Chapter 5

Vehicular Source Emission Model and Modified Traffic Noise Prediction Model

5.1 General

This chapter focuses on developing a vehicle noise emission curve that illustrates the relationship between a vehicle's speed and the sound level it generates. To develop these curves; 13,684 single pass-by events of various vehicle category were recorded on highways and various roads under real-world driving conditions, ensuring that vehicles were unobstructed. The study was motivated by the need to accurately represent vehicle noise emissions in actual traffic settings, which is essential for reliable noise impact assessments, urban planning, and the creation of effective noise mitigation strategies. Additionally, it supports the design of quieter vehicles and road surfaces. Understanding this speed-noise relationship is key to addressing growing concerns over traffic noise pollution and its impact on public health and the environment. A modified highway traffic noise model was developed by using the Federal Highway Administration (FHWA) equation, replacing the original FHWA emission curves with those obtained from this study. Various adjustment factors recommended by the FHWA were incorporated into the equation to improve the highway noise prediction model's accuracy for local conditions. This modification seeks to enhance the model’s ability to predict highway traffic noise more effectively.

5.2 Results and Discussion

5.2.1 Descriptive of $L_{AF,\max}$ data

The maximum A weighted sound pressure level with fast response time weighting characteristics ($L_{AF,\max}$) data have been recorded for each of the vehicle category on real running condition were recorded. The descriptive analysis of the noise emissions ($L_{AF,\max}$) data and vehicle speed data of various vehicle category is given on Table 5.1 and Table 5.3 respectively. Data on noise emissions from 2900 2-wheelers (2-w), 2651 cars, 1213 buses, 655 3-wheeler (3-w), 699 LCVs, 300 e-rickshaws, 4850 trucks, and 416 tractors was collected from the National Highway and other roads when they were operating at their respective actual speeds. The noise emission data collected for various vehicle types falls within specific ranges across different speed intervals Specifically:

a) For 2-wheelers, the noise emission ranges from 53.7 to 89.8 dB(A) while operating at speeds between 16 to 90 Km/h.
b) Cars exhibit noise levels ranging from 54.10 to 86.10 dB(A) while operating at speeds between 16 and 120 Km/h.
c) Buses produce noise emissions ranging from 62.1 to 89.8 dB(A) while operating at speeds between 16 and 104 Km/h.
d) 3-wheelers generate noise levels between 56.4 and 89.9 dB(A) while operating at speeds within the range of 16 to 60 Km/h.
e) LCVs exhibit noise emissions ranging from 60.2 to 88.7 dB(A) while operating at speeds between 20 and 90 Km/h.

f) e-rickshaws produce noise levels between 53.5 and 76.7 dB(A) within the speed range of 7 to 27 Km/h.

g) Trucks emit noise ranging from 62.2 to 95.4 dB(A) when operating at speeds between 16 and 85 Km/h.

h) Tractors produce noise emissions between 70.1 and 94.5 dB(A) while moving within the speed range of 14 to 59 Km/h.

Table 5.1. Descriptive statistics of noise level, dB(A) data

Vehicle Category	Observation taken	Mean	Median	Variance	Std. Deviation	Min dB(A)	Max dB(A)
2-wheeler	2900	71.11	71.8	32.37	5.68	53.7	89.8
Car	2651	74.05	75.6	32.17	5.67	54.1	86.1
Bus	1213	78.37	78.5	17.56	4.19	62.1	89.8
3-wheeler	655	74.94	76.7	33.44	5.78	56.4	89.9
LCV	699	76.26	75.9	14.86	3.85	60.2	88.7
e-rickshaws	300	64.88	65.55	22.52	4.74	53.5	76.7
Truck	4845	81.43	81.4	11.486	3.389	62.2	94.4
Tractor	416	81.9	82.25	18.14	4.259	70.1	94.5

5.2.2 Vehicular source noise emission model for various vehicle category

The correlation coefficient between data sets of noise level and speed data and its critical value were shown in Table **5.2**. Based on the analysis, the logarithmic curve yielded the most accurate representation of the measured value across all vehicle categories, as evidenced by a high coefficient of determination. The coefficient of determination (R^2) provides insight into how the models can explain noise emission data developed for each vehicle category. Specifically, 2-wheelers, cars, and bus data indicate a robust relationship between the speed and observed noise emissions. Their (R^2) values were 0.96, 0.95 and 0.93 respectively. LCVs and tractors data also exhibit an R^2 value of 0.90 and 0.91, respectively, suggesting a substantial explanatory capacity within the model. While the R^2 value for a 3-wheelers and e-rickshaws denotes a somewhat lower but still significant level of explanatory power, their R^2 values were 0.81 and 0.80, respectively. The emission curve for various vehicle category is shown in Figure 5.1. The coefficient of determination and emission equation for various vehicle category is represented in Table 5.4.

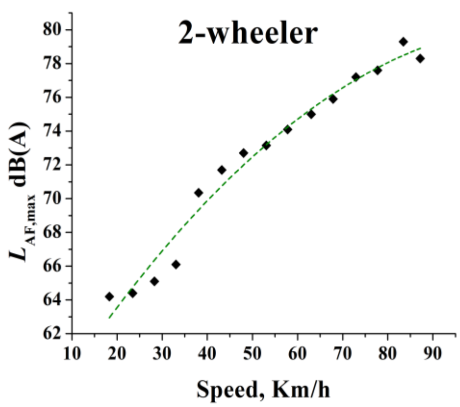
The comparison of emission curve from different category of vehicle at their speed range is shown in Figure 5.2. The tractors were the noisiest among all categories of vehicles, followed by the truck. For speed up to 62km/h the 2-wheeler emission curve was lower as compared to other vehicle category emission curve, However, beyond this speed, 2-wheeler noise emissions curve surpass those of emission curve of car . At lower speed, i.e. 20 km/h the emission curve of car was lower than the emission curve of 3-wheeler, LCV, e-rickshaw, tractor, truck and bus by 4.2 dB(A), 4.5 dB(A), 3.7 dB(A), 16.2 dB(A), 14.4 dB(A) and 7.18 dB(A) respectively. At mid-speed, i.e. 50km/h the car emission curve was lesser than emission curve of auto-rickshaw, LCVs, tractor, truck and bus by 6.8 dB(A), 2.1 dB(A), 14.51 dB(A), 9.9 dB(A) and 5.8 dB(A) respectively. At higher speeds, i.e., 80km/h car emission curve were lesser than those emission curve of 2-wheeler, LCVs, truck and bus by 0.26 dB(A), 0.86 dB(A), 7.5 dB(A) and 5.8 dB(A), respectively. Car emission curve were higher than 2-wheeler emission curve up to a speed of 62Km/h at a speed of 20km/h and 50km/h the car emission curve was greater than 2-wheeler emission curve by 1.03 dB(A) and 0.17 dB(A), respectively.

Table 5.2. Correlation coefficient between datasets

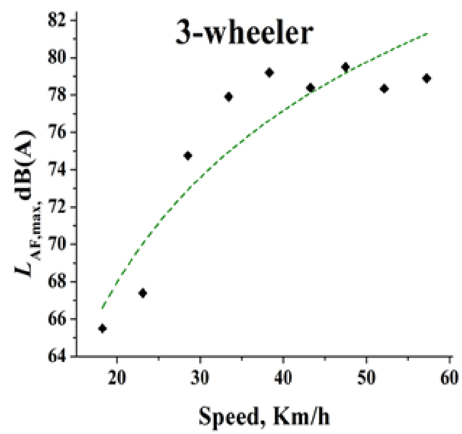
S/N	Vehicle Category	Correlation coefficient	Critical value of correlation coefficient
1	2-wheelers	0.97	0.51
2	3-wheelers	0.83	0.66
3	Car	0.94	0.55
4	LCV	0.93	0.53
5	e - rickshaws	0.83	0.75
6	Buses	0.97	0.46
7	Trucks	0.95	0.53
8.	Tractor	0.93	0.66

Table 5.3. Descriptive statistics of speed, Km/h data

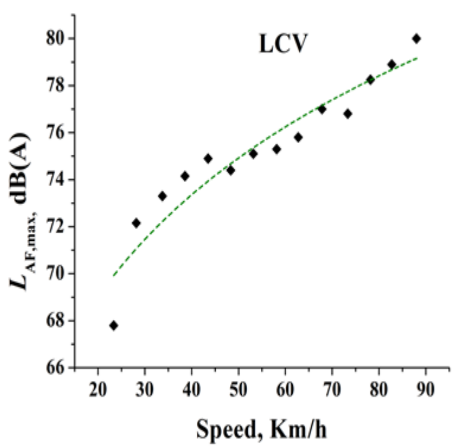
Vehicle Category	Observation taken	Mean	Median	Variance	Std. Deviation	Min Km/h.	Max Km/h.
2-wheeler	2900	45.97	47.5	305.97	17.49	16	90
Car	2651	64.04	70	654.47	25.58	16	120
Bus	1213	50.73	48	250.31	15.82	16	104
3-wheeler	655	32.37	32	63.1	7.94	16	60
LCV	699	59.16	60	208.18	14.42	20	90
e-rickshaws	300	15.56	15	13.21	3.63	7	27
Truck	4845	49.11	49	89.404	9.455	16	85
Tractor	416	25.24	25	39.983	6.323	14	59


2-wheeler
$L_{AF,max}$ dB(A)
Speed, Km/h
80
78
76
74
72
70
68
66
64
62
10 20 30 40 50 60 70 80 90

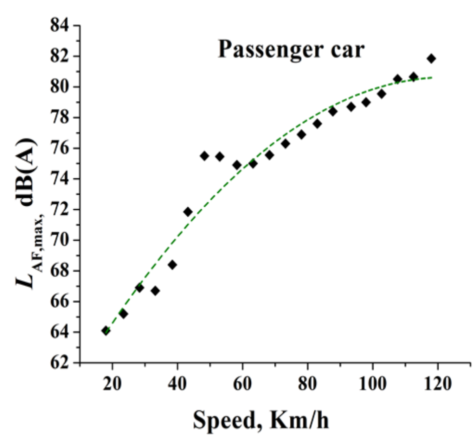
(a)


3-wheeler
$L_{AF,max,}$ dB(A)
Speed, Km/h
82
80
78
76
74
72
70
68
66
64
20 30 40 50 60

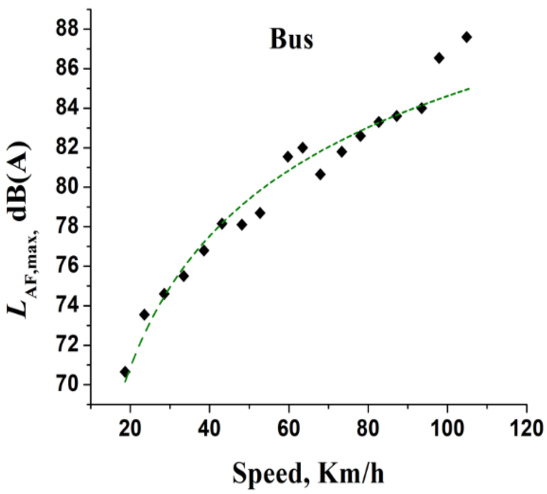
(b)


LCV
$L_{AF,max,}$ dB(A)
Speed, Km/h
80
78
76
74
72
70
68
66
20 30 40 50 60 70 80 90

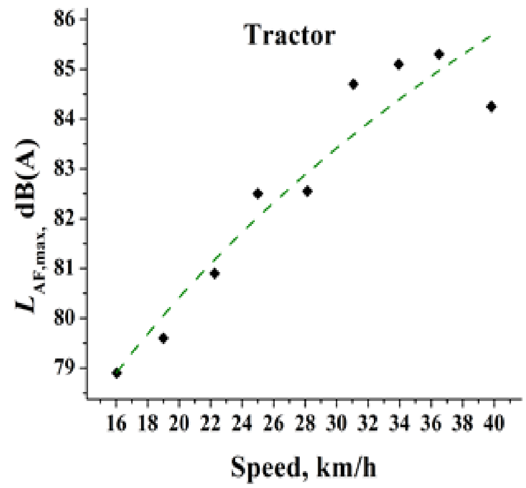
(c)


Passenger car
$L_{AF,max,}$ dB(A)
Speed, Km/h
84
82
80
78
76
74
72
70
68
66
64
62
20 40 60 80 100 120

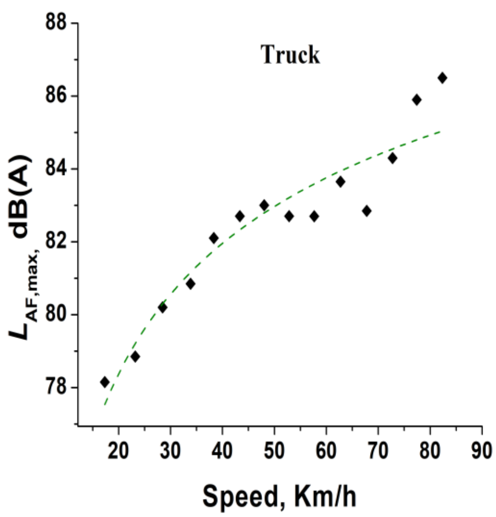
(d)



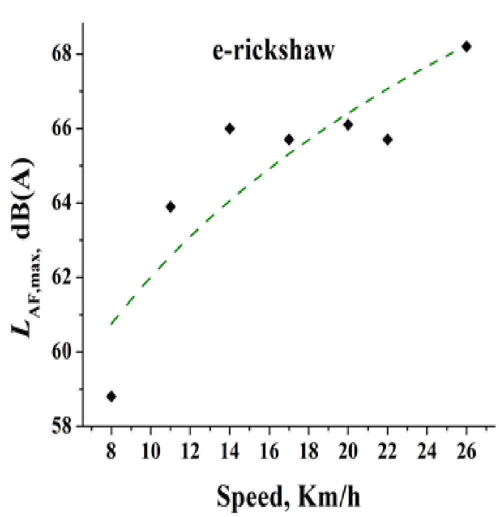
(e)



(f)



(g)



(h)

Figure 5.1. Emission curve for various vehicle category

Table 5.4. Emission curve equation of various vehicle category

S/N	Vehicle Category	Vehicular noise source intensity emission model equations	R^2 Value
1	2-wheelers	$y = 24.61 \log x + 30.94$	0.96
2	3-wheelers	$y = 28.94 \log x + 30.582$	0.81
3	Car	$y = 22.43 \log x + 34.792$	0.95
4	LCV	$y = 16.21 \log x + 47.45$	0.90
5	e - rickshaws	$y = 14.85 \log x + 47.12$	0.80
6	Buses	$y = 20.17 \log x + 44.91$	0.96
7	Trucks	$y = 8.01 \log x + 67.73$	0.93
12	Tractors	$y = 17.22 \log x + 58.01$	0.91

The emission curve of the present study was also compared with FHWA 1978 and 1995 noise emission curve. FHWA provided emission curves for five vehicle categories i.e. Cars, medium trucks, heavy trucks, buses and 2-wheelers [39]. The FHWA 1978 emission curve equation were represented from Equation (2.1) to (2.3); while 1995 FHWA emission curve were provided in Table 2.5 at S/N 7. The comparison of FHWA 1978 emission curve, FHWA 1995 emissions curve and present study emission curve are showed from Figure 5.3 to Figure 5.6. FHWA 1995 emission curves for 2-wheelers were 1.5 – 11.13 dB(A) higher than the present study emission curves. The bus emission curve for the present study was higher than the FHWA 1995 emission curve at a speed above 20km/h, with a maximum difference observed up to 1.02 dB(A) in the 40-44 km/h speed range. For cars, the FHWA 1995 emission curve was 8 – 0.1 dB(A) lesser than the present study emission curve in a speed range between 16- 54 km/h; after that, it surpasses the present study emission curve up to 4.8 dB(A) in the speed range of 56- 100 Km/h. For trucks, the present study emission curve was 8.3 – 2.9 dB(A) higher than the FHWA 1978 medium truck (MT) emission curve. In comparison to 1978 heavy truck (HT) emission curve, the present study emission curve was 2.5 dB(A) higher at speed of 50km/h and then reduces and were surpassed at higher speed. In comparison to 1995 FHWA HT and 1995 FHWA MT emission curve, the present study emission curve was higher at lower speed and then surpassed at higher speed. This all discussion shows that variation in present study emission curve with that of FHWA emission curve. In later part the validity of these emission curve was checked for highway noise prediction model.

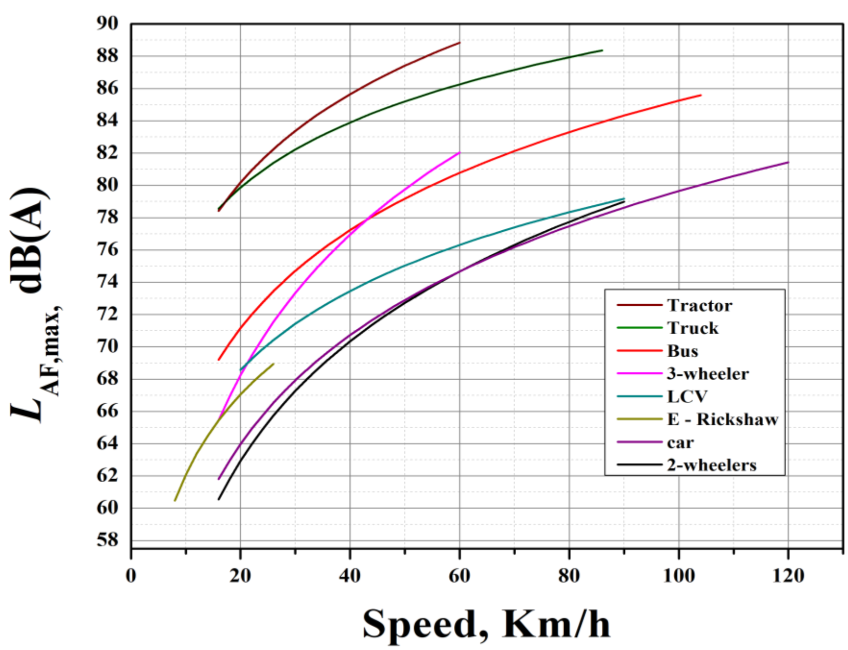


Figure 5.2. Emission curve comparison of various vehicle category

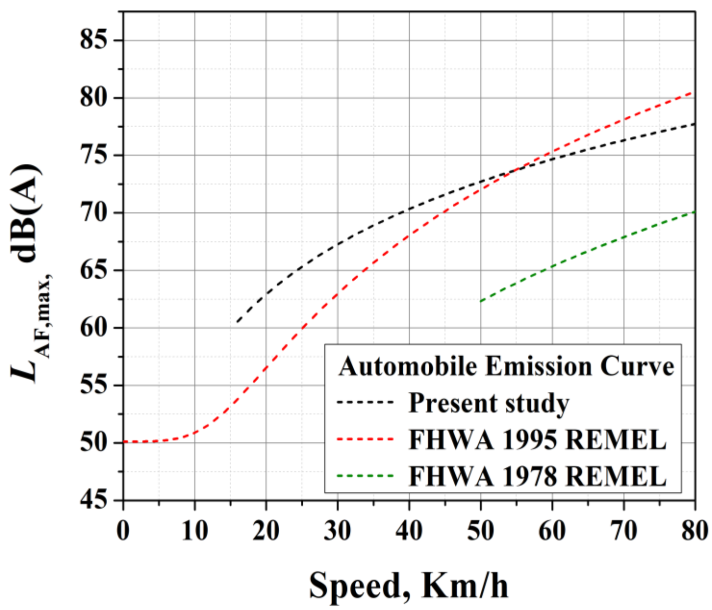


Figure 5.3. Comparison of FHWA vs present study automobile emission curve

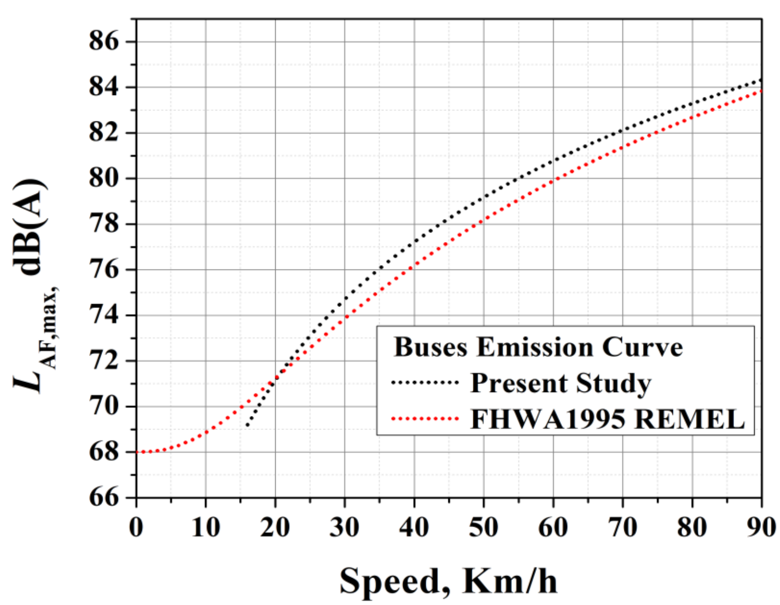


Figure 5.4. Comparison of FHWA vs present study buses emission curve

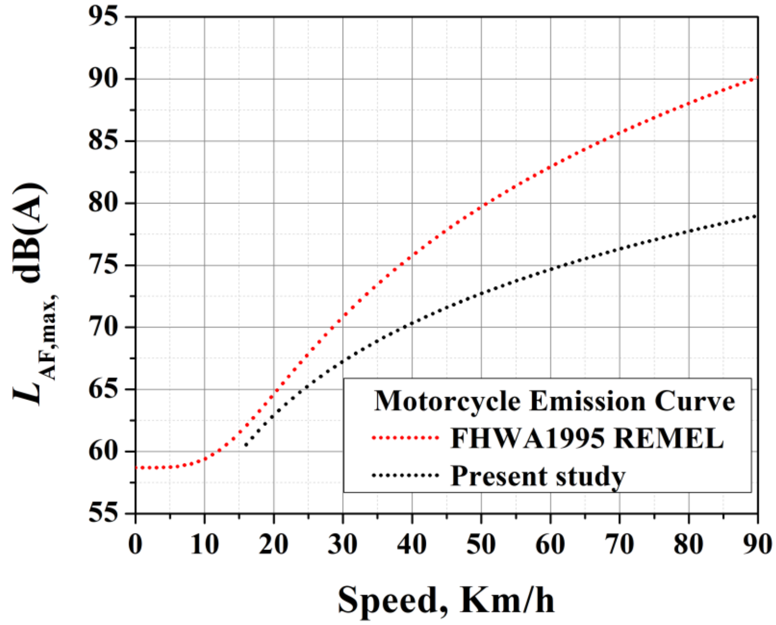


Figure 5.5. Comparison of FHWA vs present study motorcycle emission curve

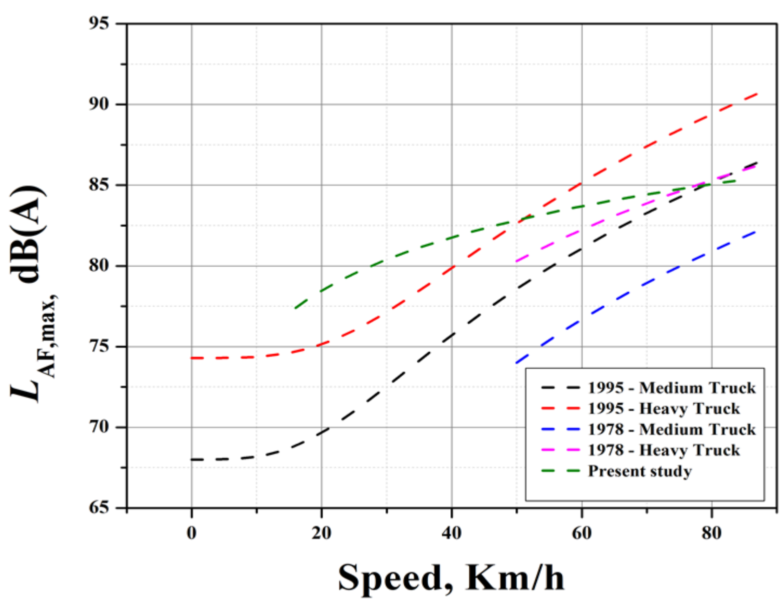


Figure 5.6. Comparison of FHWA vs present study truck emission curve

vehicle noise emissions refer to the sound vehicles produce while in motion. These emissions originate from multiple sources, such as engine combustion, exhaust systems, the interaction between tyre and the road, aerodynamics, and various mechanical components [249]. Road traffic noise can be categorized into three main sources: powertrain noise from the vehicle's engine and transmission, rolling noise produced by the tires on the road surface, and aerodynamic noise caused by airflow around the vehicle [250]. Typically, at speeds ranging from 30 km/h to 100 km/h, rolling noise tends to be the primary contributor to overall noise levels, impacting not only cars but also trucks [251]. Powertrain noise becomes more prominent at lower speeds, while aerodynamic noise becomes more significant at higher speeds [250] . In specific vehicle categories, engine and exhaust noise take precedence, while road tyre noise becomes prominent in others. During field observations, it is noted that for 2-wheelers, 3-wheeler and tractors, engine and exhaust noise overwhelmingly prevail, constituting the majority of emitted noise. In cars, LCVs, buses, and trucks, engine exhaust and tire-pavement noise contribute to overall noise emissions. In cars, buses, and trucks, it’s been observed that engine and exhaust noise are more noticeable at lower speeds. Road-tire interaction noise precedes engine and exhaust sounds at higher speeds, particularly above 30-40 km/h. This observation highlights the shift in predominant noise sources as the vehicles accelerate. In well-maintained cars, the interaction between tyre and pavement emerges as the primary sub-source at speeds exceeding approximately 50 kph (30 mph) [252]. It's important to note that the noise emitted by a vehicle can be categorized into two main components: engine noise and rolling noise. Engine noise typically dominates at speeds up to 50 km/h and is influenced by acceleration. As the vehicle accelerates to higher speeds, the engine noise becomes overshadowed by the rolling noise, which is more influenced by the vehicle's speed

[253]. Beyond 50 km/h, tyre noise emerges as a primary contributor to the overall noise generated by vehicles [254, 255].

The comparison of vehicle noise emission curves indicates a significant reduction in noise emissions for motorcycles in recent studies compared to the 1995 emission curves provided by the FHWA. This improvement can be attributed to several factors, including stricter noise and emission regulations, advancements in engine technology, the widespread adoption of catalytic converters, the use of cleaner fuels, the integration of advanced exhaust after-treatment systems, the development of better materials and manufacturing processes, and the enhancement of vehicle design and aerodynamics. These technological advancements collectively contribute to a quieter and cleaner operation of modern motorcycles.

For automobiles and trucks, the situation varies with speed. At lower speeds, emission curves are higher compared to the 1995 FHWA emission curve, likely due to the increased engine power and torque demands of modern vehicles, which can lead to higher noise emissions during acceleration and city driving. However, at higher speeds, emission curves are lower than the 1995 FHWA levels, reflecting the significant technological improvements in modern vehicles. These advancements include more efficient engine management systems, optimized transmission systems, improved aerodynamics, and noise-dampening technologies, all of which contribute to reduced emissions and quieter operation at higher speeds. This contrast between low-speed and high-speed performance highlights the complex interplay of factors influencing vehicle noise and emission levels in modern vehicles compared to those from the past. The higher emission curves for buses in the present study compared to 1995 may be attributed to increased engine power and larger vehicle sizes in modern buses, which result in higher fuel consumption and emissions.

5.2.3 Comparison of traffic volume, speed and noise

The traffic scenario in Indian mid-sized cities differs significantly from highway traffic due to the substantial presence of non-motorized vehicles, which often contribute to congestion, increased honking, and higher noise levels. These non-motorized vehicles, such as bicycles and rickshaws, frequently disrupt traffic flow by stopping to pick up and drop off passengers, and they often travel at slower speeds, disregarding traffic regulations. This leads to more frequent acceleration and deceleration among motorized vehicles, exacerbating congestion and noise. In contrast, highway traffic is typically free from these disruptions and has different percentages of heavy vehicles and average speeds. Consequently, traffic noise modeling for highway scenarios must be approached differently than for mid-sized city traffic.

The vehicles traffic percentage of highway traffic were very different from city traffic. On highways, 2-wheelers account for the highest share of traffic, followed by trucks and cars. 2-wheelers contribute between 20.7% and 57.32% of the traffic, with an average of 38.30%. Cars range from 8.2% to 52.64%, averaging 18.01%, while trucks account for 12.93% to 49.15%, with an average of 30.73%. Other vehicle categories have an average traffic share of less than 6%. In mid-sized cities, two-wheelers dominate traffic volume, contributing between 47% and 78%, with an average of 63.29%. After two-wheelers, cars, autos, non-motorized vehicles, and LCVs have significant traffic shares, while buses and trucks average less than 1%. The percentage volume for different category of vehicle travelling in highway and mid-size city is shown in Figure 5.7 and Figure 5.8. The average speed of vehicles in highways were found to be greater than vehicles travelling in roads of mid-size Indian city. The average speed of vehicles travelling in highway and mid-size city roads is illustrated in Figure 5.9. Table 5.5 shows that noise level data collected from different locations in highway were ranged from 72 to 85 dB(A). If we compared the average noise level of highway traffic with that of mid-sized city road, than noise at highways were found only 0.16 dB(A) greater that noise level at mid-size city roads. Similarly, there is nothing big difference found for maximum noise level but minimum noise level for highway is greater than 2.9 dB(A) than mid-size city roads as shown in Figure 5.10. In city roads the acceleration, deceleration of vehicles and honking seems to be major contributor of noise while in highway; speed and road-tyre interaction seems to be major contributor of noise. Descriptive statistics of data collected for highway noise modeling is shown in Table 5.5.

Table 5.5. Descriptive statistics of highway data

	Minimum	**Maximum**	**Mean Statistic**	**Std. Deviation**
Traffic Volume, Vehicle/h				
2-w	85	716	329.52	144.779
3-w	1	112	47.64	28.573
Car	39	806	145.25	67.452
LCV	13	75	34.32	11.195
Tractor	1	64	12.83	15.583
Bus	0	29	12.24	7.173
Truck	110	372	243.24	55.915
E-Rickshaw	1	7	1.61	1.203
Traffic Speed, Km/h				
2-w	29.75	66.50	45.37	8.56
3-w	19.75	50.25	36.75	6.24
Car	30.50	91.50	59.81	15.57
LCV	25	76.50	43.93	11.07
Tractor	13	32.75	21.74	4.37
Bus	15.00	82.62	42.22	17.51
Truck	18	57.50	41.96	9.07
E-Rickshaw	15	25.75	16.60	1.79
Highway Noise, dB(A)				
LA_{eq}	72.34	84.37	77.50	2.84

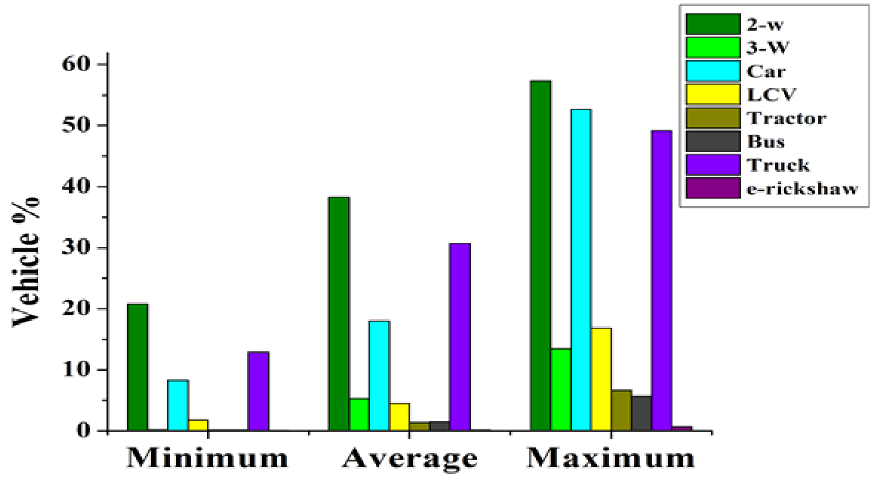


Figure 5.7. Vehicle % composition for highway traffic

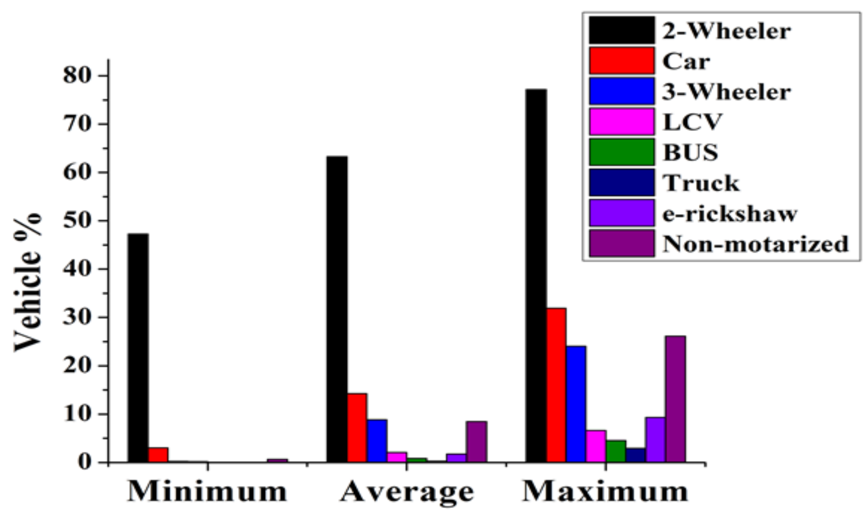


Figure 5.8. Vehicle % composition for mid-size city traffic

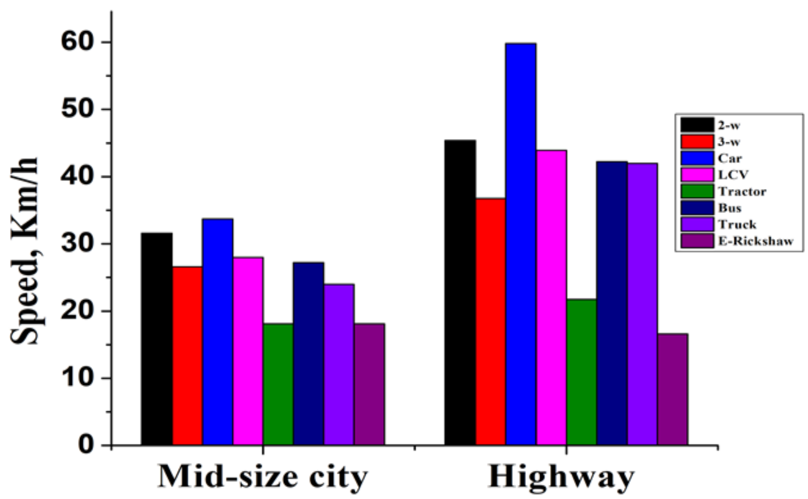


Figure 5.9. Speed comparison of highway and mid-size city traffic

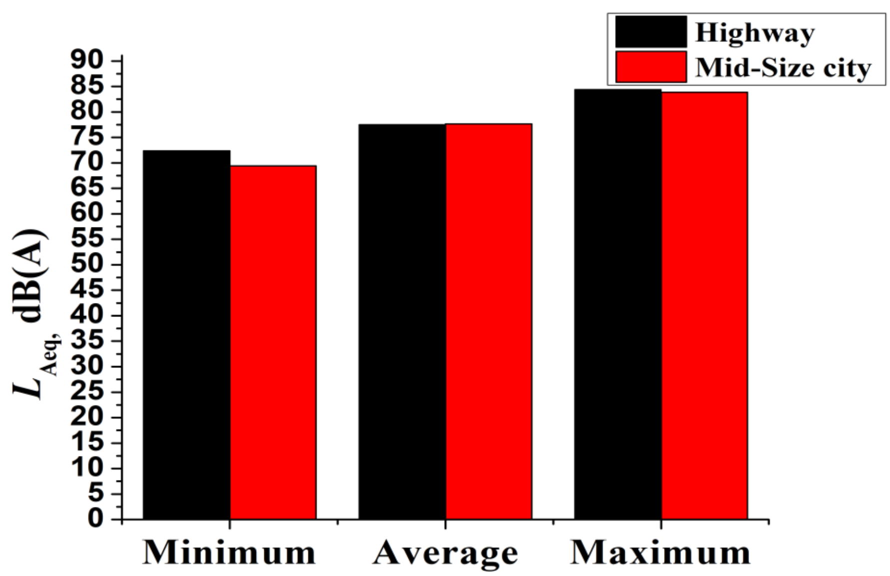


Figure 5.10. Comparison of noise level from highway traffic vs mid-size city traffic

5.2.4 Modified highway noise model results

Figure 5.11 and Figure 5.12 presents the statistical performance of L_{eq} for developed model and validated model. It can be clearly observed from that R^2 value obtained for model is 0.90. This means that the developed L_{eq} model is able to explain 90 % variability in the datasets. The value obtained for MAE and RMSE for developed model is found to be 1.68 and 1.96 respectively. The model is validated with datasets different from site which contains datasets used for model development. The explained variability obtained in datasets of validated model is 81% . The coefficient of correlation (R) value obtained for developed model and validated model is higher than 0.80 which means that the target and predicted values are well associated with each other and prediction can be made more closely to the actual value with least amount of error. The highest explained variability and lowest error achieved in developed model and validated model reveal that the maximum reliable prediction can be made. However, the overall finding establish that the developed models are efficient in predicting the L_{eq} for highway traffic .

This model's applicability is limited to bituminous roads because both the emission curves and the highway traffic data were collected specifically for this type of pavement. Consequently, the results and predictions derived from this model may not accurately reflect conditions on other types of road surfaces, such as concrete or gravel. Therefore, while the model provides valuable insights for bituminous roadways, it should be used with caution or recalibrated when applied to other road types to ensure accurate and reliable outcomes.

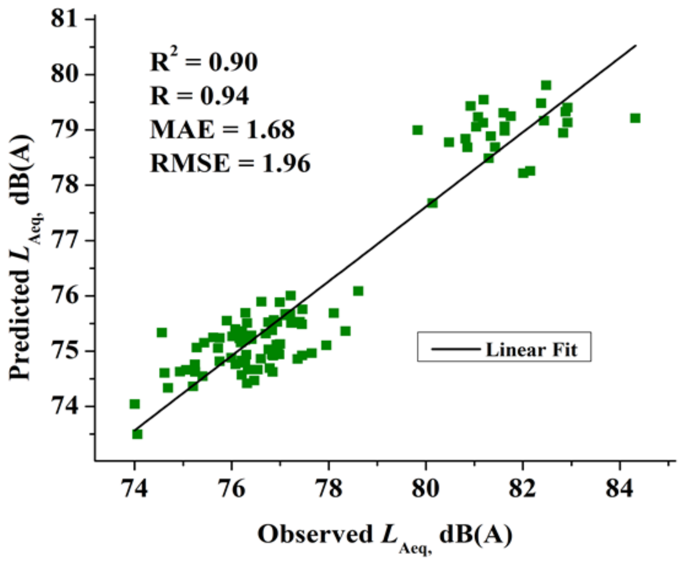


Figure 5.11. Scatter plot for developed L_{eq} model

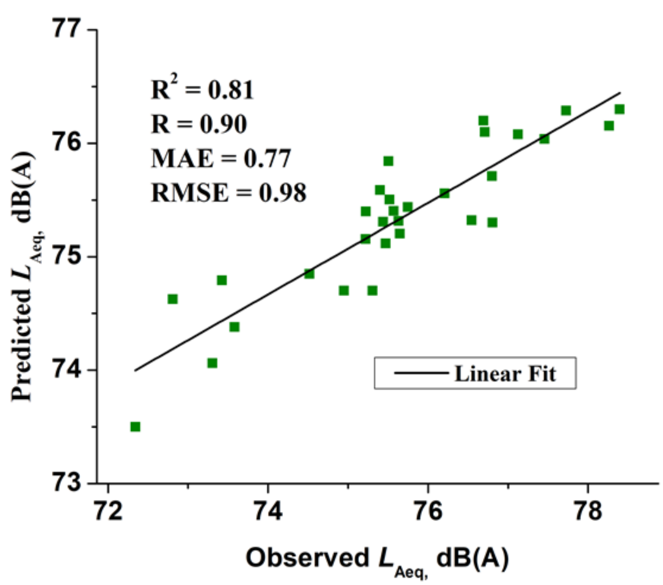


Figure 5.12. Scatter plot of the L_{eq} model used for validation

5.3 Conclusion

This research contributed by giving emission curves for different categories of vehicles. These emission curves are only applicable for vehicles operating under free-flowing conditions in real-world driving scenarios. The emission curve equations can serve as input to the future highway traffic noise model and planning mitigation measures. Various known models, i.e. FHWA TNM, ASJ-RTN, CNOSSOS-EU and others, used their respective vehicle noise emission curves to obtain the traffic noise prediction models. The emission curve results from vast data collection of around 13,684 vehicle data in actual running conditions. The noise emission curves for 8 vehicle categories were developed and compared with FHWA emission curves. The present study reveals that modern vehicle emission curves were found to be different from FHWA 1978 and 1995 emission curves, primarily due to technological advancements, stricter regulations, and enhanced fuel quality. For motorcycles, the emission curves show a significant decrease, indicating the effectiveness of cleaner engines, catalytic converters, and improved design features. Conversely, for buses, the current emission curves are higher than those from 1995, likely resulting from increased engine power and larger vehicle sizes to meet contemporary transportation needs. These findings underscore the complexity of emission trends across different vehicle types and emphasize the importance of ongoing technological innovation and regulatory initiatives aimed at further reducing emissions across the board.

The modified highway noise model was developed by replacing the FHWA emission curves with emission curves specifically developed in this research, which consider the latest vehicle technology, noise emission regulations based on Indian standards, pavement types, and other local environmental conditions. To assess the model's accuracy and reliability, it was validated using datasets collected from various locations. The results indicated that both the developed model and the validated model performed good, achieving high values for the coefficient of determination (R^2) and correlation coefficient, coupled with minimal prediction errors. These findings suggest that the modified model is effective in predicting highway traffic noise under diverse conditions, making it a valuable tool for noise management and mitigation strategies in urban planning and transportation engineering in India.