	Near Pottipadu Tollgate
2	Vijayawada-Chennai Highway	Near Nagarjuna University
3	Warangal- Khammam Highway	Near Mamnoor (Vaagdevi College)
4	Hyderabad- Nagpur Highway	Near Medchal
5	Hyderabad-Vijayawada Highway	Near Ramoji Film City
6	Hyderabad-Bengaluru Highway	Near Shamshabad Airport
7	Hyderabad- Pune Highway	Near IIT Hyderabad
8	Hyderabad- Warangal Highway	Near Ghatkesar

These eight highways are experiencing the continuous traffic flows throughout the study period. Moreover, the selected highway sections are having the carriageway width of about 11.5 meters to 21.0 meters. The study area includes highways with different carriageway widths which are experiencing different vehicle volumes and speeds are chosen to ensure diversity in sampling. Irrespective of the carriageway width of these highway sections, all noise measurements were conducted at the mid-block sections at predefined distance of 1.5 m from the adjacent traffic lane, at the height of 1.5 m above the ground. This allows the developed comprehensive model to be effectively used for the noise prediction for the highways with the similar traffic and geometric conditions in India. Moreover, noise measurements at the selected mid-block sections are not having the speech disturbance from the commuters, shop keepers, and pedestrians. Such protocol is required for assessing the uninterrupted noise levels from the traffic without any additional noise sources. Classified traffic volume on both the directions of the selected road was collected. In order to achieve this task, four trained enumerators were employed in each direction of the vehicle movement. Accordingly, vehicles are classified as Bus (B), Mini Bus (MB), Motor Cycle (MC), Scooter (SC), Bicycle (CY), Cycle Rickshaw (OT), Auto Rickshaw (A), Small Car (CS), Big Car (CB), Tractor Trailer (TT), Light Commercial Vehicle (LT), Two-Axle Truck (HT) and Multi-axle Truck (MT). As consideration of these classes on the same roadway will lead to heterogenic traffic volume, classes of all vehicles were converted into Passenger Car Units (PCUs). Accordingly, PCU factors are used as follows: 0.5 for the Motor Cycles, 0.5 for Scooters, 1.0 for Autos, 0.5 for Cycles, 1.5 for Cycle Rickshaw, 1.0 for Small Cars, 1.0 for Big Cars, 3.0 for Buses, 3.0 for Mini Buses, 3.0 for Tractors, 1.0 for Light Commercial Vehicles, 3.0 for Two- Axle Trucks and 3.0 for Multi-Axle Trucks. Spot speeds were recorded by using Laser speed gun. Two trained enumerators were employed in each direction, and the speed data was collected in tally sheets. Individual vehicle speeds were recorded in corresponding 15-minute time interval periods simultaneously with traffic volume counts. All the measurements were carried out between the time intervals of 10:00 to 17:00 hours. Traffic volume, traffic speed, and measured noise levels were processed by using MS-EXCEL Package. Accordingly, the variation of traffic volume is shown with the help of a mode share diagram at each location, which is presented below.

4.2.1 Vijayawada- Kolkata highway

The summary of the total data collected on the Vijayawada - Kolkata highway near the Pottipadu toll gate is shown in Table 4.2. Accordingly, the variation of volume and the corresponding noise levels over time is shown in Figure 4.1. The maximum volume of 239 vehicles (PCU) is observed between the time interval of 11:00 – 11:15 hours. The range of noise levels is from 102 dB to 107dB.A maximum noise level of 107.1 dB is observed between the time interval of 10:45 – 11:00 hours. Overall, Motor Cycles and Multi-Axle Trucks are predominant in the traffic flow, as shown in the mode share diagram in Figure 4.2. Whereas, the average speed of the vehicles is observed to be 52 kmph with variation between 10 – 95 kmph. Accordingly, the variation between the average traffic speeds and noise levels are shown in Figure 4.3.

Table 4.2 Summary of traffic and noise data on Vijayawada - Kolkata highway

Time of the Day, hours		**Total Volume (PCU)**	**Average Traffic Speed (kmph)**	**LAeq (dB)**	**SPL (dB)**	**SEL (dB)**	**LA10 (dB)**
From	**To**						
10:00	10:15	159.5	47.88	102.2	89.3	131.7	103
10:15	10:30	146	52.15	103.3	99.3	132.8	104.2
10:30	10:45	203.5	56.13	103.1	99.3	132.6	104.3

10:45	11:00	176	55.44	107.1	99.6	136.6	108
11:00	11:15	238.5	54.01	103.5	93.9	133	106.4
11:15	11:30	198.5	54.83	104.5	92.7	134	107.5
11:30	11:45	178.5	60.06	105.6	97.1	135.1	107.8
11:45	12:00	155	52.09	102.9	89.2	132.4	104
12:00	12:15	160	55.98	103.5	95.2	133	106.2
12:15	12:30	222.5	53.66	103.1	105	132.6	105.7
12:30	12:45	113	51.41	102.2	99.8	131.7	103.7
12:45	13:00	125	54.55	102.4	97	131.9	104.1
14:00	14:15	201	50.53	103.9	105.9	133.4	105.6
14:15	14:30	159.5	47.13	103.1	93.5	132.6	105.2
14:30	14:45	179.5	49.59	103.7	95.9	133.2	105.8
14:45	15:00	168	50.11	104.9	96.1	134.4	107.3
15:00	15:15	211	48.40	103.4	102.9	132.9	104.9
15:15	15:30	204	48.39	104.2	94.1	133.7	107.8
15:30	15:45	177	50.07	104.2	95.2	133.7	107.8
15:45	16:00	203.5	50.95	103.2	101.9	132.7	105.5
16:00	16:15	148.5	45.84	105.7	103.5	135.2	108.4
16:15	16:30	205.5	45.56	105.8	112.2	135.3	107.9
16:30	16:45	156.5	47.59	102.8	105.6	132.3	104.3
16:45	17:00	175.5	50.92	104.3	97.4	133.8	106.9

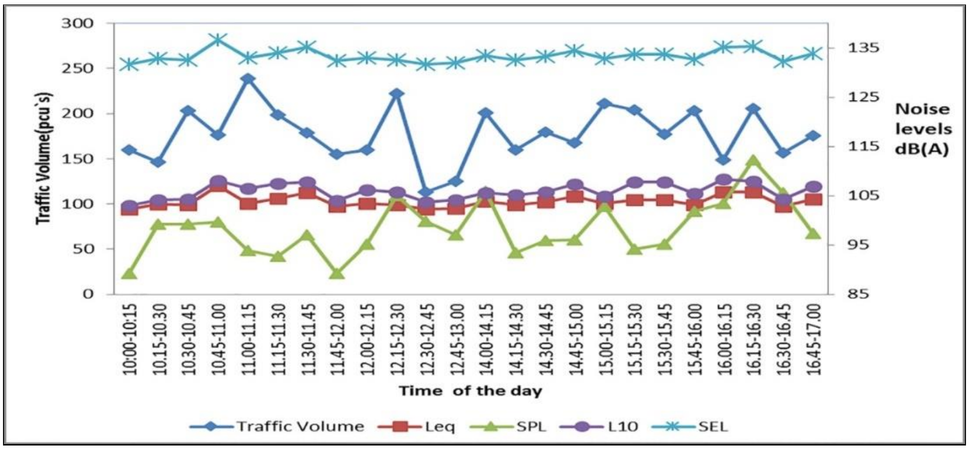

Figure 4.1 Variation of traffic volume as a function of noise levels on Vijayawada-Kolkata highway

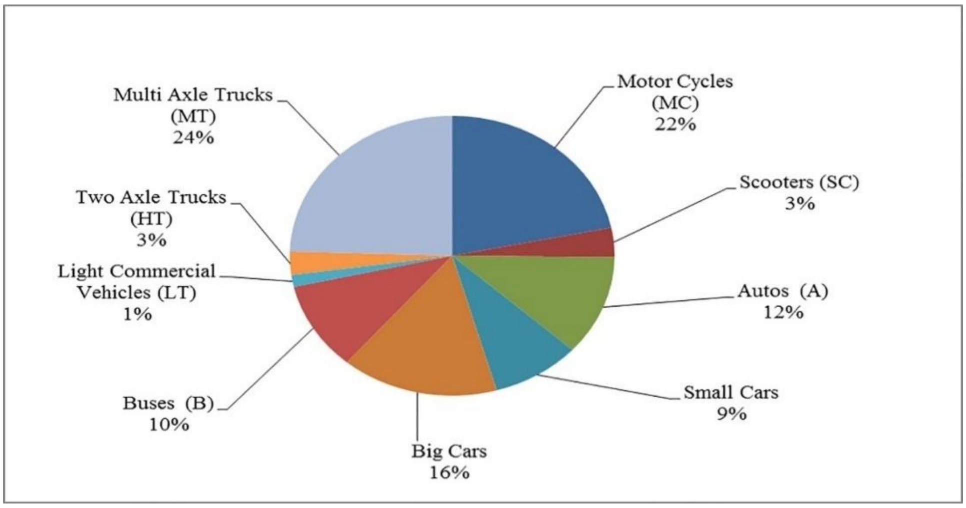

Figure 4.2 Mode share on Vijayawada-Kolkata highway

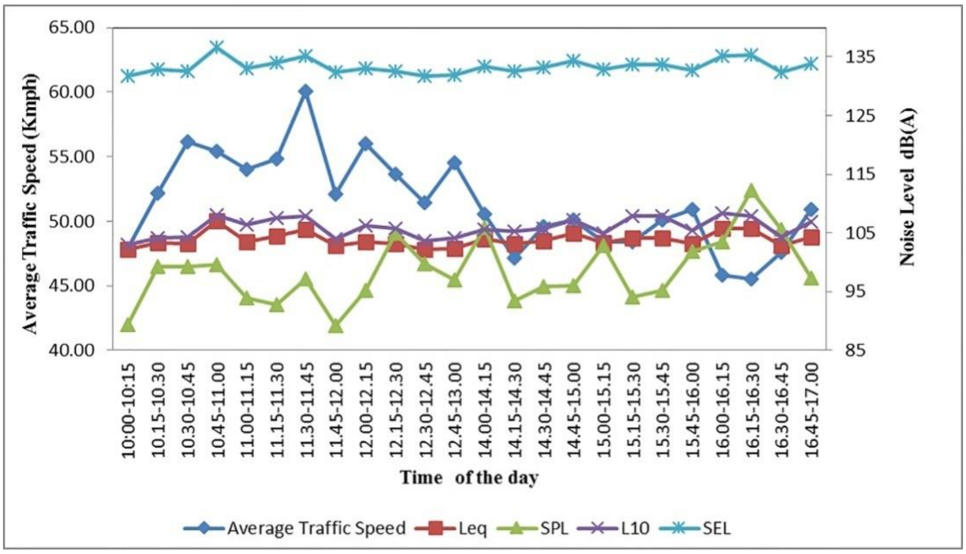

Figure 4.3 Variation of average traffic speed as a function of noise levels on Vijayawada-Kolkata highway

4.2.2 Vijayawada-Chennai highway

The summary of the total data collected on the Vijayawada - Chennai highway near Nagarjuna University is presented in Table 4.3. Accordingly, the variation of volume and the corresponding noise levels over time is shown in Figure 4.4. The maximum volume of 344 vehicles (PCU) is observed between the time interval of 10:45 – 11:00 hours. The range of noise levels is from 105 dB to 112 dB. A maximum noise level of 111.6 dB is observed between the time interval of 14:45 – 15:00 hours. Overall, Motor Cycles are predominant in the traffic flow, as shown in the mode share diagram in Figure 4.5. Whereas, the average speed of vehicles was observed to be 48.3 kmph which varied between 12 – 79 kmph. Accordingly, the variation between the average traffic speed and noise levels are shown in Figure 4.6.

Table 4.3 Summary of traffic and noise data on Vijayawada - Chennai highway

Time of the Day, hours		**Total Volume (PCU)**	**Average Traffic Speed (kmph)**	**LAeq (dB)**	**SPL (dB)**	**SEL (dB)**	**LA10 (dB)**
From	To						
10:00	10:15	273.5	52.71	107.6	107.9	137.1	110.1
10:15	10:30	247.5	46.60	107.3	97.9	136.8	109.8
10:30	10:45	196	50.65	106.3	93.6	135.8	109.4
10:45	11:00	344	47.13	106.3	110	135.8	109.1
11:00	11:15	242	47.06	106.9	103.2	136.4	108.7
11:15	11:30	232	50.01	105.5	104.8	135	108.1
11:30	11:45	276.5	53.50	105.5	106.1	135	108.2
11:45	12:00	237	47.49	108.4	98.8	137.9	111.5
12:00	12:15	283.5	48.38	106.6	100.8	134.9	109.2
12:15	12:30	255.5	45.26	106.3	92.1	135.8	109.4
12:30	12:45	244	47.95	105.6	107.6	135.1	107.9
12:45	13:00	235.5	46.83	108.2	105.6	137.7	110.8
14:00	14:15	262.5	50.11	106.1	92.6	135.6	108.5
14:15	14:30	244	50.18	106	99.9	135.5	108.3
14:30	14:45	328	49.84	104.8	103.3	133.6	106.2
14:45	15:00	217.5	42.05	111.6	104.1	141.5	114.2
15:00	15:15	237	47.36	108.6	95.9	138.1	110.5
15:15	15:30	252.5	44.35	110.3	107.2	139.8	113.5
15:30	15:45	294.5	43.15	109.8	99.7	139.3	112.4
15:45	16:00	322	50.53	108.1	98	137.6	110.1
16:00	16:15	213.5	47.87	109.8	105.3	139.3	112.4
16:15	16:30	266	52.03	106.2	107.7	135.7	109.3
16:30	16:45	279.5	49.11	108.9	103	138.4	111.6
16:45	17:00	295	48.92	106.6	96.1	136.1	108.9

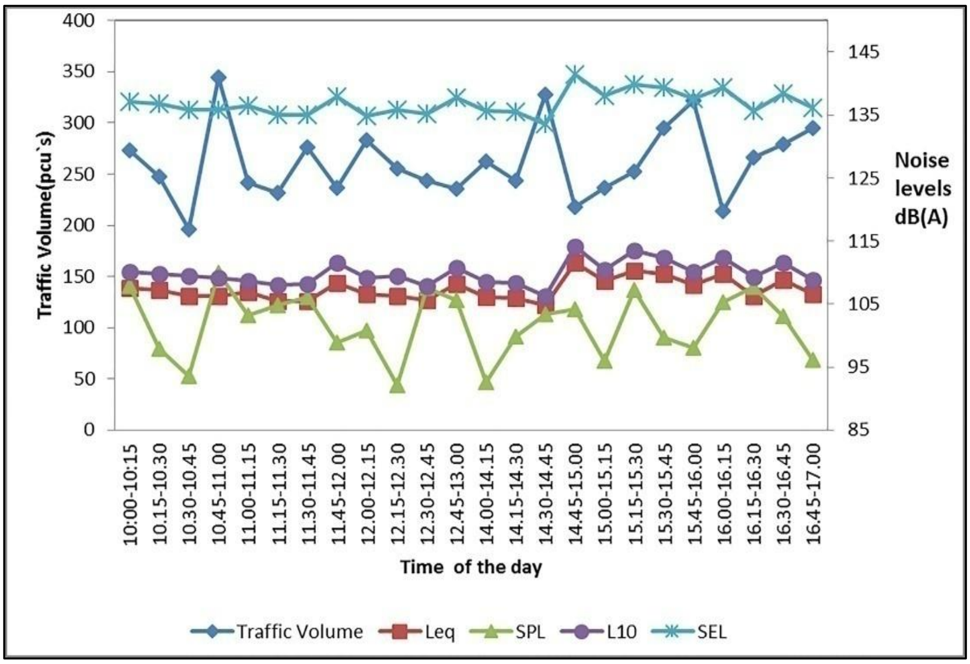

Figure 4.4 Variation of traffic volume as a function of noise levels on Vijayawada-Chennai highway

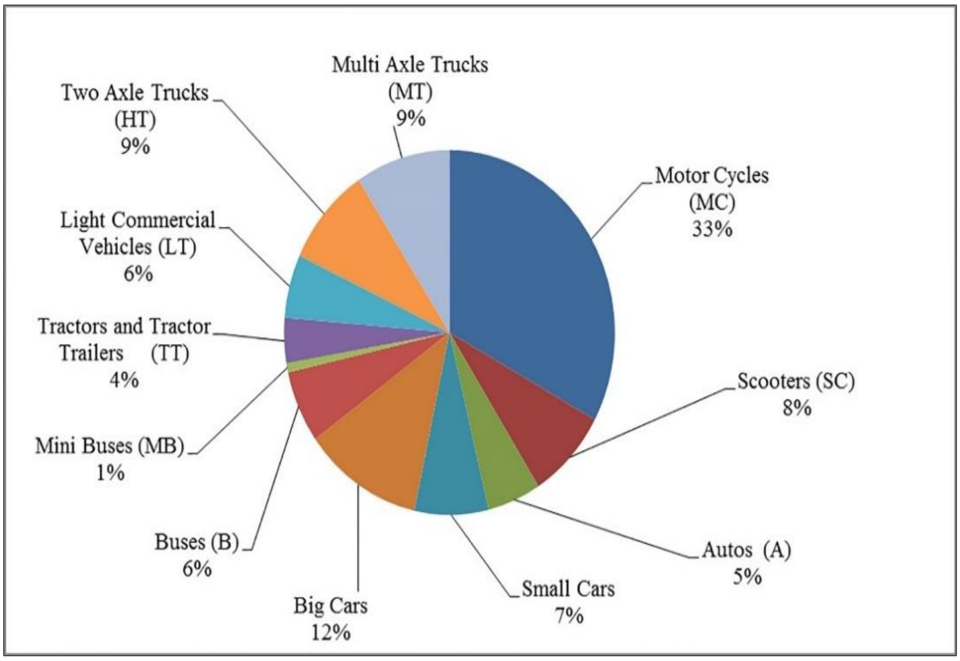

Figure 4.5 Mode share on Vijayawada-Chennai highway

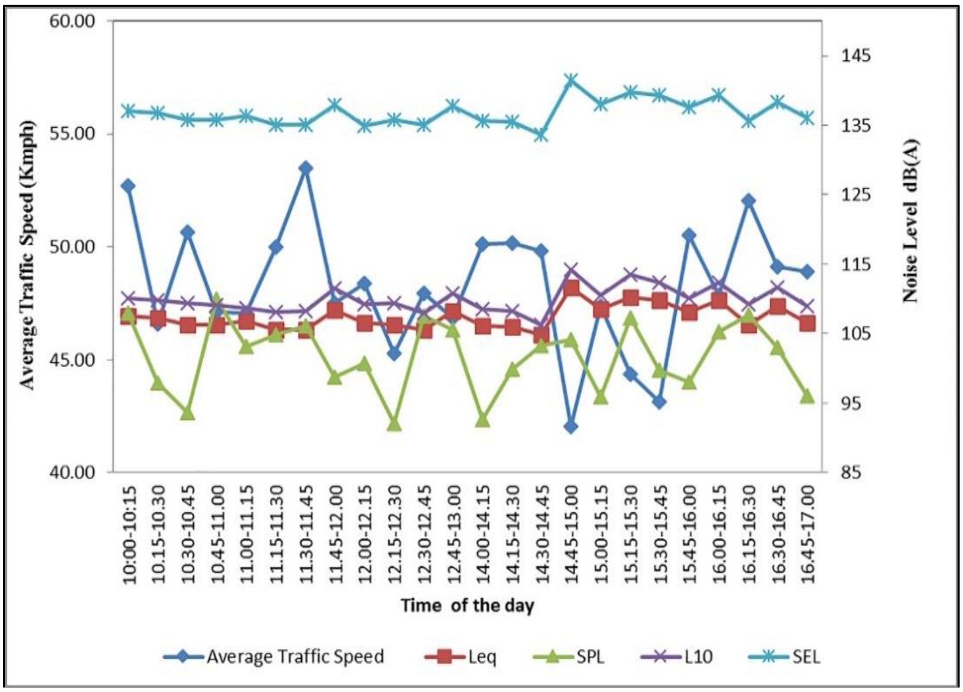

Figure 4.6 Variation of average traffic speed as a function of noise levels on Vijayawada-Chennai highway

4.2.3 Warangal- Khammam highway

The summary of the total data collected on Warangal – Khammam highway near Mamnoor is presented in Table 4.4. Accordingly, the variation of volume and the corresponding noise levels over time is shown in Figure 4.7. The maximum volume of 136 vehicles (PCU) is observed between the time intervals of 14:00 – 14:15 hours. The noise levels were ranging from 88 dB to 100 dB. A maximum noise level of 99.5 dB is observed between the time interval of 14:00 – 14:15 hours. Overall, Motor Cycles are predominant in the traffic flow, as shown in the mode share diagram in Figure 4.8. Accordingly, the variation between the average traffic speed and noise levels are shown in Figure 4.9.

Table 4.4 Summary of traffic and noise data at Warangal - Khammam highway

Time of the Day, hours		Total Volume (PCU)	Average Traffic Speed (kmph)	LAeq (dB)	SPL (dB)	SEL (dB)	LA10 (dB)
From	To						
10:00	10:15	111	37.71	95	76.7	124.5	98.1
10:15	10:30	111.5	36.55	95.9	95.1	125.4	98.3
10:30	10:45	105	39.77	95.9	89	125.4	98.3

10:45	11:00	104.5	42.42	95.2	92.9	124.7	97.9
11:00	11:15	93.5	35.33	96.9	110.3	126.4	99.2
11:15	11:30	90	37.55	95.1	89.3	124.6	97.1
11:30	11:45	70	40.85	94.6	102.2	124.1	97.4
11:45	12:00	100.5	37.91	93.7	89.9	123.2	96.2
12:00	12:15	54.5	37.98	99.2	81.1	128.7	103.2
12:15	12:30	84	37.47	95.3	83.8	124.8	98.4
12:30	12:45	80.5	41.72	94.5	83.9	124	97.3
12:45	13:00	83	39.47	97.6	94.3	125.7	99.9
14:00	14:15	135.5	45.59	99.5	95.4	124.5	103.6
14:15	14:30	105.5	46.48	97.4	93.2	123.2	100.5
14:30	14:45	57	52.25	92.6	83.7	122.1	95.3
14:45	15:00	69.5	41.21	92.4	90	121.9	95.1
15:00	15:15	91	41.62	96.3	83.1	125.8	99.8
15:15	15:30	75	49.24	93.9	95.5	123.4	96.4
15:30	15:45	90	44.39	94.1	94.7	123.6	98.1
15:45	16:00	113	50.99	93.9	89.5	123.4	95.7
16:00	16:15	78.5	45.77	93	88.7	122.5	95.1
16:15	16:30	91	48.33	94	89	123.5	97.1
16:30	16:45	79	44.18	96.7	84.5	126.2	99.2
16:45	17:00	131.5	41.25	88.4	91.9	122.7	94.2

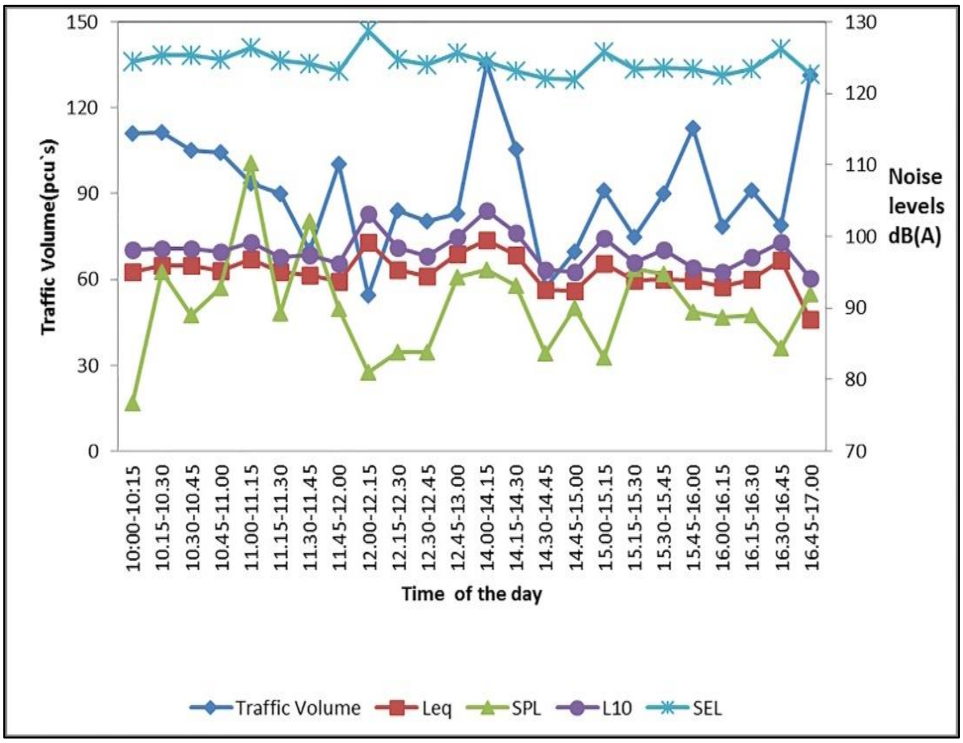

Figure 4.7 Variation of traffic volume as a function of noise levels on Warangal-Khammam highway

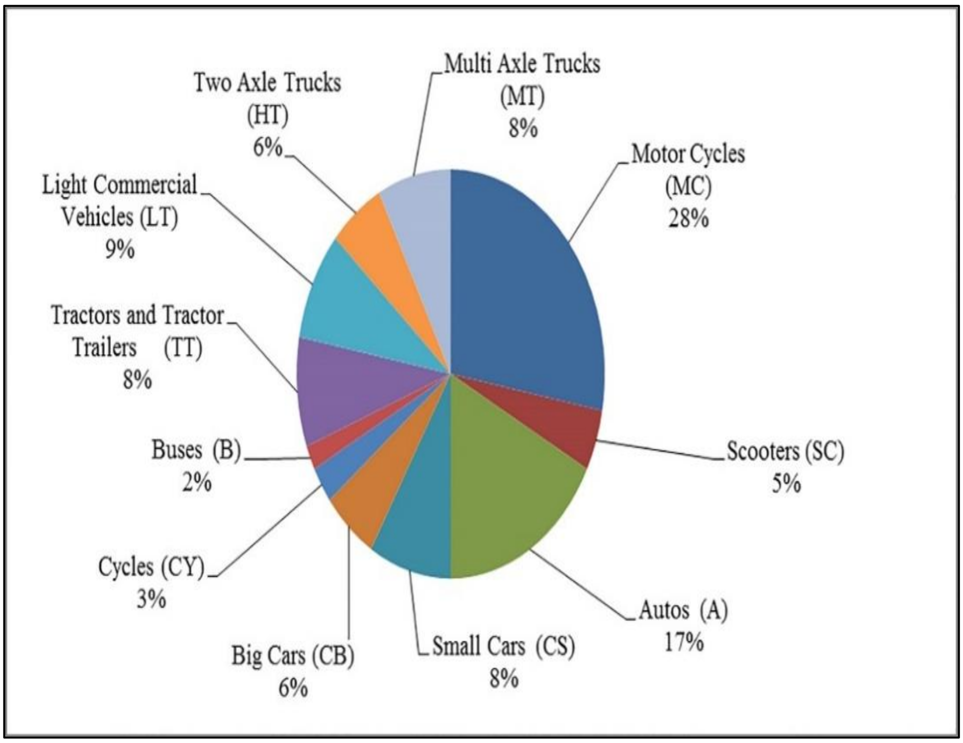

Figure 4.8 Mode share on Warangal-Khammam highway

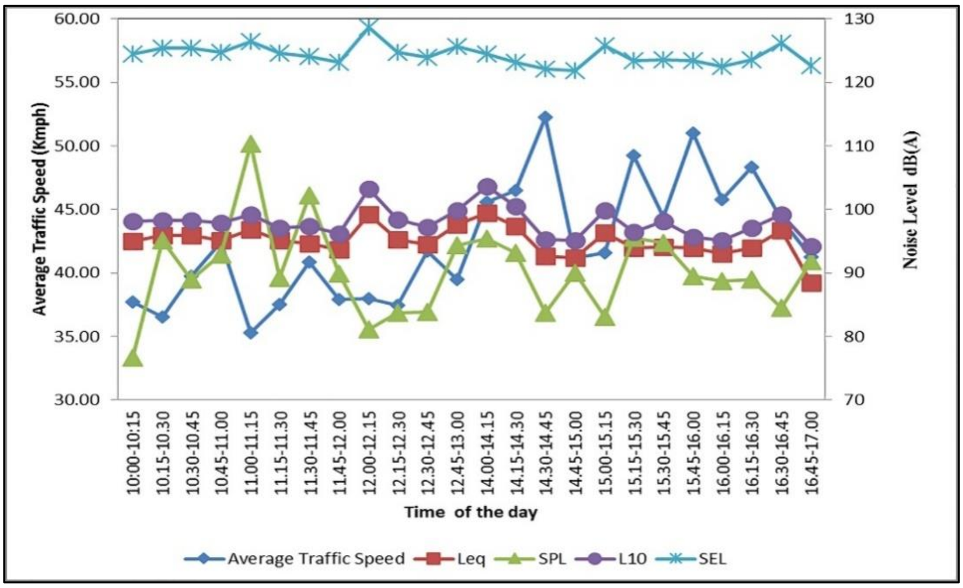

Figure 4.9 Variation of average traffic speed as a function of noise levels on Warangal-Khammam highway

4.2.4 Hyderabad - Nagpur highway

The summary of the total data collected on Hyderabad – Nagpur highway near Medchal is presented in Table 4.5. Accordingly, the variation of volume and the corresponding noise levels over time is shown in Figure 4.10. The maximum volume of 269 vehicles (PCU) is observed between the time intervals of 11:00 – 11:15 hours. The range of noise levels is from 102 dB to 107 dB. A maximum noise level of 106.8 dB is observed between the time interval of 16:30-16:45 hours. Overall, Motor Cycles are predominant in the traffic flow, as shown in the mode share diagram in Figure 4.11. Whereas, the average speed of vehicles is observed to be 52.3 kmph with a variation between 24 – 103 kmph. Accordingly, variation between the average traffic speed and noise levels are shown in Figure 4.12.

Table 4.5 Summary of traffic and noise data at Hyderabad - Nagpur highway

Time of the Day, hours		**Total Volume (PCU)**	**Average Traffic Speed (kmph)**	**LAeq (dB)**	**SPL (dB)**	**SEL (dB)**	**LA10 (dB)**
From	**To**						
10:00	10:15	161.5	58.27	105.1	102.4	134	108.4
10:15	10:30	190.5	52.44	105.3	103.2	134.8	108.7
10:30	10:45	200.5	53.55	103.5	102	133	106.3

10:45	11:00	173.5	56.04	104.6	105.1	134.1	107.8
11:00	11:15	269	51.15	103.8	101.2	133.3	106.2
11:15	11:30	182.5	56.76	103.2	96.2	132.7	106
11:30	11:45	177	60.46	104.5	110.4	134	107.2
11:45	12:00	159.5	57.69	104.5	99.5	134	107.4
12:00	12:15	176.5	51.24	104.2	102.8	133.7	107.1
12:15	12:30	194.5	56.01	103.1	105.1	132.6	106.9
12:30	12:45	158	50.66	104.6	93.5	134.1	107.9
12:45	13:00	165.5	51.97	103.5	99.5	124	106.8
14:00	14:15	165	49.86	102.5	86.7	132	105.1
14:15	14:30	113	52.92	103.7	98.4	133.2	106.2
14:30	14:45	124.5	50.75	105.1	108.4	134.6	108.7
14:45	15:00	167	52.54	104.3	106.4	135.6	107.1
15:00	15:15	147.5	52.03	103.4	105.8	134.9	106.8
15:15	15:30	153	50.18	103.9	104.7	133.8	107.1
15:30	15:45	133.5	53.50	102.8	103.9	136.7	105.1
15:45	16:00	128	55.68	102.4	103.4	133.2	105.7
16:00	16:15	137	55.37	104.5	105.7	135.4	108
16:15	16:30	143	56.50	105.3	105.1	133.3	108.6
16:30	16:45	173.5	57.85	106.8	108.9	131.2	109.8
16:45	17:00	122.5	58.51	103.3	109.4	128.9	106.7

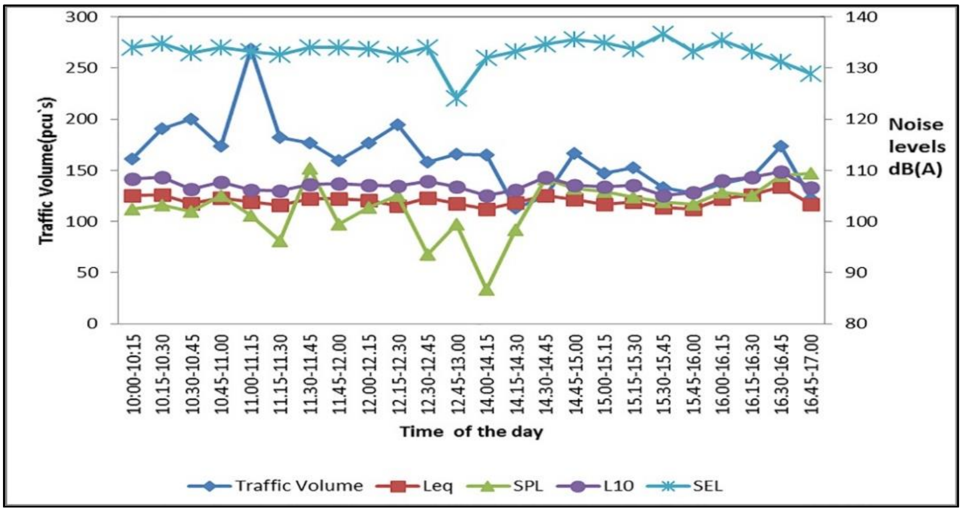

Figure 4.10 Variation of traffic volume as a function of noise levels on Hyderabad- Nagpur highway

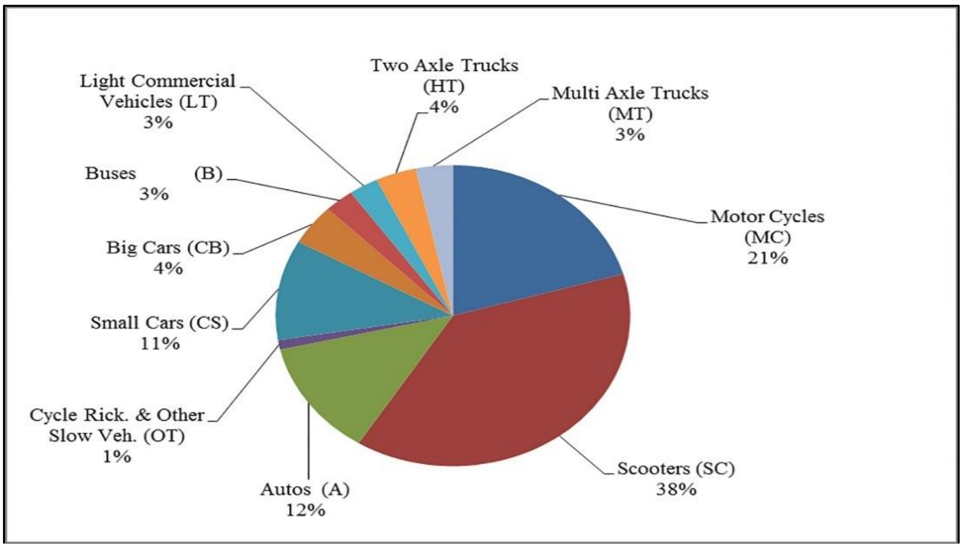

Figure 4.11 Mode share on Hyderabad - Nagpur highway

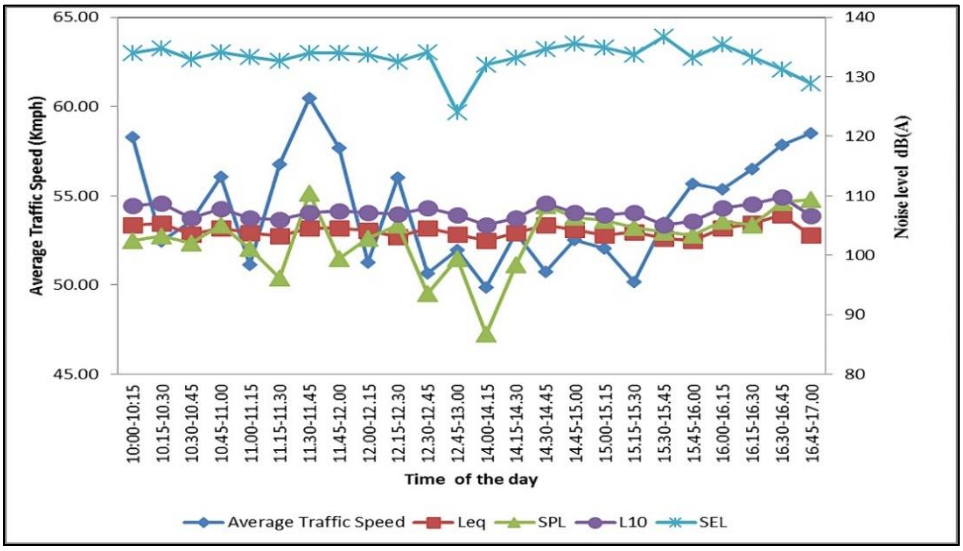

Figure 4.12 Variation of average traffic speed as a function of noise levels on Hyderabad - Nagpur highway

4.2.5 Hyderabad- Vijayawada highway

The summary of the total data collected on Hyderabad – Vijayawada highway near Ramoji film city is presented in Table 4.6. Accordingly, the variation of volume and the corresponding noise levels over time is shown in Figure 4.13. The maximum volume of 461 vehicles (PCU) is observed between the time interval of 16:45 – 17:00 hours. The range of noise levels is from 103 dB to 112 dB. A maximum noise level of 111.7 dB is observed between the time interval of 14:30 – 14.45 hours. Overall, Motor Cycles are predominant in the traffic flow, as shown in the mode share diagram in Figure 4.14. Whereas, the average speed of vehicles is observed to be 52.8 kmph with variation between 29 – 85 kmph. Accordingly, variation between the average traffic speed and noise levels are shown in Figure 4.15.

Table 4.6 Summary of traffic and noise data at Hyderabad- Vijayawada highway

Time of the Day, hours		Total Volume (PCU)	Average Traffic Speed (kmph)	LAeq (dB)	SPL (dB)	SEL (dB)	LA10 (dB)
From	To						
10:00	10:15	278.5	64.15	105.2	97.8	136.4	108.9
10:15	10:30	259.5	57.66	103.9	98.7	134.7	107.5
10:30	10:45	267.5	55.04	104.8	96.8	135.1	107.7
10:45	11:00	277.5	58.12	105	94.9	134.5	108.2
11:00	11:15	258	60.54	104.2	110.9	133.7	107.5
11:15	11:30	228	58.90	105.3	97.6	134.8	108.6
11:30	11:45	239	54.25	103.4	94.3	132.9	106.9
11:45	12:00	259	60.45	104.7	83.7	134.2	107.7
12:00	12:15	288	56.05	105.5	95.5	135	108.6
12:15	12:30	261	55.68	108.6	114.2	138.1	111.1
12:30	12:45	261	57.09	106	101.3	135.5	109.6
12:45	13:00	151	55.37	104.2	90.4	133.7	107.4
14:00	14:15	169	48.64	105.3	94.5	138.9	108.6
14:15	14:30	122.5	50.10	104.7	92.3	134.2	108.1
14:30	14:45	149	50.44	111.7	98.1	141.2	114.3
14:45	15:00	170	46.22	107.3	83.8	136.8	110.6
15:00	15:15	212	53.22	106.2	95	135.7	109.9
15:15	15:30	223.5	44.87	103.2	107.4	132.7	106.2
15:30	15:45	153	49.27	105.5	98.6	135	108.3
15:45	16:00	254.5	48.13	105.6	92.8	135.1	108.9
16:00	16:15	276	48.07	106.1	112.6	135.6	108.8
16:15	16:30	314	44.67	106.5	103.1	136	109.5
16:30	16:45	375.5	44.92	108	96.4	137.5	110.4
16:45	17:00	461	43.47	105.8	103.8	135.3	108.7

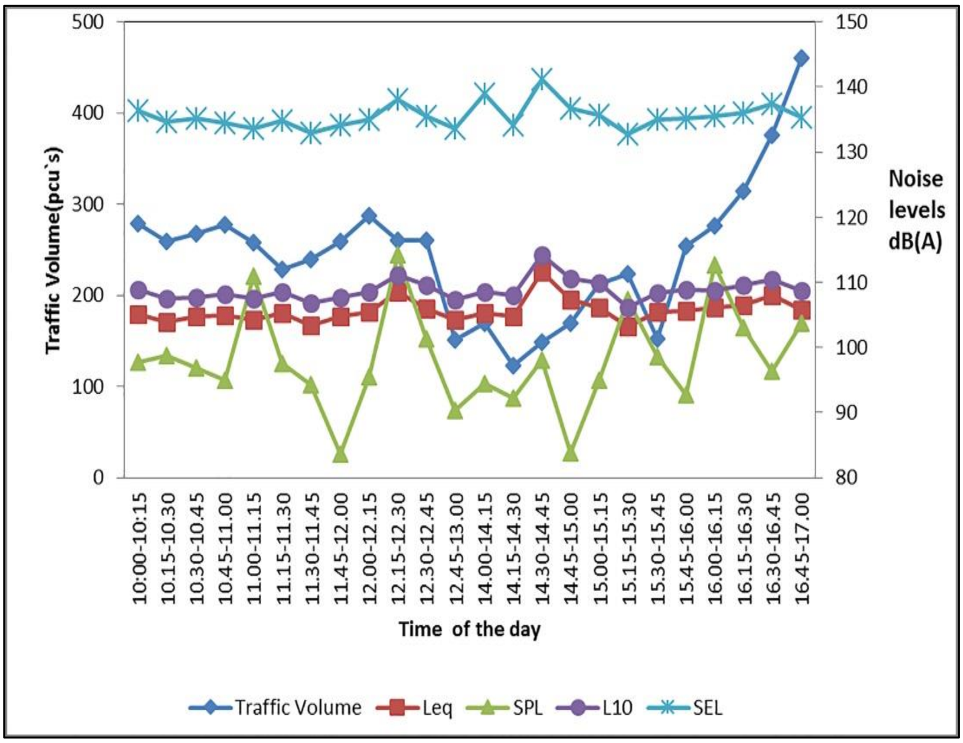

Figure 4.13 Variation of traffic volume as a function of noise levels on Hyderabad-Vijayawada highway

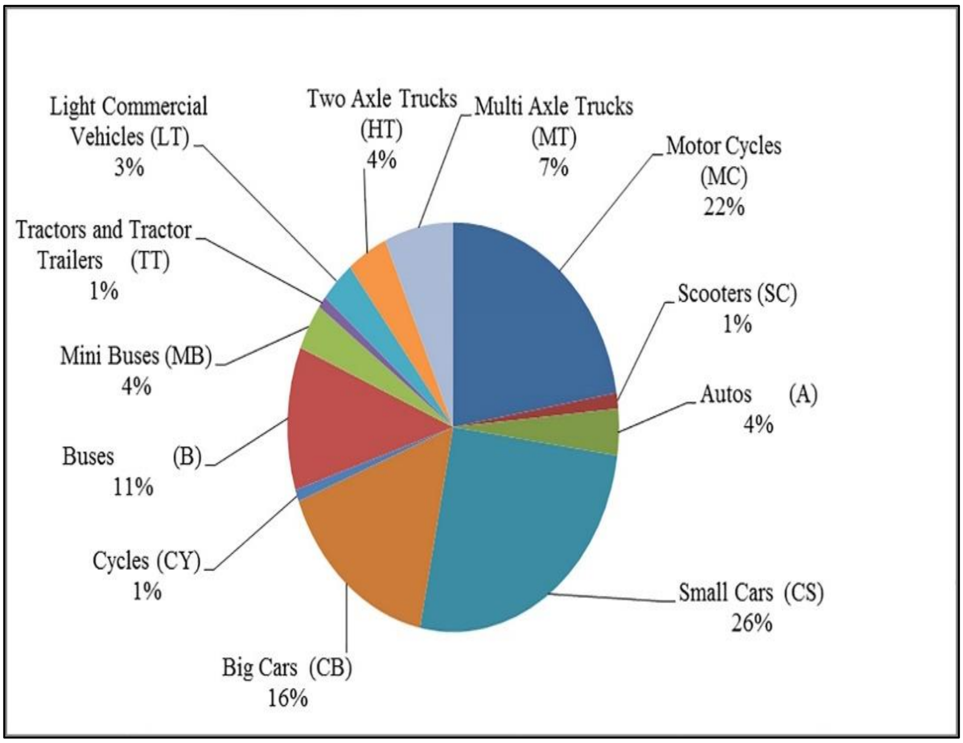

Figure 4.14 Mode share on Hyderabad - Vijayawada highway

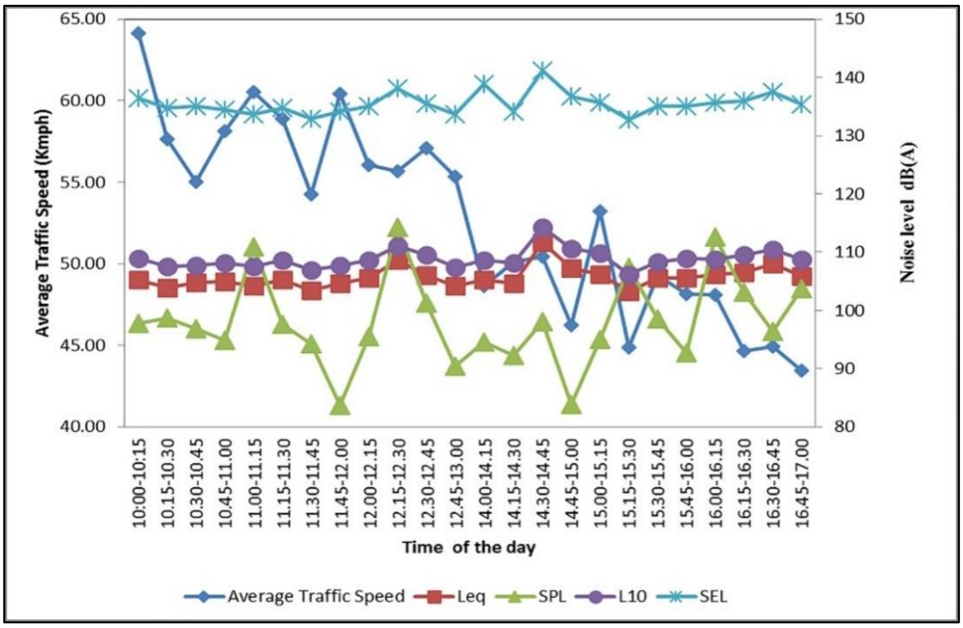

Figure 4.15 Variation of average traffic speed as a function of noise levels on Hyderabad - Vijayawada highway

4.2.6 Hyderabad- Bengaluru highway

The summary of the total data collected on Hyderabad – Bengaluru highway near Shamshabad airport is presented in Table 4.7. Accordingly, the variation of volume and the corresponding noise levels over time is shown in Figure 4.16. The maximum volume of 527 vehicles (PCU) is observed between the time interval of 10:30 – 10:45 hours. The range of noise levels is from 99 dB to 109 dB. A maximum noise level of 109.3 dB is observed between the time interval of 11:30 – 11:45 hours. Overall, Multi Axle trucks are predominant in the traffic flow, as shown in the mode share diagram in Figure 4.17. Whereas, the average speed of vehicles is observed to be 59.4 kmph with a variation between 32 – 103 kmph. Accordingly, variation between the average traffic speed and noise levels are shown in Figure 4.18.

Table 4.7 Summary of traffic and noise data at Hyderabad - Bengaluru highway

Time of the Day, hours		Total Volume (PCU)	Average Traffic Speed (kmph)	LAeq (dB)	SPL (dB)	SEL (dB)	LA10 (dB)
From	To						
10:00	10:15	362	56.55	100.4	106.8	129.9	103.8
10:15	10:30	400	65.63	100.8	114	130.3	104.1

10:30	10:45	527	65.17	99.8	97.2	129.3	103.2
10:45	11:00	271	61.07	99.8	105.3	129.3	103.2
11:00	11:15	412.5	65.78	99.2	99.4	128.7	102.5
11:15	11:30	352	60.51	100.9	102.2	130.4	103.5
11:30	11:45	435.5	56.87	109.3	101.8	138.8	112.6
11:45	12:00	481.5	56.50	101.1	93.5	130.6	104.4
12:00	12:15	462.5	57.85	99.9	104.1	129.4	102.5
12:15	12:30	332.5	58.51	101.1	86.7	130.6	104.4
12:30	12:45	509.5	62.45	102.1	101.5	129.7	105.3
12:45	13:00	384.5	59.72	102.9	103.1	131.3	105.7
14:00	14:15	405	61.64	102.8	104.5	125.6	105.3
14:15	14:30	462.5	58.50	103.1	103.2	128.9	106.9
14:30	14:45	354	57.01	101.9	106.4	121.4	104.5
14:45	15:00	357.5	56.42	98.6	105.3	124.3	101.4
15:00	15:15	368	58.08	99	109.6	128.5	102.6
15:15	15:30	338.5	60.46	100.5	99.4	130	103.5
15:30	15:45	428	52.47	100.3	95.7	129.8	103.1
15:45	16:00	509.25	54.87	100.9	95.4	127.7	104.2

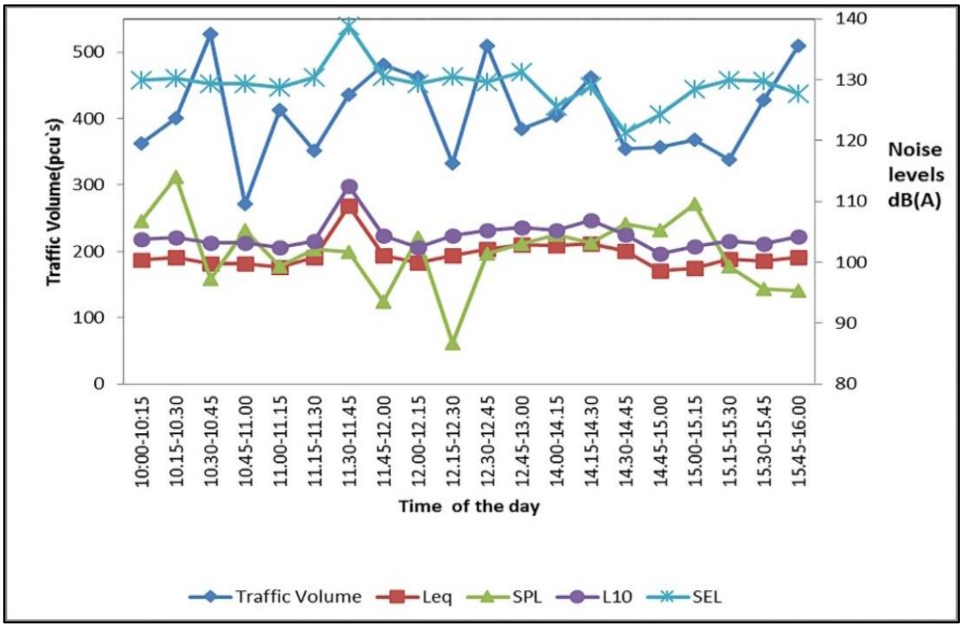

Figure 4.16 Variation of traffic volume as a function of noise levels on Hyderabad- Bengaluru highway

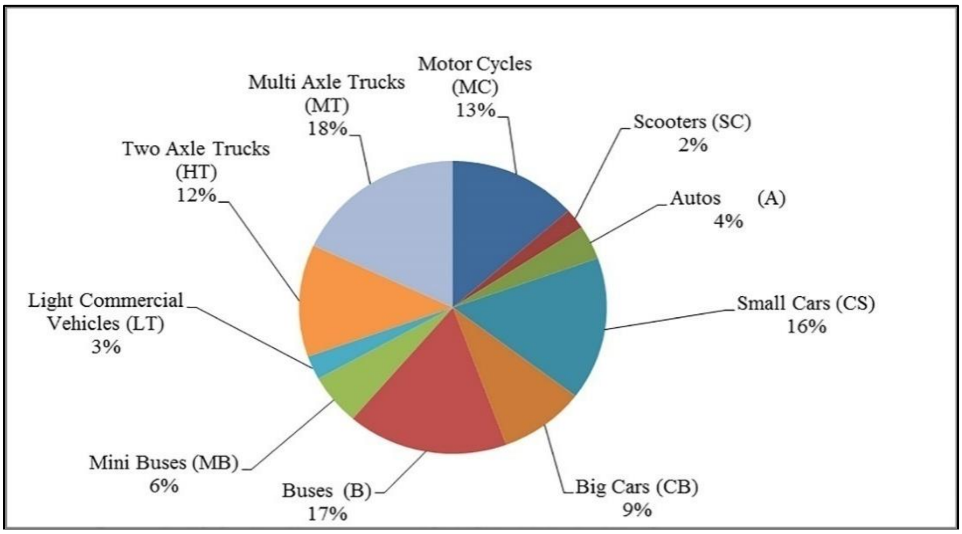

Figure 4.17 Mode share on Hyderabad - Bengaluru highway

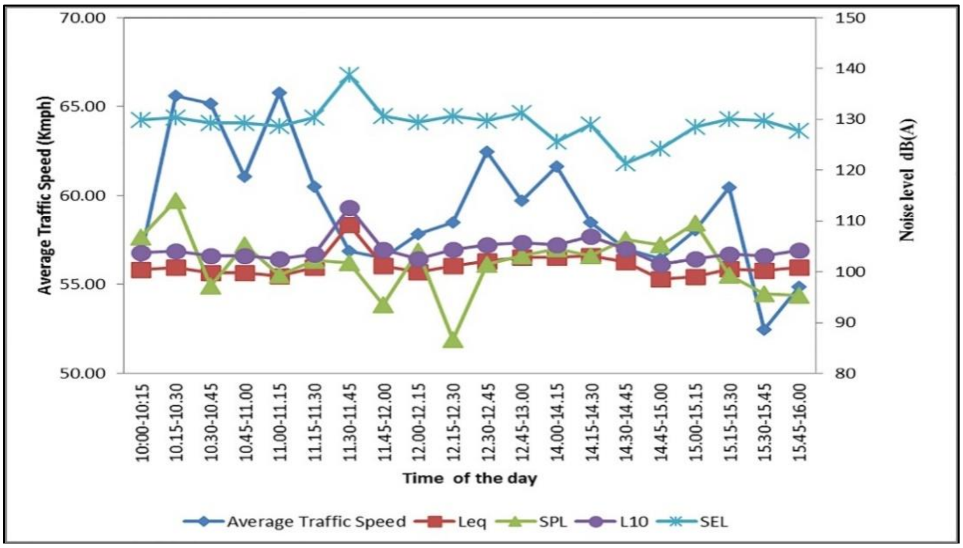

Figure 4.18 Variation of average traffic speed as a function of noise levels on Hyderabad - Bengaluru highway

4.2.7 Hyderabad- Pune highway

The summary of the total data collected on Hyderabad - Pune highway near IIT Hyderabad is presented in Table 4.8. Accordingly, the variation of volume and the corresponding noise levels over time is shown in Figure 4.19. The maximum volume of 498 vehicles (PCU) is observed between the time interval of 16:00 – 16:15 hours. The range of noise levels is from 98 dB to 104 dB. A maximum noise level of 103.4 dB is observed between the time interval of 14.45 – 15.00 hours. Overall, Motor Cycles are predominant in the traffic flow, as shown in the mode share diagram in Figure 4.20. Whereas, the average speed of vehicles is observed to be 58.4 kmph with a variation between 24 – 110 kmph. Accordingly, variation between the average traffic speed and noise levels are shown in Figure 4.21.

Table 4.8 Summary of traffic and noise data at Hyderabad- Pune highway

Time of the Day, hours		**Total Volume (PCU)**	**Average Traffic Speed (kmph)**	**LAeq (dB)**	**SPL (dB)**	**SEL (dB)**	**LA10 (dB)**
From	**To**						
10:00	10:15	209.5	61.42	101.3	97.5	125.4	104.2
10:15	10:30	204	58.86	101.9	98.3	132.1	104.8
10:30	10:45	290	61.45	102.5	97.1	127.4	105.1
10:45	11:00	383	60.97	103.4	96.7	124.5	106.2
11:00	11:15	342.5	57.87	102	96.2	129.5	105.2
11:15	11:30	212	60.62	101.3	95.3	120.4	104.7
11:30	11:45	219.5	59.35	99.2	91.1	128.7	103.2
11:45	12:00	226.5	58.15	98	103	127.5	101.5
12:00	12:15	215	62.24	101.3	108.1	130.8	104.6
12:15	12:30	205	61.51	101.5	85.8	131	104.7
12:30	12:45	258.5	58.93	102.5	99.1	132	106.1
12:45	13:00	278	53.25	100.6	89.3	130.1	104
14:00	14:15	226.5	54.72	102.9	94.5	131	105.8
14:15	14:30	191.5	59.05	98.5	88.2	128	102.3
14:30	14:45	236.5	57.31	100.4	98.4	129.9	104.7
14:45	15:00	293.5	60.71	103.4	101	132.9	106.4
15:00	15:15	313.5	55.52	100.4	99.25	129.9	103.9
15:15	15:30	307	57.48	99.2	96.2	128.7	102.4
15:30	15:45	276	55.83	103	83.6	132.5	106.5
15:45	16:00	325	61.55	100.9	99.4	130.4	104.5
16:00	16:15	498	50.07	101.3	83.6	130.8	104.2
16:15	16:30	387.5	58.15	99.7	87.5	129.2	102.3
16:30	16:45	425.5	57.69	100.7	83.9	130.2	104.5
16:45	17:00	338.5	56.78	99.2	91.1	128.7	102.8

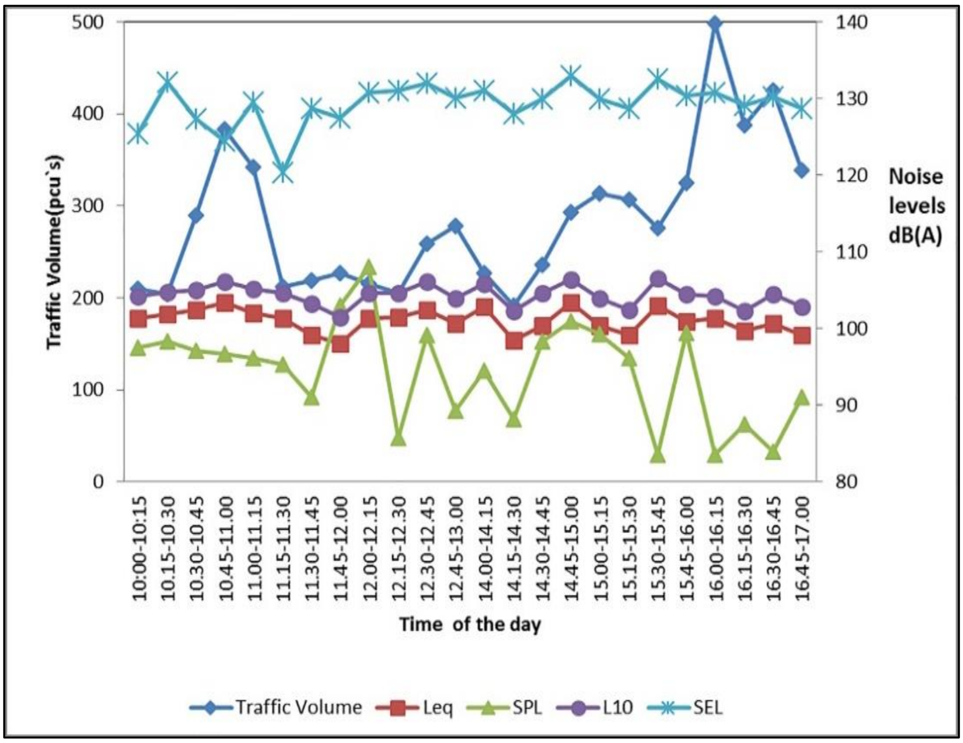

Figure 4.19 Variation of traffic volume as a function of noise levels on Hyderabad- Pune highway

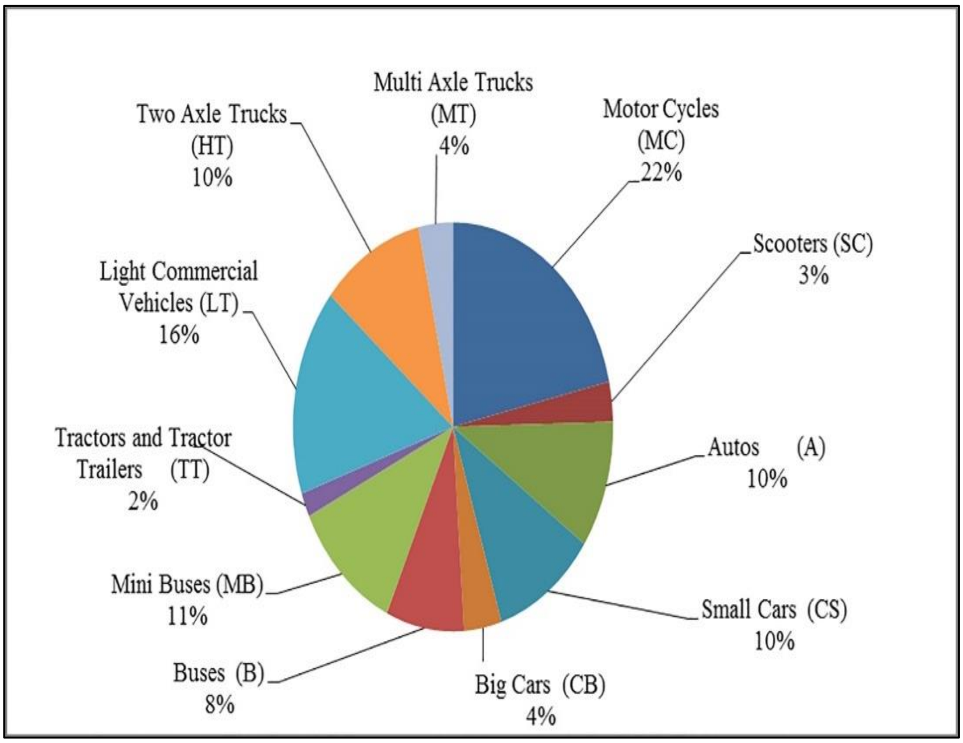

Figure 4.20 Mode share on Hyderabad - Pune highway

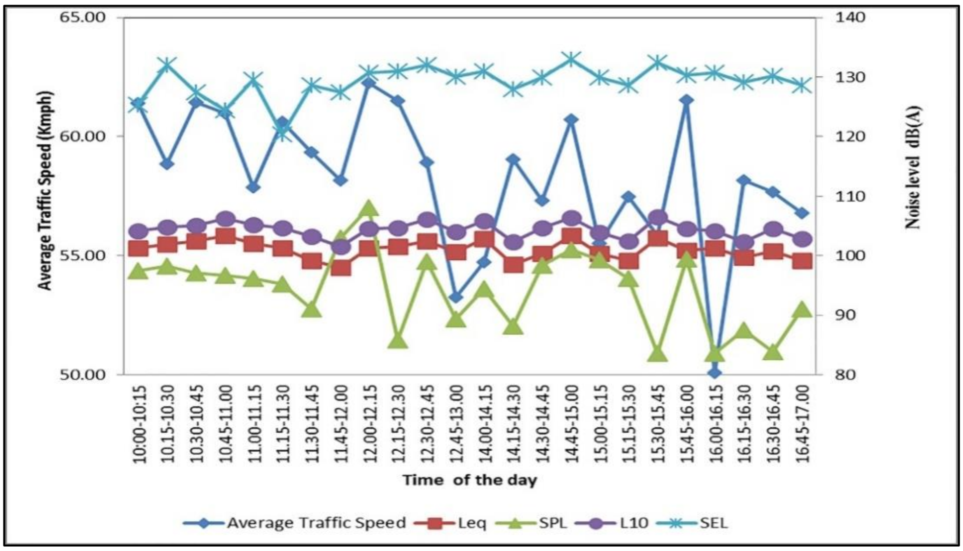

Figure 4.21Variation of average traffic speed as a function of noise levels on Hyderabad - Pune highway

4.2.8 Hyderabad- Warangal highway

The summary of the total data collected on Hyderabad - Warangal highway near Ghatkesar is presented in Table 4.9. Accordingly, the variation of volume and the corresponding noise levels over time is shown in Figure 4.22. The maximum volume of 503 vehicles (PCU) is observed between the time interval of 11:45 – 12:00 hours. The range of noise levels is from 96 dB to 103 dB. A maximum noise level of 102.2 dB is observed between the time interval of 10.15 – 10.30 hours. Overall, Motor Cycles are predominant in the traffic flow, as shown in the mode share diagram in Figure 4.23. Whereas, the average speed of vehicles is observed to be 51.5 kmph which varies between 20 – 102 kmph. Accordingly, variation between the average traffic speed and noise levels are shown in Figure 4.24.

Table 4.9 Summary of traffic and noise data at Hyderabad- Warangal highway

Time of the Day		Total Volume (PCU)	Average Traffic Speed (kmph)	LAeq (dB)	SPL (dB)	SEL (dB)	LA10 (dB)
From	To						
10:00	10:15	371.5	48.79	99.2	104	118.7	103.2
10:15	10:30	316	53.46	102.2	95.4	131.7	106.1
10:30	10:45	411.5	54.95	98.3	102.2	127.8	102.6

10:45	11:00	335	54.53	99	91.5	128.5	103.1
11:00	11:15	361	53.04	100.4	95.5	129.9	104.6
11:15	11:30	438	51.77	98.2	91.5	127.7	101.6
11:30	11:45	404	53.85	99.4	97.2	128.9	103.7
11:45	12:00	503	53.62	98.3	99.9	127.8	101.9
12:00	12:15	410.5	52.92	99.4	97.8	128.9	103.8
12:15	12:30	364.5	52.41	98.4	88.9	127.9	102
12:30	12:45	302	51.50	99.3	82	125.1	103.4
12:45	13:00	191	52.68	99.8	84.5	126.3	104.1
14:00	14:15	416	51.49	98.9	96.2	128.1	103.3
14:15	14:30	224	53.48	96.5	93.6	126	100
14:30	14:45	247.5	47.79	98	102.8	127.5	102.7
14:45	15:00	222	48.65	100	97.9	129.5	103.4
15:00	15:15	299.5	46.83	96.5	90.1	126	100
15:15	15:30	252	53.69	96.8	90	126.3	100.6
15:30	15:45	245	48.56	96.8	88.3	126.3	100.5
15:45	16:00	286.5	50.65	101.5	90.9	131	105.1
16:00	16:15	286	50.73	99.8	96.9	129.3	103.5
16:15	16:30	254	48.28	99.7	99.9	120.7	103.3
16:30	16:45	292	57.08	100.8	100.2	125.8	104.6
16:45	17:00	219.5	46.35	99.1	99.8	122.8	103.9

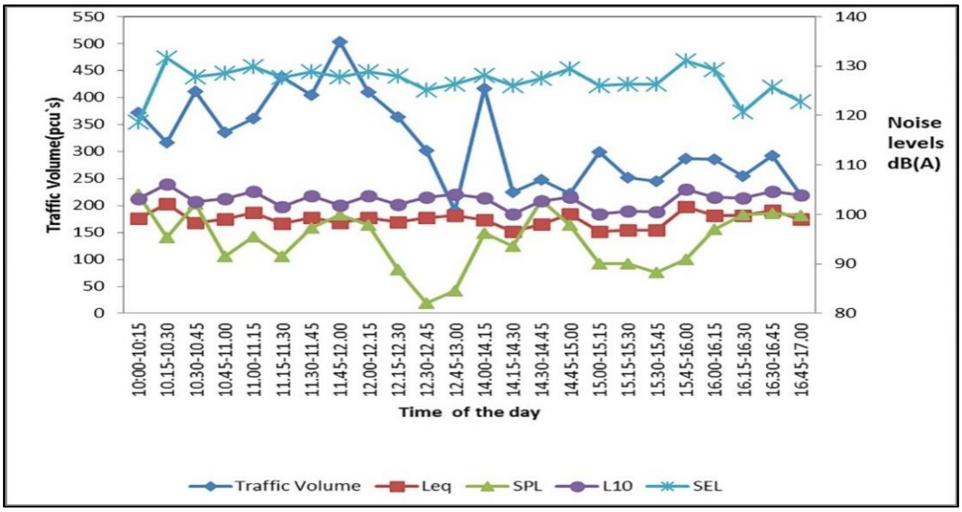

Figure 4.22 Variation of traffic volume as a function of noise levels on Hyderabad- Warangal highway

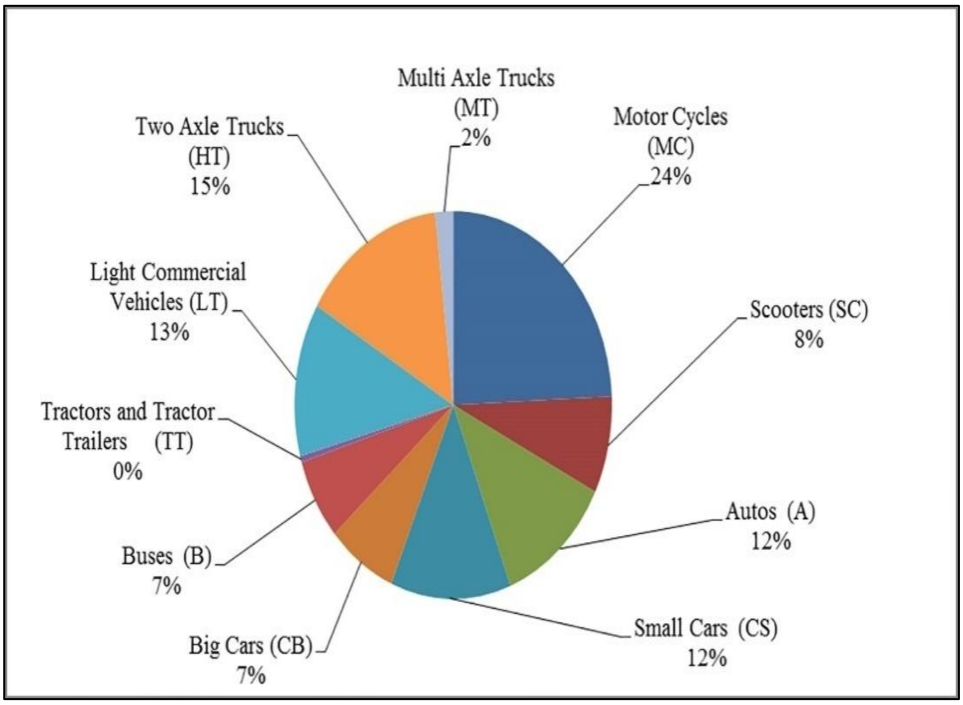

Figure 4.23 Mode share on Hyderabad - Warangal highway

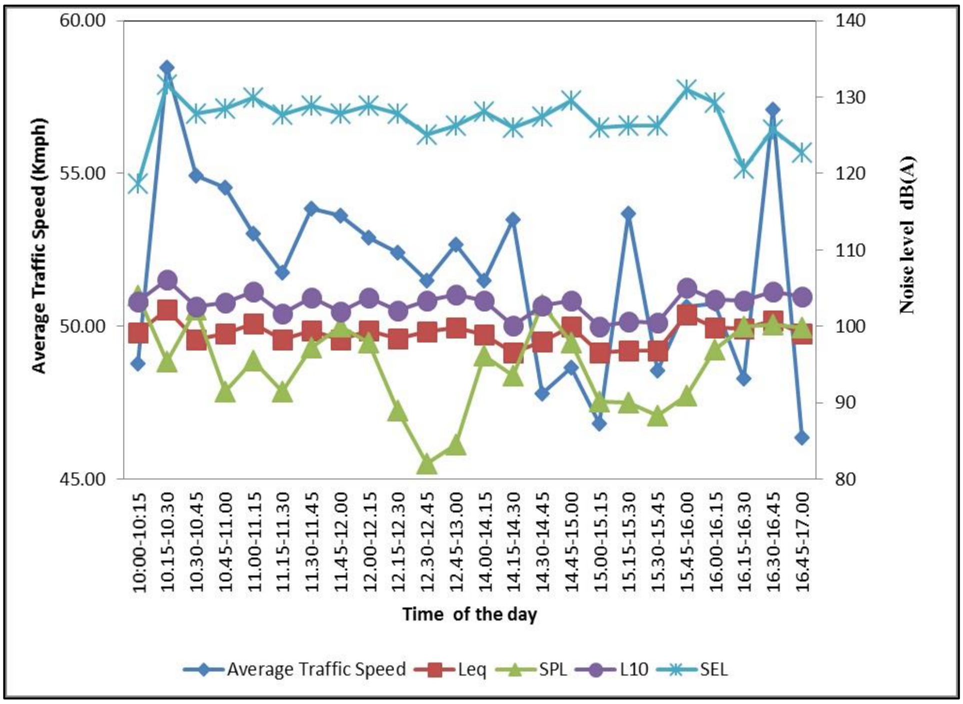

Figure 4.24 Variation of average traffic speed as a function of noise levels on Hyderabad - Warangal highway

Overall, it is observed that motorcycles have a dominant share in traffic flow among most of the selected sections. Figure 4.1 shows that the maximum LAeq (15 minutes) of 107.1 dB is observed for the vehicle volume of 176 (PCU). In the same section, for the highest volume (PCU) of 238.5, the LAeq (15 minutes) is observed to be 103.5 dB between the time interval of 11:00 – 11:15 hours. This shows that maximum LAeq (15 minutes) need not necessarily correspond to the maximum traffic volume, and vice-versa. Whereas, on Warangal-Khammam highway, maximum LAeq (15 minutes) of 99.5 dB is observed for the highest 15-minute volume of 136 (PCU), as shown in Figure 4.7. Thus, the variation of the proportion of the vehicle type can play a significant role in the generation of traffic noise levels, irrespective of the traffic volumes. Similar results are observed on other highways, as shown in Figures 4.4, 4.10, 4.13, 4.16, 4.19, and 4.22.

As the continuous noise exposure over time is fatal than the instantaneous noise source for commuter's health, along with traffic volumes, average speeds are taken for each 15-minute time interval. It is observed that individual speeds of vehicles on all the highways are ranging between 10 to 95 kmph, with an average 15-minute speed of 30- 65 kmph. With the variation being drastic, the effect of speed on the noise level will also be significant. This is because crossover speed between the engine propulsion and tire-pavement interaction for the highway traffic usually varies between 30-50 kmph. Moreover, the literature concluded that noise levels from the vehicles would vary linearly with speed. On a contradicting tone, for the highest 15-minute average traffic speed of 60.06 kmph in Figure. 4.2, LAeq (15 minutes), and LA10 (15 minutes) appeared as 105.6 dB and 107.8 dB, respectively. In the same section, for an average speed of 55.44 kmph from 10:45 –11:00 hours, the highest LAeq of 107.1 dB is observed. Similar trends were observed in Figures 4.6, 4.9, 4.12, 4.15, 4.18, 4.21, and 4.24. This clearly shows the fact that, unlike the individual traffic speeds and noise levels, average noise levels over the time frame will strongly depend upon the combination of vehicle proportion, size, and speeds. This is because the weight of the vehicle can be a judgmental factor in the noise generation. Thus, it is clearly observed that the proportion of vehicle volumes and vehicle speed combination plays a significant role in generating continuous highway noise levels.

4.3 Traffic Noise Data Collection near Traffic Rotaries

The study classified the vehicle speeds into lower (< 40 kmph) and higher (≥40 kmph) depending upon the inference drawn from the literature review, to identify the significant parameters and the noise sources affecting each vehicle class at different speeds. Accordingly, the study is initiated on evaluating the traffic noise pollution near urban units such as rotaries or roundabouts, where the traffic volumes are high, and vehicle speeds are comparatively less. Considering the importance of traffic volumes and honking on the generation of noise, the current study attempted to quantify the effect of vehicle volume and honking on the traffic noise generated at rotary intersections in an urban area. Subsequently, this study also considers the development of a model for prediction of overall noise annoyance near the rotary intersection.

As part of the Karimnagar transport study, two rotary intersections in the city are selected for the study. The prime reason for selecting the Karimnagar city as the study area is due to the growth rate in population it has experienced from 2001 to 2011, which is about 38.82 %. According to 2011 census, Karimnagar city had a population of 261185 and its projected population by 2020 is expected to reach 375000. This rise in population severely affects the vehicle dynamics which in turn results in vital change of noise pollution scenario in the city. Thus, noise studies are much needed in small cities like Karimnagar, which can become an essential tool for understanding the root cause and characteristics affecting the traffic noise pollution and can be used as a design aid in the future.

Further, a detailed procedure is presented in this study to identify the honks within the traffic noise data. In stage 1, traffic volume and noise levels along with honking were measured at two traffic rotaries, which are named with their junction names as one town police station chowrasta and court chowrasta. Both the rotaries are 3-legged major intersections with 18°25'53.5" N longitude to 79°07'53.8" E latitude and 18°26'40.1" N longitude to 79°07'29.9" E latitude. The prime reason for selecting these two rotaries for the study is due to the fact that, both rotaries are located near the residential and commercial areas. Thus, there is a high chance for extreme noise levels due to the large number of vehicular compositions passing continuously through these urban structural units, where heterogeneity of traffic may lead to extreme honking resulting in the severe effects on health to the people residing nearby. Further, Road condition and geometric characteristics are almost the same for both the rotaries with asphalt pavement surface, as shown in Figures 4.25 and 4.26.

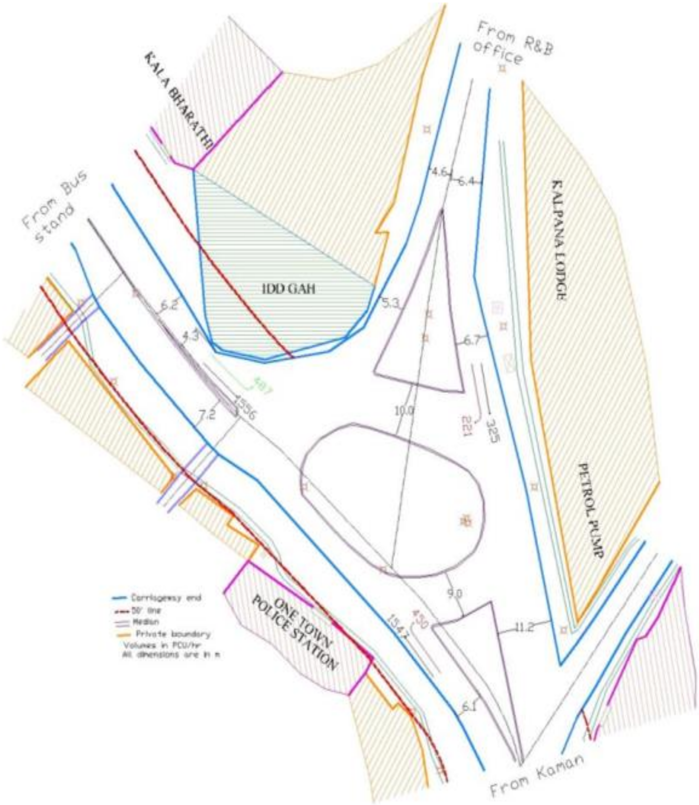

Figure 4.25 One town police station chowrasta in Karimnagar city

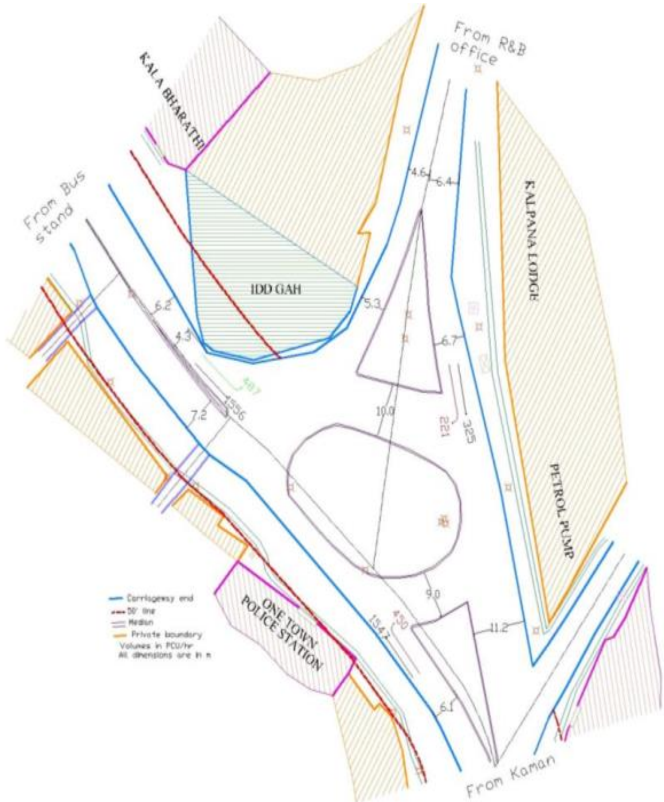

Figure 4.26 Court chowrasta in Karimnagar city

Traffic volume data was collected using video cameras from 09:00 to 13:00 hours, covering the morning peak hour flows at both the rotaries to determine the number and type of vehicles passing through the designated sections. Vehicles are categorized as Light Vehicles (LV) [motorized two-wheeler], Medium Vehicles (MV) [auto-rickshaw, car/jeep, and light commercial vehicle] and Heavy Vehicles (HV) [bus, normal truck, dumper truck, and tractor-trailer] based on their size and noise levels. Noise levels are estimated by Indian Standard (IS) methods using Cirrus Class 1 Optimus sound level meter (SLM) having the capacity of capturing the decibel levels between 20 dB to 140 dB. SLM was mounted on a tripod stand on the central island of the selected rotary at the height of 1.5 m from the ground, which includes the island height, and placed at a distance of 3.5 m from the edge of the central island, where pedestrians and roadside shopkeepers are experiencing the similar noise exposure. Such protocol is required to avoid speech disturbance from the shop keepers, and pedestrians whose activities can affect the noise levels while capturing the roadside traffic noise. Throughout the measurement duration, SLM was kept in “A” frequency weighting for the human ear response. Data logging of the 1-second interval using the fast response mode for a better indication of widely changing average noise levels in an environment is used while measuring the equivalent noise level (LAeq (dB)) was measured. Traffic speed was observed to be more or less the same during the study period at the rotary as the traffic is heavy, heterogenic, and continuous.

Considering this traffic movement, SLM was mounted at a place where vehicles are moving at a constant speed around the rotary, which is far from the entry, exit, and leaving lanes. This protocol is required to capture the noise levels with minimal vehicle speed variation during the data logging time frame. This approach helps in capturing the vehicle volume count from the video camera, which was further analyzed with respect to the traffic noise levels captured by the SLM, as they share the same time frame to the precision of seconds during the survey period. The windscreen was used for the microphone of the SLM. While extracting the data from the SLM to avoid the effect of wind direction and speed. Noise levels were estimated for each second by considering the exact time of vehicle crossing the perpendicular axis of the line joining the SLM and the video camera location. This approach was needed to separate each vehicle by class and time to determine the respective honking effect on overall LAeq (dB) generation. Noise from each type of vehicle was further analyzed for noise-class of the vehicle and noise-honking response criteria.

Traffic volume was tracked for a period of four consecutive hours to identify the peak hour in the morning. From the analysis of four-hour traffic volume, peak flows are observed between the time interval of 10:15 - 11:15 hours for both one town police station chowrasta and court chowrasta, as shown in Table 4.10 and 4.11, respectively.

Table 4.10 Summary of traffic volume and noise data in peak hour at one town police station chowrasta

Time, hours	LV	MV	HV	Total	LAeq (dB)
10:15 - 10:30	443	254	24	721	77.2
10:30-10:45	396	247	13	656	77.1
10:45-11:00	382	240	13	635	77.7
11:00 - 11:15	365	269	17	651	78.1

Table 4.11 Summary of traffic volume and noise data in peak hour at court chowrasta

Time, hours	LV	MV	HV	Total	LAeq (dB)
10:15 - 10:30	437	169	17	623	76.1
10:30-10:45	436	184	25	645	76.8
10:45-11:00	437	172	18	627	77.7
11:00 - 11:15	417	180	24	621	77.1

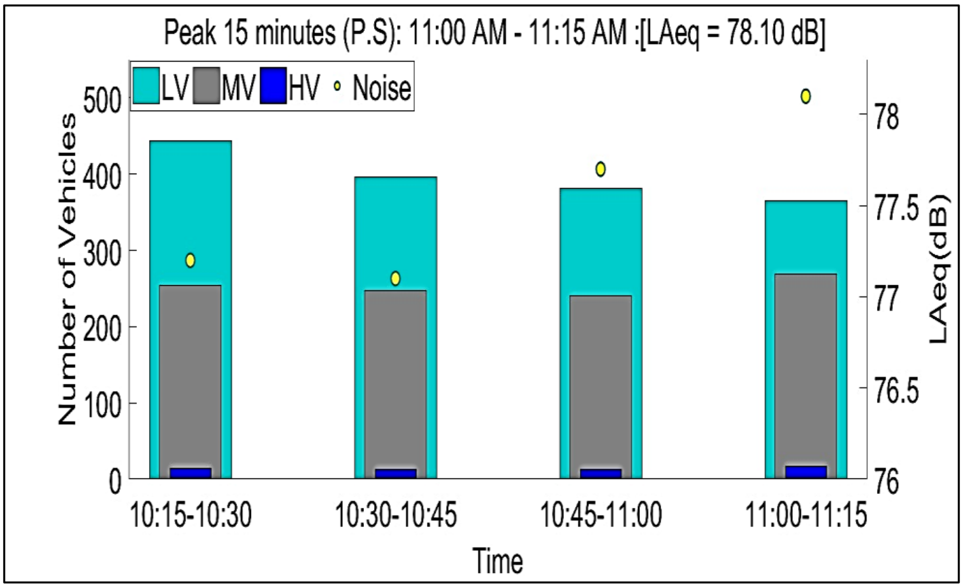

Figure 4.27 Peak hour LAeq (dB) at one town police station chowrasta

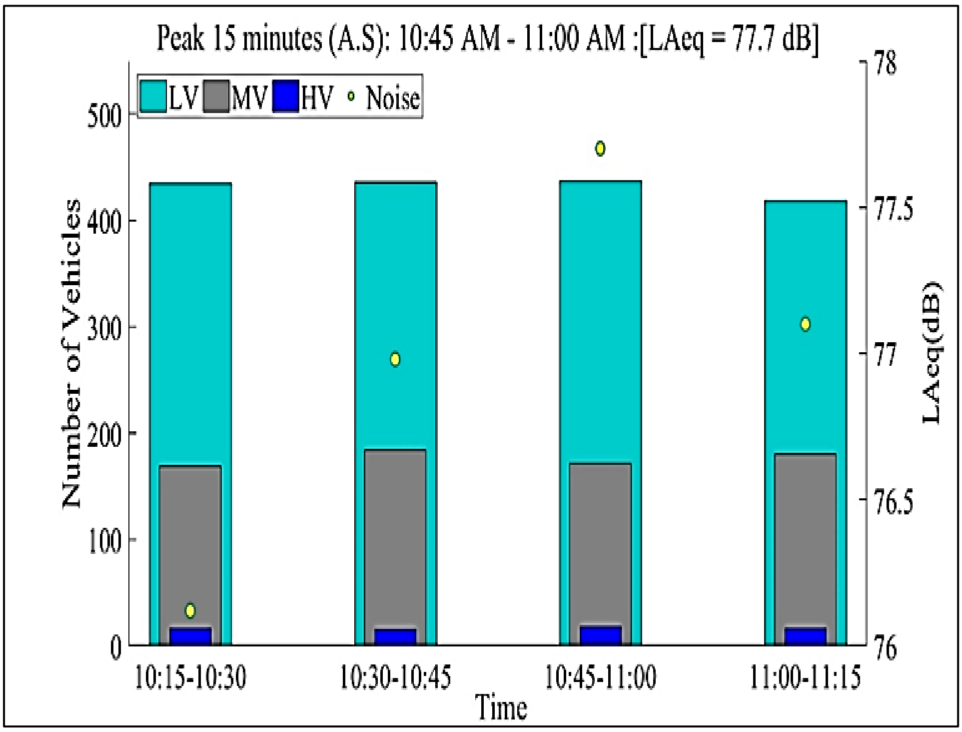

Figure 4.28 Peak hour LAeq (dB) at court chowrasta

The respective peak hour volumes of LV, MV, and HV are 1586, 1010, and 67, respectively, at one town police station chowrasta and 1727, 705 and 84, respectively, at court chowrasta. Peak hour traffic and the respective noise levels are analyzed for a 15-minute time interval to evaluate the effect of traffic volume on noise levels, as shown in Figures 4.27 and 4.28.

The results at one town police station chowrasta show that maximum LAeq [78.1 dB] is observed for traffic volume of 651 vehicles from 11:00 to 11:15 hours and minimum LAeq [77.1 dB] is observed for traffic volume of 656 vehicles. In the same peak hour, for the highest vehicle volume of 721 vehicles, LAeq of 77.2 dB is observed. This shows that maximum traffic volume need not generate the highest traffic noise level and vice versa. A similar analysis is carried out at the court chowrasta for comparing the noise levels with the traffic volume, and congruent results as above are observed. The highest LAeq [77.7 dB] is observed between 10:45 to 11:00 hours for a traffic volume of 627 vehicles, and the lowest LAeq [76.1 dB] is observed between 10:15 to 10:30 hours a traffic volume of 623 vehicles. These results show that there is no definite statistical relation between traffic volume and noise levels, which demand further analysis by considering other factors supplementing the rise in noise levels.

Table 4.12 Summary of traffic volume and noise data in peak 15 minutes at one town police station chowrasta

Minute	LV	MV	HV	LAeq (dB)	Number of Honks
1	17	23	2	75	2
2	23	12	2	74.8	3
3	21	20	2	73.7	2
4	18	22	1	82.6	5
5	33	31	1	75.4	4
6	36	19	1	73.6	4
7	32	24	2	83.6	2
8	23	14	2	76.3	6
9	23	16	2	77.5	7
10	25	14	2	76.6	3
11	21	15	0	74.2	2
12	28	12	0	79.2	7
13	24	13	0	74.2	3
14	20	18	0	78.6	3
15	21	16	0	78.2	4

The analysis is further concentrated to minute level in peak 15 minutes noise data in one town police chowrasta and court chowrasta, by counting the vehicles per each minute and their exact effect on noise levels to pinpoint the factors liable for noise levels. Such analysis is carried out using noise tools software, which can draw the data to the level of one-tenth of the second where any sudden peak in noise can be clearly observed, which can be attributed to honks. Accordingly, a set of traffic volume and noise level data is analyzed for 15 minutes time interval, as shown in Table 4.12 and Table 4.13, respectively, for one town police station chowrasta and court chowrasta.

Table 4.13 Summary of traffic volume and noise data in peak 15 minutes at court chowrasta

Minute	LV	MV	HV	LAeq (dB)	Number of honks
1	40	10	1	75.9	5
2	35	15	1	79.6	8
3	38	11	1	77.7	7

4	22	12	0	77.9	7
5	20	8	2	78.9	7
6	18	9	2	77.2	8
7	20	9	2	76.2	4
8	36	7	2	76.1	6
9	36	15	2	76	6
10	29	11	1	78.9	7
11	38	12	4	80.4	5
12	33	9	0	76.6	5
13	23	10	0	77.6	6
14	13	19	0	76.2	6
15	36	15	0	77.3	4

It is observed that maximum LAeq [83.6 dB] is detected in the seventh minute between 11:06 to 11:07 hours, and minimum LAeq [73.6 dB] is detected in the sixth minute from 11:05 to 11:06 hours near one town chowrasta rotary, as shown in Figures 4.29 and 4.30.

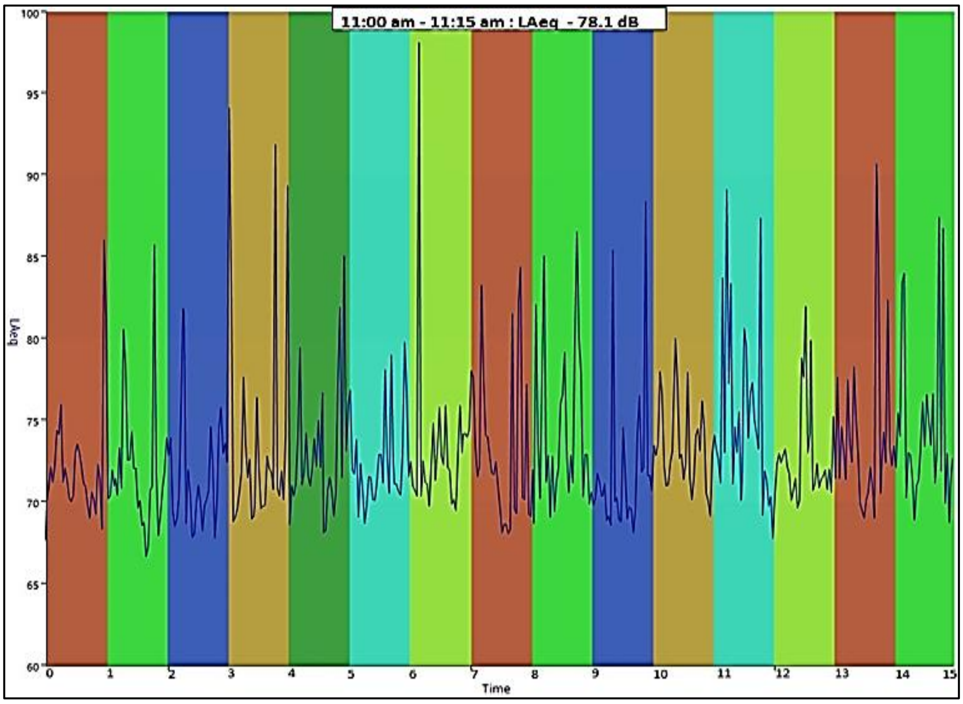

Figure 4.29 Peak 15 minutes LAeq (dB) at one town police station chowrasta in noise tools

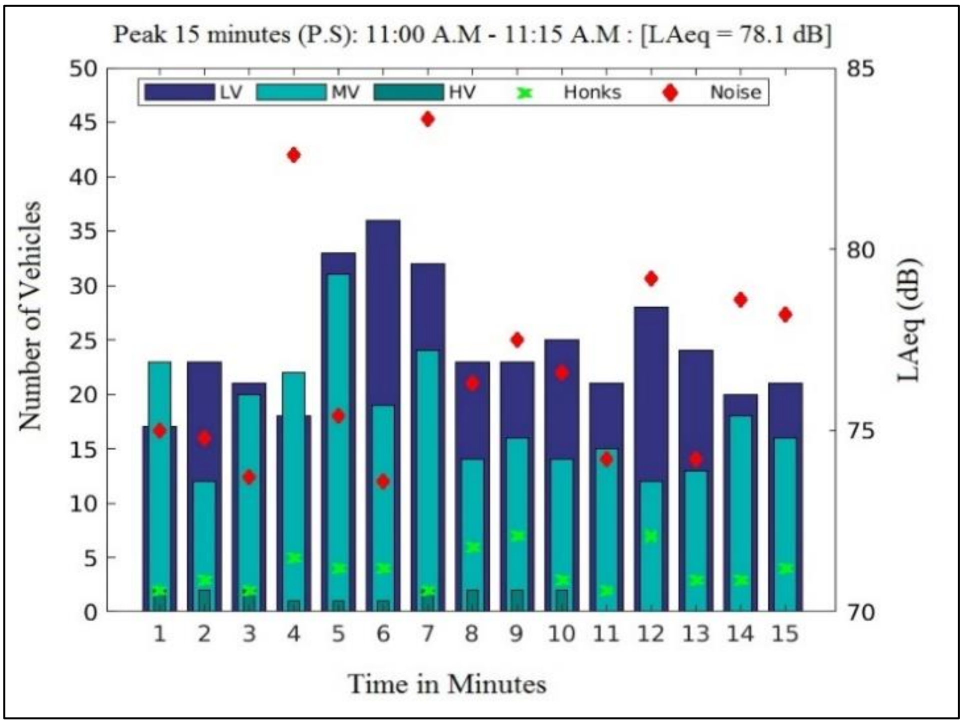

Figure 4.30 Peak 15 minutes LAeq (dB) at one town police station chowrasta

Whereas, near court chowrasta, maximum LAeq [80.4 dB] is detected in the eleventh minute between 10:55 to 10:56 hours and minimum LAeq [75.9 dB] is detected in the first minute between 11:45 to 11:46 hours as shown in Figures 4.31 and 4.32.

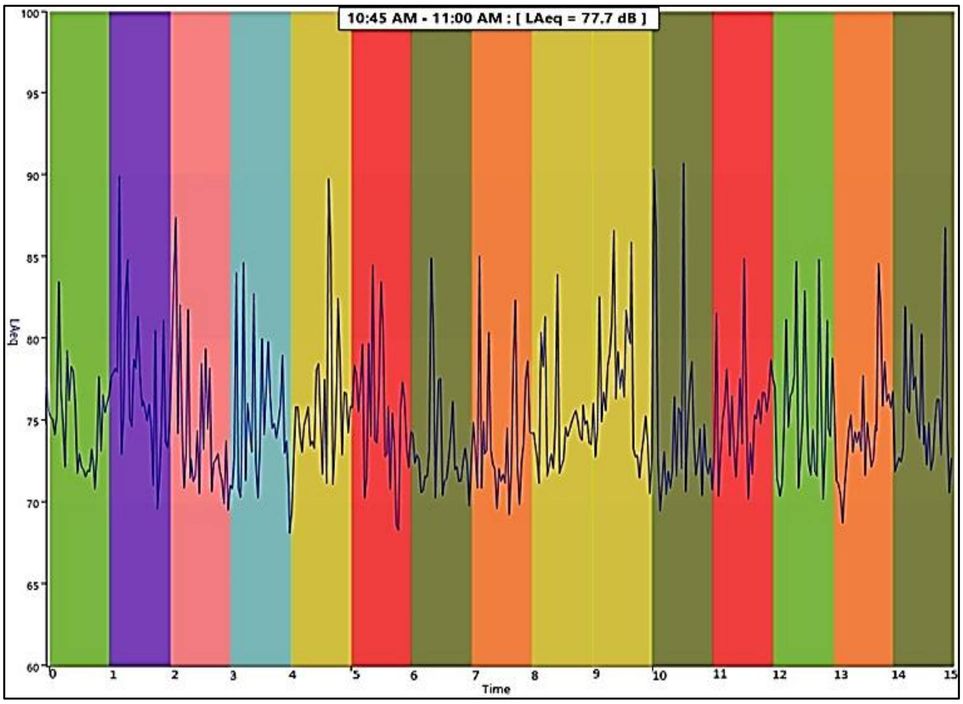

Figure 4.31 Peak 15 minutes LAeq (dB) at court chowrasta in noise tools

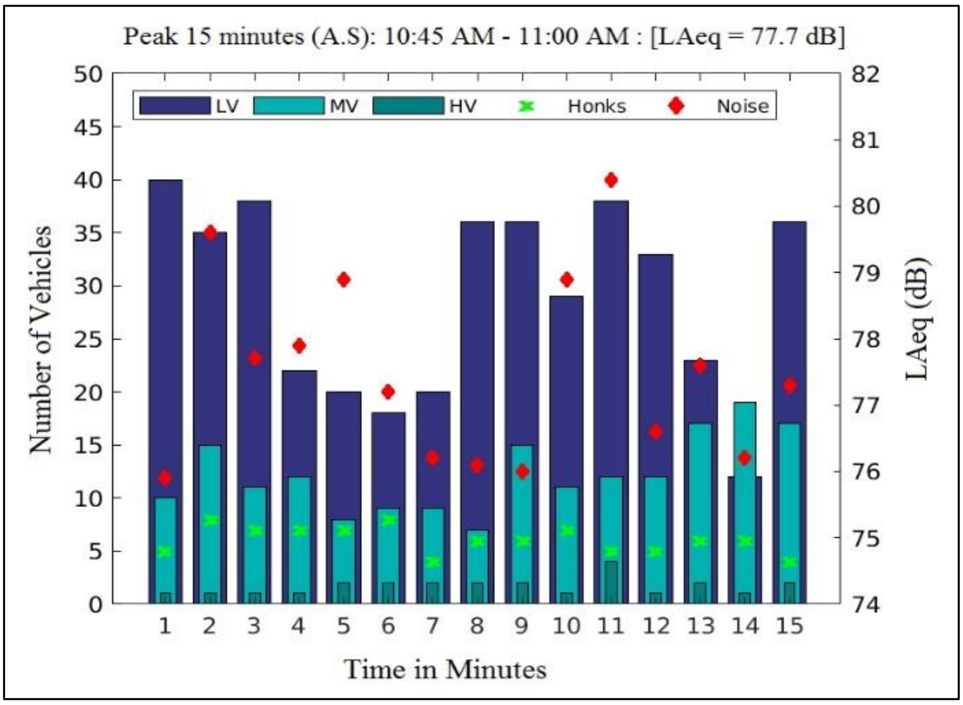

Figure 4.32 Peak 15 minutes LAeq (dB) at court chowrasta

Overall, each sudden peak observed in noise tools is attributed to honking. At both the rotaries, results fall in the nature of no statistical relationship between volumes, honking, and noise level, even at the minute level noise, which can be clearly seen from Figures 4.29 to 4.32.

The noise data is further analyzed from peak hour to peak 15 minutes and peak 15 minutes to minute level, keeping the objective of identifying the number of honks in a minute and their effect on the noise level. For achieving this, the highest and lowest minute noise in 15 minutes is further analyzed with the vehicle volume from videography for each second at the rotary to identify the vehicle class and honking effect on LAeq (dB), as shown in Figures 4.33 and 4.34.

The noise levels are analyzed with respect to the vehicle volume and respective LAeq [dB] levels by each second in a minute. This approach gives the exact noise generation by vehicles in each second, which can be used to identify the core factors generating the noise apart from volume and honks.

There are several sudden peaks observed in the data that can be contributed by engine noise or honking, which has to be identified before arriving at a conclusion. Here, noise from the vehicle is significantly due to the engine noise at lower vehicle speeds typically below 50 kmph. Thus, either the engine noise or the honking are the major factors responsible for noise generation at both the rotary intersections. However, vehicle engine noise will be added within average noise levels. Thus, the extreme peaks in noise levels can be attributed to honking.

The average noise generated by each class of vehicle at the rotary has to be known initially to analyze the sudden peaks at the second level. For accomplishing this task, irrespective of the peak hour, lowest minute noise (LAeq [71.6 dB]) in the entire four hours duration is observed from 12:30 to 12:31 hours is selected and is analyzed in noise tools along with the vehicle volume for each second. Unambiguous results are observed in this minute which is shown in Figures 4.33 and 4.34 where noise due to the light and medium vehicles are varying from LAeq [67.1 dB] to LAeq [78 dB], and heavy vehicles are contributing to the noise levels of LAeq [76.7 dB] to LAeq [82.8 dB]. To further confirm it, another low noise minute (LAeq [71.8 dB]) in the survey period from 12:19 to 12:20 hours, as shown in Figures 4.35 and 4.36, is analyzed.

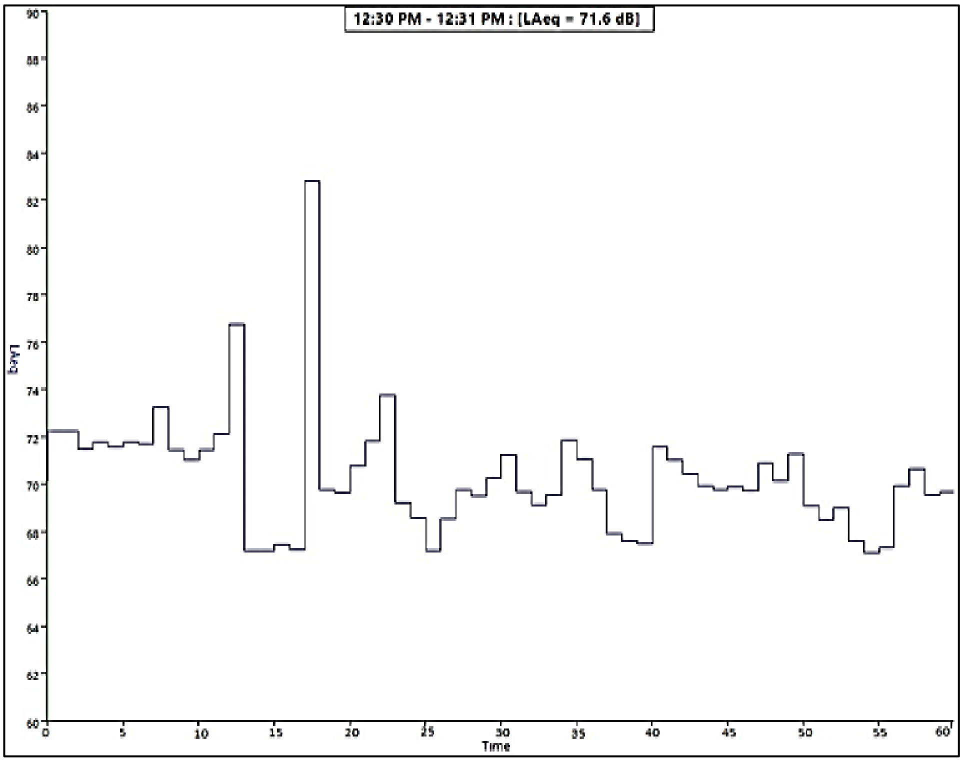

Figure 4.33 Lowest LAeq (dB) minute at one town police station chowrasta in noise tools

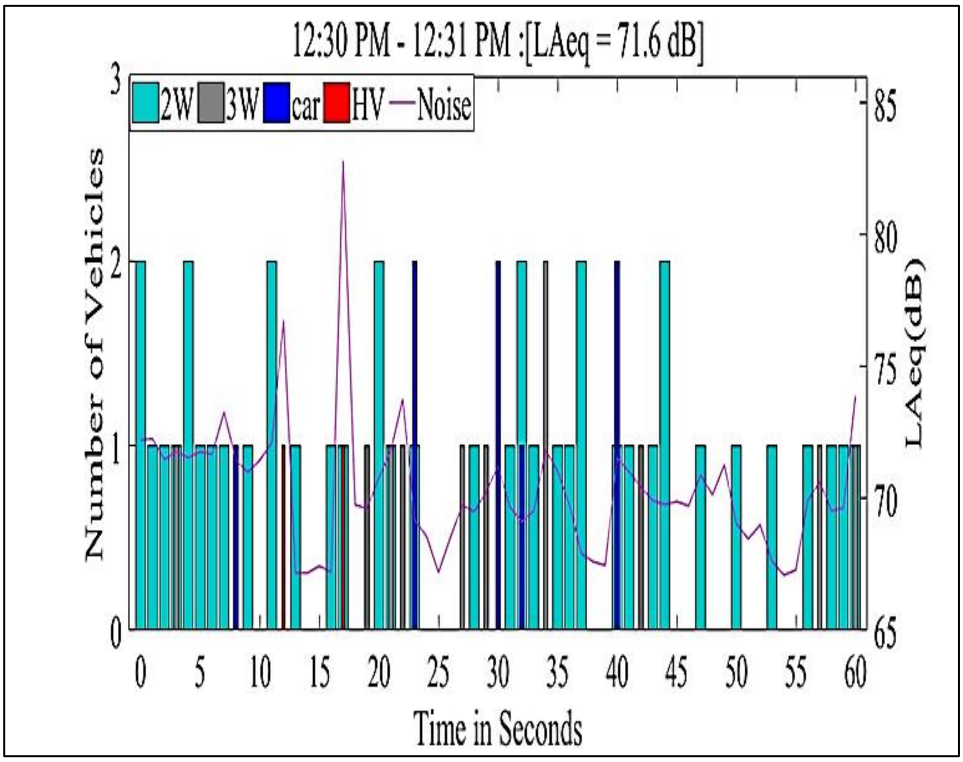

Figure 4.34 Lowest LAeq (dB) minute at one town police station chowrasta

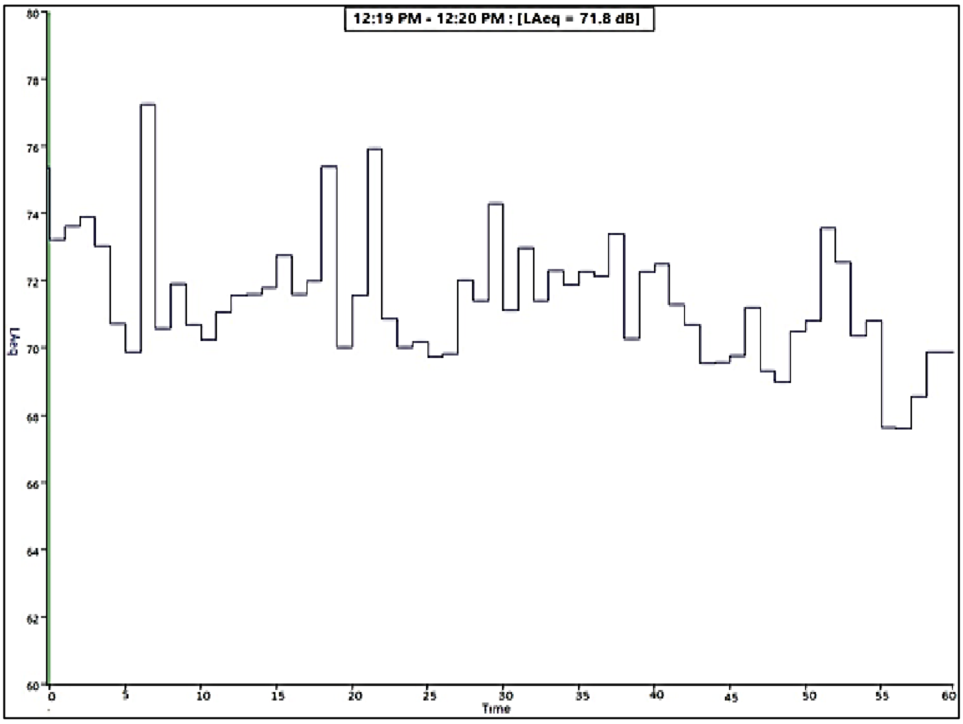

Figure 4.35 Low LAeq (dB) minute at one town police station chowrasta in noise tools

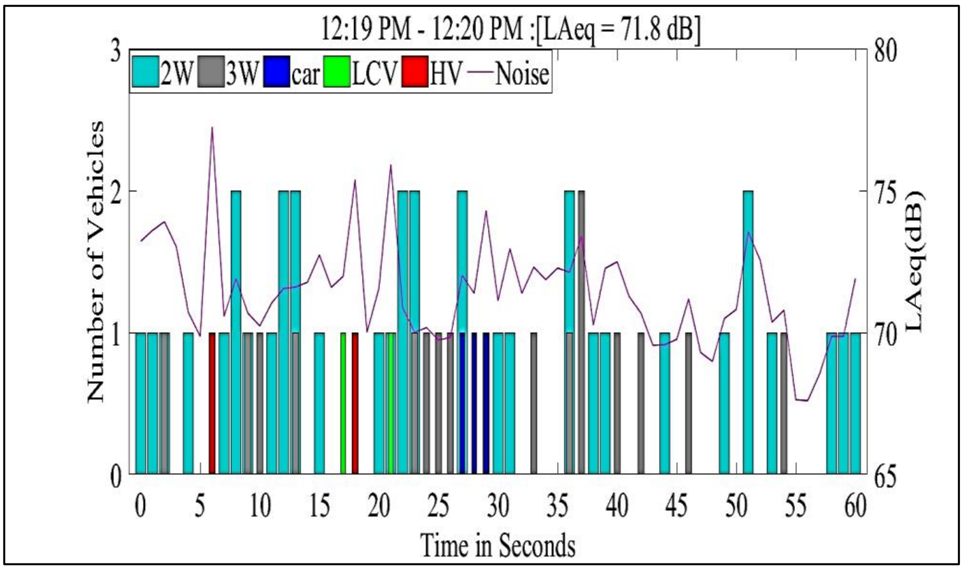

Figure 4.36 Low LAeq (dB) minute at one town police station chowrasta

It is observed that average noise levels of light and medium vehicles vary from LAeq [67.6 dB] to LAeq [73.9 dB], and heavy vehicles are contributing to the noise of LAeq [75.38 dB] to LAeq [77.24 dB]. LAeq of 82.8 dB observed in17th second of Figure 4.35 is mainly due to heavy vehicle honking, which can be justified by the average noise levels of heavy vehicles in 12th second of 12:30 to 12:31 minute and 6th, 18th and 21st seconds of 12:19 to 12:20 minute as shown in Figure 4.36. This shows the impact of heavy vehicles and their honking on overall noise generation. However, the peak observed in the graph need not be due to honk every time, which is a hurdle to identify the honks in total noise. Even though the honks can be captured in-camera mike during videography, which was placed along with sound level meter, further analysis can be questioned when honks from a particular vehicle continued beyond the second. This situation can show the peak twice where the count can be mismatched. Thus, average noise levels of vehicles passing through rotary have to be known first, which is useful for identifying the honk impact in peak minute noise. This is because the difference of vehicle noise and honking can be visualized graphically in noise tools by knowing the average noise from a different class of vehicles that are traveling at more or less same speeds as traffic is heterogenic and continuous. For accomplishing this task, the lowest minute noise in the entire survey period is analyzed for each second with respect to vehicle volume at the one town police station chowrasta, and the average noise level of classified vehicles is identified. On a similar note, by knowing the average noise levels of vehicles at the minute level, the significant factors affecting the traffic noise can be identified.Thus, the sudden peaks of noise are analyzed for the highest and lowest noise in the peak 15-minute noise data from both the rotaries using the noise tools, and the details are presented in Figure 4.37 to Figure 4.44. The highest and lowest noise levels in the peak 15-minutes at court chowrasta are analyzed with noise tools software by drawing down the data to one-tenth of the second. Each peak is observed, and the resulting noise level analyzed with respect to vehicle count at each second.

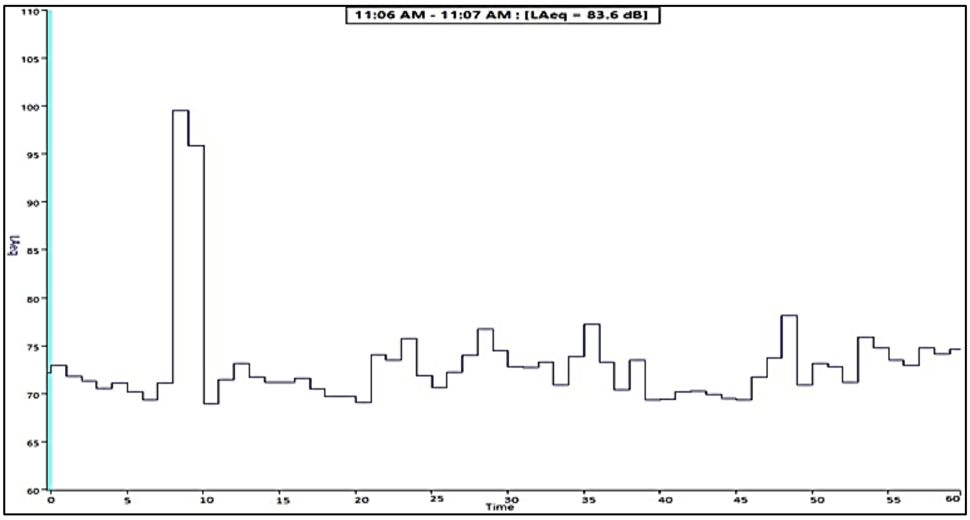

Figure 4.37 Highest LAeq (dB) minute in peak 15-minute data at one town police station chowrasta in noise tools

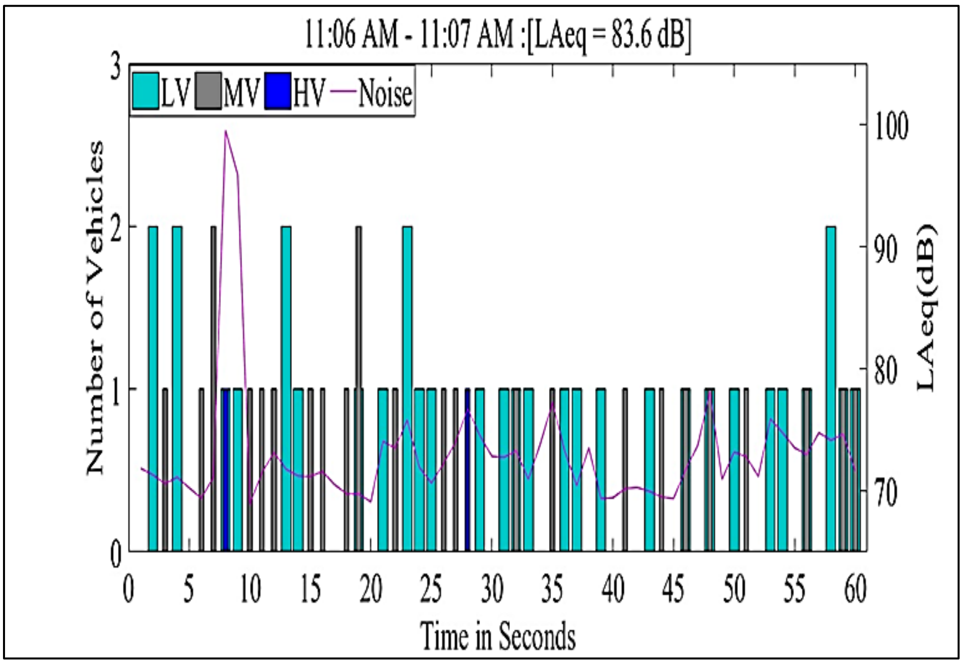

Figure 4.38 Highest LAeq (dB) minute in peak 15-minute data at one town police station chowrasta

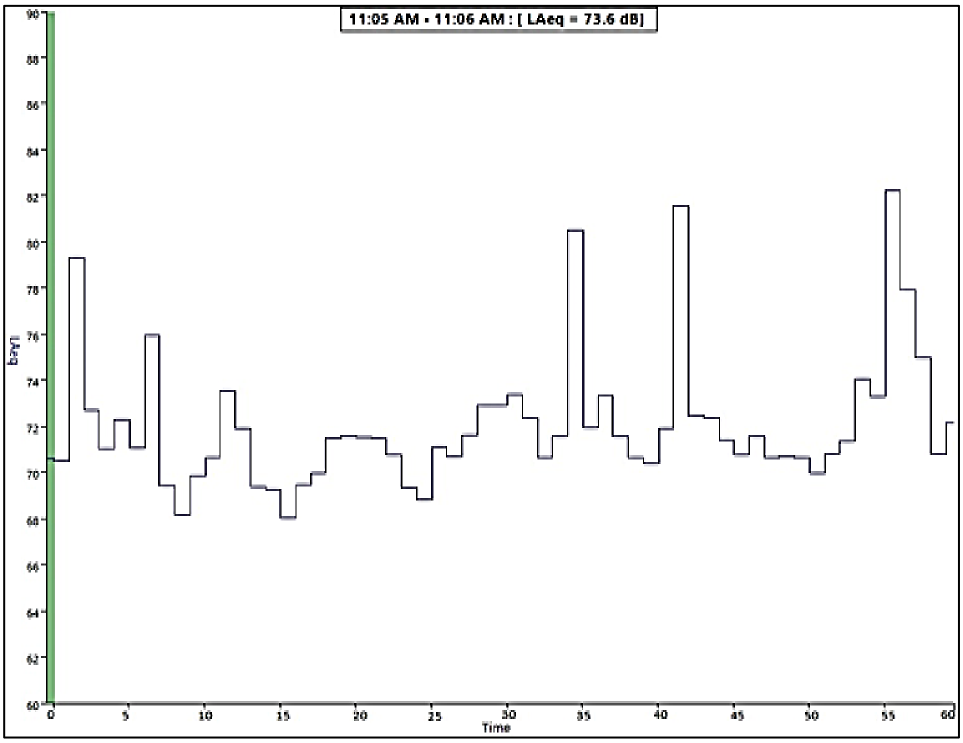

Figure 4.39 Lowest LAeq (dB) minute in peak 15-minute data at one town police station chowrasta in noise tools

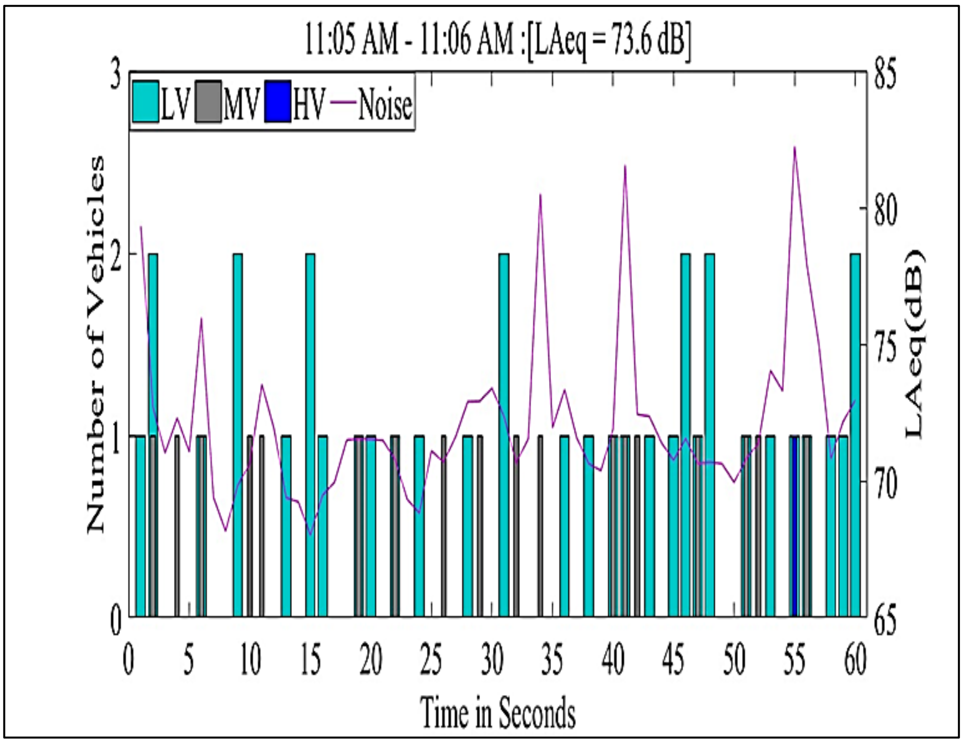

Figure 4.40 Lowest LAeq (dB) minute in peak 15-minute data at one town police station chowrasta

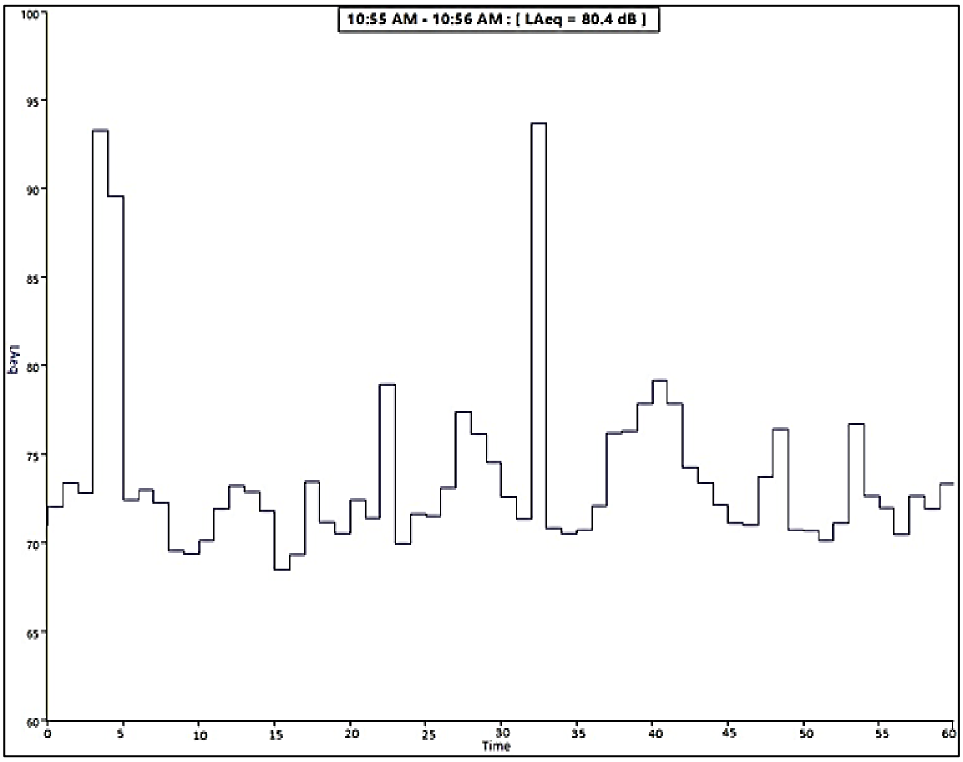

Figure 4.41 Highest LAeq (dB) minute in peak 15-minute data at court chowrasta in noise tools

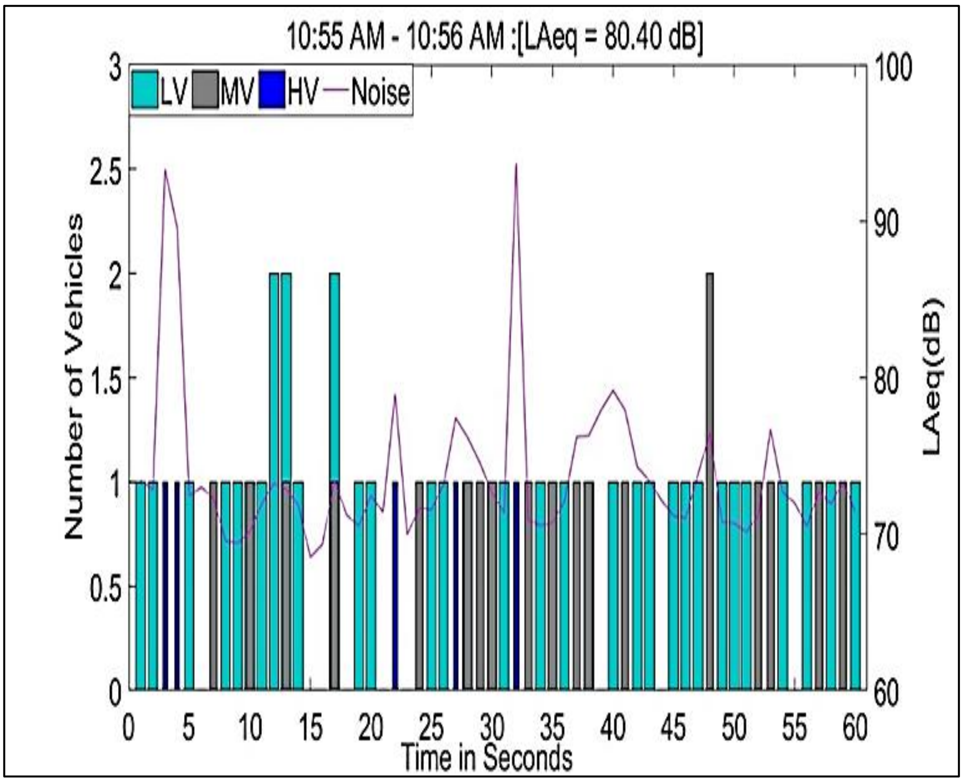

Figure 4.42 Highest LAeq (dB) minute in peak 15-minute data at court chowrasta

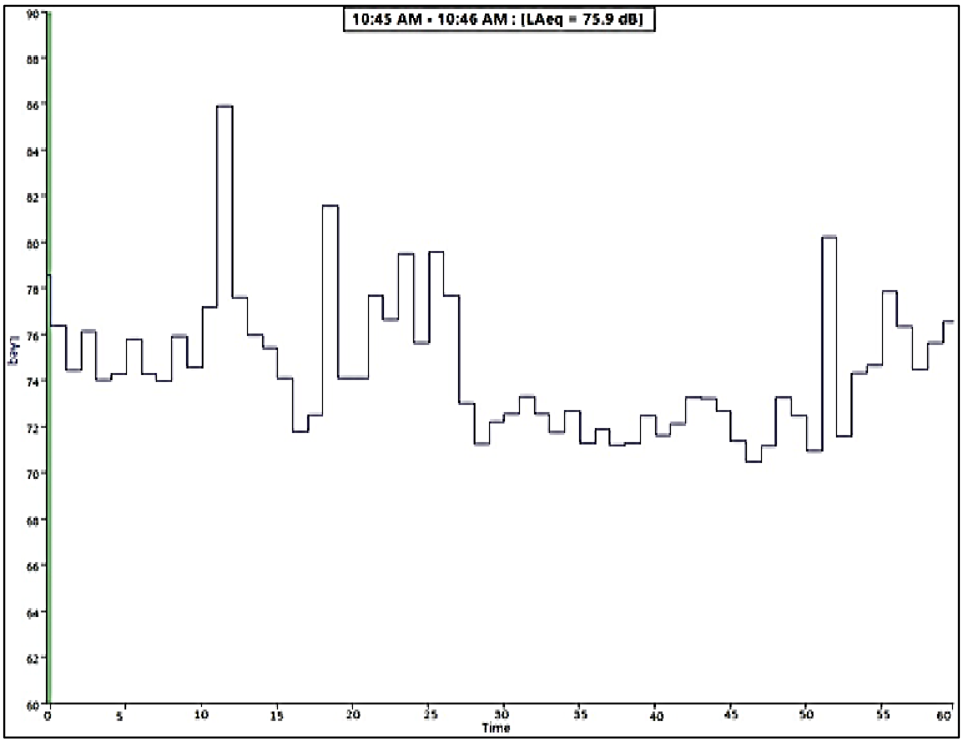

Figure 4.43 Lowest LAeq (dB) minute in peak 15-minute data at court chowrasta in noise tools

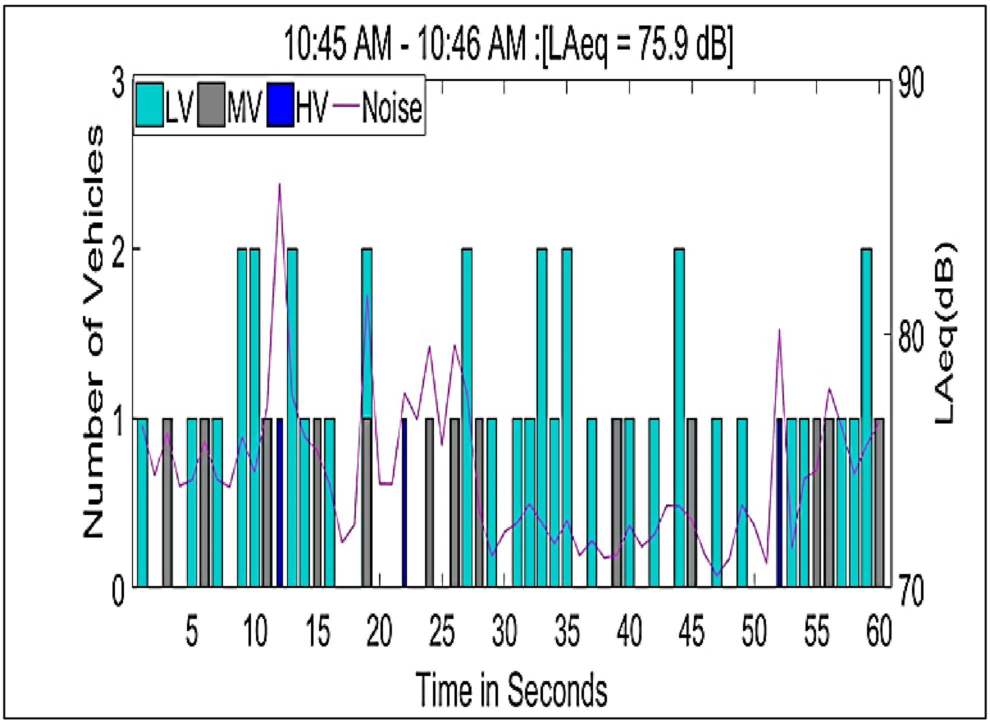

Figure 4.44 Lowest LAeq (dB) minute in peak 15-minute data at court chowrasta

In Figure 4.41, highest LAeq [80.4 dB] is observed between 10:55 to 10:56 hours in which heavy vehicle noise without honks are observed in 22nd and 27th seconds as 77.41 dB to

78.95 dB and heavy vehicle with honks are observed in 3rd, 4th and 32nd seconds as 93.3 dB, 89.52 dB, and 93.69 dB, respectively. Irrespective of the volume and honks, light and medium vehicles are generating the equivalent noise levels ranging from 68.52 dB to 77.9 dB. This indicates the major effect of heavy vehicles honking on overall noise generation. Thus, separating the honks from every vehicle is tedious, and there can be a mismatch in the analysis, as discussed elaborately in the previous section.

From the above analysis, heavy vehicle presence in overall noise contribution can result in the development of a better model to predict the noise level at a rotary intersection.

At the time frame of the minute level, the noise data shows that LAeq (dB) is mainly affected by heavy vehicle honking. However, continuous noise exposure cannot be justified at the minute level as the noise-induced over longer time intervals leads to health hazards. Thus, instead of selecting the minute in a peak hour, noise levels are analyzed for a total duration of four hours. However, the fluctuation of honks in average noise level minutes cannot be identified just with the peak noise propagation in noise tools, which might lead to poor results. Hence, taking advantage of the prime result from minute level, heavy vehicle presence is identified in the entire survey duration for every 15 minutes, and respective LAeq (dB) due to the heavy vehicle is neglected. Further, LAeq (dB) is averaged logarithmically without the presence of heavy vehicle contribution, as shown in Table 4.14 and Fig. 4.45.

Table 4.14 Summary of LAeq (dB) 15 minutes with and without the presence of heavy vehicles

Time		**2w**	**3w**	**car/jeep**	**LCV**	**Heavy vehicle**	**LAeq (dB) including heavy vehicle contribution**	**LAeq (dB) excluding the heavy vehicle contribution**
9:00	9:15	276	143	60	5	12	75.2	71.1
9:15	9:30	283	168	73	5	15	77.1	73.7
9:30	9:45	303	134	71	2	17	78.1	74.9
9:45	10:00	337	191	78	7	20	79	72.5
10:00	10:15	342	186	76	11	22	78.9	72.9
10:15	10:30	443	174	70	10	14	77.3	74.5

10:30	10:45	396	152	90	5	13	77.1	73.8
10:45	11:00	382	162	72	6	13	77.7	73.1
11:00	11:15	365	178	79	12	17	78.2	74.1
11:15	11:30	335	169	76	10	14	77.2	73.2
11:30	11:45	354	170	103	7	12	75.6	72.9
11:45	12:00	432	171	92	4	15	77.9	73.8
12:00	12:15	346	134	82	15	19	78	72.6
12:15	12:30	391	155	70	18	12	75.4	73.8
12:30	12:45	351	160	77	10	19	78.1	72.5
12:45	13:00	414	196	71	11	10	75.3	71.5

The comparison between both the noise levels in Figure 4.45 shows that heavy vehicles are responsible for an additional noise of 3 to 6 dB on overall traffic noise levels. This concludes that the proportion of heavy vehicles will play a significant role in generating continuous noise levels.

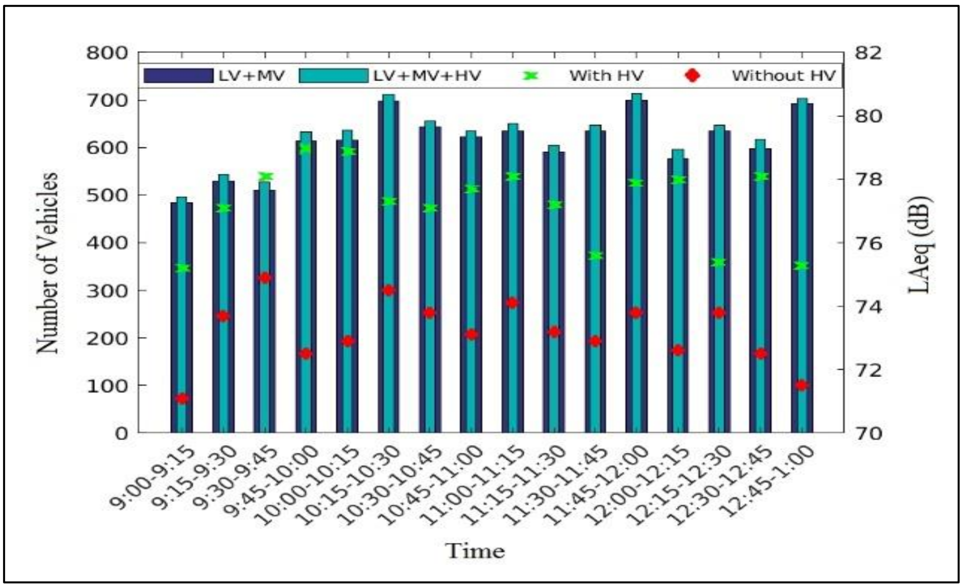

Figure 4.45 Noise level LAeq (dB) comparison with and without heavy vehicles

4.4 Effect of Vehicle Noise Sources on Pass-By Noise Levels

Studies on midblock sections and rotaries have shown that speed and vehicle type would have a significant effect on vehicular noise generation. Along with vehicular characteristics, pavement can be a significant source that has to be considered in order to form the noise regulations for the roads. Accordingly, major noise sources affecting the vehicle noise levels are classified into tire-pavement interaction noise and propulsion noise. Thus, an attempt has been made in the current study to capture the noise levels due to these sources.

Three passenger cars exhibiting different engine and tire characteristics were selected as the test vehicles for pass-by noise measurements. The test vehicles selected are equipped with a gear transmission shift from 1 to 5 and are grouped under engine variants such as diesel and petrol. Diesel cars selected for the current study are represented as car-1 and car-2, whereas the petrol engine variant selected is represented as car-3. The engine characteristics of these three cars are shown in Table 4.15.

Table 4.15 Test vehicles selected for the pass-by noise measurements

Car No.	**Displacement (cc)**	**Power (bhp@rpm)**	**Torque (Nm@rpm)**
1	1461	65bhp@4000rpm	160Nm@2000rpm
2	1248	73.94bhp@4000rpm	190Nm@2000rpm
3	1197	83bhp@6000rpm	114Nm@4000rpm

The main reason for selecting two different cars with the diesel engine is to consider the effect of tire properties on overall noise due to change in the generation of tire-pavement interaction noise measurement in the Coast-By method. Accordingly, the front and rear tire sizes are in norms of 185/70 R14 for car-1, 165/80 R14 for car-2, and car-3. The reason for selecting the car-3 with the petrol engine is to consider the effects of change in propulsion noise levels due to change in a vehicle-specific parameter, i.e., engine displacement/capacity with respect to engine type. Two asphalt and two cement concrete pavements in dry surface condition were selected as test sections in the Warangal city located in Telangana state, India, which are shown in Table 4.16.

Table 4.16 Test sections selected for the pass-by noise measurements

Road No.	**Test section location**	**Type of pavement**	**Roughness (IRI [m/km])**	**Texture depth (mm)**
1	Bypass Road	Asphalt Concrete	2.21	1.02
2	KCto BJR Road	Asphalt Concrete	2.74	1.28
3	Jawahar Colony Road	Cement Concrete	1.78	2.12
4	Teachers Colony Road	Cement Concrete	1.64	0.88

Both the Controlled Pass-By [CPB] and the Coast-By [CB] measurements were conducted on the test sections (Bypass road, KC to BJR road, Jawahar colony road, and Teachers colony road) in strict accordance with standards. All the test runs are conducted at midnight to avoid the effect of background noise disturbance. For each vehicle run, two Sound Level Meters [SLMs] operated in fast response mode were used to estimate the maximum A-weighted sound pressure level, LAmax (dB).

Measurement of tire-pavement interaction noise levels was performed with the Coast-By method. Whereas, the propulsion noise levels were measured with the subtraction method using data collected by CPB and CB methods. Tire-pavement interaction noise levels measured with CB method are subtracted from the overall vehicular noise levels obtained from CPB method. Accordingly, tire-pavement interaction and propulsion noise levels at each gear and speed combination were quantified for car-1 using method-1, and the variation of noise levels for each pavement type is shown in Table 4.17.

Table 4.17 Pass by noise level variation for Car-1 for different pavements

Car-1		Asphalt Concrete-Bypass Road			Asphalt Concrete- KC to BJR Road			Cement Concrete-Jawahar Colony Road			Cement Concrete-Teachers Colony Road		
		LAFmax (dB)			LAFmax (dB)			LAFmax (dB)			LAFmax (dB)		
Diesel Engine		CPB	CB	CPB - CB	CPB	CB	CPB - CB	CPB	CB	CPB - CB	CPB	CB	CPB - CB
Gear No	Vehicle Speed (kmph)	Overall Vehicle Noise Level	Tire-pavement interaction Noise Level	Propulsion Noise Level (dB)	Overall Vehicle Noise Level	Tire-pavement interaction Noise Level	Propulsion Noise Level (dB)	Overall Vehicle Noise Level	Tire-pavement interaction Noise Level	Propulsion Noise Level (dB)	Overall Vehicle Noise Level	Tire-pavement interaction Noise Level	Propulsion Noise Level (dB)
1	10	64.5	54.5	64.1	63.9	55.9	63.2	65.7	62.3	63.1	66.7	61.1	65.4
	20	73.2	58.6	73.1	73	60.2	72.8	73.6	67.5	72.4	74.4	65.4	73.9

2	20	69.7		62.3	63.9		61.5	68.1		59.5	66.6		60.8
	30	68.6	62.5	67.4	69.7	62.3	68.9	72.1	70.3	67.5	71.2	69.5	66.4
3	30	65.6		62.7	65.7		63.1	70.9		62.1	70.1		61.5
	40	69.9	67.4	66.5	69.4	66.9	65.9	74.1	73.5	65.5	76.3	75.9	66.1
4	40	69.4		65.2	68.8		64.5	73.9		63.9	76.1		63.5
	50	73.5	71.5	69.4	72.6	70.5	68.5	78.9	78.7	67.1	77.2	76.5	69.3
5	50	72.8		67.2	71.9		66.5	79		67.6	77		67.4
	60	75.6	74.9	67.9	74.5	73.7	66.9	82.5	82.3	69.2	81.6	81.4	68.6
	70	77.5	76.9	69.1	79.8	79.5	68.9						

Plots are generated to identify the cross-over speed between the tire-pavement interaction noise and propulsion noise levels. At the vehicle speed range of 10 kmph to 70 kmph, tire-pavement interaction noise levels varied from 54.5 dB to 79.5 dB on asphalt pavements and 61.3 dB to 82.3 dB on cement concrete pavements as shown in Figures 4.46 to 4.49.

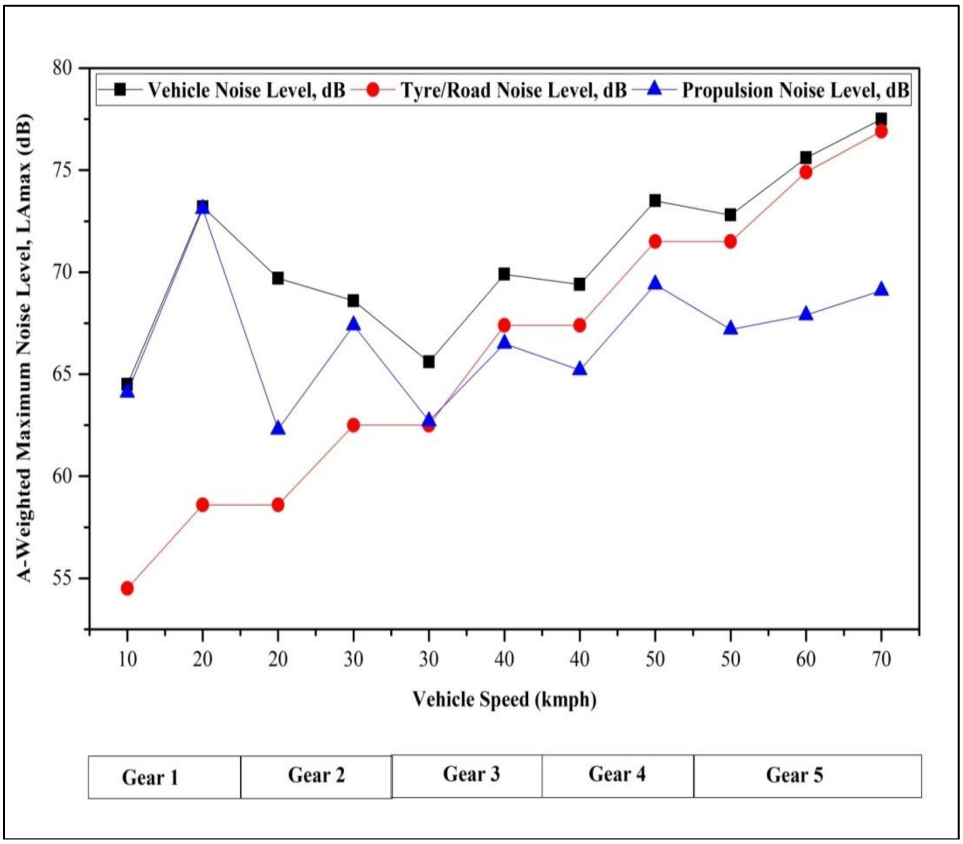

Figure 4.46 Noise level variation for car-1 on asphalt pavement [Bypass road]

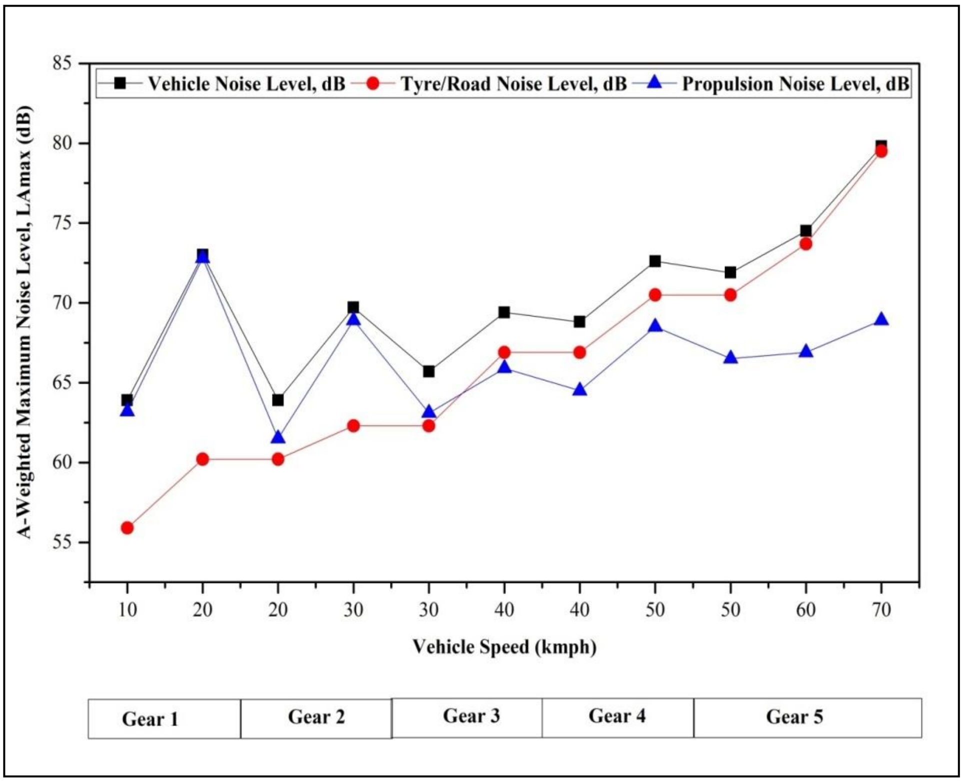

Figure 4.47 Noise level variation for car-1 on asphalt pavement [KC to BJR road]

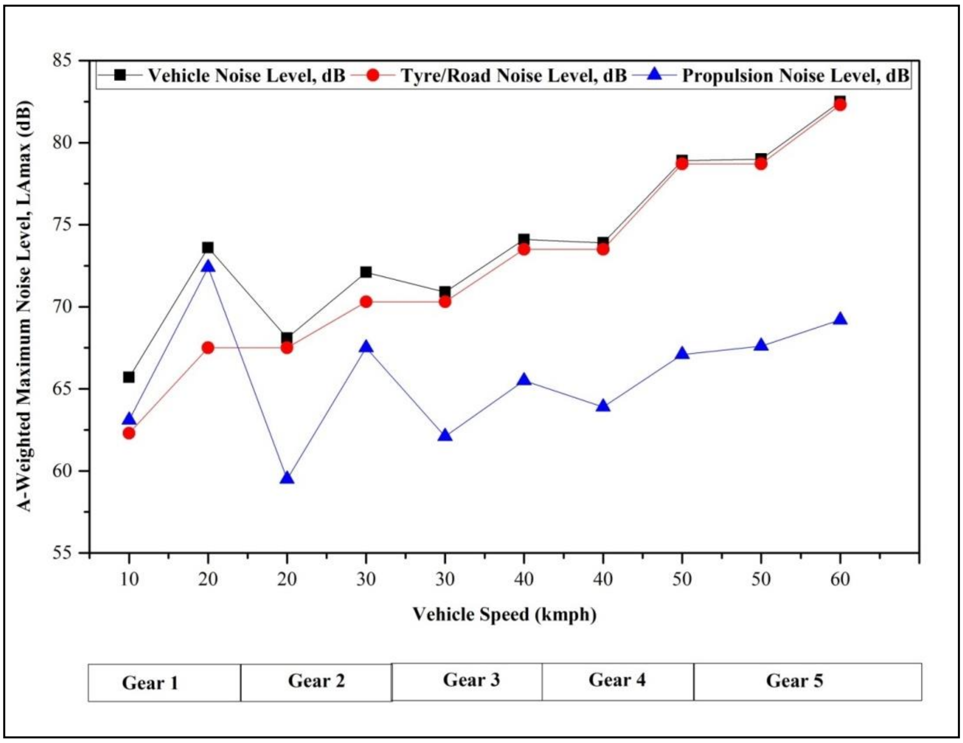

Figure 4.48 Noise level variation for car-1 on cement concrete pavement [Jawahar colony road]

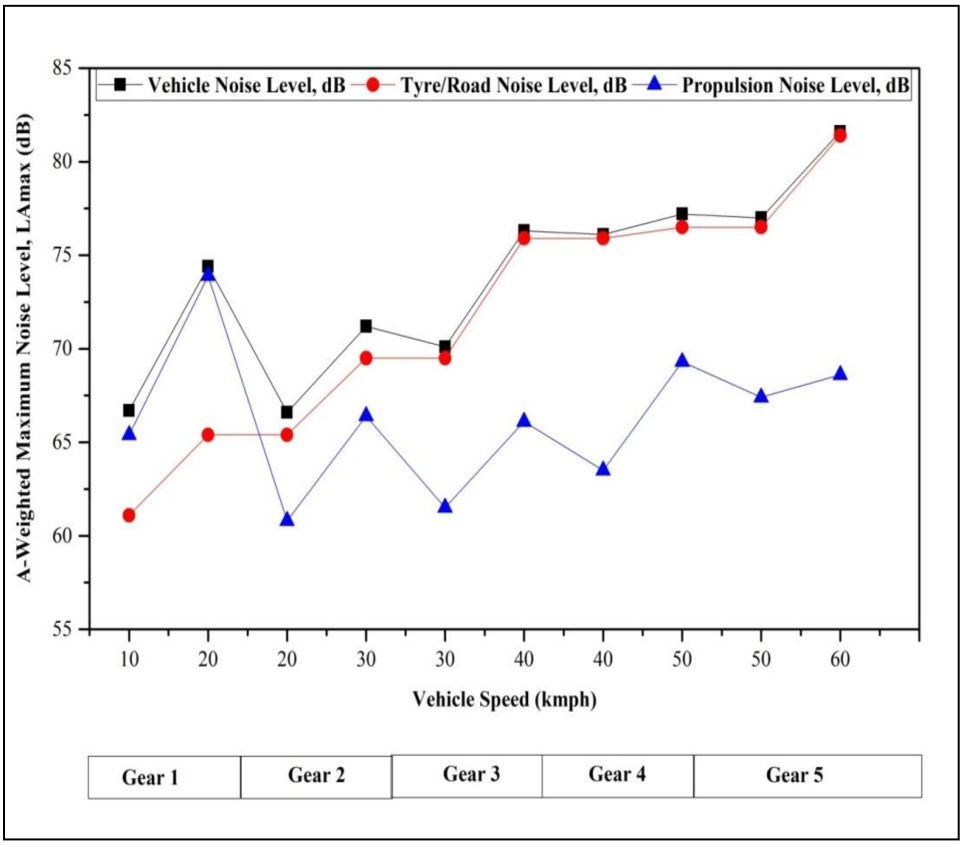

Figure 4.49 Noise level variation for car-1 on cement concrete pavement [Teachers colony road]

Tire-pavement interaction and propulsion noise levels at each gear and speed combination were quantified for car-2 using method-1 on the same pavement sections, and the details are shown in Table 4.18.

Table 4.18 Pass by noise level variation for Car-2 for different pavements

<table>
<tr><td colspan="2" rowspan="2">Car-2</td><td colspan="3">Asphalt Concrete-Bypass Road</td><td colspan="3">Asphalt Concrete-KC to BJR Road</td><td colspan="3">Cement Concrete-Jawahar Colony Road</td><td colspan="3">Cement Concrete-Teachers Colony Road</td></tr>
<tr><td colspan="3">LAFmax (dB)</td><td colspan="3">LAFmax (dB)</td><td colspan="3">LAFmax (dB)</td><td colspan="3">LAFmax (dB)</td></tr>
<tr><td colspan="2">Diesel Engine</td><td>CPB</td><td>CB</td><td>CPB – CB</td><td>CPB</td><td>CB</td><td>CPB – CB</td><td>CPB</td><td>CB</td><td>CPB - CB</td><td>CPB</td><td>CB</td><td>CPB – CB</td></tr>
<tr><td>Gear Number</td><td>Vehicle Speed (kmph)</td><td>Overall Vehicle Noise Level</td><td>Tire-pavement interaction Noise Level</td><td>Propulsion Noise Level (dB)</td><td>Overall Vehicle Noise Level</td><td>Tire-pavement interaction Noise Level</td><td>Propulsion Noise Level (dB)</td><td>Overall Vehicle Noise Level</td><td>Tire-pavement interaction Noise Level</td><td>Propulsion Noise Level (dB)</td><td>Overall Vehicle Noise Level</td><td>Tire-pavement interaction Noise Level</td><td>Propulsion Noise Level (dB)</td></tr>
<tr><td rowspan="2">1</td><td>10</td><td>63.3</td><td>53.3</td><td>62.8</td><td>62.9</td><td>54.8</td><td>62.1</td><td>64.5</td><td>60.1</td><td>62.5</td><td>63.8</td><td>58.6</td><td>62.2</td></tr>
<tr><td>20</td><td>73.4</td><td rowspan="2">56.3</td><td>73.3</td><td>73.5</td><td rowspan="2">58.6</td><td>73.3</td><td>73.9</td><td rowspan="2">64.6</td><td>73.3</td><td>73.7</td><td rowspan="2">60.5</td><td>73.4</td></tr>
<tr><td rowspan="2">2</td><td>20</td><td>63.1</td><td>62.1</td><td>64.3</td><td>62.9</td><td>66.4</td><td>61.7</td><td>64.5</td><td>62.3</td></tr>
<tr><td>30</td><td>67.1</td><td rowspan="2">60.1</td><td>66.1</td><td>66.6</td><td rowspan="2">59.6</td><td>65.6</td><td>71</td><td rowspan="2">69.1</td><td>66.4</td><td>71.2</td><td rowspan="2">68.3</td><td>68.1</td></tr>
<tr><td rowspan="2">3</td><td>30</td><td>63.9</td><td>61.5</td><td>65.5</td><td>64.2</td><td>69.7</td><td>60.8</td><td>68.9</td><td>60</td></tr>
<tr><td>40</td><td>67.6</td><td rowspan="2">63.7</td><td>65.3</td><td>68.1</td><td rowspan="2">64.2</td><td>65.8</td><td>73.8</td><td rowspan="2">72.5</td><td>67.9</td><td>74.2</td><td rowspan="2">73.1</td><td>67.7</td></tr>
<tr><td rowspan="2">4</td><td>40</td><td>66.2</td><td>62.6</td><td>67</td><td>63.7</td><td>73.1</td><td>64.2</td><td>73.8</td><td>65.5</td></tr>
<tr><td>50</td><td>70.9</td><td rowspan="2">67.9</td><td>67.8</td><td>70.8</td><td rowspan="2">67.6</td><td>67.9</td><td>74.1</td><td rowspan="2">73.5</td><td>65.2</td><td>76.9</td><td rowspan="2">76.3</td><td>68</td></tr>
<tr><td rowspan="3">5</td><td>50</td><td>70.1</td><td>66.1</td><td>69.5</td><td>64.9</td><td>74</td><td>64.3</td><td>76.6</td><td>64.8</td></tr>
<tr><td>60</td><td>73.3</td><td>71.9</td><td>67.7</td><td>72.1</td><td>70.1</td><td>67.7</td><td>78.6</td><td>78</td><td>69.7</td><td>81.3</td><td>81</td><td>69.5</td></tr>
<tr><td>70</td><td>73.7</td><td>72.3</td><td>68.1</td><td>73.6</td><td>71.6</td><td>69.2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

For car-2, the tire-pavement interaction noise levels varied between 53.3 dB to 72.3 dB on asphalt concrete pavements and 58.6 dB to 81 dB on cement concrete pavements as shown in Figures4.50 to 4.53

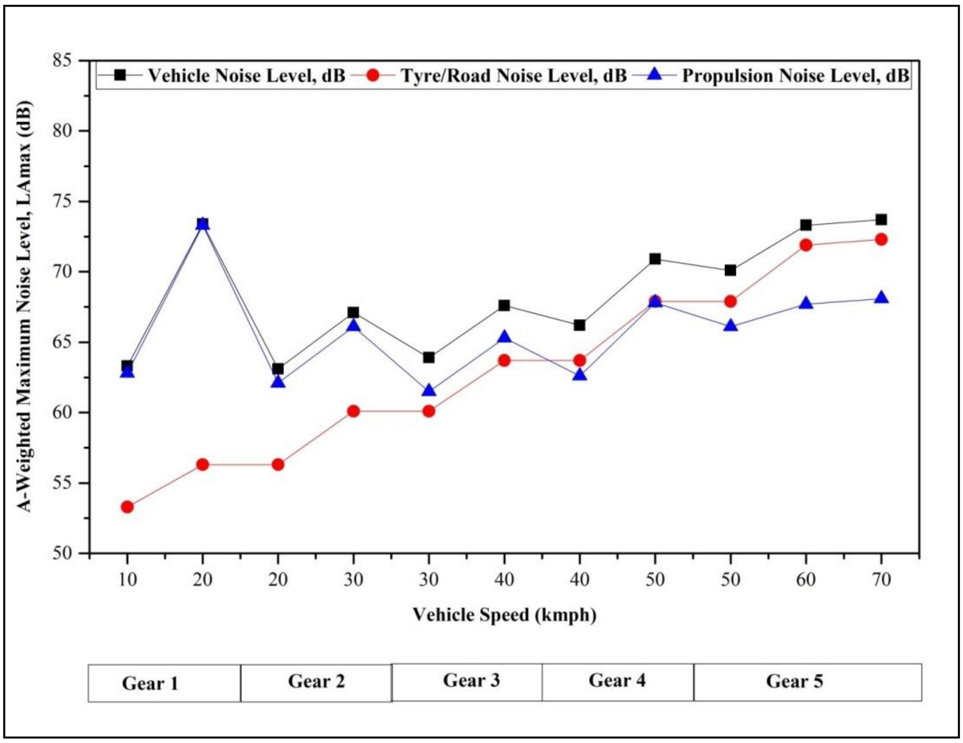

Figure 4.50 Noise level variation for car-2 on asphalt pavement [Bypass road]

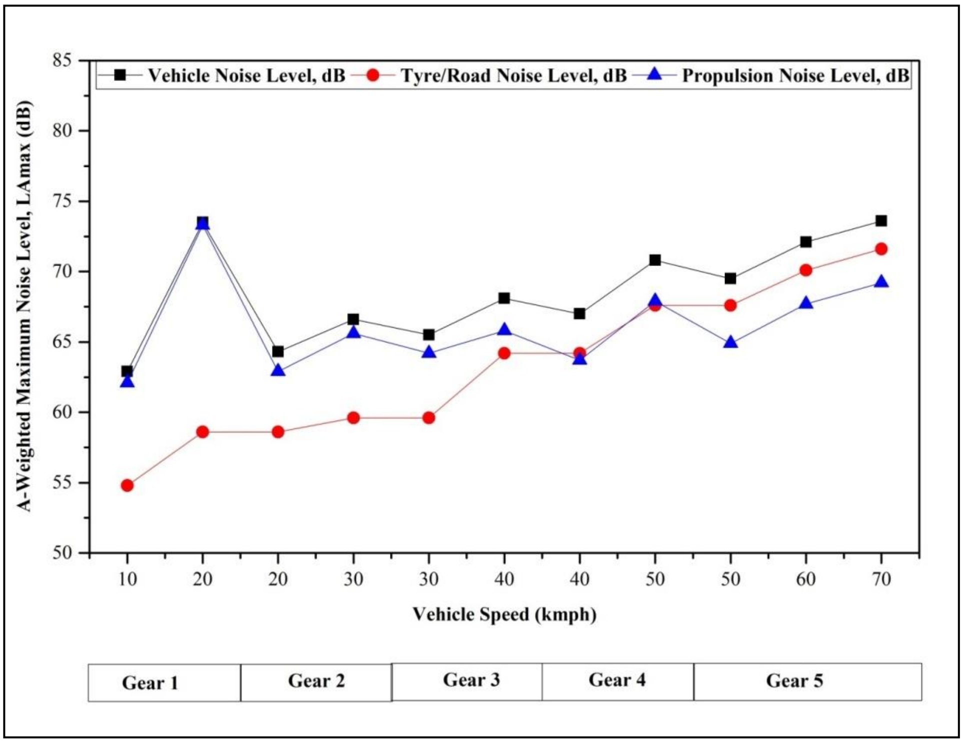

Figure 4.51 Noise level variation for car-2 on asphalt pavement [KC to BJR road]

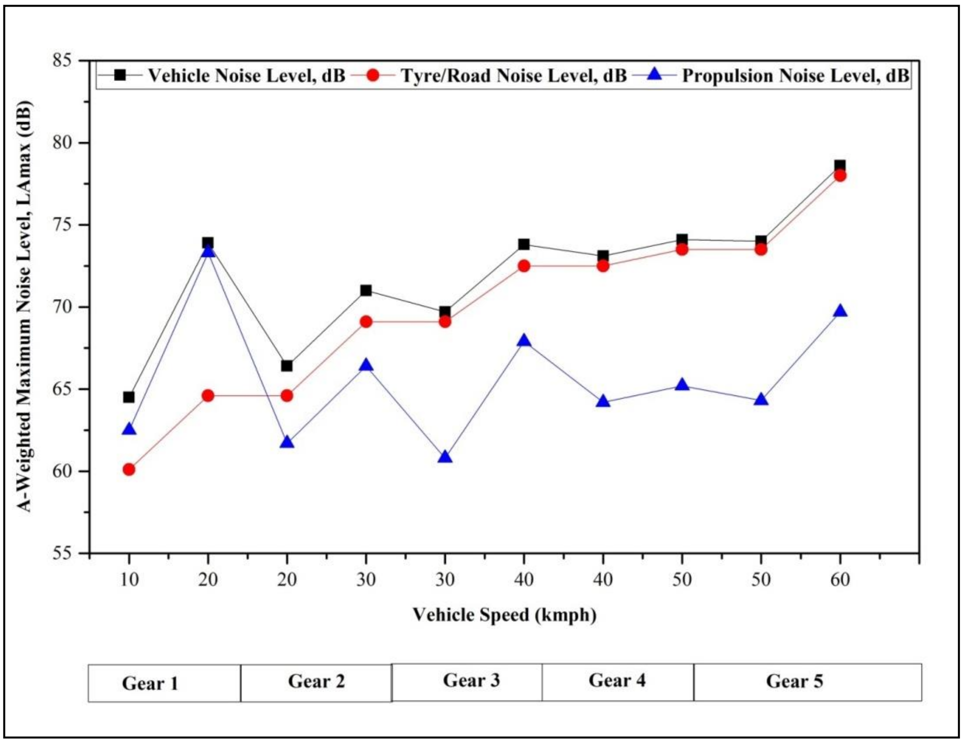

Figure 4.52 Noise level variation for car-2 on cement concrete pavement [Jawahar colony road]

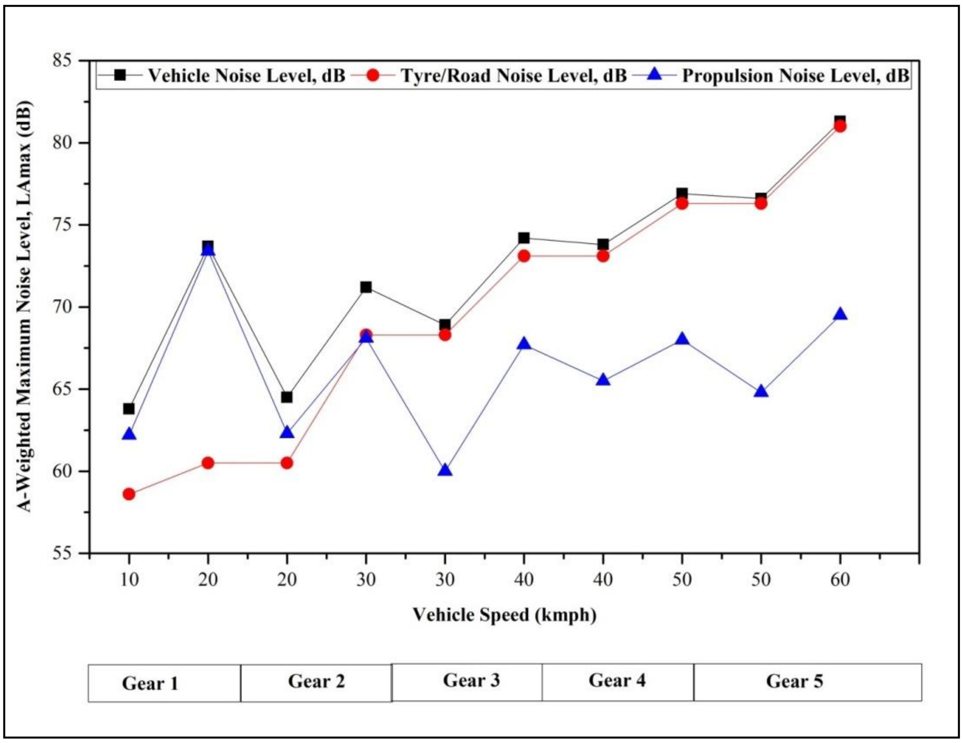

Figure 4.53 Noise level variation for car-2 on cement concrete pavement [Teachers colony road]

The third test vehicle with the petrol-powered engine named car-3 has shown different propulsion noise level patterns in comparison with diesel-powered vehicles, as shown in Table 4.19.

Table 4.19 Pass by noise level variation for Car-3 for different pavements

Car-3		Asphalt Concrete-Bypass Road			Asphalt Concrete-KC to BJR Road			Cement Concrete-Jawahar Colony Road			Cement Concrete-Teachers Colony Road		
		LAFmax (dB)			LAFmax (dB)			LAFmax (dB)			LAFmax (dB)		
Petrol	Engine	CPB	CB	CPB – CB	CPB	CB	CPB - CB	CPB	CB	CPB - CB	CPB	CB	CPB – CB
Gear Number	Vehicle Speed (kmph)	Overall Vehicle Noise Level	Tire-pavement interaction Noise Level	Propulsion Noise Level (dB)	Overall Vehicle Noise Level	Tire-pavement interaction Noise Level	Propulsion Noise Level (dB)	Overall Vehicle Noise Level	Tire-pavement interaction Noise Level	Propulsion Noise Level (dB)	Overall Vehicle Noise Level	Tire-pavement interaction Noise Level	Propulsion Noise Level (dB)
1	10	60.5	53.9	59.4	60.9	53.2	60.1	63	61.2	58.3	62.7	60.1	59.2
	20	71.7	57.2	71.5	71.9	58.9	71.6	72.8	65.3	71.9	72.1	61.3	71.7
2	20	60.9		58.4	62.1		59.2	66.9		61.7	64.1		60.8
	30	64.1	59.7	62.1	65.4	60.2	63.8	69.3	68.7	60.4	68	66.9	61.4
3	30	63.2		60.6	63.9		61.4	69.1		58.5	67.9		61.1
	40	66.9	64.5	63.1	66.1	63.6	62.5	72	71.6	61.4	72.7	72.3	62.1
4	40	66.2		61.3	65.8		61.7	71.9		60.1	72.5		59.1
	50	69.2	68	63	68.7	66.9	64	74.8	74.6	61.3	76.7	76.5	63.2
5	50	68.8		61.1	67.7		59.9	74.7		58.2	76.6		60.1
	60	73	72.5	63.3	72.1	71.5	63.2	78	77.9	61.5	79.8	79.7	63.3
	70	73.6	72.8	65.8	74.1	73.6	64.4						

The propulsion noise levels dropped from 71.5 dB to 58.4 dB for the shift from gear 1 to gear 2 for the vehicle run at 20 kmph. The propulsion noise levels exhibited by the petrol vehicle are lower compared to the diesel vehicles at most of the gear and speed combinations. This is due to the increase in combustion noise levels due to pre-injection in diesel-powered vehicles (car-1 and car-2). For car-3, the respective tire-pavement interaction noise variation is observed between 53.2 dB to 73.6 dB and 60.1 dB to 79.7 dB, as shown in Figures4.54 to 4.57 for the asphalt pavements and cement concrete pavements, respectively.

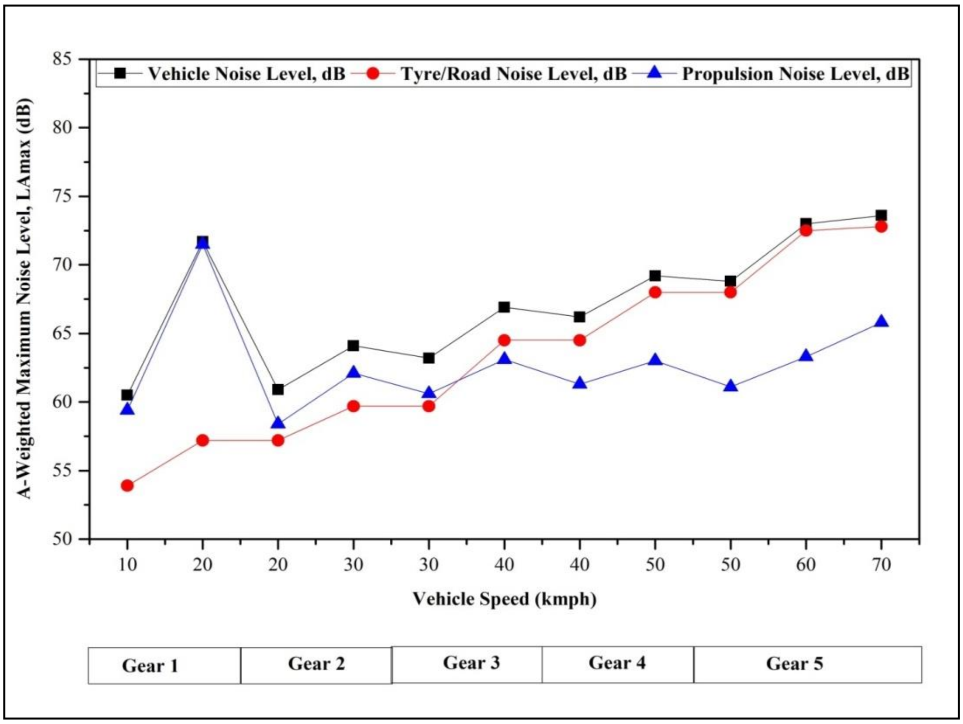

Figure 4.54 Noise level variation for car-3 on asphalt pavement [Bypass road]

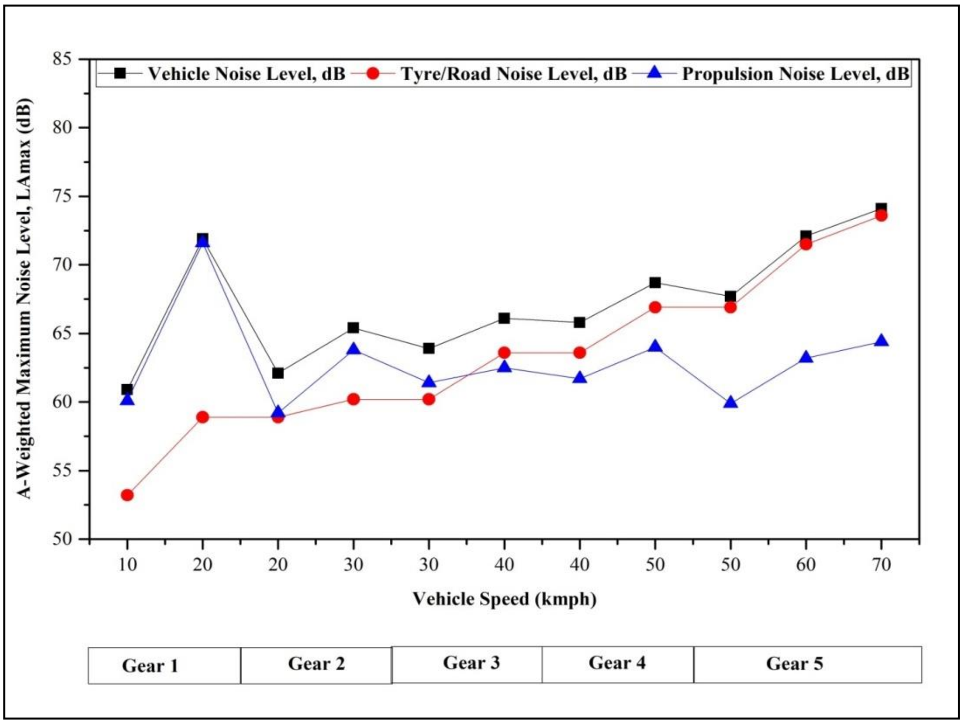

Figure 4.55 Noise level variation for car-3 on asphalt pavement [KC to BJR road]

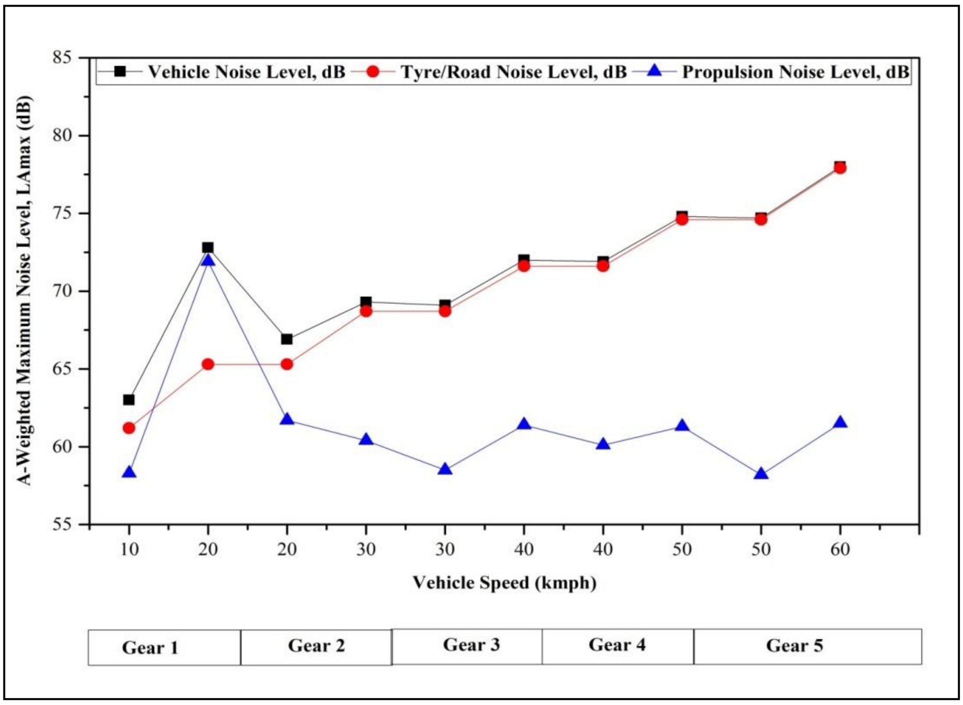

Figure 4.56 Noise level variation for car-3 on cement concrete pavement [Jawahar colony road]

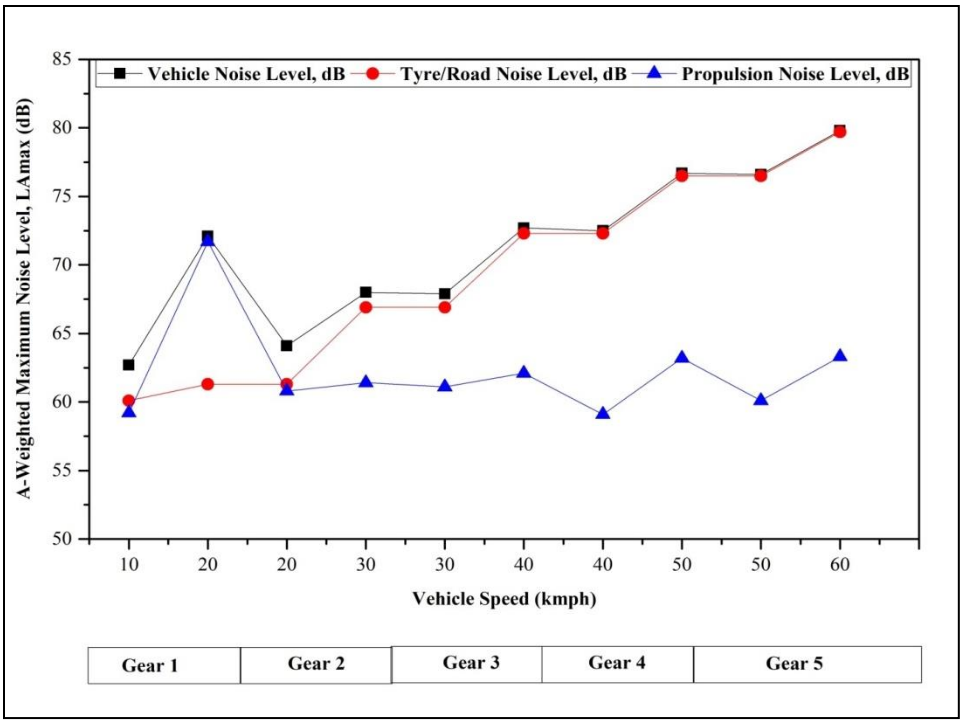

Figure 4.57 Noise level variation for car-3 on cement concrete pavement [Teachers colony road]

Overall, logarithmic subtraction of coast-by levels from the controlled pass-by levels is carried out at each gear and road speed combination for estimating the respective propulsion noise levels for each test vehicle. It is observed that the propulsion noise variation of 60 dB to 73.4 dB is observed for car-2, and 59.5 dB to 73.9 dB is observed for car-1. Apart from the common observation for both the diesel-powered vehicles, the highest propulsion noise levels for both the vehicles are observed for the run at 20 kmph in gear 1. For the same vehicle speed of 20 kmph, the propulsion noise levels dropped from 73.4 dB to 62.3 dB with a shift from gear 1 to gear 2 for car-2, and similar drop is observed for car-1. A similar trend is observed with the shift from gear 2 to gear 3, gear 3 to gear 4, and gear 4 to gear 5 for both the vehicles. For the same road speed, the propulsion noise levels decreased with an increase in gear number.

These results also indicate that irrespective of the vehicle type, cement concrete pavements produce high tire-pavement interaction noise levels compared to the asphalt concrete pavements. This is due to the fact that asphalt concrete pavement dissipates high acoustic energy due to its viscoelastic nature. At the same time, results highlighted the importance of tire size is an important factor in tire-pavement interaction noise generation. This can be a primitive reason for high tire-pavement interaction levels for car-1 compared to the other two test vehicles (car-2 and car-3). For all the test vehicles, among all the pavement sections, tire-pavement interaction noise levels increased with an increase in vehicle speed, as shown in Figures4.58 to 4.60.

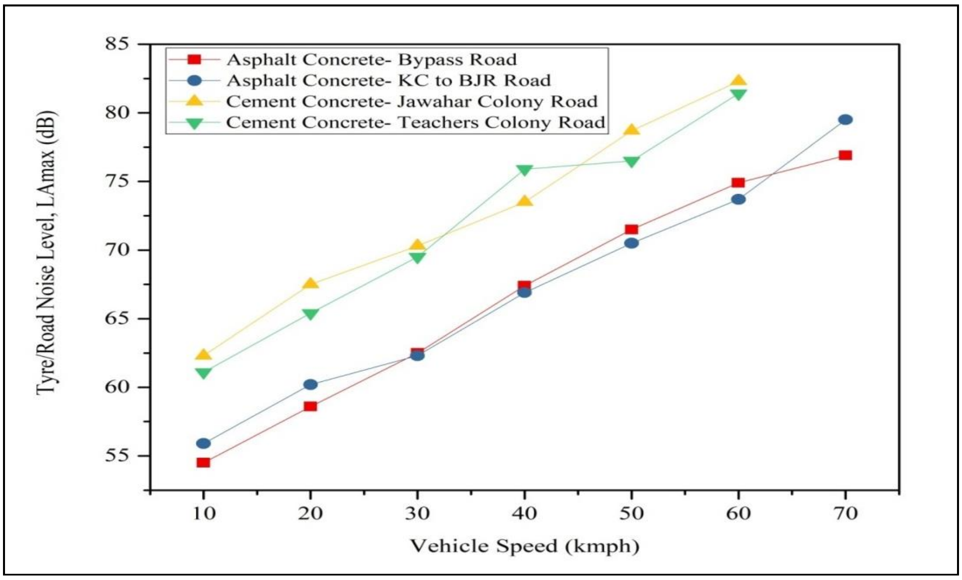

Figure 4.58 Variation of tire-pavement interaction noise level for car-1 among different pavements

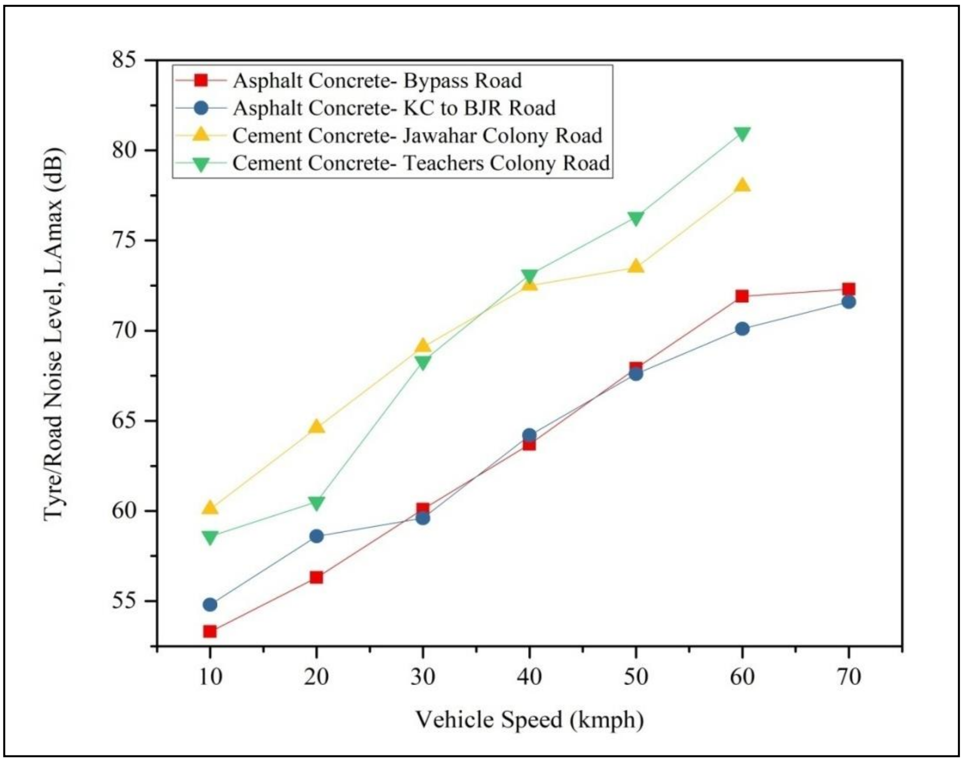

Figure 4.59 Variation of tire-pavement interaction noise levels for car-2 among different pavements

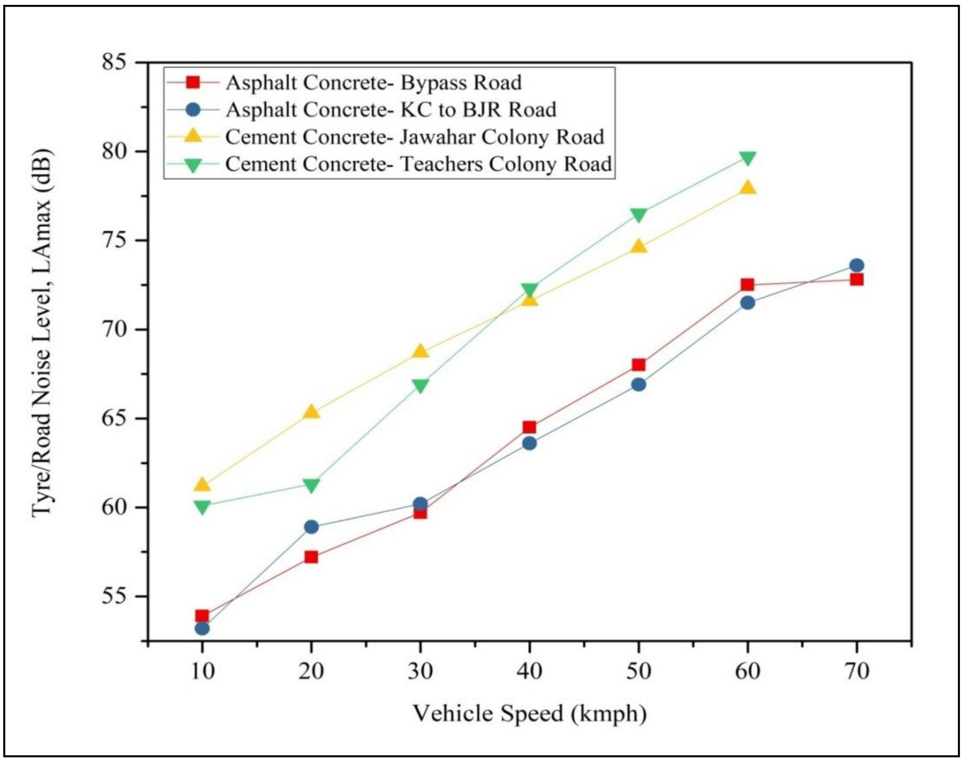

Figure 4.60 Variation of tire-pavement interaction noise level for car-3 among different pavements

Overall, the cross-over speeds for the test vehicles vary between 30 kmph to 50 kmph on asphalt concrete pavements, and 20 kmph to 30 kmph on cement concrete pavements. This proves that the tire-pavement interaction noise occurs at much slower speeds on cement concrete pavements when compared to asphalt concrete pavements. The test results also indicate an overall deviation of 4 to 5 dB for propulsion noise levels on a linear scale, except for the first gear. The highest propulsion noise level for all three test vehicles is observed for the vehicle run at 20 kmph in the first gear. The noise levels observed for all the selected test vehicles prove that propulsion noise level generation strictly depends upon the selection of optimum gear for the specified vehicle speeds.

The current study also presents the engine propulsion noise levels estimated using the developed integrated jack method for car-2 and car-3. Propulsion noise levels at each gear and speed combinations in the jack method are subtracted from the overall vehicle noise levels to obtain the tire-pavement interaction noise levels. Moreover, to compare the tire-pavement interaction noise levels obtained with the standard coast-by noise levels, tire-pavement interaction noise levels are averaged at each gear. The respective results on selected pavement sections are presented in Table 4.20 and Table 4.21 for car-2 and car-3, respectively.

Overall, car-2 (diesel-powered vehicle) is generating the higher propulsion noise levels compared to car-3 (petrol-powered vehicle) at most gear and speed combinations. This is due to the increase in combustion noise levels due to pre-injection in car-2 (diesel-powered vehicle). Measurements conclude that a significant relationship exists between the tire-pavement interaction noise levels quantified from both the methods.

The maximum linear difference between the coast by noise levels and the tire-pavement interaction noise levels measured from subtraction in the integrated jack method differs by 2.9 dB for car-2 and is 2.4 dB for car-3. This deviation is observed due to the considerable increase in propulsion noise levels in the jack method at most gears compared to the pass-by level subtraction. There can be any engine parameter significantly affecting this change, which can only be identified by OBD tool usage.

Interestingly, the tire-pavement interaction noise levels are almost equal to vehicle noise levels, at speeds greater than 60 kmph, measured in LAmax (dB). Both coast-by levels and vehicle noise levels appear to differ by a maximum of 1 dB to 2 dB. This shows the dominance of tire-pavement interaction noise on roads at higher speeds.

Table 4.20 Measured tire-pavement interaction noise levels for Car-2 using CB and Jack method

<table>
<tr><td colspan="2" rowspan="2">Car-2</td><td colspan="4">Asphalt Concrete- Bypass Road</td><td colspan="4">Asphalt Concrete- KC to BJR Road</td><td colspan="4">Cement Concrete- Jawahar Colony Road</td><td colspan="4">Cement Concrete- Teachers Colony Road</td></tr>
<tr><td colspan="4">LAFmax (dB)</td><td colspan="4">LAFmax (dB)</td><td colspan="4">LAFmax (dB)</td><td colspan="4">LAFmax (dB)</td></tr>
<tr><td colspan="2">Diesel Engine</td><td>CPB</td><td>Jack</td><td>CPB - Jack</td><td>CB</td><td>CPB</td><td>Jack</td><td>CPB - Jack</td><td>CB</td><td>CPB</td><td>Jack</td><td>CPB - Jack</td><td>CB</td><td>CPB</td><td>Jack</td><td>CPB - Jack</td><td>CB</td></tr>
<tr><td>Gear Number</td><td>Vehicle Speed (kmph)</td><td>Overall Vehicle Noise</td><td>Propulsion Noise</td><td>Tire-pavement interaction Noise</td><td>Tire-pavement interaction Noise</td><td>Overall Vehicle Noise</td><td>Propulsion Noise</td><td>Tire-pavement interaction Noise</td><td>Tire-pavement interaction Noise</td><td>Overall Vehicle Noise</td><td>Propulsion Noise</td><td>Tire-pavement interaction Noise</td><td>Tire-pavement interaction Noise</td><td>Overall Vehicle Noise</td><td>Propulsion Noise</td><td>Tire-pavement interaction Noise</td><td>Tire-pavement interaction Noise</td></tr>
<tr><td rowspan="2">1</td><td>10</td><td>63.3</td><td>62.5</td><td>55.5</td><td>53.3</td><td>62.9</td><td>62.5</td><td>52.3</td><td>54.8</td><td>64.5</td><td>62.5</td><td>60.1</td><td>60.1</td><td>63.8</td><td>62.5</td><td>57.9</td><td>58.6</td></tr>
<tr><td>20</td><td>73.4</td><td>73.3</td><td>56.9</td><td rowspan="2">56.3</td><td>73.5</td><td>73.3</td><td>60</td><td rowspan="2">58.6</td><td>73.9</td><td>73.3</td><td>65</td><td rowspan="2">64.6</td><td>73.7</td><td>73.3</td><td>63.1</td><td rowspan="2">60.5</td></tr>
<tr><td rowspan="2">2</td><td>20</td><td>63.1</td><td>61.8</td><td>57.2</td><td>64.3</td><td>61.8</td><td>60.7</td><td>66.4</td><td>61.8</td><td>64.5</td><td>64.5</td><td>61.8</td><td>61.1</td></tr>
<tr><td>30</td><td>67.1</td><td>64.5</td><td>63.6</td><td rowspan="2">60.1</td><td>66.6</td><td>64.5</td><td>62.4</td><td rowspan="2">59.6</td><td>71</td><td>64.5</td><td>69.8</td><td rowspan="2">69.1</td><td>71.2</td><td>64.5</td><td>70.1</td><td rowspan="2">68.3</td></tr>
<tr><td rowspan="2">3</td><td>30</td><td>63.9</td><td>62.3</td><td>58.7</td><td>65.5</td><td>62.3</td><td>62.6</td><td>69.7</td><td>62.3</td><td>68.8</td><td>68.9</td><td>62.3</td><td>67.8</td></tr>
<tr><td>40</td><td>67.6</td><td>64.8</td><td>64.3</td><td rowspan="2">63.7</td><td>68.1</td><td>64.8</td><td>65.3</td><td rowspan="2">64.2</td><td>73.8</td><td>64.8</td><td>73.2</td><td rowspan="2">72.5</td><td>74.2</td><td>64.8</td><td>73.6</td><td rowspan="2">73.1</td></tr>
<tr><td rowspan="2">4</td><td>40</td><td>66.2</td><td>63.2</td><td>63.1</td><td>67</td><td>63.2</td><td>64.6</td><td>73.1</td><td>63.2</td><td>72.6</td><td>73.8</td><td>63.2</td><td>73.4</td></tr>
<tr><td>50</td><td>70.9</td><td>69.3</td><td>65.7</td><td rowspan="2">67.9</td><td>70.8</td><td>69.3</td><td>65.4</td><td rowspan="2">67.6</td><td>74.1</td><td>69.3</td><td>73.3</td><td rowspan="2">73.5</td><td>76.9</td><td>69.3</td><td>76.1</td><td rowspan="2">76.3</td></tr>
<tr><td rowspan="3">5</td><td>50</td><td>70.1</td><td>67.8</td><td>66.2</td><td>69.5</td><td>67.8</td><td>64.6</td><td>74</td><td>67.8</td><td>72.8</td><td>76.6</td><td>67.8</td><td>75.9</td></tr>
<tr><td>60</td><td>73.3</td><td>69.3</td><td>71.1</td><td>71.9</td><td>72.1</td><td>69.3</td><td>68.8</td><td>70.1</td><td>78.6</td><td>69.3</td><td>78.3</td><td>78</td><td>81.3</td><td>69.3</td><td>81</td><td>81</td></tr>
<tr><td>70</td><td>73.7</td><td>69.6</td><td>71.5</td><td>72.3</td><td>73.6</td><td>69.6</td><td>71.3</td><td>71.6</td><td>80.2</td><td>69.6</td><td>79.8</td><td>-</td><td>82.4</td><td>69.6</td><td>82.1</td><td>-</td></tr>
</table>

Table 4.21 Measured tire-pavement interaction noise levels for Car-3 using CB and Jack method

Car-3		Asphalt Concrete- Bypass Road				Asphalt Concrete- KC to BJR Road				Cement Concrete- Jawahar Colony Road				Cement Concrete- Teachers Colony Road			
		LAFmax (dB)				LAFmax (dB)				LAFmax (dB)				LAFmax (dB)			
Petrol Engine		CPB	Jack	CPB - Jack	CB	CPB	Jack	CPB - Jack	CB	CPB	Jack	CPB - Jack	CB	CPB	Jack	CPB - Jack	CB
Gear Number	Vehicle Speed (kmph)	Vehicle Noise	Propulsion Noise	Tire-pavement interaction Noise	Tire-pavement interaction Noise	Vehicle Noise	Propulsion Noise	Tire-pavement interaction Noise	Tire-pavement interaction Noise	Vehicle Noise	Propulsion Noise	Tire-pavement interaction Noise	Tire-pavement interaction Noise	Vehicle Noise	Propulsion Noise	Tire-pavement interaction Noise	Tire-pavement interaction Noise
1	10	60.5	59.1	54.9	53.9	60.9	59.1	56.2	53.2	63	59.1	60.7	61.2	62.7	59.1	60.2	60.1
	20	71.7	71.4	59.9	57.2	71.9	71.4	62.2	58.9	72.8	71.4	67.2	65.3	72.1	71.4	63.8	61.3
2	20	60.9	58.5	57.7		62.1	58.5	59.6		66.9	58.5	66.2		64.1	58.5	62.7	
	30	64.1	61.2	60.9	59.7	65.4	61.2	63.3	60.2	69.3	61.2	68.5	68.7	68	61.2	66.9	66.9
3	30	63.2	59.5	60.7		63.9	59.5	61.9		69.1	59.5	68.5		67.9	59.5	67.2	
	40	66.9	65.5	61.3	64.5	66.1	63.2	62.9	63.6	72	65.5	70.8	71.6	72.7	65.5	71.7	72.3
4	40	66.2	64.2	61.8		65.8	61.5	63.7		71.9	64.2	71.1		72.5	64.2	71.8	
	50	69.2	65.5	66.7	68	68.7	65.5	65.8	66.9	74.8	65.5	74.2	74.6	76.7	65.5	76.3	76.5
5	50	68.8	64.2	66.9		67.7	64.2	65.1		74.7	64.2	74.3		76.6	64.2	76.3	
	60	73	66.9	71.7	72.5	72.1	66.9	70.5	71.5	78	66.9	77.6	77.9	79.8	66.9	79.5	79.7
	70	73.6	68.2	72.1	72.8	74.1	68.2	72.8	73.6	79.6	68.2	79.2	-	81.2	68.2	80.9	-

4.5 Effect of Tire-Pavement Interaction Noise Source on In-vehicle Noise Levels

For measuring the in-vehicle noise levels generated due to the tire-pavement interaction, two asphalt pavements and two cement concrete pavements were selected in the Warangal city located in the south-central state of Telangana in India, and the test section details are shown in Table 4.22 and Figure 4.61.

Table 4.22 Test sections selected for the noise measurements

Road No.	Test section location	Type of pavement
1	Bypass Road	Asphalt Concrete
2	KC to BJR Road	Asphalt Concrete
3	Jawahar Colony Road	Cement Concrete
4	Teachers Colony Road	Cement Concrete

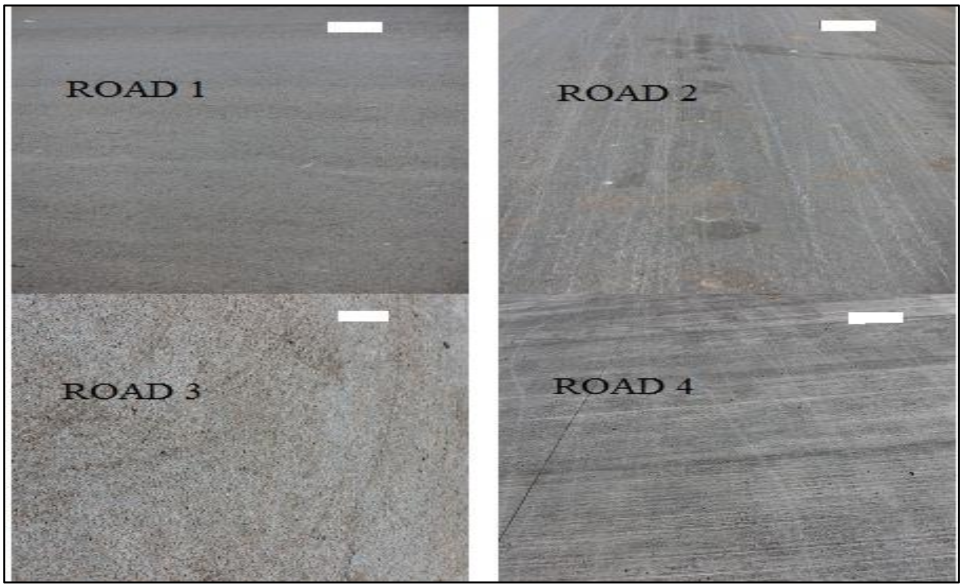

Figure 4.61 Schematic diagram showing the test sections selected for noise measurements

Similar to pass-by noise level measurement, a pair of measurements were taken for each speed run and were repeated if the simultaneous measurements differed by more than 1 dB. For each run, both the SLMs (Handheld and Stabilizer mounted) were calibrated using an acoustic calibrator to avoid the errors in measurement. The handheld stabilizer used in the study is shown in Figure 4.62.

Figure 4.62 Handheld stabilizer used for mounting the SLM-2 (Yelangu, 2018)

For the study, Car-1 is used for measuring the noise levels which is having no additional sound absorber material and noise sealing tapes under the hood. Moreover, the car interior is not equipped with the sound dampening mats on interior floor. The car is selected as the test vehicle to strictly check the effect of tire-pavement interaction noise levels during the coast-by condition which is not equipped with any interior sound dampening materials. Accordingly, in order to measure the tire-pavement noise in coast-by condition, the vehicle was driven at the desired speeds ranging from 40 kmph to 70 kmph. The noise levels were recorded for each speed increment of 10 kmph and were averaged logarithmically. Wind caps were mounted on the microphones of both the SLMs to minimize the effect of wind direction and wind speed on the noise measurements. All the test runs were conducted at midnight from 1:00 AM to 4:00 AM to avoid the fluctuations in background noise and traffic intrusion disturbances. Air condition in the car was switched off during the in-vehicle noise measurements as the focus is kept on to measure the tire-pavement interaction effect only. For the windows closed and windows open conditions, separate measurements were taken and the results were compared for each speed run.

Vehicle speeds were varied from 40 kmph to 70 kmph on asphalt concrete pavements [Road 1 and Road 2], and 40 kmph to 60 kmph on cement concrete (CC) pavements [Road 3 and Road 4]. The highest speed on the cement concrete pavements was limited to 60 kmph as these roads are connected by the surrounding sub-arterials which might lead to chaos in controlling the vehicle running in the switched-off condition at speeds greater than 60 kmph.

The noise levels measured on all the four roads using handheld SLM-1 and stabilizer mounted SLM-2 under windows-closed and windows-open conditions are consolidated in Table 4.23 to Table 4.26.

Table 4.23 In-vehicle noise levels due to tire-pavement interaction on road-1

Vehicle speed, kmph	**Tire-pavement interaction noise [LAeq (dB)]**			
	Windows closed condition		**Windows open condition**	
	Handheld	**Stabilizer mounted**	**Handheld**	**Stabilizer mounted**
40	62.7	61.2	62.9	61.7
50	63.0	61.9	63.3	62.4
60	63.2	62.4	64.2	63.1
70	64.9	63.0	68.4	66.9

Table 4.24 In-vehicle noise levels due to tire-pavement interaction on road-2

Vehicle speed, kmph	**Tire-pavement interaction noise [LAeq (dB)]**			
	Windows closed condition		**Windows open condition**	
	Handheld	**Stabilizer mounted**	**Handheld**	**Stabilizer mounted**
40	63.9	62.1	64.5	62.6
50	65.1	63.8	65.3	64.2
60	65.8	65.0	67.9	66.3
70	66.8	65.5	69.4	68.2

Table 4.25 In-vehicle noise levels due to tire-pavement interaction on road-3

Vehicle speed, kmph	**Tire-pavement interaction noise [LAeq (dB)]**			
	Windows closed condition		**Windows open condition**	
	Handheld	**Stabilizer mounted**	**Handheld**	**Stabilizer mounted**
40	65.6	64.1	66.9	64.5
50	67.1	65.9	68.5	67.4
60	69.8	67.9	71.2	69.1

Table 4.26 In-vehicle noise levels due to tire-pavement interaction on road-4

Vehicle speed, kmph	**Tire-pavement interaction noise [LAeq (dB)]**			
	Windows closed condition		**Windows open condition**	
	Handheld	**Stabilizer mounted**	**Handheld**	**Stabilizer mounted**
40	67.4	65.4	68.6	66.3
50	68.1	66.5	68.9	68.5
60	70.8	68.6	72.5	70.9

It is observed that CC pavements are producing 3 dB to 5 dB higher noise levels compared to the asphalt pavements at speeds ranging from 40 kmph to 60 kmph. Overall, In-vehicle noise levels due to tire-pavement interaction were checked with the windows open and closed condition for all the vehicle runs. Overall, average in-vehicle noise levels observed during the windows closed condition is lower by about 0.2 dB to 3.5dB, compared to the windows open condition, as shown in Figures 4.63 and 4.64.

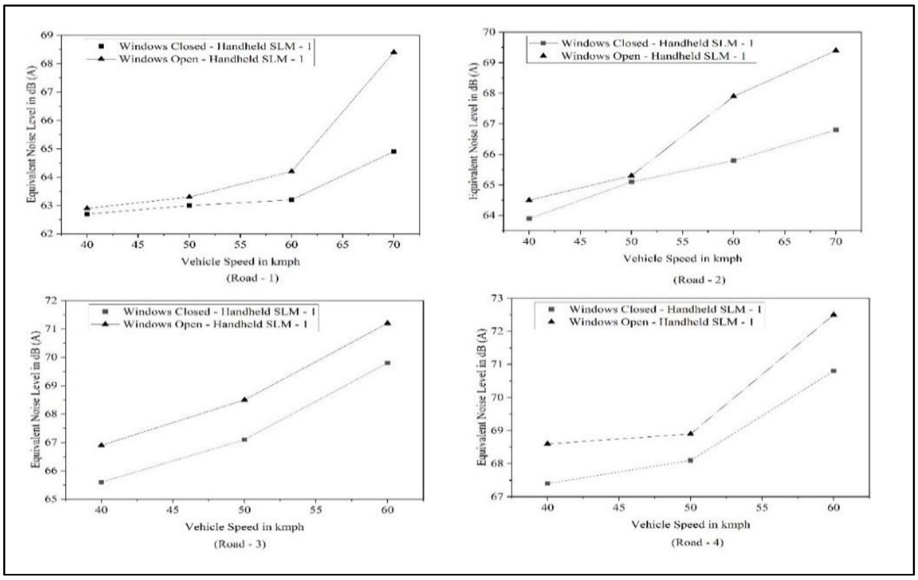

Figure 4.63 Measured in-vehicle noise level (LAeq (dB)) with hand held sound level meter [SLM-1] for the windows open and windows closed vehicle runs

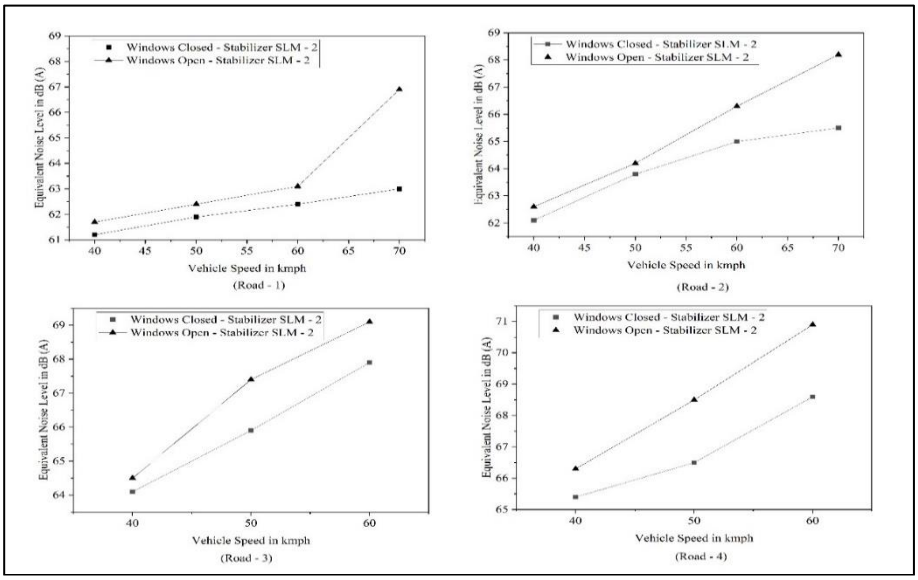

Figure 4.64 Measured in-vehicle noise level (LAeq (dB)) with stabilizer mounted sound level meter [SLM-2] for the windows open and windows closed vehicle runs

On the four pavement surfaces, the noise levels recorded in the handheld SLM-1 are 0.8 dB to 2.2 dB higher compared to the stabilizer mounted SLM-2 in windows-closed condition as shown in Figure 4.65. Similarly, the noise levels recorded in the handheld SLM-1 are 0.4 dB to 2.4 dB higher compared to the stabilizer mounted SLM-2 in windows-open condition as shown in Figure 4.66. This shows that irrespective of whether the windows are closed or open, the noise levels recorded in the handheld SLM-1 are always higher than the stabilizer mounted SLM-2 highlighting the dominance of vibrations on the measurement unit during the vehicle movement.

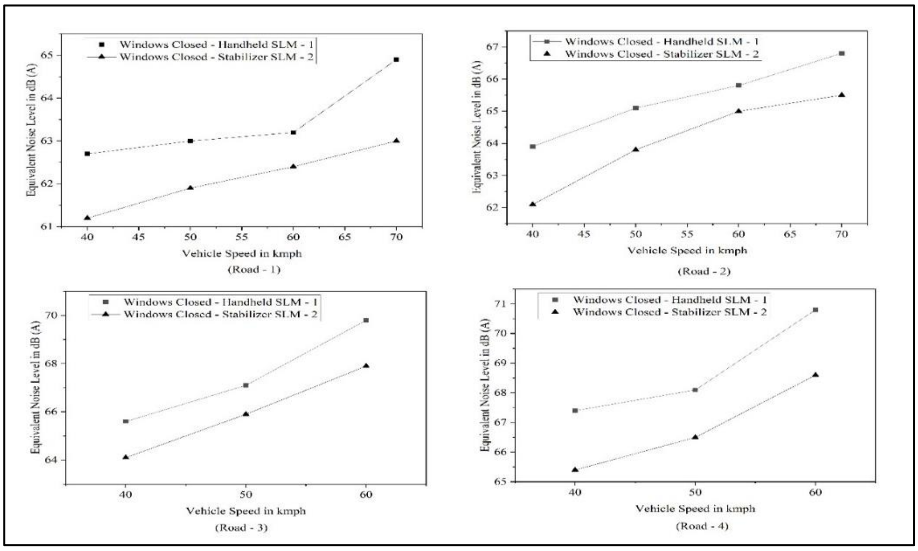

Figure 4.65 Comparison of in-vehicle noise level [LAeq (dB)] measured with SLM-1 and SLM-2 during windows closed vehicle run

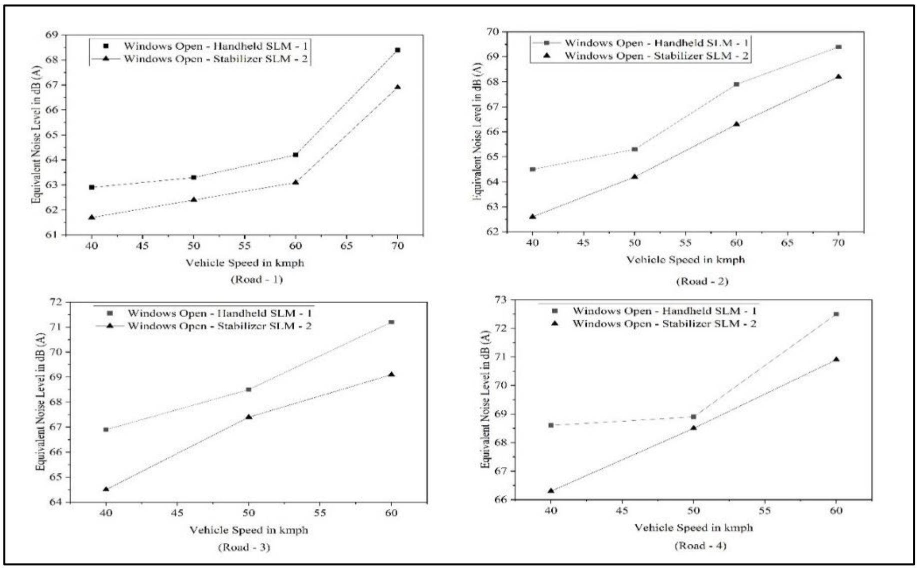

Figure 4.66 Comparison of in-vehicle noise level [LAeq (dB)] measured with SLM-1 and SLM-2 during windows open vehicle run

Overall, it is observed that along with the type of sound level meter mounting and windows open or closed conditions, the type of pavement also plays a significant role in the generation of the in-vehicle noise levels especially due to the tire-pavement interaction.

4.6 Summary

The data related to vehicle volume and vehicle speed were collected and analyzed using the noise tools software for assessing the effect of traffic noise pollution on roadusers near highway midblock sections and rotaries. It is observed that the proportion of vehicles, speed and honking are increasing the traffic noise levels. Thus, an attempt has been made in collecting the data related to the major sources (tire-pavement interaction and engine propulsion) of vehicle and pavement affecting the noise levels with the development of suitable methodologies. Among the selected test sections, cement concrete pavements are generating more noise compared to the asphalt pavements. Whereas, the effect of engine propulsion is dominant at lower speeds. Further, the analysis has shown the effect of engine type on propulsion noise levels. Petrol engine vehicles are generating lesser propulsion noise levels compared to diesel engine vehicles. It is also observed from the analysis that roadusers are experiencing higher noise levels at most speeds due to the tire-pavement interaction. Thus, an attempt has been made in assessing the effect of the tire-pavement interaction on commuters. With the developed methodology, the tire-pavement interaction was measured at different speeds in windows closed and windows open conditions. Analysis has shown that tire-pavement interaction alone can generate the extreme noise levels which show the need for minimizing the tire-pavement interaction at the source level. Further, the model developed for predicting the noise levels using the data collected is presented and discussed in detail in the next chapter.

CHAPTER 5

MODEL DEVELOPMENT AND VALIDATION

5.1 General

This chapter includes the database used for the development of the noise prediction model in heterogenic traffic conditions. The data collected over highway midblock sections and rotaries are used for the development of noise prediction models. Further, the correlation between tire-pavement interaction noise levels measured by standard Coast-By methodology and the developed integrated jack method in this study is verified. Finally, the total in-vehicle noise data collected using handheld SLM-1 and stabilizer mounted SLM-2 is checked for statistical significance using the Student t-test.

5.2 Heterogeneous Traffic Noise Database on Highways using the Model Development

Four national highways named, NH-16 (previously NH-5), NH-65 (previously NH-9), NH-44 (previously NH-7), NH-163 (previously NH-202) are selected as the study locations. From the field studies, the following data corresponding to traffic and roadway parameters were collected and used as a database for the model development.

i. Classified traffic volume,
ii. The average speed of vehicles, and
iii. Noise levels

The traffic volume data collected in the study area proves the dominant proportion of model classes including Motor Cycle (MC), Scooter (SC), Auto Rickshaw (A), Small Car (CS), Big Car (CB), Bus (B), Two-Axle Truck (HT) and Multi-axle Truck (MT). Thus, for model development, the vehicle classes are classified in to 2wheelers (MC and SC), 3wheelers (A), 4wheelers (CS, CB), Bus (B), Heavy vehicles (Two-Axle Truck (HT) and Multi-axle Truck (MT)). These five classes are chosen based on the geometric and performance characteristics of the vehicles. The data was collected for a 15-minute time interval. Further, the data was processed using MS-Excel Package. Accordingly, two separate data sets were prepared for 15 minutes and one-hour time intervals. For obtaining hourly LAeq from 15-minutes LAeq data, the following equations are used.

$$LAeq(h) = 10*\log [10^{(L_1/10)}*t_1 + 10^{(L_2/10)}*t_2 + 10^{(L_3/10)}*t_3 + 10^{(L_4/10)}*t_4] \quad (5.1)$$

$$LA10(h) = 10*\log [10^{(L_1/10)}*t_1 + 10^{(L_2/10)}*t_2 + 10^{(L_3/10)}*t_3 + 10^{(L_4/10)}*t_4] \quad (5.2)$$

Where,

LAeq(h) = A-Weighted equivalent noise level for one hour,

LA10(h) = A- Weighted noise levels exceed 10% of total observations for one hour, and

L_1, L_2, L_3, and L_4 are fluctuating noise levels for an interval of t_1, t_2, t_3, and t_4, respectively.

Noise Level = f (total traffic volume, traffic speed, %2w, %3w, %cars, % buses, %heavy vehicles) (5.3)

$LAeq = a_0 + a_1$*Traffic Volume + a_2*Average Traffic Speed+ a_3* % of Heavy Vehicles + a_4*% of Cars + a_5* % of Buses + a_6*% of 2W + a_7*% of 3W (5.4)

$LA10 = a_0 + a_1$*Traffic Volume + a_2*Average Traffic Speed+ a_3* % of Heavy Vehicles + a_4*% of Cars + a_5* % of Buses + a_6*% of 2W + a_7*% of 3W (5.5)

$SPL = a_0 + a_1$*Traffic Volume + a_2*Average Traffic Speed+ a_3* % of Heavy Vehicles + a_4*% of Cars + a_5* % of Buses + a_6*% of 2W + a_7*% of 3W (5.6)

5.3 National Highways Noise Models

Noise models are developed for the national highways of Andhra Pradesh and Telangana states in India, as shown below.

5.3.1 Development of noise models for NH-16

Vijayawada- Kolkata highway and Vijayawada- Chennai highway field study data is averaged for 15 minutes interval and 1-hour interval. Data sets were prepared for both LAeq and LA10 values and processed using the SPSS package to develop linear noise models. The calibrated models are presented in Tables 5.1 to 5.4.

All the Developed models (model-1 to model-7) were tested for the following.

- Logical sign of each coefficient,
- Student t-test value of each coefficient,
- R^2 Value, and
- Significance of each variable

Table 5.1 Noise models for 15 min average LAeq for NH-16

Parameters	**Beta weights**						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0166 (1.006)	0.0146 (1.028)	-	0.0134 (1.156)	0.013 (1.158)	-	-
Average Traffic Speed	0.0167 (0.129)	-	-0.0004 (-0.05)	0.0274 (0.304)	-	-	0.0153 (0.170)
% of Heavy Vehicles	0.451 (1.703)	0.449 (1.749)	0.496 (1.896)	0.181 (1.459)	0.165 (1.506)	0.496 (1.958)	0.197 (1.581)
% of Cars	0.704 (2.545)	0.701 (2.619)	0.777 (2.911)	0.441 (2.811)	0.423 (2.975)	0.778 (3.016)	0.491 (3.229)
% of Buses	0.420 (1.558)	0.417 (1.60)	0.460 (1.725)	0.173 (1.052)	0.157 (1.034)	0.460 (1.783)	0.186 (1.127)
% of 2W	0.309 (1.150)	0.314 (1.219)	0.345 (1.293)	-	-	0.345 (1.342)	-
% of 3W	0.655 (2.043)	0.641 (2.181)	0.540 (1.803)	0.488 (1.692)	0.449 (1.785)	0.541 (1.947)	0.332 (1.290)
Intercept	54.37	55.20	53.74	65.54	67.68	53.70	63.45
Sample Size	48	48	48	48	48	48	48
R^2	**0.646**	0.646	0.629	0.617	0.615	0.624	0.587
R	0.840	0.840	0.790	0.786	0.784	0.790	0.766

*Value in ( ) indicate t-value of the parameter

Table 5.2 Noise Models for 15 min average LA10 for NH-16

Parameters	Beta weights						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0271 (2.195)	0.0270 (2.256)	0.0269 (2.246)	-	0.0564 (2.080)	0.0272 (2.199)	-
Average Traffic Speed	0.0168 (0.145)	-	0.3265 (0.341)	-	-	0.156 (0.644)	0.0089 (0.142)
% of Heavy Vehicles	0.381 (0.285)	0.484 (0.439)	0.0367 (0.432)	0.244 (0.201)	0.0973 (0.759)	-	0.225 (0.150)
% of Cars	0.633 (0.464)	0.737 (0.654)	0.582 (2.488)	0.565 (0.454)	0.281 (2.953)	0.254 (3.058)	0.589 (0.361)
% of Buses	0.353 (0.258)	0.457 (0.406)	-	0.208 (0.168)	-	-	0.189 (0.154)
% of 2W	0.388 (0.279)	0.502 (0.452)	-	0.217 (0.178)	0.0579 (0.330)	-	0.178 (0.145)
% of 3W	0.675 (0.531)	0.759 (0.668)	0.03182 (0.170)	0.181 (0.152)	0.326 (1.194)	0.283 (1.234)	0.162 (0.137)
Intercept	57.66	48.20	66.24	63.52	68.56	64.82	61.25
Sample Size	48	48	48	48	48	48	48
R^2	**0.636**	0.635	0.634	0.526	0.631	0.629	0.546
R	0.797	0.797	0.796	0.725	0.795	0.793	0.748

*Value in ( ) indicate t-value of the parameter

Table 5.3 Noise models for 1 h average LAeq for NH-16

Parameters	Beta Weights						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0298 (3.364)	0.0235 (1.342)	0.0296 (2.644)	0.0312 (1.498)	-	0.0312 (2.637)	0.0235 (1.437)
Average Traffic Speed	0.631 (2.320)	0.576 (1.535)	0.530 (1.296)	0.545 (1.486)	0.392 (0.760)	0.545 (2.105)	0.482 (1.617)
% of Heavy Vehicles	0.103 (0.685)	0.113 (0.578)	-	-	0.358 (0.643)	-	-
% of Cars	-	0.179 (0.431)	-	-	0.872 (1.229)	-	0.434 (0.793)
% of Buses	-	-	-	0.0594 (0.045)	0.530 (0.461)	-	-
% of 2W	-	-	-0.0139 (-0.04)	-	-	-	-
% of 3W	-	-	-	0.116 (0.175)	-	0.116 (0.260)	0.515 (0.731)
Intercept	49.18	53.50	59.41	56.48	55.66	56.50	57.11
Sample Size	48	48	48	48	48	48	48
R^2	0.864	0.886	0.833	0.838	0.736	0.838	**0.901**
R	0.930	0.941	0.913	0.915	0.858	0.915	0.949

*Value in ( ) indicate t-value of the parameter

Table 5.4 Noise models for 1 h average LA10 for NH-16

Parameters	Beta weights						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0159 (1.068)	0.0179 (2.251)	-	0.0203 (0.991)	-	0.01396 (0.703)	0.0283 (1.170)
Average Traffic Speed	0.456 (1.425)	0.479 (2.245)	0.248 (0.944)	0.145 (0.356)	0.328 (0.996)	0.125 (0.521)	0.259 (0.974)
% of Heavy Vehicles	0.381 (2.381)	0.379 (3.295)	0.378 (2.283)	-	0.569 (1.663)	-	-
% of Cars	0.056 (0.194)	-	0.264 (1.195)	-	0.383 (1.224)	0.267 (0.654)	-
% of Buses	-	-	-	-	0.638 (0.677)	-	-
% of 2W	-	-	-	0.187 (0.256)	-	-	-
% of 3W	-	-	-	0.886 (0.898)	-	0.968 (1.673)	0.794 (1.748)
Intercept	56.55	54.27	64.25	63.87	57.64	67.12	65.89
Sample Size	48	48	48	48	48	48	48
R^2	**0.891**	0.887	0.767	0.717	0.840	0.809	0.712
R	0.944	0.942	0.856	0.847	0.917	0.899	0.844

*Value in ( ) indicate t-value of the parameter

It is observed from Tables 5.1 to 5.4 that regression coefficients of traffic speeds are positive and significant enough. Regression coefficients for the percentage of heavy vehicles are positive, concluding the significance of the heavy vehicles. Similarly, buses are generally known to produce higher noise levels with an increase in proportion. On a similar note, the coefficients appeared to be positive for cars, three-wheelers, and two-wheelers. Thus, each model was tested for the logical sign for every coefficient, and the student t-test values were compared with table values to know their significance of contribution in order to explain the variation in overall noise levels. Out of all seven models proposed, the model having a better R^2 value was selected for indicating better explanatory power. Accordingly, the following models are selected over seven different combinations and the respective logical testing for each combination is presented below.

15-minutes average noise model for NH-16

LAeq (15 min) dB = 54.37+ 0.0166*Traffic Volume + 0.0167*Average Traffic Speed+ 0.451* % of Heavy Vehicles + 0.704 *% of Cars + 0.420* % of Buses +0.309*% of 2W +0.655*% of 3W

$R^2 = 0.646$ (5.7)

LA10 (15 min) dB = 57.66+ 0.0271*Traffic Volume + 0.0168*Average Traffic Speed+ 0.381* % of Heavy Vehicles + 0.633*% of Cars + 0.353* % of Buses +0.388*% of 2W +0.675*% of 3W

$R^2 = 0.636$ (5.8)

1-hour average noise model for NH-16

LAeq (h) dB = 57.11+ 0.0235*Traffic Volume + 0.482*Average Traffic Speed+ 0.434 *% of Cars + 0.515* % of 3W

$R^2 = 0.901$ (5.9)

LA10 (h) dB = 56.55+ 0.0159*Traffic Volume + 0.456*Average Traffic Speed+ 0.381* % of Heavy Vehicles +0.056 *% of Cars

$R^2 = 0.891$ (5.10)

5.3.2 Development of noise models for NH-65

Hyderabad-Vijayawada highway and Hyderabad-Pune highway field study data is averaged for 15 minutes interval and 1-hour interval. Data sets were prepared for both LAeq and LA10 values and are processed using SPSS Package to develop linear noise models. The calibrated models are presented in Tables 5.5 to 5.8.

Table 5.5 Noise models for 15 min average LAeq for NH-65

Parameters	Beta weights						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.02321 (0.538)	0.0236 (0.564)	-	0.0042 (1.030)	-	0.0054 (1.125)	-
Average Traffic Speed	0.119 (1.341)	0.121 (1.405)	0.135 (1.654)	-	0.138 (1.732)	-	-
% of Heavy Vehicles	0.518 (0.879)	0.370 (3.489)	0.509 (0.884)	0.559 (0.928)	0.349 (3.582)	0.350 (3.246)	0.553 (0.917)
% of Cars	0.218 (0.503)	0.151 (1.155)	0.273 (0.471)	0.388 (0.643)	0.112 (1.029)	0.180 (1.365)	00.360 (0.596)
% of Buses	0.448 (0.767)	0.301 (3.027)	0.452 (0.791)	0.477 (0.799)	0.293 (3.025)	0.270 (2.710)	0.494 (0.826)
% of 2W	0.156 (0.256)	-	0.169 (0.283)	0.220 (0.353)	-	-	0.264 (0.425)
% of 3W	0.754 (1.260)	0.612 (2.836)	0.714 (1.228)	0.871 (1.437)	0.560 (2.930)	0.672 (3.096)	0.821 (1.357)
Intercept	54.71	69.38	55.38	55.02	66.29	65.82	56.50
Sample Size	48	48	48	48	48	48	48
R^2	**0.723**	0.721	0.718	0.691	0.716	0.689	0.672
R	0.850	0.849	0.847	0.832	0.846	0.830	0.820

*Value in ( ) indicate t-value of the parameter

Table 5.6 Noise models for 15 min average LA10 for NH-65

Parameters	Beta weights						
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Traffic Volume	0.0032 (0.874)	0.0049 (1.319)	-	-	0.0032 (0.909)	-	0.008 (1.392)
Average Traffic Speed	0.137 (1.753)	-	0.155 (2.079)	0.156 (2.173)	0.137 (1.821)	-	-
% of Heavy Vehicles	0.415 (0.800)	0.474 (0.863)	0.428 (0.831)	0.359 (4.064)	0.386 (4.124)	0.508 (0.909)	0.357 (3.642)
% of Cars	0.359 (0.690)	0.469 (0.858)	0.351 (0.679)	0.282 (2.851)	0.330 (2.929)	0.480 (0.860)	0.354 (2.973)
% of Buses	0.401 (0.779)	0.448 (0.822)	0.433 (0.848)	0.364 (2.851)	0.372 (4.211)	0.511 (0.921)	0.331 (3.648)
% of 2W	0.0309 (0.057)	0.123 (0.217)	0.0729 (0.137)	-	-	0.214 (0.371)	-
% of 3W	0.915 (1.741)	1.025 (1.906)	0.895 (1.715)	0.828 (4.780)	0.887 (4.771)	1.046 (1.860)	0.939 (4.810)
Intercept	59.83	59.21	58.37	65.23	62.18	56.55	65.59
Sample Size	48	48	48	48	48	48	48
R^2	**0.684**	0.623	0.669	0.669	0.684	0.585	0.622
R	0.827	0.789	0.818	0.818	0.827	0.765	0.789

*Value in ( ) indicate t-value of the parameter

Table 5.7 Noise models for 1 h average LAeq for NH-65

Parameters	Beta weights						
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Traffic Volume	0.0089 (1.060)	-	-	0.0913 (1.954)	-	0.0008 (0.451)	-
Average Traffic Speed	0.0049 (0.027)	0.453 (.244)	0.189 (0.884)	-	0.681 (0.859)	0.650 (1.269)	0.531 (1.847)
% of Heavy Vehicles	0.625 (1.590)	0.490 (0.325)	0.225 (2.748)	0.631 (2.810)	0.154 (0.812)	0.251 (1.125)	0.122 (1.386)
% of Cars	0.926 (1.129)	0.302 (0.235)	0.0874 (0.523)	0.941 (2.312)	-	-	-
% of Buses	-	0.260 (0.182)	-	-	0.0778 (0.218)	-	-
% of 2W	-	-	-	-	-0.606 (-0.809)	-0.742 (-1.003)	-0.574 (-1.254)
% of 3W	-	-	-	-	-	-	-
Intercept	53.22	52.84	69.56	53.02	64.18	67.78	64.25
Sample Size	48	48	48	48	48	48	48
R^2	**0.905**	0.804	0.797	0.905	0.887	0.894	0.881
R	0.951	0.892	0.893	0.951	0.942	0.946	0.939

*Value in ( ) indicate t-value of the parameter

Table 5.8 Noise models for 1 h average LA10 for NH-65

Parameters	Beta weights						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0101 (1.332)	-	0.0054 (1.897)	0.0147 (2.529)	0.0034 (0.897)	-	0.0098 (1.054)
Average Traffic Speed	0.146 (0.967)	0.639 (0.191)	0.889 (2.880)	-	0.495 (1.395)	0.530 (1.359)	0.297 (2.356)
% of Heavy Vehicles	0.525 (1.493)	0.244 (0.136)	-	0.726 (2.597)	-	0.112 (1.001)	0.145 (1.388)
% of Cars	0.857 (1.169)	0.141 (0.063)	-	1.362 (2.689)	-	-	-
% of Buses	-	0.273 (0.110)	-	-	-	-	-
% of 2W	-	-	-0.987 (-2.145)	-	-0.354 (-0.845)	-0.085 (-0.325)	-
% of 3W	-	-	-	-	-	-0.351 (-0.685)	-
Intercept	53.30	55.06	63.75	37.04	68.76	63.57	70.94
Sample Size	48	48	48	48	48	48	48
R^2	**0.893**	0.706	0.869	0.792	0.656	0.798	0.746
R	0.945	0.840	0.932	0.890	0.810	0.893	0.864

*Value in ( ) indicate t-value of the parameter

15-minutes average noise model for NH-65

LAeq (15 min) dB = 54.71+ 0.0232*Traffic Volume + 0.119*Average Traffic Speed+ 0.518* % of Heavy Vehicles + 0.218 *% of Cars + 0.448* % of Buses +0.156*% of 2W +0.754*% of 3W

$R^2 = 0.723$ (5.11)

LA10 (15 min) dB= 59.83+ 0.0032*Traffic Volume + 0.137*Average Traffic Speed+ 0.415* % of Heavy Vehicles + 0.359*% of Cars + 0.401* % of Buses +0.0309*% of 2W +0.915*% of 3W

$R^2 = 0.684$ (5.12)

1-hour average noise model for NH-65

LAeq (h) dB = 53.22+ 0.0089*Traffic Volume + 0.0049*Average Traffic Speed+ 0.625 *% of Cars+ 0.926* % of Cars

$R^2 = 0.901$ (5.13)

LA10 (h) dB = 53.30+ 0.0101*Traffic Volume + 0.146*Average Traffic Speed+ 0.525* % of Heavy Vehicles +0.857*% of Cars

$R^2 = 0.893$ (5.14)

5.3.3 Development of noise models for NH-44

Both Hyderabad-Nagpur highway and Hyderabad-Bengaluru highway field study data was collected. The collected data was averaged for 15 minutes time interval and 1-hour time intervals. Data sets were prepared for both A-Weighted equivalent noise level (LAeq) and A-Weighted sound level exceeded for 10% of the measurement time (LA10) values, and processed using SPSS package to develop linear noise models. Accordingly, the calibrated models for 15 minutes and 1-hour time intervals are presented in Table 5.9 to 5.12.

Table 5.9 Noise models for 15 min average LAeq for NH-44

Parameters	**Beta weights**						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0133 (2.489)	0.0148 (3.390)	-	0.00896 (1.325)	0.0101 (1.909)	-	0.0252 (3.3796)
Average Traffic Speed	0.063 (0.493)	-	0.241 (1.962)	0.145 (0.931)	0.102 (0.775)	-	0.0516 (0.831)
% of Heavy Vehicles	0.408 (1.168)	0.382 (1.131)	0.464 (1.164)	0.047 (1.063)	0.0874 (1.256)	0.354 (0.832)	0.055 (1.842)
% of Cars	0.394 (1.074)	0.377 (1.056)	0.419 (1.00)	0.0763 (0.626)	0.0457 (0.521)	0.342 (0.762)	0.363 (4.208)
% of Buses	0.351 (1.014)	0.327 (0.957)	0.400 (1.023)	-	-	0.295 (0.699)	0.128 (3.527)
% of 2W	0.521 (1.493)	0.505 (1.484)	0.496 (1.247)	-	-	0.398 (0.936)	-
% of 3W	0.521 (1.454)	0.507 (1.453)	0.485 (1.186)	0.290 (3.159)	0.290 (3.159)	0.391 (0.89)	0.577 (4.664)
Intercept	55.09	60.46	45.48	69.28	69.54	68.07	63.93
Sample Size	48	48	48	48	48	48	48
R^2	**0.679**	0.674	0.554	0.528	0.530	0.454	0.625
R	0.824	0.821	0.745	0.727	0.728	0.673	0.813

*Value in ( ) indicate t-value of the parameter

Table 5.10 Noise models for 15 min average LA10 for NH-44

Parameters	Beta weights						
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Traffic Volume	0.0178 (1.824)	0.0141 (2.669)	-	-	0.0087 (0.956)	-	0.0121 (1.887)
Average Traffic Speed	0.102 (0.656)	-	0.258 (1.873)	-	0.196 (1.085)	0.240 (1.759)	0.0908 (0.529)
% of Heavy Vehicles	0.411 (0.978)	0.369 (0.904)	0.460 (1.029)	0.342 (0.724)	0.0504 (0.398)	0.0270 (0.544)	0.0408 (0.448)
% of Cars	0.453 (1.029)	0.427 (0.989)	0.475 (1.012)	0.393 (0.788)	0.0466 (0.635)	0.1214 (0.329)	0.0662 (0.713)
% of Buses	.389 (0.934)	0.349 (0.863)	0.432 (0.975)	0.319 (0.681)	-	-	-
% of 2W	0.586 (1.399)	0.561 (1.369)	0.564 (1.265)	0.459 (0.971)	-	0.136 (1.708)	0.502 (2.453)
% of 3W	0.502 (1.167)	0.480 (1.140)	0.470 (1.027)	0.369 (0.761)	0.254 (2.327)	0.0373 (0.335)	0.114 (1.019)
Intercept	53.48	62.04	45.0	68.28	66.38	69.83	63.542
Sample Size	48	48	48	48	48	48	48
R^2	**0.656**	0.647	0.584	0.499	0.509	0.561	0.637
R	0.810	0.804	0.764	0.706	0.713	0.749	0.798

*Value in ( ) indicate t-value of the parameter

Table 5.11 Noise models for 1 h average LAeq for NH-44

Parameters	Beta weights						
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Traffic Volume	0.0239 (0.072)	0.0006 (0.502)	-	0.0001 (0.019)	0.0013 (0.140)	0.0019 (0.623)	-
Average Traffic Speed	0.904 (1.749)	0.905 (2.453)	0.896 (2.506)	0.995 (0.836)	0.876 (1.298)	0.739 (1.283)	0.921 (0.675)
% of Heavy Vehicles	0.0275 (0.134)	-	0.042 (0.529)	-	-	-	0.0322 (0.078)
% of Cars	0.167 (0.599)	0.146 (0.884)	0.179 (1.126)	0.153 (0.625)	0.132 (0.412)	0.179 (0.812)	0.174 (0.522)
% of Buses	-	-	-	0.0286 (0.084)	-	-	0.0072 (0.020)
% of 2W	-	-	-	-	0.0273 (0.065)	-	-
% of 3W	-	-	-	-	-	0.128 (0.492)	-
Intercept	52.38	53.22	52.41	47.71	54.25	59.43	51.13
Sample Size	48	48	48	48	48	48	48
R^2	0.920	0.919	0.892	0.914	0.919	**0.935**	0.885
R	0.959	0.959	0.944	0.957	0.959	0.967	0.931

*Value in ( ) indicate t-value of the parameter

Table 5.12 Noise models for 1 h average LA10 for NH-44

Parameters	Beta weights						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.00092 (0.216)	0.015 (1.159)	-	0.0027 (0.812)	0.0029 (0.646)	0.0014 (0.250)	0.0031 (0.535)
Average Traffic Speed	0.905 (1.677)	0.906 (2.324)	0.933 (0.567)	0.750 (1.208)	0.94 (2.106)	0.908 (0.736)	0.898 (1.240)
% of Heavy Vehicles	0.0399 (0.186)	-	0.0723 (0.152)	-	0.0205 (0.096)	-	-
% of Cars	0.118 (0.407)	0.0855 (0.509)	0.156 (0.432)	0.119 (0.503)	-	0.0875 (0.339)	-
% of Buses	-	-	0.0171 (0.039)	-	-	0.0007 (0.002)	-
% of 2W	-	-	-	-	-	-	0.0552 (0.182)
% of 3W	-	-	-	0.121 (0.431)	0.0949 (0.276)	-	0.0567 (0.172)
Intercept	55.73	57.00	52.89	60.87	51.10	56.86	56.12
Sample Size	48	48	48	48	48	48	48
R^2	**0.895**	0.892	0.888	0.909	0.882	0.892	0.880
R	0.946	0.730	0.942	0.953	0.941	0.944	0.939

*Value in ( ) indicate t-value of the parameter

15-minutes average noise model for NH-44

LAeq (15 min) dB= 55.09+ 0.0133*Traffic Volume + 0.0603*Average Traffic Speed+ 0.408* % of Heavy Vehicles + 0.394 *% of Cars + 0.351* % of Buses +0.521*% of 2W +0.521*% of 3W

$R^2 = 0.626$ (5.15)

LA10 (15 min) dB= 53.48+ 0.0178*Traffic Volume + 0.102*Average Traffic Speed+ 0.411* % of Heavy Vehicles + 0.453 *% of Cars + 0.389* % of Buses +0.586*% of 2W +0.502*% of 3W

$R^2 = 0.656$ (5.16)

1-hour average noise model for NH-44

LAeq (h) dB = 59.43+ 0.0019*Traffic Volume + 0.739*Average Traffic Speed + 0.179 *% of Cars+0.128*% of 3W

$R^2 = 0.935$ (5.17)

LA10 (h) dB = 60.87+ 0.0027*Traffic Volume + 0.750*Average Traffic Speed + 0.119 *% of Cars + 0.121*% of 3W

R^2 = 0.909 (5.18)

5.3.4 Development of noise models for NH-163

Hyderabad-Warangal highway field study data was averaged for 15 minutes and 1-hour time intervals. Data sets were prepared for both A-Weighted equivalent noise level (LAeq) and A-Weighted sound level exceeded for 10% of the measurement time (LA10) values, and processed using SPSS package to develop linear noise models. Accordingly, the calibrated models for 15 minutes and 1-hour time intervals are presented in Table 5.13 to 5.16.

Table 5.13 Noise models for 15 min average LAeq for NH-163

Parameters	**Beta weights**						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.00102 (0.284)	-	0.00294 (0.792)	0.0012 (0.364)	-	0.00087 (0.214)	-
Average Traffic Speed	0.195 (1.934)	0.203 (2.153)	-	0.198 (2.031)	-	0.229 (2.405)	0.209 (2.312)
% of Heavy Vehicles	0.283 (0.493)	0.321 (0.591)	0.426 (0.694)	0.124 (2.836)	0.563 (0.966)	0.0960 (2.412)	0.127 (3.016)
% of Cars	0.162 (0.277)	0.198 (0.358)	0.284 (0.455)	-	0.414 (0.694)	-	-
% of Buses	0.420 (0.739)	0.454 (0.841)	0.547 (0.892)	0.263 (5.317)	0.665 (1.143)	0.231 (5.405)	0.261 (5.438)
% of 2W	0.539 (0.941)	0.567 (1.034)	0.718 (1.179)	0.383 (3.765)	0.829 (1.414)	0.342 (3.508)	0.374 (3.882)
% of 3W	0.270 (0.450)	0.304 (0.530)	0.440 (0.687)	0.185 (1.147)	0.565 (0.920)	-	0.101 (1.220)
Intercept	55.44	51.85	50.43	68.25	38.72	63.10	67.25
Sample Size	24	24	24	24	24	24	24
R^2	**0.683**	0.681	0.609	0.652	0.594	0.653	0.679
R	0.826	0.825	0.780	0.805	0.771	0.808	0.824

*Value in ( ) indicate t-value of the parameter

Table 5.14 Noise models for 15 min average LA10 for NH-163

Parameters	Beta weights						
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Traffic Volume	0.0007 (0.203)	-	0.0033 (0.838)	-	0.001 (0.305)	0.0019 (0.575)	0.0039 (1.048)
Average Traffic Speed	0.262 (2.650)	0.267 (2.90)	-	-	0.266 (2.799)	0.307 (3.166)	-
% of Heavy Vehicles	0.295 (0.525)	0.321 (0.605)	0.487 (0.750)	0.640 (1.036)	0.0072 (1.686)	-	0.103 (2.120)
% of Cars	0.226 (0.397)	0.252 (0.466)	0.391 (0.592)	0.536 (0.848)	-	-	-
% of Buses	0.442 (0.794)	0.466 (0.882)	0.607 (0.943)	0.744 (1.206)	0.222 (4.576)	0.173 (4.248)	0.227 (4.001)
% of 2W	0.484 (0.862)	0.503 (0.938)	0.724 (1.124)	0.848 (1.365)	0.265 (2.654)	0.160 (1.952)	0.448 (3.025)
% of 3W	0.310 (0.528)	0.344 (0.595)	0.538 (0.794)	0.678 (1.047)	0.0998 (0.946)	0.0101 (0.069)	0.341 (1.680)
Intercept	54.88	52.41	48.15	35.05	66.79	69.45	66.20
Sample Size	24	24	24	24	24	24	24
R^2	**0.653**	0.652	0.500	0.480	0.649	0.591	0.490
R	0.808	0.807	0.707	0.692	0.806	0.768	0.700

*Value in ( ) indicate t-value of the parameter

Table 5.15 Noise models for 1 h average LAeq for NH-163

Parameters	Beta weights						
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Traffic Volume	0.0022 (0.625)	-	0.0023 (0.930)	-	-	-	0.0319 (0.346)
Average Traffic Speed	0.735 (1.205)	0.951 (2.274)	0.810 (2.102)	0.929 (1.990)	0.956 (1.288)	0.951 (2.274)	0.436 (0.332)
% of Heavy Vehicles	0.0373 (0.250)	0.0523 (0.434)	-	-	0.0625 (0.079)	0.0537 (0.434)	-
% of Cars	0.287 (1.580)	0.30 (1.998)	0.265 (2.273)	0.266 (1.983)	0.306 (0.565)	0.300 (1.98)	-
% of Buses	-	-	-	-0.0819 (-0.419)	0.0148 (0.012)	-	-
% of 2W	-	-	-	-	-	-	0.0506 (0.088)
% of 3W	-	-	-	-	-	-	-0.308 (-1.023)
Intercept	57.40	48.20	54.99	53.38	47.21	48.19	68.34
Sample Size	24	24	24	24	24	24	24
R^2	**0.914**	0.881	0.909	0.880	0.836	0.881	0.841
R	0.956	0.939	0.953	0.938	0.914	0.939	0.917

*Value in ( ) indicate t-value of the parameter

Table 5.16 Noise models for 1 h average LA10 for NH-163

Parameters	Beta weights						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0017 (0.437)	-	0.0018 (0.654)	0.0015 (1.159)	-	0.035 (0.526)	-
Average Traffic Speed	0.793 (1.047)	0.960 (1.905)	.835 (1.840)	0.906 (2.334)	0.961 (0.734)	0.619 (0.420)	0.927 (1.488)
% of Heavy Vehicles	0.0195 (0.103)	0.0358 (0.245)	-	-	0.0360 (0.035)	-	-
% of Cars	0.513 (2.248)	0.533 (3.085)	0.505 (3.340)	0.0855 (0.509)	0.534 (0.665)	0.245 (0.382)	0.507 (2.975)
% of Buses	-	-	-	-	0.016 (0.001)	-	-0.041 (-0.240)
% of 2W	-	-	-	-	-	-	-
% of 3W	-	-	-	-	-	-0.484 (-1.012)	-
Intercept	56.14	48.89	54.72	57.07	48.79	64.60	56.46
Sample Size	24	24	24	24	24	24	24
R^2	**0.887**	0.866	0.856	0.812	0.866	0.732	0.872
R	0.942	0.931	0.928	0.905	0.931	0.855	0.935

*Value in ( ) indicate t-value of the parameter

15-minutes average noise model for NH-163

LAeq (15 min) dB= 55.44+ 0.00102*Traffic Volume + 0.195*Average Traffic Speed+ 0.283* % of Heavy Vehicles + 0.162 *% of Cars + 0.420* % of Buses +0.539*% of 2W +0.270*% of 3W

$R^2 = 0.683$ (5.19)

LA10 (15 min) dB= 54.88+ 0.0007*Traffic Volume + 0.262*Average Traffic Speed+ 0.295* % of Heavy Vehicles + 0.226*% of Cars + 0.442* % of Buses +0.484*% of 2W +0.310*% of 3W

$R^2 = 0.653$ (5.20)

1-hour average noise model for NH-163

LAeq (h) = 57.40+ 0.00215*Traffic Volume + 0.735*Average Traffic Speed+ 0.0373 *% of Cars + 0.287* % of 3W

$R^2 = 0.914$ (5.21)

LA10 (h) dB = 56.14+ 0.0017*Traffic Volume + 0.793*Average Traffic Speed+ 0.0195* % of Heavy Vehicles +0.513 *% of Cars

$R^2 = 0.887$ (5.22)

5.4 City Noise Models

Noise models were developed for some of the important cities of Andhra Pradesh and Telangana, and are presented below. Each model was tested for the logical sign for every coefficient, and then student t-test values were compared with table values to know their significance of contribution in order to explain the variation in noise levels. Out of all models proposed, models with better R^2 value are selected. Non-parametric testing (chi-square test) was conducted for all the models to know the difference between observed and predicted values and to accept or reject the hypothesis.

5.4.1 Vijayawada city

Vijayawada- Kolkata highway and Vijayawada- Chennai highway field study data was averaged for 15 minutes and 1-hour time intervals. Data sets were prepared for both LAeq and LA10values and processed using the SPSS package to develop linear noise models. The calibrated models were the same as NH-5 noise models since only two locations were selected in the Vijayawada study, which was calibrated and presented in Table 5.1 to 5.4. Similarly, noise model equations for LAeq and LA10measurements for the 15 minute and 1-hour average values are presented in Equations (5.7) to (5.10).

5.4.2 Warangal city

Warangal- Khammam highway field study data was averaged for 15 minutes, and 1-hour time intervals and data sets were prepared for LAeq and LA10 values, which were processed using SPSS package to develop linear noise models. The calibrated models are presented in Table 5.17 to 5.20.

Table 5.17 Noise models for 15 min average LAeq for Warangal city

Parameters	Beta weights						
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Traffic Volume	0.026 (0.808)	0.0273 (0.888)	-	0.0013 (0.064)	-	0.004 (0.715)	0.023 (0.117)
Average Traffic Speed	0.0201 (0.217)	-	0.034 (0.378)	0.0031 (0.344)	0.0541 (0.645)	-	-
% of Heavy Vehicles	0.384 (2.054)	0.390 (2.170)	0.275 (2.143)	0.215 (2.813)	0.162 (4.056)	0.150 (3.011)	0.217 (2.926)
% of Cars	0.204 (0.99)	0.209 (1.056)	0.075 (0.583)	-	-	-0.014 (-0.21)	-
% of Buses	0.206 (1.245)	0.216 (1.388)	0.10 (1.001)	0.0619 (0.785)	-	-	0.0706 (0.969)
% of 2W	0.341 (1.397)	0.343 (1.448)	0.210 (1.162)	0.129 (1.094)	0.0939 (0.888)	0.058 (3.165)	0.124 (1.083)
% of 3W	0.543 (2.542)	0.42 (2.613)	0.419 (2.843)	0.352 (3.863)	0.322 (3.991)	0.280 (2.745)	0.342 (4.052)
Intercept	55.25	55.79	64.114	69.412	68.841	66.256	70.56
Sample Size	24	24	24	24	24	24	24
R2	**0.626**	0.625	0.610	0.603	0.587	0.572	0.60
R	0.791	0.790	0.781	0.776	0.766	0.763	0.775

*Value in ( ) indicate t-value of the parameter

Table 5.18 Noise models for 15 min average LA10 for Warangal city

Parameters	Beta weights						
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Traffic Volume	0.0269 (0.819)	0.0458 (0.237)	-	0.0281 (0.898)	-	0.0068 (0.321)	-
Average Traffic Speed	0.0196 (0.207)	0.0298 (0.320)	0.034 (0.370)	-	0.033 (0.368)	-	-
% of Heavy Vehicles	0.422 (2.210)	0.272 (3.504)	0.310 (2.360)	0.428 (2.333)	-	0.196 (2.824)	0.311 (2.427)
% of Cars	0.182 (0.865)	-	0.0488 (0.368)	0.187 (0.924)	0.271 (3.592)	-	0.0469 (0.366)
% of Buses	0.227 (1.342)	0.0983 (1.230)	0.187 (1.148)	0.236 (1.489)	0.0913 (1.263)	0.0478 (0.656)	0.124 (1.271)
% of 2W	0.425 (1.708)	0.237 (1.977)	0.290 (1.573)	0.427 (1.769)	0.238 (2.045)	-	0.282 (1.579)
% of 3W	0.334 (1.535)	0.164 (1.778)	0.207 (1.372)	0.334 (1.576)	0.163 (1.815)	0.0935 (1.089)	0.194 (1.356)
Intercept	58.12	65.92	62.161	58.39	66.367	72.79	65.82
Sample Size	24	24	24	24	24	24	24
R2	**0.592**	0.573	0.575	0.591	0.571	0.474	0.571
R	0.769	0757	0.758	0.768	0.756	0.689	0.756

*Value in ( ) indicate t-value of the parameter

Table 5.19 Noise models for 1 h average LAeq for Warangal city

Parameters	Beta weights						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0319 (1.712)	0.0321 (1.159)	-	0.0254 (1.076)	-	0.069 (0.717)	-
Average Traffic Speed	0.391 (2.571)	0.352 (1.161)	0.483 (2.094)	0.183 (0.963)	0.469 (0.923)	0.252 (0.708)	.271 (0.849)
% of Heavy Vehicles	0.383 (2.926)	0.319 (0.780)	0.391 (2.211)	-	0.372 (0.611)	-	0.172 (0.408)
% of Cars	-	0.179 (0.177)	-	0.884 (2.185)	0.0493 (0.611)	-	0.439 (0.411)
% of Buses	-	-	0.168 (0.975)	-	0.164 (0.602)	-	-
% of 2W	-	-	-	-	-	-0.832 (-0.65)	-
% of 3W	-	-	-	-	-	0.0567 (0.083)	-
Intercept	55.16	58.24	59.58	64.93	60.58	69.15	67.02
Sample Size	24	24	24	24	24	24	24
R^2	0.868	**0.872**	0.779	0.794	0.780	0.637	0.70
R	0.932	0.934	0.883	0.891	0.883	0.798	0.836

*Value in ( ) indicate t-value of the parameter

Table 5.20 Noise models for 1 h average LA10 for Warangal city

Parameters	Beta weights						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0364 (1.254)	-	0.135 (1.472)	0.0254 (1.085)	0.0364 (1.918)	-	0.0241 (0.771)
Average Traffic Speed	0.350 (1.056)	0.355 (0.689)	0.289 (1.029)	0.135 (0.731)	0.350 (2.239)	0.311 (1.186)	0.167 (0.635)
% of Heavy Vehicles	0.385 (0.819)	0.304 (0.464)	-	-	0.385 (2.934)	0.341 (1.434)	-
% of Cars	0.0429 (0.038)	0.217 (0.138)	-	0.881 (2.089)	-	-	0.930 (1.603)
% of Buses	-	0.157 (0.563)	-	-	-	-	0.0738 (0.350)
% of 2W	-	-	-2.093 (-1.42)	-	-	0.157 (1.057)	-
% of 3W	-	-	0.403 (0.767)	-	-	-	-
Intercept	58.13	59.38	63.96	67.42	58.14	64.28	66.59
Sample Size	24	24	234	24	24	24	24
R^2	**0.844**	0.696	0.795	0.740	0.840	0.576	0.795
R	0.919	0.834	0.892	0.860	0.916	0.759	0.892

*Value in ( ) indicate t-value of the parameter

15-minutes average noise model for Warangal city

LAeq (15 min) dB= 55.25+ 0.026*Traffic Volume + 0.0201*Average Traffic Speed+ 0.384* % of Heavy Vehicles + 0.204 *% of Cars + 0.206* % of Buses +0.341*% of 2W +0.543*% of 3W

$R^2 = 0.626$ (5.23)

LA10 (15 min) dB= 58.12+ 0.0269*Traffic Volume + 0.0196*Average Traffic Speed+ 0.422* % of Heavy Vehicles + 0.182 *% of Cars+ 0.227* % of Buses +0.425*% of 2W +0.334*% of 3W

$R^2 = 0.592$ (5.24)

1-hour average noise model for Warangal city

LAeq (h) dB = 58.24+ 0.0321*Traffic Volume + 0.352*Average Traffic Speed+ 0.319* % of Heavy Vehicles + 0.179 *% of Cars

$R^2 = 0.872$ (5.25)

LA10 (h) dB = 58.14+ 0.0364*Traffic Volume + 0.350*Average Traffic Speed+ 0.385* % of Heavy Vehicles + 0.0429* % of Cars

$R^2 = 0.844$ (5.26)

5.4.3 Hyderabad city

In Hyderabad, five important national highways, namely Hyderabad-Nagpur, Hyderabad-Vijayawada, Hyderabad- Pune, Hyderabad- Bengaluru, and Hyderabad- Warangal highways are selected for the study. Accordingly, field study data was averaged for 15 minutes and 1-hour time intervals. Data sets were prepared for both LAeq and LA10 values and processed using SPSS Package to develop linear noise models. The respective calibrated models are presented in Table 5.21 to 5.24.

Table 5.21 Noise models for 15 min average LAeq for Hyderabad city

Parameters	Beta weights						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.017 (1.385)	0.0179 (1.490)	0.0252 (3.796)	-	0.0267 (4.240)	-	0.0226 (3.245)
Average Traffic Speed	0.0485 (0.770)	-	0.0516 (0.831)	0.0579 (0.893)	-	0.118 (1.503)	0.0214 (0.312)
% of Heavy Vehicles	0.135 (1.288)	0.133 (1.283)	0.055 (1.842)	0.247 (3.544)	0.0474 (1.683)	0.0277 (0.724)	-
% of Cars	0.557 (2.162)	0.564 (2.218)	0.363 (4.208)	0.830 (4.868)	0.359 (4.198)	0.323 (2.850)	0.313 (3.588)
% of Buses	0.201 (2.036)	0.202 (2.068)	0.128 (3.527)	0.296 (4.002)	0.134 (3.477)	0.105 (1.689)	0.152 (2.965)
% of 2W	0.433 (0.799)	0.459 (0.859)	-	1.062 (3.488)	-	-	-
% of 3W	0.764 (2.883)	0.787 (3.025)	0.577 (4.664)	1.011 (5.025)	0.550 (4.843)	0.459 (2.903)	0.520 (4.076)
Intercept	57.89	59.67	63.94	36.02	66.87	61.12	65.21
Sample Size	116	116	116	116	116	116	116
R^2	**0.705**	0.694	0.693	0.669	0.685	0.433	0.632
R	0.904	0.833	0.833	0.818	0.825	0.658	0.795

*Value in ( ) indicate t-value of the parameter

Table 5.22 Noise models for 15 min average LA10 for Hyderabad city

Parameters	Beta weights						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0217 (1.438)	0.0223 (1.519)	0.03481 (4.203)	-	0.0357 (4.606)	-	0.0339 (4.172)
Average Traffic Speed	0.0248 (0.321)	-	0.0678 (0.584)	0.0362 (0.456)	-	-	0.0256 (0.334)
% of Heavy Vehicles	0.204 (1.579)	0.203 (1.614)	0.09631 (2.145)	0.347 (4.028)	0.0845 (2.147)	0.350 (4.169)	0.0875 (1.954)
% of Cars	0.397 (1.250)	0.400 (1.297)	0.0956 (0.885)	0.745 (3.536)	0.896 (0.852)	0.762 (2.760)	-
% of Buses	0.259 (2.129)	0.260 (2.190)	-	0.380 (4.158)	0.145 (3.198)	0.384 (4.329)	0.148 (3.125)
% of 2W	0.690 (1.033)	0.703 (1.084)	0.153 (3.241)	1.494 (3.968)	-	1.541 (4.349)	-
% of 3W	0.825	0.836	0.527	1.41	0.574	1.169	0.458

	(1.652)	(2.650)	(3.416)	(4.585)	(3.574)	(4.957)	(3.256)
Intercept	55.96	56.88	62.54	28.01	63.24	28.42	65.35
Sample Size	116	116	116	116	116	116	116
R^2	**0.653**	0.651	0.630	0.608	0.627	0.603	0.615
R	0.808	0.807	0.794	0.780	0.792	0.777	0.784

*Value in ( ) indicate t-value of the parameter

Table 5.23 Noise models for 1 h average LAeq for Hyderabad city

Parameters	**Beta weights**						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0069 (0.647)	0.0043 (0.282)	-	0.0268 (1.247)	0.0185 (3.40)	-	0.0136 (2.716)
Average Traffic Speed	0.491 (0.754)	0.638 (0.694)	-	0.356 (1.345)	-	0.883 (4.077)	-
% of Heavy Vehicles	0.263 (1.725)	0.281 (1.381)	0.516 (1.649)	-	0.196 (1.454)	0.312 (2.448)	0.250 (1.711)
% of Cars	-	0.145 (0.418)	0.373 (0.889)	0.221 (0.446)	0.125 (0.874)	0.185 (0.795)	0.235 (0.557)
% of Buses	-	-	-	0.014 (0.096)	-	-	-
% of 2W	-	-	1.519 (1.986)	-	-	-	-
% of 3W	-	-	0.347 (0.659)	-	-	-	0.217 (0.597)
Intercept	60.56	52.99	51.45	61.25	65.89	41.28	69.85
Sample Size	116	116	116	116	116	116	116
R^2	0.891	0.907	0.859	0.848	0.862	0.900	0.901
R	0.944	0.952	0.927	0.921	0.929	0.949	0.949

*Value in ( ) indicate t-value of the parameter

Table 5.24 Noise models for 1 h average LA10 for Hyderabad city

Parameters	**Beta weights**						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0049 (0.328)	0.0084 (0.774)	-	-	0.0544 (3.125)	-	-
Average Traffic Speed	0.574 (0.640)	0.387 (0.586)	0.724 (1.707)	0.852 (3.994)	-	0.704 (0.744)	-
% of Heavy Vehicles	0.329 (1.681)	0.312 (2.019)	0.318 (1.627)	0.362 (2.884)	0.258 (2.191)	0.421 (1.325)	0.588 (2.635)
% of Cars	0.207 (.531)	-	-	0.262 (1.004)	-	-	0.413 (1.130)
% of Buses	-	-	-0.051 (-0.415)	-	-	-	-
% of 2W	-	-	-	-	-	0.327 (0.178)	1.599 (2.922)

% of 3W	-	-	-	-	0.256 (0.745)	-	0.153 (0.443)
Intercept	55.53	62.292	58.83	42.05	65.43	49.20	50.52
Sample Size	116	116	116	116	116	116	116
R^2	0.907	0.881	0.858	0.897	0.874	0.848	0.885
R	0.953	0.939	0.926	0.947	0.935	0.921	0.942

*Value in ( ) indicate t-value of the parameter

15-minutes average noise model for Hyderabad city

LAeq (15 min) dB= 57.89+ 0.017*Traffic Volume + 0.0485*Average Traffic Speed+ 0.135* % of Heavy Vehicles + 0.557 *% of Cars + 0.201* % of Buses +0.423*% of 2W +0.764*% of 3W

R^2 = 0.705 (5.27)

LA10 (15 min) dB= 55.96+ 0.0217*Traffic Volume + 0.0248*Average Traffic Speed+ 0.204* % of Heavy Vehicles + 0.397*% of Cars + 0.259* % of Buses +0.690*% of 2W +0.825*% of 3W

R^2 = 0.653 (5.28)

1-hour average noise model for Hyderabad city

LAeq (h) dB = 52.99+ 0.0043*Traffic Volume + 0.638*Average Traffic Speed+ 0.281 *% of Cars + 0.145* % of 3W

R^2 = 0.907 (5.29)

LA10 (h) dB = 55.53+ 0.00497*Traffic Volume + 0.574*Average Traffic Speed+ 0.329* % of Heavy Vehicles +0.207 *% of Cars

R^2 = 0.907 (5.30)

5.5 Individual Highway Noise Models

Noise models were developed for some of the important highways in Andhra Pradesh and Telangana and are presented below.

5.5.1 Vijayawada-Kolkata highway

Vijayawada-Kolkata highway field study data was averaged for 15 minutes and 1-hour time intervals. Data sets are prepared for both LAeq and LA10 values and processed using SPSS package to develop linear noise models. The calibrated models are presented below.

15-minutes average noise model for Vijayawada-Kolkata highway

LAeq (15 min) dB= 53.69+ 0.0221*Traffic Volume + 0.209*Average Traffic Speed+ 0.389* % of Heavy Vehicles + 0.368 *% of Cars+ 0.306* % of Buses +0.128*% of 2W +0.418*% of 3W

$R^2 = 0.620$ (5.31)

LA10 (15 min) dB= 56.21+ 0.0215*Traffic Volume + 0.0602*Average Traffic Speed+ 0.467* % of Heavy Vehicles + 0.488*% of Cars + 0.366* % of Buses +0.240*% of 2W +0.419*% of 3W

$R^2 = 0.638$ (5.32)

1-hour average noise model for Vijayawada-Kolkata highway

LAeq (h) dB = 43.02+ 0.00174*Traffic Volume + 0.381*Average Traffic Speed+ 0.729 *% of Heavy Vehicles + 0.697* % of 3W

$R^2 = 0.888$ (5.33)

LA10 (h) dB = 53.52+ 0.00074*Traffic Volume + 0.219*Average Traffic Speed+ 0.806* % of Heavy Vehicles +0.138 *% of Cars

$R^2 = 0.832$ (5.34)

5.5.2 Vijayawada-Chennai highway

Vijayawada-Chennai highway field study data was averaged for 15 minutes and 1-hour time intervals. Data sets were prepared for both LAeq and LA10 values and processed using SPSS package to develop linear noise models. The calibrated models are presented below.

15-minutes average noise model for Vijayawada-Chennai highway

LAeq (15 min) dB= 57.74+ 0.0113*Traffic Volume + 0.135*Average Traffic Speed+ 0.281* % of Heavy Vehicles + 0.675 *% of Cars + 0.490* % of Buses +0.259*% of 2W +0.738*% of 3W

$R^2 = 0.630$ (5.35)

LA10 (15 min) dB= 56.28+ 0.0081*Traffic Volume + 0.0247*Average Traffic Speed+ 0.366* % of Heavy Vehicles + 0.754*% of Cars + 0.566* % of Buses +0.435*% of 2W +0.749*% of 3W

$R^2 = 0.642$ (5.36)

1-hour average noise model for Vijayawada-Chennai highway

LAeq (h) dB = 55.37+ 0.0293*Traffic Volume + 0.361*Average Traffic Speed+ 0.0865 *% of Heavy Vehicles + 0.383* % of Cars

$R^2 = 0.867$ (5.37)

LA10 (h) dB = 58.80+ 0.0339*Traffic Volume + 0.269*Average Traffic Speed+ 0.135* % of Heavy Vehicles +0.131 *% of Cars

$R^2 = 0.869$ (5.38)

5.5.3 Warangal- Khammam highway

Warangal- Khammam highway field study data was averaged for 15 minutes and 1-hour time intervals and data sets were prepared for LAeq and LA10values which were processed using SPSS package to develop linear noise models. The calibrated models are already presented in Table 5.17 to 5.20.

5.5.4 Hyderabad-Nagpur highway

Hyderabad- Nagpur highway field study data was averaged for 15 minutes and 1-hour time intervals and the data sets were prepared for LAeq and LA10values which were processed using SPSS package to develop linear noise models. The calibrated models are presented below.

15-minutes average noise model for Hyderabad- Nagpur highway

LAeq (15 min) dB= 54.96+ 0.0154*Traffic Volume + 0.126*Average Traffic Speed+ 0.455* % of Heavy Vehicles + 0.256 *% of Cars + 0.439* % of Buses +0.456*% of 2W +0.399*% of 3W

R^2 = 0.653 (5.39)

LA10 (15 min) dB= 55.54+ 0.0159*Traffic Volume + 0.260*Average Traffic Speed+ 0.380* % of Heavy Vehicles + 0.218*% of Cars+ 0.395* % of Buses +0.425*% of 2W +0.396*% of 3W

R^2 = 0.648 (5.40)

1-hour average noise model for Hyderabad- Nagpur highway

LAeq (h) dB = 53.53+ 0.0024*Traffic Volume + 0.821*Average Traffic Speed+ 0.310 *% of Heavy Vehicles + 0.00864* % of Cars

R^2 = 0.879 (5.41)

LA10 (h) dB = 55.04+ 0.0078*Traffic Volume + 0.828*Average Traffic Speed+ 0.329 *% of Heavy Vehicles + 0.0145* % of Cars

R^2 = 0.879 (5.42)

5.5.5 Hyderabad-Vijayawada highway

Hyderabad- Vijayawada highway field study data was averaged for 15 minutes and 1-hour time intervals and data sets were prepared for LAeq and LA10values which were processed using SPSS package to develop linear noise models. The calibrated models for 15 minutes and 1-hour time intervals are presented below.

15-minutes average noise model for Hyderabad- Vijayawada highway

LAeq (15 min) dB= 56.02+ 0.0231*Traffic Volume + 0.0921*Average Traffic Speed+ 0.423* % of Heavy Vehicles + 0.438 *% of Cars + 0.584* % of Buses +0.391*% of 2W +0.211*% of 3W

R^2 = 0.682 (5.43)

LA10 (15 min) dB= 52.66+ 0.0021*Traffic Volume + 0.213*Average Traffic Speed+ 0.429* % of Heavy Vehicles + 0.468*% of Cars+ 0.602* % of Buses +0.301*% of 2W +0.162*% of 3W

R^2 = 0.683 (5.44)

1-hour average noise model for Hyderabad- Vijayawada highway

LAeq (h) dB = 57.61+ 0.0121*Traffic Volume + 0.0135*Average Traffic Speed+ 0.641 *% of Heavy Vehicles + 0.607* % of Cars

R^2 = 0.881 (5.45)

LA10 (h) dB = 58.92+ 0.01286*Traffic Volume + 0.009*Average Traffic Speed+ 0.489 *% of Heavy Vehicles + 0.754* % of Cars

R^2 = 0.873 (5.46)

5.5.6 Hyderabad-Bengaluru highway

Hyderabad- Bengaluru highway field study data was averaged for 15 minutes and 1-hour time intervals and the data sets were prepared for LAeq and LA10values which were processed using SPSS package to develop linear noise models. The calibrated models are presented below.

15-minutes average noise model for Hyderabad- Bengaluru highway

LAeq (15 min) dB= 57.65+ 0.0191*Traffic Volume + 0.0531*Average Traffic Speed+ 0.135* % of Heavy Vehicles + 0.557 *% of Cars+ 0.212* % of Buses +0.441*% of 2W +0.723*% of 3W

R^2 = 0.676 (5.47)

LA10 (15 min) dB= 55.86+ 0.0021*Traffic Volume + 0.0242*Average Traffic Speed+ 0.214* % of Heavy Vehicles + 0.356*% of Cars+ 0.267* % of Buses +0.685*% of 2W +0.746*% of 3W

R^2 = 0.668 (5.48)

1-hour average noise model for Hyderabad- Bengaluru highway

LAeq (h) dB = 52.35+ 0.0197*Traffic Volume + 0.0161*Average Traffic Speed+ 0.365 *% of Heavy Vehicles

R^2 = 0.898 (5.49)

LA10 (h) dB = 51.24+ 0.0307*Traffic Volume + 0.152*Average Traffic Speed+ 0.0057 *% of Heavy Vehicles

R^2 = 0.890 (5.50)

5.5.7 Hyderabad-Pune highway

Hyderabad- Pune highway field study data was averaged for 15 minutes and 1-hour time intervals and the data sets were prepared for LAeq and LA10values which were processed using the SPSS package to develop linear noise models. The calibrated models are presented below.

15-minutes average noise model for Hyderabad- Pune highway

LAeq (15 min) dB = 58.10+ 0.0101*Traffic Volume + 0.293*Average Traffic Speed+ 0.256* % of Heavy Vehicles + 0.201 *% of Cars + 0.171* % of Buses +0.198*% of 2W +0.462*% of 3W

R^2 = 0.714 (5.51)

LA10 (15 min) dB= 52.83+ 0.0184*Traffic Volume + 0.434*Average Traffic Speed+ 0.185* % of Heavy Vehicles + 0.310*% of Cars + 0.149* % of Buses +0.0976*% of 2W +0.456*% of 3W

R^2 = 0.686 (5.52)

1-hour average noise model for Hyderabad- Pune highway

LAeq (h) dB = 57.53+ 0.0046*Traffic Volume + 0.649*Average Traffic Speed+ 0.0064 *% of Heavy Vehicles + 0.206* % of Cars

R^2 = 0.918 (5.53)

LA10 (h) dB = 56.92+ 0.0061*Traffic Volume + 0.490*Average Traffic Speed+ 0.173 *% of Heavy Vehicles + 0.556* % of Cars

R^2 = 0.895 (5.54)

5.5.8 Hyderabad-Warangal highway

Hyderabad-Warangal highway field study data was averaged for 15 minutes and 1-hour time intervals and data sets were prepared for LAeq and LA10values which were processed using SPSS package to develop linear noise models. The calibrated models are already presented in Table 5.13 to 5.16. Noise model equations for LAeq and LA10 15 min and 1-h time intervals are already presented in Equations (5.19) to (5.22).

5.6 Comprehensive Noise Model

Field data collected at all study locations was taken and averaged for 15 minutes and a 1-hour interval. Accordingly, data sets were prepared for both LAeq and LA10 values and processed using SPSS Package to develop linear noise models. The calibrated models are presented in Tables 5.25 to 5.28.

Table 5.25 Comprehensive noise models for 15 min average LAeq

Parameters	**Beta weights**						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0147 (2.335)	0.0168 (2.606)	0.009 (1.178)	0.008 (1.262)	-	0.0132 (1.667)	0.008 (1.114)
Average Traffic Speed	0.134 (1.653)	-	0.122 (1.140)	0.111 (1.229)	0.173 (1.943)	-	0.134 (1.229)
% of Heavy Vehicles	0.356 (4.543)	0.343 (4.191)	0.199 (2.272)	0.244 (3.449)	0.243 (3.511)	0.241 (3.356)	0.195 (2.452)
% of Cars	0.275 (3.402)	0.275 (3.241)	0.159 (1.609)	0.202 (2.393)	0.221 (2.539)	0.207 (2.421)	-
% of Buses	0.505 (5.071)	0.444 (4.101)	-	0.377 (3.983)	0.441 (4.101)	0.334 (3.745)	0.262 (2.965)
% of 2W	0.345 (3.721)	0.339 (3.487)	0.284 (2.682)	0.309 (2.988)	0.298 (2.930)	0.306 (2.923)	0.224 (2.051)
% of 3W	0.296 (2.381)	0.272 (2.10)	0.219 (1.349)	-	0.167 (1.334)	-	0.136 (0.929)
Intercept	55.23	61.74	65.11	64.37	65.38	66.37	66.23
Sample Size	188	188	188	188	188	188	188
R^2	**0.641**	0.579	0.574	0.518	0.518	0.470	0.381
R	0.800	0.761	0.730	0.720	0.720	0.686	0.617

*Value in ( ) indicate t-value of the parameter

Table 5.26 Comprehensive noise models for 15min average LA10

Parameters	Beta weights						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0116 (1.522)	-	0.0182 (2.22)	0.0113 (1.416)	-	0.0053 (0.625)	-
Average Traffic Speed	0.252 (2.519)	0.305 (3.123)	-	0.258 (2.463)	0.309 (3.057)	0.261 (2.198)	0.287 (2.627)
% of Heavy Vehicles	0.358 (4.415)	0.295 (4.070)	0.353 (3.804)	0.299 (3.938)	0.239 (3.685)	0.281 (3.111)	0.255 (3.226)
% of Cars	0.152 (1.626)	0.149 (1.532)	0.161 (1.498)	-	-	0.124 (1.039)	0.115 (1.07)
% of Buses	0.469 (4.469)	0.471 (4.329)	0.365 (3.301)	0.362 (4.229)	0.367 (4.173)	0.403 (3.332)	0.410 (3.458)
% of 2W	0.384 (3.045)	0.373 (2.851)	0.340 (2.385)	0.307 (2.506)	0.297 (2.367)	0.420 (2.822)	0.411 (2.824)
% of 3W	0.331 (2.799)	0.279 (2.372)	0.340 (2.507)	0.303 (2.472)	0.252 (2.096)	-	-
Intercept	55.07	58.29	64.12	61.49	63.40	61.43	62.37
Sample Size	188	188	188	188	188	188	188
R^2	**0.654**	0.604	0.517	0.597	0.549	0.484	0.473
R	0.809	0.777	0.719	0.772	0.741	0.696	0.687

*Value in ( ) indicate t-value of the parameter

Table 5.27 Comprehensive noise models for 1 h average LAeq

Parameters	Beta weights						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0199 (1.297)	0.0328 (1.522)	0.033 (3.093)	0.0301 (0.786)	-	0.0241 (1.215)	-
Average Traffic Speed	0.292 (1.059)	0.041 (0.111)	-	0.171 (0.321)	0.708 (1.961)	0.181 (0.526)	0.579 (3.168)
% of Heavy Vehicles	-	-	-	0.0691 (0.316)	0.0181 (0.089)	-	-
% of Cars	0.311 (1.651)	-	-	0.328 (1.268)	0.458 (1.308)	-	0.406 (2.112)
% of Buses	-	-	-0.177 (-0.92)	-	0.254 (0.599)	-	-
% of 2W	-	-0.224 (-1.01)	-	-	-	-	-
% of 3W	-	0.084 (0.607)	0.093 (0.854)	-	-	0.116 (0.849)	-
Intercept	63.19	70.38	68.04	56.32	55.26	69.25	66.28
Sample Size	188	188	188	188	188	188	188
R^2	0.882	0.898	0.836	**0.892**	0.872	0.795	0.782
R	0.939	0.934	0.914	0.945	0.934	0.891	0.875

*Value in ( ) indicate t-value of the parameter

Table 5.28 Comprehensive noise models for 1 h average LA10

Parameters	**Beta weights**						
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**
Traffic Volume	0.0345 (1.234)	-	0.0372 (2.750)	0.0385 (2.080)	0.0416 (2.253)	0.0366 (1.597)	0.039 (1.867)
Average Traffic Speed	0.133 (0.641)	0.700 (0.827)	0.147 (1.436)	-	-	0.0489 (0.311)	-
% of Heavy Vehicles	0.328 (0.984)	0.194 (0.406)	0.370 (2.094)	0.306 (1.239)	0.342 (1.575)	0.311 (1.049)	0.312 (1.117)
% of Cars	0.093 (0.766)	0.268 (0.876)	-	-	-	-	0.052 (0.597)
% of Buses	-	0.197 (0.614)	-	-	-	-	-
% of 2W	-	-	0.0592 (2.181)	-	-	-	-
% of 3W	-	-	-	-	.042 (1.394)	-	-
Intercept	55.27	57.79	51.01	60.69	55.66	59.84	58.98
Sample Size	188	188	188	188	188	188	188
R^2	0.906	0.811	**0.934**	0.843	0.920	0.850	0.867
R	0.952	0.901	0.987	0.918	0.959	0.922	0.931

*Value in ( ) indicate t-value of the parameter

15-minutes average comprehensive noise model

LAeq (15 min) dB= 55.23+ 0.0147*Traffic Volume + 0.134*Average Traffic Speed+ 0.356* % of Heavy Vehicles + 0.275 *% of Cars + 0.505* % of Buses +0.345*% of 2W +0.296*% of 3W

$R^2 = 0.641$ (5.55)

LA10 (15 min) dB= 55.07+ 0.0116*Traffic Volume + 0.252*Average Traffic Speed+ 0.358* % of Heavy Vehicles + 0.152 *% of Cars + 0.469* % of Buses +0.384*% of 2W +0.331*% of 3W

$R^2 = 0.654$ (5.56)

1-hour average comprehensive noise model

LAeq (h) dB = 56.32+ 0.0301*Traffic Volume + 0.171*Average Traffic Speed+ 0.0691* % of Heavy Vehicles + 0.328 *% of Cars

$R^2 = 0.892$ (5.57)

LA10 (h) dB = 51.071+ 0.0372*Traffic Volume + 0.147*Average Traffic Speed+ 0.370* % of Heavy Vehicles +0.0592*% of 2W

R^2 = 0.934 (5.58)

The following observations are made based on the models presented in Tables 5.25 to 5.28.

i. Noise levels increased with an increase in the speed of the vehicle.
ii. It is observed that the percentage of heavy vehicles, the percentage of cars, the percentage of two-wheelers and three-wheelers had a prominent influence on traffic noise.
iii. R^2 values are observed to increase in the 1-hour model compared to the 15-minute interval model. It indicates that the data averaged over the one-hour interval is closer to reality than 15-minute interval data.

One hundred eighty sample observations within the noise data collected from all the highway sections were utilized to check the validity of the comprehensive model developed in this study. Non-parametric testing (chi-square test) for all models was conducted to know the difference between observed and predicted values. Accordingly, the Chi-square test (χ^2) was performed between the observed and predicted values of LAeq (dB), where χ^2 (calculated) appeared to be 22.825 and χ^2 (Critical) at 5% level of significance was 69.90. Since the χ^2 (calculated) is less than χ^2 (critical), it can be concluded that the difference between observed and predicted values is insignificant, shown in Figure5.1.

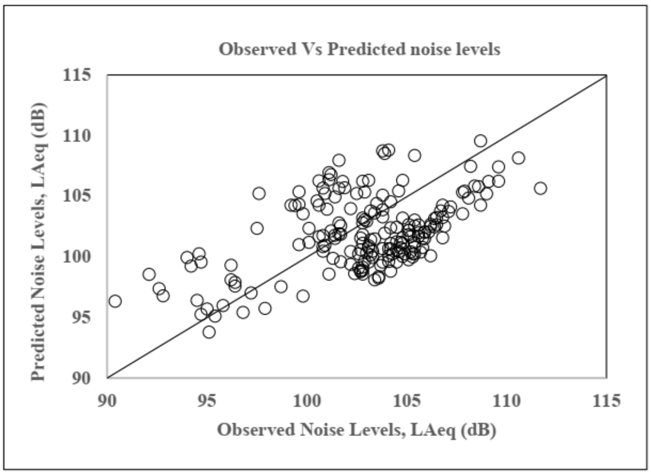

Figure 5.1 Observed v/s predicted noise level LAeq (dB) for the developed model.

Overall, a comparison can be made with the developed comprehensive model in the current study with some of the models developed over the years in India. In earlier years, researchers (Gupta et al. 1984; Raghavachari and Narsimhamurthy, 1986; Rao, 1997) reported that, along with the vehicular characteristics, traffic and roadway parameters will affect the traffic noise levels. By considering the effect of these parameters, Lokhande et al. (2018) focussed on comparing the geographical transferability of Federal Highway Administration (FHWA) Model. Further, suggested the applicability of FHWA model in Indian conditions, and concluded that minimizing the speed limits on highways can be a constructive means of reducing the traffic noise at urban units. Agarwal and Swami (2011) was focussed on capturing the traffic noise levels in the commercial zones of the urban areas of Jaipur city in India where, a regression model was developed to represent the Leq (dB) from traffic volume and traffic speed. Traffic speed variation is huge and the respective noise levels exceeded the local noise limits. Moreover, contribution from the heavy vehicles on the measured noise levels was observed to be significant in their study. This shows the necessity of considering the proportion of the vehicles in order to develop the traffic noise prediction models for any road. On the whole, the mixed traffic will affect the noise levels from both the corners of volume and speeds. As each type of vehicle can generate different noise levels at the same speeds, consideration of independent proportion of vehicles in quantifying the noise levels is necessary while considering the broad range of speeds occurring on highways, which is lacking in the most of the previous studies. Thus, the current study developed the noise prediction model by considering the wider spectrum of vehicle speeds along with consideration of independent proportion of vehicle mix in heterogeneous traffic conditions.

5.7 Model Development for the Heterogeneous Traffic Noise Data Collected at the Rotaries

Data related to vehicle volume and honking were collected and analyzed using noise tools software for assessing the effect of traffic noise pollution on roadusers near rotaries. It is observed that the proportion of heavy vehicles, speed, and honking was increasing traffic noise levels.

The results obtained were compared with LAeq (dB) levels, including heavy vehicle contribution using noise tools, and statistical significance was checked using SPSS through t-test, where the p-value obtained was less than 0.05. It concludes that both noise level variations are significant and the respective noise level comparison is shown in Figure 5.2

Table 5.29 Analysis of noise levels based on vehicle volume for HV, and LV+MV

Noise Coefficients				
Independent Variable	**Unstandardized Coefficients**		**t**	**p-value**
	Values	**Std. Error**		
Constant	69.990	1.839	38.05	0.00
HV (15 min.)	0.333	0.047	7.10	0.00
LV+MV (15 min.)	0.004	0.003	1.41	0.18

As shown in Table 5.29, the “p-value” is less than 0.05 for Heavy Vehicles [HV], and "p-value" is greater than 0.05 for a combination of Light and Medium vehicles. Thus, there is a notable impact of heavy vehicles in response to equivalent noise level [LAeq (dB)] in traffic [Confidence Interval (CI) 95%]. Hence, a new regression equation is developed by dropping vehicle volume of low and medium classes, and a linear model is developed for 15 minute time interval for estimating the equivalent noise level [LAeq (dB)] by using heavy vehicle volume alone for four-hour traffic noise data at one town police station rotary as shown by Equation (5.59). As shown in Table 5.30, the “p-value” is less than 0.05 for Heavy vehicles [HV]. Thus, there is a notable impact of heavy vehicles on the response of equivalent noise level [LAeq (dB)] from traffic [Confidence Interval (CI) 95%].

$$LAeq\ (dB)\ (15min.) = 72.37+0.32 \times HV \qquad (5.59)$$

Table 5.30 Analysis of noise levels based on vehicle volume for HV alone

Noise Coefficients				
Independent Variable	**Unstandardized Coefficients**		**t**	**p-value**
	Values	**Std. Error**		
Constant	72.37	0.743	97.43	0.00
HV (15 min)	0.320	0.047	6.73	0.00

The developed model is validated for traffic data collected at court chowrasta rotary, and the comparison between the observed and predicted noise levels is shown in Figure 5.2.

Statistical test of significance (p-value obtained is 0.318, which is greater than 0.05) was checked using the Bland Altman method in the Microsoft Excel tool XLSTAT. The analysis shows that the model can be used effectively for predicting the traffic noise levels for the rotaries having similar characteristics.

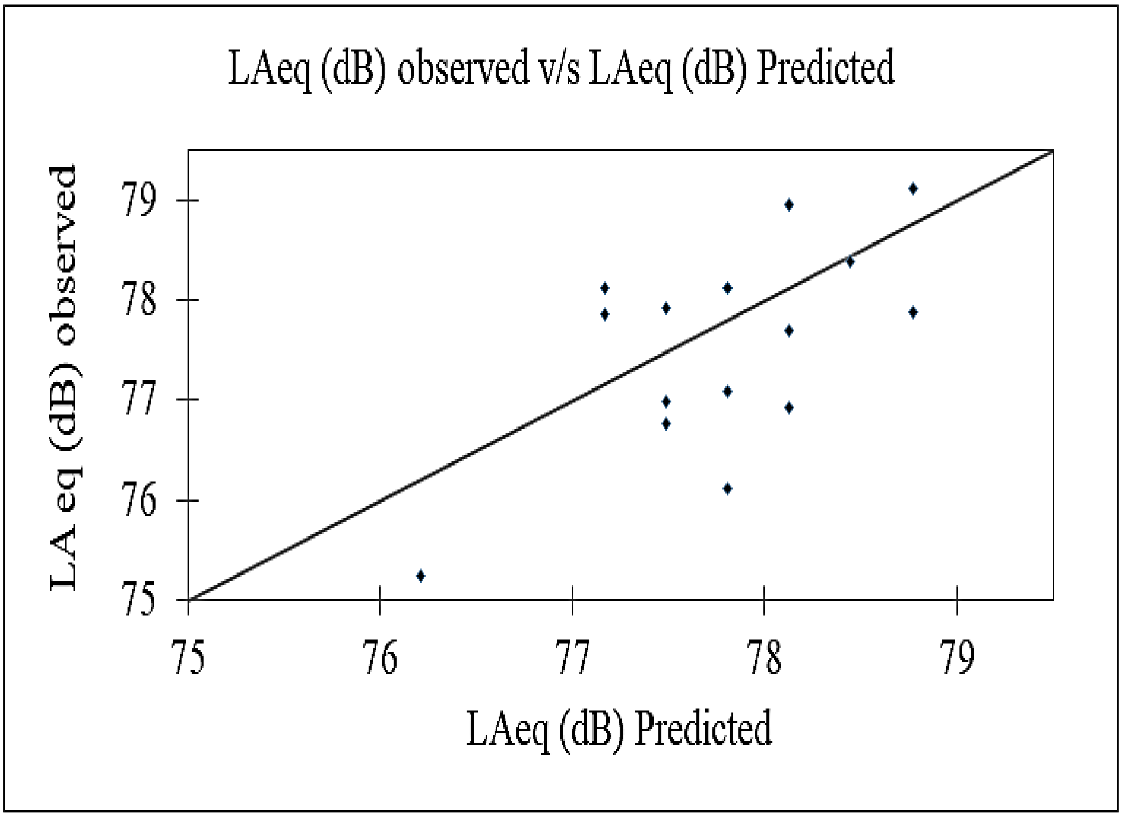

Figure 5.2 Observed v/s predicted noise level LAeq (dB) for the developed model at court chowrasta

5.8 Correlation between the Measured Tire-Pavement Interaction Noise Levels in Coast-By Method and Estimated Tire-Pavement Interaction Noise Levels through Developed Integrated Jack Method

To determine the correlation, a comparative analysis was made for both test vehicles (car-2 and car-3). The correlation obtained for car-2 and car-3 is 0.965, as shown in Figures 5.3 and 5.4, respectively. Measurements conclude that a significant relationship exists between the tire-pavement interaction noise levels quantified from both the methods.

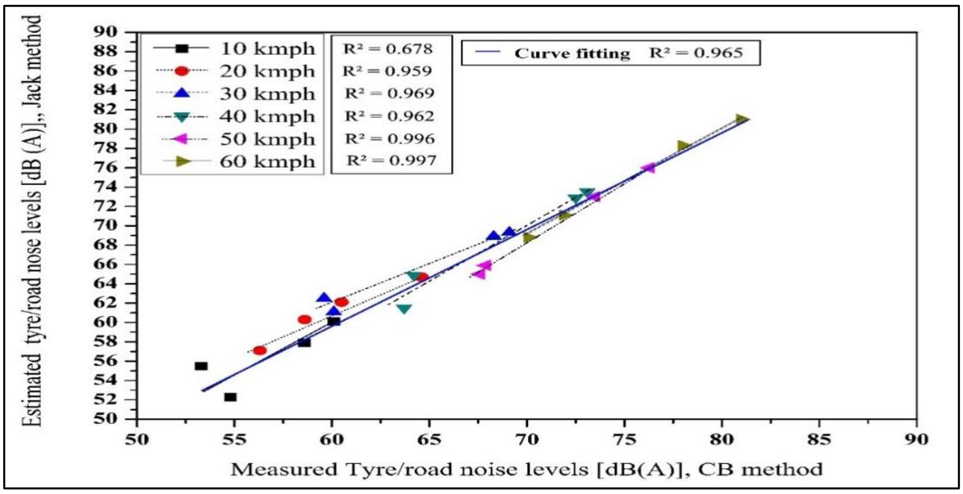

Figure 5.3 Correlation between measured tire-pavement interaction noise levels between coast-by and jack methods for car-2

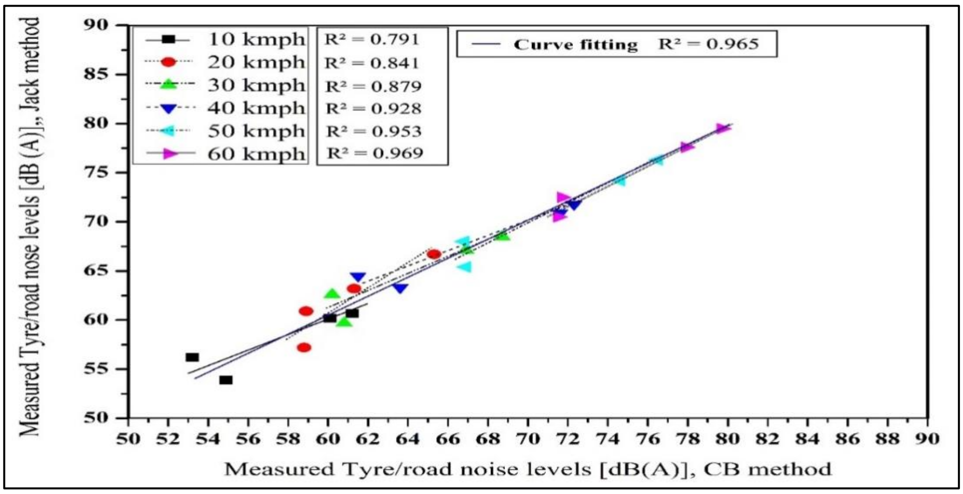

Figure 5.4 Correlation between measured tire-pavement interaction noise levels between coast-by and jack methods for car-3

5.9 Statistical Significance Check Using the Student t-test on the In-Vehicle Noise Data

The entire in-vehicle noise data collected using handheld SLM-1 and stabilizer mounted SLM-2 in the current study is checked for statistical significance using the Student t-test. Irrespective of the type of pavement surface and the windows open or windows closed condition, the t-statistic value was very much higher than the t-critical value, as shown in Table 5.31.

Table 5.31 Analysis of noise levels based on Student t-test

Reference variable	Variable 1	Variable 2	t-statistic	t-critical
-	Handheld SLM-1	Stabilizer SLM-2	15.70	1.703
SLM-2	Windows Open	Windows Closed	4.791	1.771
SLM-2/ Windows closed	CC Pavement	Asphalt Pavement	8.864	2.015
SLM-2/ Windows open	CC Pavement	Asphalt Pavement	9.822	2.015

This validates that the noise levels measured using the handheld SLM-1 are significantly different from the noise levels measured using stabilizer mounted SLM-2. Thus, SLM-2 data is further analyzed in both the windows open, and windows closed conditions. It can be observed from Table 5.31 that the t-statistic value is greater than the t-critical value. Further, a significant difference is observed between the noise levels measured on cement concrete pavements and the asphalt pavements with both windows closed and windows open conditions. This shows that apart from the type of sound level meter mounting and windows open or windows closed conditions, the type of pavement also plays a significant role in the generation of in-vehicle noise, especially due to tire-pavement interaction.

5.10 Summary

It is observed that vehicle type and the noise sources from a moving vehicle are proven to be significant sources on both roadusers and commuters. Accordingly, noise prediction models were developed for heterogeneous traffic noise levels, which have proven to be effective when checked for validation. Moreover, the method developed for measuring noise levels has proved to be effective when compared to the standard CB method. Similarly, measurement methodology introduced in the current study for in-vehicle noise levels due to tire-pavement interaction has proved to be effective in reducing vibrations on the measuring equipment. Further, conclusions drawn from the current study are discussed in detail in the next chapter.

CHAPTER 6
SUMMARY AND CONCLUSIONS

6.1 Summary

The complexity of heterogeneous traffic for variation in vehicle speeds is different from that of homogenous traffic. With the presence of various vehicle sizes, different engine characteristics, and maneuvering abilities, the road traffic movements result in a vast spectrum of noise levels. Moreover, vehicle speeds have a direct relationship with principal noise sources, which generates noise from vehicular movement making heterogeneous traffic noise generation into a more complex phenomenon compared to homogeneous traffic. Thus, there is a need for traffic noise prediction models and assessment of the effect of dominant noise sources for mixed traffic conditions. As the speeds in midblock are different from urban units such as rotaries, study areas are considered at both midblock and rotaries to assess the impact of vehicular movement assessed on overall noise levels. It is observed that a combination of volume proportion and vehicle speeds would play a significant role in highway noise level generation. Moreover, even though traffic calming can be achieved with reduced speeds and steady flows at rotaries, heavy vehicles in the traffic stream can affect noise levels to a great extent with their honks and high engine noise at low speeds. These results summarise the impact of noise sources arising from vehicle and speeds on noise generation. Thus, with an added advent to the standard pass-by methods by using the vehicle jack, the tire-pavement interaction and propulsion noise levels are measured in this study. Correlation proved to be strong at all the vehicle speeds between the method developed and the standard coast-by method. It is also clearly observed that tire-pavement interaction noise is a significant noise source at higher speeds (≥40 kmph), and propulsion noise proved to be a dominant source of noise at lower speeds (<40 kmph). Moreover, tire-pavement interaction and vehicle noise levels were reaching a similar edge on fine-tuned A-weighted noise levels at speeds exceeding 60 kmph for all selected test vehicles. This shows the dominance of tire-pavement interaction noise on overall noise levels. Thus, the pavement effect is checked for understanding noise level generation. It is observed that cross-over speeds for test vehicles fall between 30kmph to 50 kmph on asphalt pavements, and 20 kmph to 30kmph on cement concrete pavements. This shows the effect of pavement type on tire-pavement interaction noise levels and on overall noise levels experienced by roadusers. Thus, the effect of tire-pavement interaction noise experienced by the commuter was also checked with the development of a method for reducing the effect of vibrations on measured noise levels. Results revealed that the tire-pavement interaction noise alone could generate LAeq of 61 dB to 71 dB for commuters at moderate road speeds. Overall, the heterogeneous traffic noise level variation (96.5 dB to 107.1 dB) at speeds greater than 30 kmph on the highways shown that, the incidental noise levels observed are way more than the noise limit of 70 dB prescribed by World Health Organization (Schwela, 2001; Swain et al., 2012; Lokhande et al., 2018).

Overall, both roadusers and commuters are experiencing the maximum noise levels solely due to the tire-pavement interaction alone at most road speeds. This shows the immediate need for constructing low noise pavements to mitigate the overall noise at the source level.

6.2 Conclusions

The conclusions drawn from the current study are presented below.

1. The current study shows that the percentage of two and three-wheelers are dominating the volume proportion on most of the selected highways. With 15 minutes LAeq (dB) variation of 96.5 dB to 107.1 dB was observed from the vehicular traffic at an average speed of 30 to 65 kmph on the highways, necessitating improvement in public transportation facilities for reducing the noise levels. The comprehensive models developed in this study are validated, which resulted in a predicted difference of 1 to 10 dB with observed values. Therefore, the comprehensive model developed in this study can be effectively used for noise prediction on highways with similar traffic and geometric conditions.

2. With 3 dB to 6 dB additional noise for 15-minute time interval, heavy vehicles can affect noise levels to a large extent with their honks, reduced speeds, and steady flows near the rotaries. Thus, there is a notable impact of heavy vehicles on the response to the equivalent noise level [LAeq (dB)] from traffic. Accordingly, a statistical test of significance (p-value obtained is 0.318, which is greater than 0.05) of the developed model shows that it can be used effectively for predicting traffic noise levels for the

rotaries having similar characteristics.

3. The pass-by noise levels measured with the method designed for the purpose show the dominance of tire-pavement interaction noise over propulsion noise for speeds, which varied between 30kmph – 50 kmph on asphalt pavements and 20 kmph – 30kmph on cement concrete pavements. This shows that the tire-pavement interaction noise occurs at much slower speeds on cement concrete pavements compared to asphalt pavements. The reason being the asphalt pavement dissipates high acoustic energy due to its viscoelastic nature. Whereas, on average, the petrol car produces 4 dB to 5 dB less propulsion noise levels compared to diesel-powered vehicles. The reason being the increase in combustion noise levels due to pre-injection in diesel-powered vehicles. These results reveal the major effects of tire-pavement interaction and propulsion noise levels at different road speeds, which are high enough for both free flow and heterogenic traffic in reality.
4. The decibel subtraction on measured noise levels with the developed integrated jack method showed a good correlation with coast-by noise levels, with an R^2 value of 0.965. The correlation proved to be strong at all vehicle speeds. It can be concluded that, for estimating coast-by noise levels at higher speeds in urban streets, the integrated jack method developed in this study can be used.
5. It was observed that cement concrete pavements are producing 3.4 dB to 5.4 dB higher in-vehicle tire-pavement interaction noise levels compared to asphalt pavements at speeds ranging from 40 kmph to 60 kmph. That is, for every 10 kmph increase in the speed, the cement concrete pavements generate 1 dB more noise than asphalt pavements. This is essentially due to the dissipation of high acoustic energy in asphalt concrete pavements due to its viscoelastic nature.
6. The noise levels recorded in the handheld SLM are higher compared to the stabilizer mounted SLM in the windows-open condition (1.81% to 2.71%) and windows-closed condition (1.99% to 2.81%). Thus, the minimized effect of tremor vibrations on reduced in-vehicle noise levels of about 2 dB was observed in SLM mounted on stabilizer which proved the need for considering the predominance of vibrations on the sound level meter while measuring in-vehicle noise levels.
7. Overall, the current study shows that the tire-pavement interaction noise alone can generate LAeq of 61.2 dB to 70.9 dB for commuters and 75.9 dB to 81.4 dB for roadusers at moderate road speeds (40 kmph to 60 kmph). This shows the immediate

need for constructing low noise pavements to mitigate the noise at the source for better living standards.

6.3 Limitations of the Study

The limitations of the current study are presented below.

1. Further research is needed for the measurement of noise levels from the developed integrated jack methodology by consideration of engine parameters using OBD tools, which are not considered in this study.

2. The study focused only on the pavement type and ignored the influence of the pavement mix design parameters in this study.

6.4 Scope for Further Work

This study can be extended further by taking into account the following points.

1. The integrated jack method developed in this study can be checked for different modes to obtain a fair representation of noise levels from the actual traffic scenario.
2. To measure the noise levels over the entire pavement length as in CPX and OBSI methods, SLM was mounted on the running vehicle. In doing so, coasting down the vehicle is not possible without a confined section length for measuring the tire-pavement interaction noise level. This can be modified by further research using the developed jack method to decrease the error in quantifying tire-pavement interaction levels from decibel subtraction. This enables the chance of assessing noise levels on test sections without coasting down the vehicle.
3. The in-vehicle noise measurement methodology developed in this study can be used further to measure in-vehicle noise as perceived by the commuters for different vehicle types plying on different types of pavement surfaces. These measurements can be used to quantify the effects of tire-pavement interaction on the overall in-vehicle noise spectrum.

REFERENCES

1. Abbate, C., Concetto, G., Fortunato, M., Brecciaroli, R., Tringali, M. A., Beninato, G., and Domenico, G. (2005). “Influence of environmental factors on the evolution of industrial noise-induced hearing loss.” *Environmental Monitoring and Assessment*,107(1-3), 351-361.

2. Abouel-Seoud, S. A. (2016). “Active control analysis of passenger vehicle interior noise produced from tire-pavement interaction.” *International Journal of Vehicle Noise and Vibration*, 12(2), 138-161.

3. Adnadjevic, M., Goossens, B., and Botteldooren, D. (2018). “On the array configuration and accuracy of remote in-ear level sensing for in-vehicle noise control applications.” *Applied Acoustics*, 129, 229-238.

4. Agarwal, S., and Swami, B. L. (2011). “Comprehensive approach for the development of traffic noise prediction model for Jaipur city.” *Environmental Monitoring and Assessment*, 172(1-4), 113-120.

5. Aladdin, M. F., Jalil, N. A. A., Guan, N.Y., Rezali, K. A. M., and Adam, S. A. (2019). Evaluation of human discomfort from combined noise and whole-body vibration in passenger vehicle.” *International Journal of Automotive and Mechanical Engineering*, 16(2),6808-6824.

6. Alessandrini, A., Filippi, F., and Ortenzi, F. (2012). “Consumption calculation of vehicles using OBD data.” In *20th International Emission Inventory Conference-Emission Inventories-Meeting the Challenges Posed by Emerging Global, National, and Regional and Local Air Quality Issues*.

7. Ali, S. M. J., and Sarna, S. P. (1978). “Noise levels inside passenger cars.” *Applied Acoustics*, 11(4), 277-284.

8. Al-Mutairi, N. Z., Al-Attar, M. A., and Al-Rukaibi, F. S. (2011). “Traffic-generated noise pollution: exposure of roadusers and populations in Metropolitan Kuwait.” *Environmental Monitoring and Assessment*, 183(1-4), 65-75.

9. American Association of State and Highway Transportation Officials (AASHTO): Standard method of test for measurement of tire/pavement noise using the On-Board Sound Intensity (OBSI) method. AASHTO TP76-10 (2010). Washington DC, USA.

10. Arana, M., San Martin, R., Nagore, I., and Perez, D. (2013). "Main results of strategic noise maps and action plans in Navarre (Spain)". *Environmental Monitoring and Assessment*, 185(6), 4951-4957.

11. Ballesteros, J. A., Sarradj, E., Fernandez, M. D., Geyer, T., and Ballesteros, M. J. (2015). "Noise source identification with Beamforming in the pass-by of a car." *Applied Acoustics*, 93, 106-119.

12. Banerjee, D., Das, P. P., and Foujdar, A. (2014). "Association between road traffic noise and prevalence of coronary heart disease." *Environmental Monitoring and Assessment*, 186(5), 2885-2893.

13. Bekke, D. A., Wijnant, Y. H., and De Boer, A. (2010). "Experimental review on interior tire-road noise models." *Proceedings of ISMA2010*, Sep 20.

14. Bennert, T., Hanson, D., Maher, A., and Vitillo, N. (2005). "Influence of pavement surface type on tire/pavement generated noise." *Journal of Testing and Evaluation*, 33(2), 94-100.

15. Bilova, M., and Lumnitzer, E. (2012). "Tire radiated noise level influenced by road surface quality." *trans&MOTAUTO 12*, 186-188.

16. Boodihal, M. A., Chethan, A., Swamy, R., Sahu, R., and Biligiri, K. P. (2014). "Development of tire-pavement interaction noise assessment methodology in India." *Case Studies in Construction Materials*, 1, 115-124.

17. Braun, M. E., Walsh, S. J., Horner, J. L., and Chuter, R. (2013). "Noise source characteristics in the ISO 362 vehicle pass-by noise test: Literature review." *Applied Acoustics*, 74(11), 1241-1265.

18. Bryan, M. E. (1976). "A tentative criterion for acceptable noise levels in passenger vehicles." *Journal of Sound and Vibration*, 48(4), 525-535.

19. Buhlmann, E. (2019). “Improvements in the CPX method and its ability to predict traffic noise emissions.” In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 259 (2), 7064-7075.

20. Buchheim, R., Dobrzynski, W., Mankau, H., and Schwabe, D. (1982). “Vehicle interior noise related to external aerodynamics.” *International Journal of Vehicle Design*, 3(4), 398-410.

21. Campillo-Davo, N., Peral-Orts, R., Velasco-Sanchez, E., and Campello-Vicente, H. (2013). “An experimental procedure to obtain sound power level of tire-pavement interaction noise under Coast-By conditions.” *Applied Acoustics*, 74(5), 718-727.

22. Cao, Y., Wang, D., Zhao, T., Liu, X., Li, C., Hou, H. (2016). “Electric vehicle interior noise contribution analysis*.”* SAE Technical Paper, 2016-01-1296.

23. Central Pollution Control Board: The noise pollution (Regulation and control rules, 2000a). http://cpcbenvis.nic.in/noisepollution/noise_rules_2000.pdf. Accessed 01 December 2018.

24. Central Pollution Control Board: WHO guidelines for noise quality, (2000b). http://cpcb.nic.in/who-guidelines-for-noise-quality/. Accessed 01 December 2018.

25. Cesbron, J., and Klein, P. (2017). “Correlation between tire-pavement interaction noise levels measured by the Coast-By and the Close-Proximity methods.” *Applied Acoustics*, 126, 36-46.

26. Chevallier, E., Can, A., Nadji, M., and Leclercq, L. (2009). “Improving noise assessment at intersections by modeling traffic dynamics.” *Transportation Research Part D: Transport and Environment*, 14(2), 100-110.

27. Cho, D. S., and Mun, S. (2008). “Study to analyze the effects of vehicles and pavement surface types on noise.” *Applied Acoustics*, 69(9), 833-843.

28. Cirrus Research Plc. Noise Tools. [Accessed 15 June 2017]. Available: https://www.cirrusresearch.co.uk/library/software/

29. Constant, M., Leyssens, J., Penne, F., and Freymann, R. (2001). “Tire and car contribution and interaction to low frequency interior noise.” *SAE Technical Paper*, 1528.

30. Covaciu, D., Florea, D., and Timar, J. (2015). “Estimation of the noise level produced by road traffic in roundabouts.” *Applied Acoustics*, 98, 43-51.

31. Directive 2001/43/EC. (2001). European Council Directive 92/23/EEC relating to tires for motor vehicles and their trailers and to their fitting.

32. Donavan, P. R. (2014). “Effect of porous pavement on wayside traffic noise levels.” *Transportation Research Record: Journal of the Transportation Research Board*, 2403(1), 28-36.

33. Doygun, H., and Gurun, D. K. (2008). “Analysing and mapping spatial and temporal dynamics of urban traffic noise pollution: a case study in Kahramanmaraş, Turkey.” *Environmental Monitoring and Assessment*, 142(1-3), 65-72.

34. Eisenblaetter, J., Walsh, S. J., and Krylov, V. V. (2006). “Experimental investigations into the air pumping effect at the tire-pavement interaction interface.” *Proceedings of the Institute of Acoustics*, 28.

35. Estevez-Mauriz, L., andForssen, J. (2018). “Dynamic traffic noise assessment tool: A comparative study between a roundabout and a signalized intersection.” *Applied Acoustics*, 130, 71-86.

36. Fedorko, G., Heinz, D., Molnar, V. and Brenner, T. (2019). “Modelling noise exposure by means of infrared technology.” *Advances in Science and Technology: Research Journal*, 13(4).

37. Freitas, E., Torres, H., Vuye, C., and Pereira, P. (2019). “Effect of road pavement defects on tire-road noise.” *In INTER-NOISE and NOISE-CON Congress and Conference Proceedings,* Institute of Noise Control Engineering,259 (4), 5534-5544.

38. Ghotbi, M. R., Monazzam, M. R., Baneshi, M. R., Asadi, M., and Fard, S. M. B. (2012). “Noise pollution survey of a two-storey intersection station in Tehran metropolitan subway system.” *Environmental Monitoring and Assessment*, 184(2), 1097-1106.

39. Golik, B. (2006). "Development of a test method for image stabilizing systems." *University of Applied Sciences, Cologne*, Oct 21.

40. Guarnaccia, C. (2010). "Analysis of traffic noise in a road intersection configuration." *WSEAS Transactions on Systems*, 1(8), 865-874.

41. Guite, K. (2017). Road Transport Year Book. New Delhi: Ministry of Road Transport and Highways [accessed: Feb 8, 2017]. https://data.gov.in/catalog/road-transport-year-book-2013-14-and-2014-15

42. Gupta, A. K., Khanna, S. K., and Gopal, M. (1984). "Nomographic procedure for road traffic noise evaluation." *Indian Highways*, 12(1), 23-29.

43. Hanson, D. I., Donavon, P., and James, R. (2005). "Tire/Pavement Noise Characteristics of HMA Pavements (With Discussion)." *Journal of the Association of Asphalt Paving Technologists*, 74, 1005-1039.

44. He, J. F., Jin, X. X., and Wang, W. Y. (2011). "Analysis of tire tread pattern's impact on interior vibration and noise based on wavelet transform." *In: Applied Mechanics and Materials*, 66, 1755-1761.

45. Heritier, H., Vienneau, D., Frei, P., Eze, I., Brink, M., Probst-Hensch, N., and Roosli, M. (2014). "The association between road traffic noise exposure, annoyance and health-related quality of life (HRQOL)." *International Journal of Environmental Research and Public Health*, 11(12), 12652-12667.

46. Higaki, T., Ahuja, K., and Funk, R. (2005). "Dissection of Automobile Interior Noise Spectrum with Emphasis on the Infrasound Region." *In: 11th AIAA/CEAS Aeroacoustics Conference*, 23-25 May, Monterey, California (p.3077).

47. Ho, K. Y., Hung, W. T., Ng, C. F., Lam, Y. K., Leung, R., and Kam, E. (2013). "The effects of road surface and tire deterioration on tire-pavement interaction noise emission." *Applied Acoustics*, 74(7), 921-925.

48. Hyden, C., and Svensson, A. (2009). "Traffic Calming in India: Report on the theory of Traffic Calming and empirical trials in the city of Jaipur." *Bulletin/*3000.

49. Indian Standard, IS: 3098. Noise emitted by moving road vehicles, measurement. Indian Standards Institution, ManakBhavan, 9 Bahadur Shah Zafar Marg, New Delhi 110002.1980.

50. International Organization for Standardization, ISO 11819-1. (1997). Acoustics – measurement of the influence of road surfaces on traffic noise – Part 1: Statistical Pass-By method. https://www.iso.org/obp/ui/#iso:std:iso:11819:-1:ed-1:v1:en

51. International Organization for Standardization, ISO 11819-2. (2017). Acoustics – measurement of the influence of road surfaces on traffic noise – Part 2: The close-proximity method. https://www.sis.se/api/document/preview/921712/

52. Jamrah, A., Al-Omari, A., and Sharabi, R. (2006). "Evaluation of traffic noise pollution in Amman, Jordan." *Environmental Monitoring and Assessment*, 120(1-3), 499-525.

53. Jonasson, H. G. (1999). "Measurement and modelling of noise emission of road vehicles for use in prediction models." *SP report*, 35, Nordtest project 1452-99, KFB Project 1998-0659/1997-0223.

54. Kim, G. J., Holland, K. R., and Lalor, N. (1997). "Identification of the airborne component of tire-induced vehicle interior noise." *Applied Acoustics*, 51(2), 141-156.

55. Kim, B. S., Kim, G. J., and Lee, T. K. (2007). "The identification of tire induced vehicle interior noise." *Applied Acoustics*, 68(1), 134-156.

56. Knabben, R. M., Triches, G., Gerges, S. N., and Vergara, E. F. (2016). "Evaluation of sound absorption capacity of asphalt mixtures." *Applied Acoustics*, 114, 266-274.

57. Kobiki, Y., Kinoshita, A., and Yamada, H. (1990). "Analysis of interior booming noise caused by tire and powertrain–suspension system vibration." *International Journal of Vehicle Design*, 11(3), 303-313.

58. Koike, H., and Ito, A. (2014). "Effect of road surfaces on road traffic noise on the public roads of Japan-An investigation based on tire-pavement interaction noise measurements." In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 249(3), 4112-4119.

59. Konbattulwar, V., Velaga, N. R., Jain, S., and Sharmila, R. B. (2016). "Development of in-vehicle noise prediction models for Mumbai Metropolitan Region, India." *Journal of Traffic and Transportation Engineering (English Edition)*, 3(4), 380-387.

60. Kuemmel, D. A., Jaeckel, J. R., Satanovsky, A., Shober, S. F., Dobersek, M. M. (1996). "Noise characteristics of pavement surface texture in Wisconsin." *Transportation Research Record*, 1544(1), 24-35.

61. Kumar, V. S., Kumar, R. R., Ramachandran, E., and Karanth, N. V. (2010). "Methodology for assessing tire structural contribution to vehicle interior noise." *17th International Congress on Sound and Vibration*, 4, 2474–2481.

62. Kumar, R., Mukherjee, A., and Singh, V. P. (2017). "Traffic noise mapping of Indian roads through smartphone user community participation." *Environmental Monitoring and Assessment*, 189(1), 17.

63. Lam, K. C., Ma, W., Chan, P. K., Hui, W. C., Chung, K. L., Chung, Y. T. T., and Lin, H. (2013). "Relationship between road traffic noisescape and urban form in Hong Kong." *Environmental Monitoring and Assessment*, 185(12), 9683-9695.

64. Leong, S. T., and Laortanakul, P. (2003). "Monitoring and assessment of daily exposure of roadside workers to traffic noise levels in an Asian city: a case study of Bangkok streets." *Environmental Monitoring and Assessment*, 85(1), 69-85.

65. Lewis, P. T., and James, A. (1980). "Noise levels in the vicinity of traffic roundabouts." *Journal of Sound and Vibration*, 72(1), 51-69.

66. Li, M. (2013). "Tire-road noise, surface characteristics and material properties". *PhD thesis*, Delft University of technology, The Netherlands.

67. Li, Q., Qiao, F., and Yu, L. (2016). "Impacts of pavement types on in-vehicle noise and human health." *Journal of the Air & Waste Management Association*, 66(1), 87-96.

68. Lokhande, S. K., Pathak, S. S., Kokate, P. A., Dhawale, S. A. and Bodhe, G. L. (2018). "Assessment of heterogeneous road traffic noise in Nagpur." *Archives of Acoustics*, 43.

69. Ma, G., Tian, Y., Ju, T., and Ren, Z. (2006). "Assessment of traffic noise pollution from 1989 to 2003 in Lanzhou city." *Environmental Monitoring and Assessment*, 123(1-3), 413-430.

70. Mandal, P., Prakash, M., and Bassin, J. K. (2012). "Impact of Diwali celebrations on urban air and noise quality in Delhi City, India." *Environmental Monitoring and Assessment*, 184(1), 209-215.

71. McNerney, M. T., Landsberger, B. J., Turen, T., and Pandelides, A. (1998). "Comparative field measurements of tire pavement noise of selected Texas pavements." *Transportation Research Record*, 1626(1), 78-84.

72. Measurement procedure for proximity stationary noise level, Attachment 38 [accessed 09 Novemeber 2017]. http://oica.net/wp-content/uploads/attachment38.pdf

73. Meiarashi, S., Nakasiba, F., Niimi, H., Hasebe, M., and Makatsuji, T. (1995). "Quantitative comparison on the noise reduction factors of drainage asphalt pavement." *Applied Acoustics*, 44, 165-179.

74. Mogrovejo, D. E., Flintsch, G. W., de Leon Izeppi, E. D., McGhee, K. K., and Burdisso, R. A. (2014). "Short-Term Effect of Pavement Surface Aging on Tire–Pavement Noise Measured with Onboard Sound Intensity Methodology." *Transportation Research Record: Journal of the Transportation Research Board*, 2403(1), 17-27.

75. Morel, J., Marquis-Favre, C., and Gille, L. A. (2016). "Noise annoyance assessment of various urban road vehicle pass-by noises in isolation and combined with industrial noise: A laboratory study." *Applied Acoustics*, 101, 47-57.

76. Morgan, A. (2008) "Innovative mitigation measures for road traffic noise." *IPG research report – DVS-2008-18*, Delft, The Netherlands.

77. Morrison, D. W., and Clarke, R. M. (1972). "*Regulation of commercial motor vehicle interior noise levels* (No. 720697)." *SAE Technical Paper*. Warrendale, PA: Society of Automotive Engineers.

78. Mukherjee, A. K., Bhattacharya, S. K., Ahmed, S., Roy, S. K., Roychowdhury, A., and Sen, S. (2003). "Exposure of drivers and conductors to noise, heat, dust and volatile

organic compounds in the state transport special buses of Kolkata city." *Transportation Research Part D: Transport and Environment*, 8(1), 11-19.

79. Narayan, S. (2015). "Analysis of noise emitted from diesel engines." In *Journal of Physics: Conference Series,* 662(1), 012018.

80. Nelson, P. M., and Piner, R. J. (1977). "Classifying road vehicles for the prediction of road traffic noise*". Berkshire: TRRL Laboratory Report*, (No. TRRL LR 752).

81. Nopiah, Z. M., Junoh, A. K., and Ariffin, A. K. (2015). "Vehicle interior noise and vibration level assessment through the data clustering and hybrid classification model." *Applied Acoustics*, 87, 9-22.

82. Ohiduzzaman, M., Sirin, O., and Kassem, E. (2018). "Comprehensive evaluation of asphalt pavement acoustic performance by using onboard sound intensity method." *Transportation Research Board 97th Annual Meeting*, Washington DC, United States.

83. Oyedepo, O. S., and Saadu, A. A. (2009). "A comparative study of noise pollution levels in some selected areas in Ilorin Metropolis, Nigeria." *Environmental Monitoring and Assessment*, 158(1-4), 155.

84. Ozer, S., Irmak, M. A., and Yilmaz, H. (2008). "Determination of roadside noise reduction effectiveness of Pinus sylvestris L. and Populus nigra L. in Erzurum, Turkey." *Environmental Monitoring and Assessment*, 144(1-3), 191-197.

85. Paiva, K. M., Cardoso, M. R. A., and Zannin, P. H. T. (2019). "Exposure to road traffic noise: Annoyance, perception and associated factors among Brazil's adult population."*Science of the Total Environment*, 650, 978-986.

86. Palanivelu, S., and Ramarathnam, K. K. (2015). "Synthesis of Structure Borne Vehicle Interior Noise due to Tire/Road Interaction." *In:ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, American Society of Mechanical Engineers Digital Collection.

87. Pallas, M. A., Berengier, M., Chatagnon, R., Czuka, M., Conter, M., and Muirhead, M. (2016). "Towards a model for electric vehicle noise emission in the European prediction method CNOSSOS-EU." *Applied Acoustics*, 113, 89-101.

88. Pandya, G. H. (2001). "Urban noise–a need for acoustic planning." *Environmental Monitoring and Assessment*, 67(3), 379-388.

89. Pathak, V., Tripathi, B. D., and Mishra, V. K. (2008). "Dynamics of traffic noise in a tropical city Varanasi and its abatement through vegetation." *Environmental Monitoring and Assessment*, 146(1-3), 67-75.

90. Prascevic, M. R., Mihajlov, D. I., and Cvetkovic, D. S. (2014). "Measurement and evaluation of the environmental noise levels in the urban areas of the city of Nis (Serbia)." *Environmental Monitoring and Assessment*, 186(2), 1157-1165.

91. Priede, T. (1975). "The effect of operating parameters on sources of vehicle noise." *Journal of Sound and Vibration*, 43(2), 239-252.

92. Raghavachari, S., and Narasimhamurthy, C. (1986). "A study of highway traffic noise for Hyderabad city." *Indian Highways*, 14(9), 19-40.

93. Rao, P. R. (1997). "Prediction of road traffic noise." *Indian Journal of Environment Protection*, 11(4), 25-32.

94. Rasmussen, R. O., Sohaney, R., and Wiegand, P. (2011). "Measuring and reporting tire-pavement noise using on-board sound intensity (OBSI)." *National Concrete Pavement Technology Center, Iowa State University, Ames, Iowa*.

95. Saguchi, T., Yumii, K., and Zakelj, P. (2007). "Vehicle interior noise prediction using tire characteristics and vehicle transmissibility." *SAE Technical Paper*, 1533.

96. Sandberg, U. and Ejsmont, J. A. (2002). "Tire/road noise reference book*." Informex*, 1-640.

97. Schwela, D. (2001). "World Health Organization guidelines on community noise." *presentation at the TRB session*, 391.

98. Singh, B. B., and Jain, V. K. (1995). "A comparative study of noise levels in some residential, industrial and commercial areas of Delhi." *Environmental Monitoring and Assessment*, 35(1), 1-11.

99. Singh, D., Prakash, A., Srivastava, A. K., Kumar, K., and Jain, V. K. (2013). "The effects of meteorological parameters in ambient noise modelling studies in Delhi." *Environmental Monitoring and Assessment*, 185(2), 1873-1882.

100. Skarlatos, D., and Drakatos, P. (1988). "Environmental noise-annoyance in Patras, Greece." *Environmental Monitoring and Assessment*, 11(2), 171-182.

101. Sottek, R., and Philippen, B. (2010). "Separation of airborne and structure-borne tire-road noise based on vehicle interior noise measurements." *SAE Technical Paper*, 1430.

102. Staiano, M. A. (2018). "Tire–pavement noise and pavement texture." *Journal of Transportation Engineering Part B: Pavements*, 144, 04018034.

103. Stoker, R., Ahuja, K., and Hsu, J. (1996). "Separation of wind-tunnel background noise and wind noise from automobile interior measurements." In *Aeroacoustics Conference*, 1763.

104. Swain, B. K., Goswami, S. and Panda, S. K. (2012). "Road traffic noise assessment and modeling in Bhubaneswar, India: a comparative and comprehensive monitoring study." *International Journal of Earth Sciences and Engineering*, 5(1), 1358-1370.

105. Tempest, W., and Bryan, M. E. (1972). "Low frequency sound measurement in vehicles." *Applied Acoustics*, 5(2), 133-139.

106. Tokairin, T., and Kitada, T. (2005). "Study on the effect of porous fence on air quality and traffic noise level around a double-decked road structure." *Environmental Monitoring and Assessment*, 105(1-3), 121-143.

107. Tsuge, K., Kanamaru, K., Kido, T., and Masuda, N. (1985). "A study of noise in vehicle passenger compartment during acceleration." *SAE Technical Paper*, (No.850965). https://doi.org/10.4271/850965.

108. Tsujiuchi, N., Koizumi, T., Takenaka, T., and Iwagase, T. (2001). "An optimization of rubber mounting for vehicle interior noise reduction." *In: Proceedings of SPIE, the International Society for Optical Engineering*, 4359, 275-281.

109. Victoria, E. P. A. (1991). "EPA Information Bulletin (A guide to the measurement and analysis of noise". https://www.epa.vic.gov.au/. Accessed 15 February 2019

110. Watts, G. R., Chandler-Wilde, S. N., and Morgan, P. A. (1999). "The combined effects of porous asphalt surfacing and barriers on traffic noise." *Applied Acoustics*, 58(3), 351-377.

111. Watts, G. (2005). "*Harmonoise Prediction Model for Road Traffic Noise." In Published Project Report PPR034*, Transport Research Laboratory, Wokingham, UK.

112. Winroth, J., Kropp, W., Hoever, C., Beckenbauer, T., and Männel, M. (2017). "Investigating generation mechanisms of tire-pavement interaction noise by speed exponent analysis." *Applied Acoustics*, 115, 101-108.

113. Yelangu: Its strengths and weakness, (2018). https://beststeadicam.com/yelangu-s60t-review/.Accessed 01 December 2018

114. Yilmaz, G., and Hocanli, Y. (2006). "Mapping of noise by using GIS in Şanliurfa." *Environmental Monitoring and Assessment*, 121(1-3), 103-108.

115. Yuan, M., Ni, D., Zhang, D., Wei, X., Wang, Z., and Wang, C. (2019). "Effect of temperature on road pass-by noise of light vehicle." In *IOP Conference Series: Earth and Environmental Science*, 310 (2), 022003.

116. Zannin, P. H., Diniz, F. B., Giovanini, C., and Ferreira, J. A. (2003). "Interior noise profiles of buses in Curitiba." *Transportation Research Part D: Transport and Environment*, 8(3), 243-247.

117. Zannin, P. H. T., Ferreira, A. M. C., and Szeremetta, B. (2006). "Evaluation of noise pollution in urban parks." *Environmental Monitoring and Assessment*, 118(1-3), 423-433.

118. Zofka, E., Zofka, A., and Mechowski, T. (2017). "Pavement noise measurements in Poland." In *IOP Conference Series: Materials Science and Engineering*, 236(1), 012103.

PUBLICATIONS

International Journals

1. **Aditya, K.,** Kumar, D. S., Chowdary, V., and Prasad, C. S. R. K. (2019). "Modelling of noise pollution due to heterogeneous highway traffic in India." *Transport and Telecommunication Journal*, 20 (1), 22-39. (**Scopus**)
2. **Kamineni, A.,** and Chowdary, V. (2020). "Development of a methodology to measure the in-vehicle noise levels due to the tire-pavement interaction." *Journal of the Institute of Engineers (India): Series A*. doi:10.1007/s40030-019-00426-3 (**Scopus**)
3. **Aditya, K.,** and Chowdary, V. (2020). "Influence of honking on the road traffic noise generated at urban rotaries for heterogeneous traffic." *Environmental and Climate Technologies*, 24(1), 23-42. (**Scopus**)
4. **Aditya, K.,** and Chowdary, V. (2020). "Quantification of pass-by noise levels on urban roads: effect of engine propulsion and tire-road interaction." *Fluctuation and Noise Letters*, 2050030. (**SCI**)