

**A Comparative Analysis of Noise and Vibration Levels in Conventional and Electric
Buses in Montreal Considering Comfort Perceptions**

Emmanuel Davies

A Thesis

in

The Department of

Building, Civil and Environmental Engineering

Presented in Partial Fulfillment of the Requirements

for the Degree of Master of Applied Science (Building Engineering) at

Concordia University

Montreal, Quebec, Canada

October 2025

© Emmanuel Davies, 2025

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

By: **Emmanuel Davies**

Entitled: **A Comparative Analysis of Noise and Vibration Levels in Conventional and Electric Buses in Montreal Considering Comfort Perceptions**

and submitted in partial fulfilment of the requirements for the degree of

Master of Applied Science in Building Engineering

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

_____ Chair

Dr. Joonhee Lee

_____ Examiner

Dr. Archie Huang

_____ Supervisor

Dr. Fuzhan Nasiri

Approved by _____

Dr. Chunjiang An, Graduate Program Director

Dr. Mourad Debbabi Dean of Gina Cody School of Engineering and Computer Science

ABSTRACT

A Comparative Analysis of Noise and Vibration Levels in Conventional and Electric Buses in Montreal Considering Comfort Perceptions

Emmanuel Davies

Buses are the most utilized mode of public transportation worldwide. However, existing investigations show that they are major contributors to transit noise and vibration in urban areas, leading to environmental concerns, adverse health effects on riders and residents, reduced ridership, and lower transit sustainability. With the growing shift towards electric buses as quieter and more sustainable alternatives, it is imperative to assess their vibroacoustic performance under real-world conditions. Thus, this study evaluates the vibroacoustic levels of conventional and electric buses in Montreal. It also analyzes the influences of eight operational factors, namely bus age, average speed, road surface conditions, road network characteristics, day and time of operation, passenger occupancy, and distance travelled, on vibroacoustic generation. Data was collected using validated mobile measurement tools (Sound Meter Pro and iDynamics) and rider interviews. Descriptive statistics and machine learning models, including XGBoost and Ridge Regression, were applied to analyze the relationships between operational factors, vibroacoustic emissions, and rider comfort perceptions. Results show that electric buses consistently exhibit lower noise and vibration levels than conventional buses. Furthermore, operational factors such as rougher road conditions, higher average speeds, and older buses significantly increased vibroacoustic emissions across both bus types. Using these results, vibroacoustic policy implications were established. These policy implications provide transit agencies with practical guidance for improving rider comfort, improving bus fleet operations, and supporting sustainable transit planning. The study contributes to new insights by integrating empirical vibroacoustic measurements with multi-factor operational analysis, offering a comprehensive foundation for future transit noise and vibration mitigation strategies. Further research is encouraged to validate and implement the proposed policies across diverse transit systems.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my deepest gratitude to my supervisor, Dr. Fuzhan Nasiri, for his invaluable guidance, encouragement, and support throughout the course of this research. His insights and expertise have been instrumental in shaping this work.

I am also sincerely thankful to my colleagues in the research group, whose collaboration, discussions, and insights provided essential academic and personal support that enriched my experience.

Additionally, my heartfelt appreciation goes to my family and friends for their unwavering love, patience, and encouragement during the challenging moments of this journey. Their constant belief in me has been a source of strength and motivation.

Finally, I would like to acknowledge the Société de transport de Montréal (STM) for their assistance during the data collection phase, without which this research would not have been possible.

TABLE OF CONTENTS

TABLE OF CONTENTS.....	v
LIST OF FIGURES	ix
LIST OF TABLES.....	xi
1. INTRODUCTION.....	1
1.1. Background	1
1.2. Problem Statement	2
1.3. Research Objectives	4
1.4. Overview of Research Methodology.....	5
1.5. Research Novelty and Contributions.....	6
1.6. Structure of the Thesis.....	7
2. LITERATURE REVIEW	8
2.1. Sources of Noise and Vibration in Buses.....	8
2.2. Noise Generation in Conventional and Electric Buses	10
2.3. Vibration Generation in Conventional and Electric Buses	11
2.4. Influence of Operational Factors on Bus Vibroacoustic Levels	12
2.4.1 Bus Age	12
2.4.2 Average Speed.....	13
2.4.3 Road Surface Conditions	13
2.4.4 Road Network.....	14
2.4.5 Bus Operation Schedules (Day and Time)	14
2.4.6 Passenger Occupancy Levels.....	14
2.4.7 Distance Travelled.....	15
2.5. Comfort Perceptions of Bus Vibroacoustic Levels	15
2.5.1 Objective Vibroacoustic Perceptions.....	16

2.5.2 Subjective Vibroacoustic Perceptions	16
2.6. Overview of Existing Vehicle Vibroacoustic Models.....	17
2.6.1. Noise Models	17
2.6.2. Vibration Models.....	19
3. RESEARCH METHODOLOGY	22
3.1. Scope of Study	22
3.2. Bus and Rider Sampling.....	23
3.3. Data Collection Instruments.....	25
3.3.1 Bus Vibroacoustic Measurement Instruments.....	25
3.3.2 Rider Perception Instrument.....	27
3.3.3 Operational Factors Data Collection Instruments	28
3.4. Data Collection Process	28
3.4.1 Bus Vibroacoustic Data Collection Process	28
3.4.2 Rider Comfort Perception Data Collection Process	29
3.4.3 Operational Factors Data Collection Process	30
3.5. Data Analysis	31
3.5.1 Data Preparation	31
3.5.2 Descriptive Statistical Analysis	31
4. RESULTS AND DISCUSSIONS	38
4.1. Overview of Bus Noise and Vibration Levels in Montreal.....	38
4.1.1 Conventional Bus Noise Levels	38
4.1.2 Electric Bus Noise Levels.....	41
4.1.3 Conventional Bus Vibration Levels	43
4.1.4 Electric Bus Vibration Levels.....	46
4.1.5 Rider Perceptions.....	49

4.2.	Models	50
4.2.1	Conventional and Electric Noise Models	50
4.2.2	Conventional and Electric Vibration Models	53
4.2.3	Noise Perception Model	56
4.2.4	Vibration Perception Model	56
4.3.	Factor Importance	57
4.3.1	Conventional and Electric Noise	57
4.3.2	Conventional and Electric Vibration	58
4.4.	Relational Impacts of Operational Factors on Bus Vibroacoustic Levels	59
1.1.1	4.4.1 Conventional Bus Noise	59
	4.4.2 Electric Bus Noise	60
	4.4.3 Conventional Bus Vibration	62
	4.4.4 Electric Bus Vibration	63
4.5.	Isolated Contributive Effects of Operational Factors to Bus Vibroacoustic Levels	65
4.5.1	Isolated Effects of Operational Factors on Bus Conventional Noise	65
4.5.2	Isolated Effects of Operational Factors on Electric Bus Noise	68
4.5.3	Isolated Effects of Operational Factors on Conventional Bus Vibration	70
4.5.4	Isolated Effects of Operational Factors on Electric Bus Vibration	73
4.6.	Interactive Effects	76
4.6.1	Conventional and Electric Noise	76
4.6.2	Conventional and Electric Vibration	78
5.	POLICY IMPLICATIONS.....	81
5.1.	Conventional and Electric Bus Noise.....	81
5.2.	Conventional and Electric Bus Vibration.....	83
6.	CONCLUSIONS	86

6.1. Research Summary.....	86
6.2. Contributions of the Study	86
6.3. Limitations of the Study	88
6.4. Suggestions for Future Research.....	88
REFERENCES	90
APPENDIX A: VERBAL INVITATION SCRIPT	105
APPENDIX B: VERBAL CONSENT SCRIPT AND INTERVIEW GUIDE.....	106
APPENDIX C: ETHICS CERTIFICATE	109

LIST OF FIGURES

Figure 1.1: Simplified Study Methodology Flowchart	6
Figure 2.1: Sources of Noise and Vibration in Vehicles [41]	8
Figure 3.1. 2024 STM Transit Network Map (Bus Network in Blue and Purple)	22
Figure 3.2: Interfaces of (a) Sound Meter Pro and (b) iDynamics on the LG G6 ThinQ.	27
Figure 3.3: Measurement of Noise and Vibration Levels in Buses	29
Figure 3.4: Seats Considered for Rider Comfort Perception Data Collection	30
Figure 4.1: Conventional Bus Noise Levels across Different Operational Factors	39
Figure 4.2: Electric Bus Noise Levels across Different Operational Factors	42
Figure 4.3: Conventional Bus Vibration Levels across Different Operational Factors	45
Figure 4.4: Electric Bus Vibration Levels across Different Operational Factors	48
Figure 4.5: Average Rider Perceptions of Bus Noise and Vibration Levels	49
Figure 4.6: Upper Bound Iterations for Conventional and Electric Buses	51
Figure 4.7: Lower Bound Iterations for Conventional and Electric Buses	52
Figure 4.8: Upper Bound Iterations for Conventional and Electric Buses	54
Figure 4.9: Lower Bound Iterations for Conventional and Electric Buses	55
Figure 4.10: Operational Factor Rankings for Conventional and Electric Buses	58
Figure 4.11: Operational Factor Rankings for Conventional and Electric Buses	59
Figure 4.12: SHAP Summary Plot for Important Conventional Bus Noise Generation Features	60
Figure 4.13: SHAP Summary Plot for Important Electric Bus Noise Generation Features	61
Figure 4.14: SHAP Summary Plot for Important Conventional Bus Vibration Generation Features	62
Figure 4.15: SHAP Summary Plot for Important Electric Bus Vibration Generation Features ...	64
Figure 4.16: Isolated Effects of Operational Factors on Conventional Bus Noise Generation	66
Figure 4.17: Isolated Effects of Operational Factors on Electric Bus Noise Generation	69

Figure 4.18: Isolated Effects of Operational Factors on Conventional Bus Vibration Generation	72
Figure 4.19: Isolated Effects of Operational Factors on Electric Bus Vibration Generation	74
Figure 4.20: Interactive Effects of Operational Factors in Bus Noise Generation	77
Figure 4.21: Interactive Effects of Operational Factors in Bus Vibration Generation	78

LIST OF TABLES

Table 3.1: Results of Noise Data Collection Instruments Accuracy Tests	26
Table 4.1: Bus Noise Model Performance	53
Table 4.2: Bus Vibration Model Performance	56

1. INTRODUCTION

1.1. Background

It is a well-known fact that public transportation is essential to the economic development and urbanization of cities and nations around the world. Research has emphasized its major contributions such as improved access to goods and services [1], reduced private transit dependency [2], cheaper means of movement [3], and lower transit emissions per capita [4]. Given the growing global population and need for mobility, most nations have continued to invest in and improve the efficiency of their public transportation systems. These efforts have led to the holistic operation of diverse transit modes to achieve safe and accessible transportation, aligning with the United Nations Sustainable Development Goal 11 [1]. Predominant among these diverse modes are buses, trains, metros, and trams, which mobilize people and goods over varying distances [5].

Over the years, Canada has significantly invested in its public transportation systems, following its Transportation 2030 Strategic Plan [6]. This initiative has led to the development and operation of numerous proficient transportation networks, interconnecting cities and communities across the vast Canadian landmass. Among these networks, Montreal's public transit system stands as one of the best in the country and the American continent [7]. Serving the second most populous city in Canada, the public transit, managed by the Société de Transport de Montreal (STM) and Exo, uses different transit modes such as buses, metro, and train systems to mobilize residents [8, 9]. Of these, buses serve as the predominant mode, traversing more than 424 km, compared to 71 km for metro and 225 km of train lines [10, 11].

Buses are not only essential to Montreal's public transit network but also to many transportation systems worldwide. A report by [12] indicated that buses collectively account for 63% of the 243 billion public transport journeys worldwide, making them central to global transportation research. As a result, numerous studies have been conducted on various bus transit concepts such as rider demographics and comfort [13], rider satisfaction [14], bus transit efficiency [15], and the integration of innovative technologies in buses [16]. More recently, with the growing emphasis of environmental sustainability, extensive research has explored the sustainable operations of buses. According to [17], these studies have identified buses, specifically the conventional types, as major contributors to urban noise and vibration, ranking second to subways.

Concurring, [18] attributed this to the presence of vibroacoustic sources such as the engine and, and road/tire interactions, which generate unwanted noise and vibration during bus operations. Additionally, operational factors such as vehicle age, road surface conditions, and speed have been identified to exacerbate bus vibroacoustic generation [19, 20, 21]. Thus, the combined influence of these sources and operational conditions has driven researchers to seek alternative solutions to mitigate bus vibroacoustic pollution.

One major solution to excessive bus vibroacoustic generation is the adoption of electric buses as replacements for the conventional buses [22]. This is because electric buses are characterized by quieter propulsion systems and smoother travel, resulting in an overall better vibroacoustic performance, bus comfort, and improved bus rider perception. This is empirically backed by studies showing that, electric buses typically generate relatively lower vibroacoustic levels in the ranges of 57 to 78 dB and 0.098 to 0.539 m/s² [23, 24] compared to 68.2 to 87.6 dB and 0.12 to 0.641 m/s² for conventional buses [17, 25]. Although these vibroacoustic differences are in favor of electric buses, this advantage is not constant across all operational conditions. In fact, studies like [26, 27, 28] have revealed that electric buses are prone to generating high whistling noises from their electric motors, while being equally susceptible to excessive vibration generation during their operations. Thus, it can be concluded that the vibroacoustic performances of both conventional and electric buses are significantly dependent on their real-world operational conditions. This underscores an important need to assess bus vibroacoustic levels from this perspective.

1.2.Problem Statement

Despite the widespread use of buses in public transit systems and the ongoing transition to electric buses, the issue of excessive vibroacoustic generation persists. This problem has led to many adverse effects on rider health, the environment, and the efficacy of bus transit. Concurring, [29] and [30] identified some of the health issues as long-term hearing impairment, sleep disturbances, decreased concentration and performance, tiredness, and mental fatigue. Beyond the health concerns, high vibroacoustic levels also have environmental consequences such as disturbances of roadside structures like buildings and leisure spaces, and uninhabitable urban

spaces [31]. Additionally, these bus noise and vibration levels affect public perceptions of bus transit, making it less appealing to riders and leading to a decline in ridership [32].

Given the dire effects of bus vibroacoustic levels, many studies have explored the issue from different perspectives, offering valuable insights into their causes and impacts. Studies such as [33] and [34] investigated vibroacoustic sources and their contributions, focusing on the vehicle's powertrain and interior structure components. Additionally, [35] and [36] analyzed how operational factors such as road surface conditions and speed influence bus noise and vibration levels. Other works like [37] covered the impacts of bus noise and vibration levels generated by these sources from a general perspective, while [38] assessed the impacts on rider comfort perceptions. Together, these studies have provided an extensive foundation of knowledge, crucial for grasping the complexities of bus vibroacoustic concepts. However, a review of literature reveals several gaps that need to be addressed to help mitigate excessive bus noise and vibration levels.

The first gap identified from the existing literature is the lack of generalizability in vibroacoustic studies. This is because prior research focuses on specific geographic locations such as Iran [39] and North India [40], with results that are highly dependent on the differences in bus types, transit operations, and environmental conditions in these areas. Consequently, these results cannot be utilized as a basis for implementing effective vibroacoustic mitigation strategies in other locations. Thus, there is a pressing need to establish a benchmark study assessing vibroacoustic performance and perceptions in both conventional and electric buses operating in Montreal. Addressing this gap will ensure that the city's public transit system has an empirical foundation on which decisions can be made to improve the vibroacoustic performance of bus transit.

The second critical gap is the non-existent research on how multiple operational factors individually and collectively influence bus noise and vibration levels. While existing studies have investigated specific aspects such as powertrain mechanics [41], they often neglect the complex interplay between various operational factors. Furthermore, the studies that consider these operational factors, like [42] and [43], tend to adopt a narrow, unifactorial approach, failing to account for varying influences across different transit conditions. This fragmented perspective restricts a comprehensive understanding of how bus vibroacoustic levels evolve under diverse operational scenarios, making it difficult to develop targeted mitigation strategies. To bridge this

gap, a more integrated study is needed to evaluate multiple operational factors and their distinct impact on the overall vibroacoustic performance of conventional and electric buses.

Lastly, the final gap is related to the absence of detailed policy directions that address bus vibroacoustic performance, operational conditions, and rider comfort perceptions. This is because existing regulations such as the ISO 2631-1 and the U.S. Environmental Protection Agency CFR Vehicle Noise Emission Standards focus on operational vibroacoustic thresholds without offering concrete guidelines on how to achieve them. This leaves transit agencies in limbo as to how they can effectively attain the thresholds, especially under dynamic real-world conditions. Thus, establishing policy directions that integrate empirical vibroacoustic data would provide transit agencies with actionable insights to improve bus vibroacoustic performance, ultimately enhancing the overall public transportation experience.

Given this, the study aims to comprehensively assess the vibroacoustic performance of conventional and electric buses by examining the interplay between noise and vibration levels, rider comfort perceptions, and operational factors. Achieving this aim will help ascertain the vibroacoustic performance of Montreal's conventional and electric buses, identify key operational factors affecting bus noise and vibration, and develop guidelines to enhance rider comfort, increase ridership, and improve environmental sustainability.

1.3. Research Objectives

Given the established aim, the study's research objectives are:

1. To quantify and compare the vibroacoustic levels and rider perceptions of conventional and electric buses in Montreal across various bus and operational characteristics.
2. To ascertain the importance, relational impacts, isolated effects, and interactive strengths of multiple operational factors on the vibroacoustic performance of conventional and electric buses.
3. To develop policy guidelines that focus on bus vibroacoustic performance and operational conditions to optimize bus transit systems and enhance sustainability.

It should be noted that this study considers eight operational factors, namely bus age, average speed, road conditions, road network, bus operation day, bus operating time, distance travelled, and passenger occupancy levels. Existing research on these operational factors is presented in the Literature Review section of the thesis.

1.4.Overview of Research Methodology

To achieve the stated objectives, a quantitative research approach was employed. First, conventional and electric buses alongside a number of riders were sampled from the STM's bus fleet and ridership pool. The STM was selected because it serves as the primary bus transit system in Montreal with the most ridership, making it ideal for this study. After sampling, data on bus noise and vibration levels, their operational conditions, and rider comfort perceptions were collected. Bus noise and vibration levels were measured using vibroacoustic mobile apps (Sound Meter Pro for noise and iDynamics for vibration), verified through empirical studies. Data on operational factors were obtained using an array of processes, including observations, while rider comfort perceptions were ascertained through brief interviews. The collected data underwent statistical analysis using descriptive statistics to summarize and compare noise and vibration levels across different operational conditions. In addition to this, models were created to establish the influences of operational factors on bus vibroacoustic performance and bus vibroacoustic performance on rider perception. XGBoost models and Shapley Additive Explanations (SHAP) were adopted for the operational factors and bus vibroacoustic performance models while Ridge Regression models were adopted for the bus vibroacoustic performance and rider perception models. These models served as the analytical and insight basis for the study and its policy guidelines. Figure 1.1 shows a simplified methodology flowchart for this study.

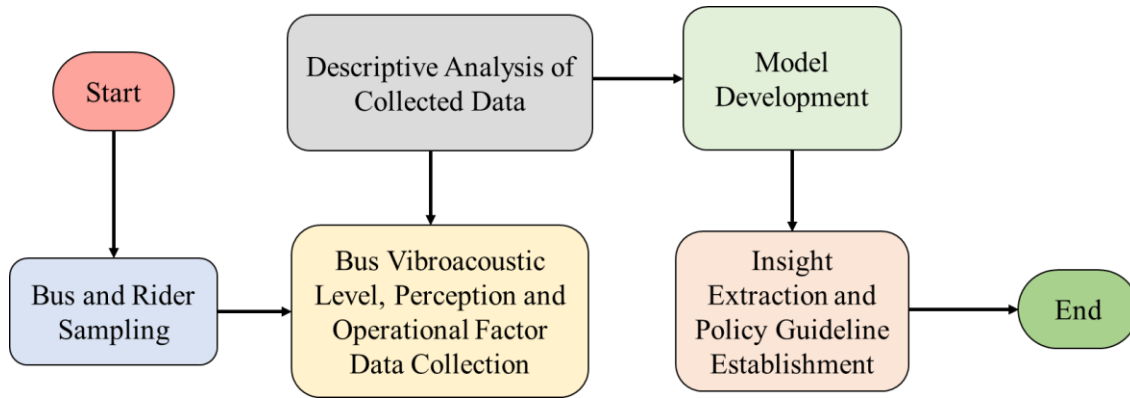


Figure 1.1: Simplified Study Methodology Flowchart

1.5. Research Novelty and Contributions

This research introduces several key novelties and contributions to the study of bus vibroacoustic performance.

- a. Firstly, the study adopts a multi-factor approach, analyzing a wide range of operational variables simultaneously rather than in isolation. Unlike prior studies that examined single-variable effects, this approach reflects the real-world complexity of bus operations, where multiple factors interact to influence noise and vibration generation in buses.
- b. Secondly, the study performs a comparative analysis of conventional and electric buses, providing one of the few data-driven evaluations of how operational factors impact bus vibroacoustic levels across both bus types. This comparison enables a clearer understanding of whether electric buses consistently offer acoustic benefits under different conditions or if those benefits are context dependent.
- c. Thirdly, the study employs SHAP-based interaction analysis to explore relationships between operational factors, for instance, whether an interaction exists between average speed and bus age in relation to noise generation. These insights go beyond general trends, enabling more targeted and effective planning strategies based on the most influential operational factors to reduce excessive bus noise and vibration.
- d. Lastly, the study empirically links bus vibroacoustic performance with rider perceptions, bridging the gap between technical noise and vibration metrics and the subjective experience of passengers. By quantifying how vibroacoustic performance influences user

perception, the research provides transit agencies with practical models to monitor and predict rider satisfaction.

1.6. Structure of the Thesis

The remainder of this study is divided into five chapters, namely the literature review, research methodology, results and discussions, policy implications, and conclusions. The literature review (chapter 2) presents and examines existing studies on the sources of bus noise and vibration, noise and vibration generation in buses, influences of operational factors on bus vibroacoustic levels, comfort perceptions of bus noise and vibration, and an overview of existing vibroacoustic models. The research methodology (chapter 3) extensively covers the study scope, bus and rider sampling, data collection instruments and processes, and data analysis. The results and discussions (chapter 4) report and discuss the insights obtained from the data analysis. The policy implications (chapter 5) present policy guidelines extracted from the study's insights. Lastly, the conclusions (chapter 6) summarize the entire study and its contributions alongside the study's limitations and directions for future research.

2. LITERATURE REVIEW

2.1.Sources of Noise and Vibration in Buses

As established in the preceding chapter, buses are prone to generating significant noise and vibration during their operations, which originate from various vibroacoustic sources. These sources can be associated with the vehicle's mechanics, occupants, or external interactions with the environment. Concurring, [44] identified some vibroacoustic sources associated with the vehicle's mechanics as the propulsion mechanism (engine or electric motor), intake, and exhaust systems. Additionally, [39] and [45] cited passengers as another significant source of noise and vibration in buses, while [46] identified wind effect and road/tire interactions as externalities that also contribute to bus vibroacoustic levels. Reference [41] extensively summarized these vibroacoustic sources and their interlinks in Figure 2.1.

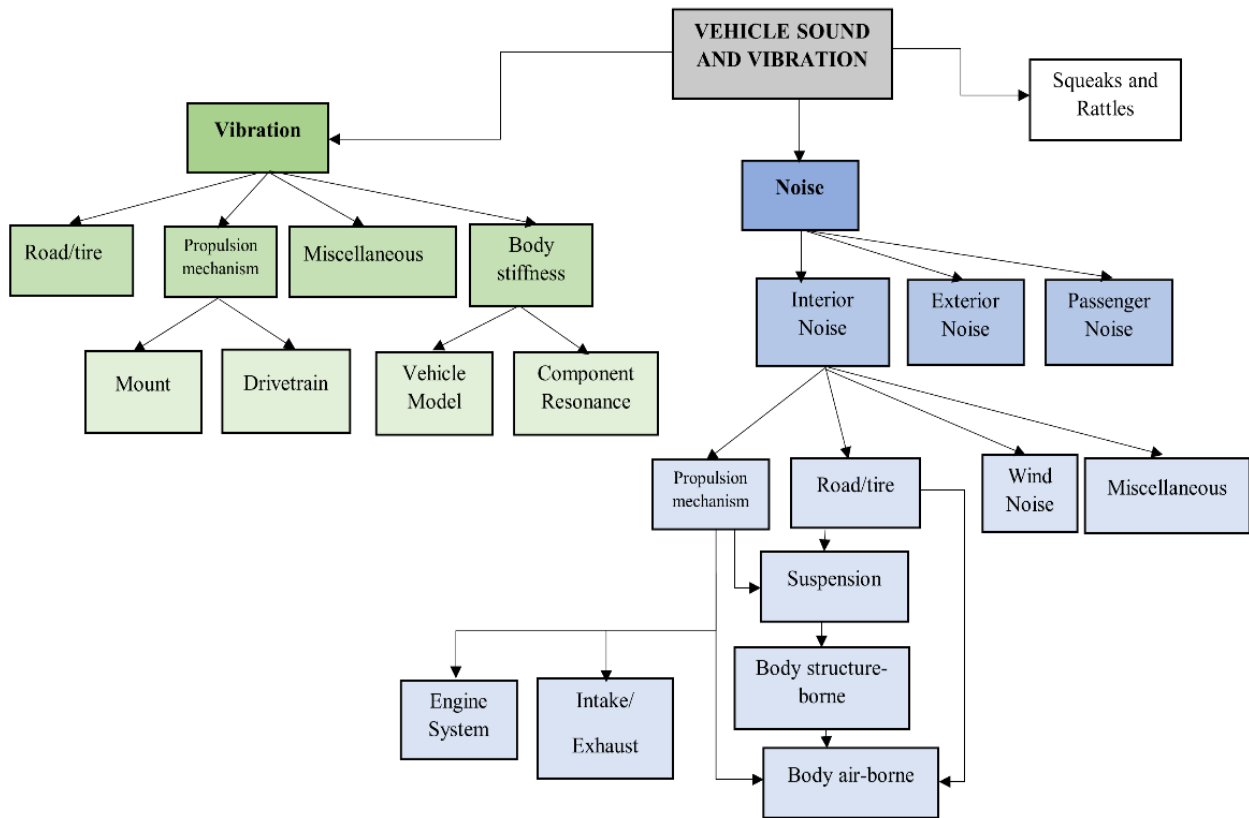


Figure 2.1: Sources of Noise and Vibration in Vehicles [41]

Despite the diverse nature of vibroacoustic sources, as illustrated in Figure 2.1, a few of them stand out as prominent contributors to bus noise and vibration levels. Reference [41] identified these prominent sources as the propulsion mechanism, road/tire interactions, and wind effect for noise. Additionally, they cited vehicle body stiffness, road/tire interactions, and the propulsion mechanism for vibrations. Notably, road/tire interactions and the propulsion mechanism were seen to be central to both noise and vibration generation [18], concurring with most research in the domain. However, the extent of their influence was dependent on the operational state of the bus. According to [47] and [48], in the idle state, the propulsion mechanism was seen to be the most dominant source due to the absence of road/tire interactions and wind effect. However, in the state of motion, the road/tire interactions were seen to be the most dominant, far exceeding the propulsion mechanism [49].

Based on these studies, many investigations were conducted to quantify the contributions of vibroacoustic sources to vehicle noise and vibration. Reference [50] assessed the vibroacoustic contributions of the powertrain components and discovered the exhaust system as the highest contributor to bus vibroacoustic level, with 25 to 35% contribution to the total vibroacoustic levels measured. This was followed by the engine with 22 to 30% contributions and the transmission with 12 to 15%. The lowest contributors were the tires, fan and cooling system, and intake systems, with contributions ranging between 9 and 15%. Reference [33] also investigated vibroacoustic contributions through the categories of airborne and structure-borne sources. Their research revealed the panel subframe as the biggest structure-borne vibroacoustic source with over 22% contribution and the engine as the biggest airborne vibroacoustic source with approximately 14% contribution. Lastly, the road/tire interactions was seen as the least contributor, with less than 7% contributing to the total vibroacoustic levels. Conversely, [51] assessed the contribution of various vibroacoustic sources in electric vehicles using the principle of transfer path analysis. Their study showed that structure-borne road vibroacoustic levels were the most prominent contributors with 52.2% contribution, while airborne tire vibroacoustic levels were the least with 0.5% contribution.

A critical review of this literature shows a disparity between the study findings which can be attributed to a lack of foundational consensus owing to the use of vehicles with different models, build and operational conditions, alongside a methodological shortcoming of a single vehicle experiment. Nevertheless, the positives drawn from these studies reveal that despite different

contributions, the vibroacoustic sources highlighted across the studies remain constant, which establishes a solid baseline for this study's investigation into bus vibroacoustic levels.

2.2.Noise Generation in Conventional and Electric Buses

The noise generated in buses as a result of vibroacoustic sources is not constant across all buses. Rather, it varies based on the vehicle's build and operational conditions. Reference [52] concurred, explaining that bus noise differs based on its propulsion mechanism type and operational speed. Regarding the propulsion mechanism, buses can be categorized as either conventional (buses with internal combustion engines) or electric (buses with electric motors). According to [19], conventional buses generate more noise than electric buses. Empirical investigations show that conventional buses generate noise levels in the ranges of 69.3–92 dBA [53], 63.4–90.5 dB [54], or 68.2–87.6 dB [17] across their operational states. These decibel levels are significantly higher than that of electric buses, which typically range between 59.8–67.2 dB [55]. Reference [24] attributed this significant difference to the contributions of the internal combustion engine to the overall noise level of conventional buses.

Aside from the noise generation differences brought about by the propulsion mechanism, operational speeds also play a key role in bus noise generation. Concurring, [56] explained that the influence of operational speeds on bus noise generation was seen through the intensities of road/tire interactions and wind effects. Reference [19] explored this concept and reported that conventional and electric buses emitted noise levels between 71.5–75.6 dB and 67.3–70 dB at 30–40 km/h speed, respectively. Additionally, [23] focused on a broader speed range of 0–50 km/h and disclosed that conventional buses produced noise levels of 65–78 dB, while electric buses generated 57–78 dB within the same operational speed range. As an emphasis on findings, [57] also considered the same speed range and cited noise levels of 73–78 dBA and 68.6–73.6 dBA for conventional and electric buses, respectively. Furthermore, [58] reported noise levels at 10–50 km/h for conventional buses as 61–72 dBA and electric buses as 52–72 dBA.

Other works also sought to quantify the difference in noise generation between the two bus types and their operational speeds. Reference [59] investigated and found out that conventional buses generated 34.7 dBA noise above background noise level, compared to 11.9 dBA for electric

buses. Considering operational speed, [60] measured a 20 dB difference between conventional and electric buses in their idle state (0 km/h). At 10 km/h, a 15 dB noise difference was discovered between the two bus types [61]. At 15 km/h, [23] reported a maximum noise difference of 12 dB between the bus types. Additionally, [19] observed that conventional bus noise was 7.1% and 10.9% higher than electric bus noise at 30 km/h and 40 km/h, respectively. References [57] and [58] also found a range difference of 5 to 9 dBA, concluding that conventional buses were roughly twice as noisy as electric buses. These differences have cemented electric buses as a bus type option with better noise performance, further advancing the shift from conventional buses. In support of this, [62] found that replacing 90% of conventional buses with electric buses could result in 3–4 dBA reductions in traffic noise. Similarly, [63] found that a 2–10 dBA noise reduction should occur if conventional buses are replaced with electric buses. Conclusively, it can be confirmed that electric buses are significantly less noisy across different speed operations.

2.3.Vibration Generation in Conventional and Electric Buses

Buses also generate vibrations during their operations, primarily due to their contact with road surfaces [64]. The intensities of these vibrations depend on factors such as road type, presence of speed bumps, and the frequency of road maintenance [65]. Just like noise, vibration generation in buses also differs based on the propulsion mechanism. In this view, conventional buses were seen to typically generate vibration levels within the ranges of 0.1 to 0.22 m/s² [39] and 0 to 0.4 m/s² [66]. Additionally, [67] also measured the average vibrations across four different sections of a conventional bus, namely, “driver’s seat,” “rear axle seating area,” “front door seating area,” and “last row seating area,” with ranges of 0.664 to 1.072 m/s², 0.647 to 0.761 m/s², 0.649 to 0.748 m/s² and 0.737 to 1.033 m/s² respectively. In contrast, electric buses were seen to have relatively lower vibration levels, which fell within the ranges of 0.001–0.055 g, equivalent to 0.019–0.539 m/s² [24]. However, studies investigating these vibration levels are limited, presenting a potential gap, which this study contributes to fulfilling.

Aside from the propulsion mechanism, other features contribute to the variations in bus vibration levels. Concurring, [68] focused on bus vibration across two different road surfaces, revealing significant differences. On “Road Condition A,” average vibration measurements of 0.832, 1.147, and 1.659 m/s² were recorded in the x, y, and z-axes, whereas “Road Condition B”

showed lower vibration levels of 0.282, 0.182, and 1.713 m/s². Furthermore, [69] examined vibration level variations on buses with different floor levels (high-floor coaches vs low-floor city buses). Their findings indicated that the high-floor buses experienced a greater variance in vibration levels than the low-floor buses, due to their higher center of gravity and propensity to displace their equilibrium state during the bus operations. Similarly, [70] studied bus driver seats, considering variations in seat types and bus floor types. Their analysis concurred with [69], revealing that low-floor city buses experienced better vibration attenuation with both air suspension and pedestal seats, compared to high-floor buses. Reference [39] also considered bus vibrations in the context of engine position and concluded that buses with engines above the cabin exhibited the highest levels of vibration. Additionally, [71] also investigated average bus vibrations with variations in positions and reported that bus vibrations were most prominent in the midsection of buses (0.832 m/s²), compared to the back (0.641 m/s²) and the front (0.411 m/s²). Together, these studies, with their distinct methodologies and perspectives, concur on the fact that electric buses generate less vibration compared to conventional buses and that a bus's build significantly influences its vibration levels.

2.4. Influence of Operational Factors on Bus Vibroacoustic Levels

Existing literature alludes to the fact that operational factors significantly determine the vibroacoustic performance of buses. These operational factors can be classified under bus-related and external factors. Bus-related factors are defined as factors directly tied to the vehicle's build and vibroacoustic sources. They include bus age and average speed. Conversely, external factors are elements unrelated to a vehicle's inherent build and vibroacoustic sources but still influence a bus's vibroacoustic performance. They include road conditions, road networks, bus operation schedules (day and time), and passenger occupancy levels. These factors are reviewed in the following sub-sections.

2.4.1 Bus Age

Bus age is considered a major influential factor affecting bus vibroacoustic generation [35]. According to [19], a significant aspect of noise and vibration variations that occur in different buses can be attributed to their varying ages. Reference [54] established a positive correlation

between bus age and vibroacoustic generation, reporting that older buses produced higher noise and vibration levels. Furthermore, [32] explored this relationship by categorizing buses into three age groups: up to 5 years, 6–10 years, and above 10 years. Their study found average noise of 79.01 dB, 79.12 dB, and 80.51 dB and vibration levels of 0.53 m/s², 0.61 m/s² and 0.69 m/s² for the three categories, respectively. Thus, aligning with the assertions of [54]. In contrast, [39] reported no significant correlation between bus age and vibroacoustic levels. Nevertheless, the prevailing view advocates for the notion that bus age is a crucial determinant of vibroacoustic generation.

2.4.2 Average Speed

Average vehicle speed is another important factor of bus noise and vibration. According to [72] and [73], there exists a positive and significant relationship between average speed and the amount of noise produced. By inference, vehicle noise increased with speed, which can be attributed to the enhanced effects of propulsion and road/tire noise [74]. Examining this relationship, [75] observed a 4 to 5 dB noise difference between conventional and electric vehicles at similar speeds, attributing this to the absence of combustion engine noise. Conversely, [76] identified average speed as a key factor in determining vehicle vibrations, primarily due to its effect on road/tire interaction. Further investigations revealed a positive and significant relationship between speed and vibration, indicating that vehicle vibrations increased progressively with speed [77].

2.4.3 Road Surface Conditions

Road surface condition is another significant factor in bus vibroacoustic generation [78]. This factor relates to the smoothness or roughness of the roads on which vehicles travel [79]. Due to this, variations in road surface conditions can affect vehicle noise and vibration, owing to the different structural noise and tire vibrations transmitted to the vehicle [80, 81]. Reference [21] explored the correlation between road conditions and bus vibroacoustic levels, finding that vehicles travelling on “good or smoother roads” produced less noise and vibration compared to vehicles that travelled on poor or rougher roads. The differences observed in the two cases were approximately 2.5 to 2.6 dB for noise and 0.7 to 1.4 m/s² for vibration.

2.4.4 Road Network

Another road-based factor considered important in determining bus noise and vibration is the road network. According to [82], this factor includes the directional features of the road on which the vehicle travels, including intersections, bends, curves, and straight road sections. Reference [83] examined this factor, finding a significant correlation with vehicle vibroacoustic levels. Concurring, [84] linked variations in noise and vibration to the road network factor based on its effect on the vehicle's acceleration and deceleration. However, there is a lack of detailed examination of the precise relationship between road networks and vehicle vibroacoustic levels. Therefore, additional research is required to establish how specific road network elements impact vehicle noise and vibration, which this study covers.

2.4.5 Bus Operation Schedules (Day and Time)

Research indicates that bus vibroacoustic levels are influenced to an extent by the days and times of operation [85]. Generally, higher bus noise levels are recorded on weekdays than on weekends [86], largely due to the increased frequency of peak transit periods during the weekdays. Reference [40] investigated this assertion and observed a 10 dB difference between average bus noise on weekdays and weekends, whereas [87] noted a smaller difference of 1.25 dB. Additionally, [88] expounded that the higher bus noise during the weekdays was affected by rush hours, particularly between 6 to 8 am and 4 to 6 pm. In terms of vibration, [82] reported that buses produce more vibrations on weekdays compared to weekends, mainly due to the greater speeds needed to handle the rush hour passenger traffic.

2.4.6 Passenger Occupancy Levels

Passengers are considered as one of the dominant sources of vibroacoustic levels in buses alongside propulsion, road/tire, and external traffic noise [45]. However, their impact is directly related to occupancy levels. Thus, higher passenger occupancy levels typically correlate with higher noise and vibration. In contrast, [39] observed that the number of passengers and their activities was insignificant to noise and vibration levels in buses, citing the generally quiet behavior of bus occupants during the data collection process as the reason. Reference [89] supported this by noting that passengers during transit were more likely to focus on individual activities like reading or listening to music rather than engaging other riders socially. Despite these

findings, there is no unanimous academic agreement on the exact relationship between passenger occupancy levels and bus noise and vibration. This is because most studies on passenger occupancy focus on other bus-related concepts like comfort and ridership but not a factor of bus vibroacoustic generation [90]. Nevertheless, due to its prominence as a vibroacoustic source, it is evaluated as a factor in this study regardless of the limited evidence of its influence.

2.4.7 Distance Travelled

Trip distance is a potentially influential but underexplored factor in bus noise generation, with a noticeable lack of studies directly examining its impact. Despite this gap in the literature, its relevance can be justified through its inherent relationship with average speed and road conditions, two well-established determinants of vehicular noise. For instance, longer distances often imply prolonged exposure to variable road surfaces and sustained vehicle operation at higher speeds, both of which can contribute to mechanical fatigue and increased noise output. Additionally, extended driving durations may accelerate wear and tear in components such as tires, suspension, and engine systems, which are known contributors to noise. Thus, this study addresses a critical gap by incorporating distance travelled as a distinct operational factor in evaluating bus noise levels.

2.5.Comfort Perceptions of Bus Vibroacoustic Levels

Vibroacoustic levels in buses significantly impact rider comfort, which is a pivotal factor influencing public bus transit preference over personal vehicles [91]. Vibroacoustic perceptions can be categorized under two standpoints: objective and subjective. Objective perceptions are based on predefined thresholds that assert acceptable and harmful levels for noise and vibration. It is usually used in vehicle design and testing and environmental assessments to ensure compliance and vibroacoustic safety [92]. In contrast, subjective perceptions reflect individual experiences of noise and vibration during actual bus rides, providing insights into personal comfort levels, preferences, and ultimately ridership. These two standpoints are further explored in the following sub-sections.

2.5.1 Objective Vibroacoustic Perceptions

Objective perceptions of noise and vibration are based on limits set by international and national organizations from rigorous experiments. Many organizations define the thresholds from the perspective of workers, riders, and environmental safety. For example, the United States' National Institute of Occupational Safety and Health (NIOSH), the Canadian Centre for Occupational Health and Safety (CCOHS), and the Brazilian Ministry of Labor concur on an 85 dBA noise threshold [93, 94, 95]. For vibration, ISO 2631-1 [96] is widely accepted globally for assessing whole-body vibration in vehicles. In this standard, the whole-body vibration levels are categorized based on the perceived discomfort of riders, obtained through experiments. Acceleration levels below 0.315 m/s^2 are considered comfortable, while those between 0.315 and 0.63 m/s^2 may cause slight discomfort. As vibration intensity increases, values ranging from 0.5 to 1 m/s^2 are deemed fairly uncomfortable, whereas levels between 0.8 and 1.6 m/s^2 are classified as uncomfortable. Lastly, higher accelerations of 1.25 to 2.5 m/s^2 result in very uncomfortable conditions, and any vibration exceeding 2 m/s^2 is regarded as extremely uncomfortable.

Using these objective thresholds, researchers have examined vibroacoustic perceptions across various geographical regions. For instance, [97] measured noise levels in the driver's section and found them to be below the standard of 85 dBA, inferring that the buses were suitable for operations. Additionally, [39] also reported "comfortable" bus vibrations based on the ISO 2631-1. It should be noted that even though the objective perceptions have broader applications and are not specific to a single bus type, their adoption may not always reflect the actual perceptions of individual riders. Therefore, there is a need for subjective perceptions to remedy this shortcoming.

2.5.2 Subjective Vibroacoustic Perceptions

Subjective vibroacoustic perceptions are shaped by riders' sensitivity and tolerance thresholds. Many studies across the years consistently infer that riders perceive conventional bus noise and vibration levels to be intolerable. For instance, [98] stated that passengers found it uncomfortable, based on questionnaires completed by 808 commuters. Similarly, [99] reported that 80% of 500 riders rated conventional bus noise as very annoying, attributing this negative perception to factors such as bus engine noise and vehicle age. Reference [35] also found that passengers generally regarded conventional bus noise as uncomfortable, identifying the engine as

a primary source of discomfort, while [13] observed that passengers classified noise levels in conventional buses as moderately annoying. Regarding vibration levels, [66] and [100] reported that passengers found vibration to be slightly uncomfortable, whereas [67] found that passengers experienced greater discomfort. Additionally, [101] and [102] observed that passengers experienced varying levels of discomfort, ranging from mild to moderate, depending on their seating position on the bus. Nevertheless, few studies, such as [39], indicated that some passengers did not find vibration levels uncomfortable in conventional buses, suggesting individual variations in tolerance and the continued need for research on subjective vibroacoustic perceptions, which this study contributes to.

On the other hand, electric buses generally receive more favorable comfort perceptions due to their lower noise and vibration levels. While limited studies have explicitly examined passenger perceptions of electric bus vibroacoustic performance, [22] posited that their reduced vibroacoustic levels are likely to enhance rider comfort. Supporting this assertion, [55] found that passengers generally perceived noise levels in electric buses as low and comfortable. Thus, from a comparative standpoint, the trend in existing literature reveals a consistent pattern in which passengers perceive the vibroacoustic conditions of conventional buses as a major source of discomfort, with engine noise being a primary contributor. In contrast, the absence of an engine in electric buses provides a vibroacoustic advantage, generally leading to more favorable comfort perceptions.

2.6. Overview of Existing Vehicle Vibroacoustic Models

2.6.1. Noise Models

The need for a comprehensive noise assessment has resulted in the development of many vehicular noise models. These models, predominantly utilized by transit agencies, serve as predictive tools for ascertaining the vibroacoustic performance of different vehicle types, including buses. According to [103], the models estimate noise levels using factor inputs like vehicle speed, acceleration, and road conditions. Notable examples include the ISO 9613, Thailand's Environmental Research and Training Centre Noise Model, and Lan et al.'s [73] Electric Vehicle Noise Emission Model, which are explored in the subsequent sub-sections.

1. ISO 9613

The ISO 9613 provides a straightforward model for using sound attenuation during transmission to accurately predict exterior noise levels [104]. This model is applicable to both static and moving noise sources, making it ideal for buses in their idle and motion states. It assumes the free flow of vehicles for surrounding noise contributions and flat or constant slope terrains for road conditions. Additionally, it ensures accuracy by accounting for several attenuation factors. These factors include geometric divergence A_{div} , atmospheric absorption A_{atm} , ground effects A_{gr} , barriers A_{bar} , and other miscellaneous effects A_{misc} [105]. The total attenuation effect is computed as a sum of the individual factors, as shown in Equation 1.

$$A = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{misc} \quad (1)$$

Using the total attenuation (A), the equivalent sound pressure level of the noise source is predicted using Equation 2.

$$L_{eq}(DW) = L_w + Dc - A \quad (2)$$

Where $L_{eq}(DW)$ is the equivalent sound pressure level at the receiver, L_w is the sound power level from the source and Dc is the directivity correction accounts for the deviations of the sound pressure level.

2. Environmental Research and Training Centre (ERTC) Model

The ERTC model is a noise model for determining traffic noise for environmental impact assessments through vehicle classifications [106]. The model uses two vehicle classifications, namely small vehicles and large vehicles. Small vehicles are vehicles with four or fewer wheels, while large vehicles are vehicles with more than four wheels. Additionally, the model is based on four assumptions: unlimited traffic volume, equal distance between vehicles, average vehicle speed range of 30 to 140 km/h, and constant speed of vehicles on a straight path [107]. Given these, the equivalent sound pressure levels of vehicles are estimated using Equations 3 and 4, respectively.

$$L_{eq(small\ vehicles)} = [67.8 + 20.4 \log V] - 10 \log 2 \left(\frac{1000Vl}{Q} \right) \quad (3)$$

$$L_{eq(large\ vehicles)} = [75.1 + 20.4 \log V] - 10 \log 2 \left(\frac{1000Vl}{Q} \right) \quad (4)$$

To cater for the combined effects of both vehicle types on a given road segment, the combined model is presented as follows:

$$L_{eq(combined)} = 67.8 + 20.4 \log V + 10 \log((1 - a) + 53.7a) - 10 \log 2ld + L_d + L_g \quad (5)$$

Where V is the average vehicle speed, Q is the traffic volume (number of vehicles per hour), l is the distance from the road to the receiving point, a is the ratio of large to small vehicles, d is the distance between two consecutive vehicles, L_d is the sound diffraction correction and L_g is the ground surface attenuation.

3. Electric Vehicle Noise Emission Model

Reference [73] also developed an exterior noise emission model specifically for electric vehicles (EVs). This model set out to address the lack of accurate EV representation in existing noise models. The model predicts noise emission through the motions of electric vehicles under acceleration, constant speed, and deceleration states. To predict EV noise levels, the vehicle's velocity is measured using two speedometers positioned at the start and end of a selected road segment, and vehicle acceleration is calculated. Using this computation, the model then predicts the A-weighted sound pressure level of the noise L_A during the constant speed (Equation 6), acceleration (Equation 7), and deceleration states (Equation 8).

$$L_A(Constant\ Speed) = 15.91 + 28.28 \log(v) \quad (6)$$

$$L_A(Acceleration) = 18.52 + 26.04 \log(v) + 1.10a \quad (7)$$

$$L_A(Deceleration) = 16.20 + 31.29 \log(v) + 2.40a \quad (8)$$

Where, a is the vehicle acceleration and v is the speed of the vehicle.

2.6.2. Vibration Models

Just like noise, many models exist to predict vehicle vibrations during their operations. These models originate from vehicle dynamics, an engineering discipline that studies vehicular motion under the x, y and z-axes coordinate system [108]. They center on driving, braking and rider comfort in the context of induced tire force and vehicle vibrations [109]. Some of these models are the vehicle planar model, and the full vehicle model. They models are explored extensively in the following subsections.

1. Vehicle Planar Model

The vehicle planar model is considered the simplest vehicle dynamics model [110]. The vehicle planar model computes the motions of a four-wheel vehicle under the assumption that the front wheels have the same steering angles, and the vehicle remains parallel to the ground throughout its motion [111]. Due to these assumptions, the model neglects roll, pitch, and bounce motions, resulting in rotation occurring only around the z-axis (vehicle's yaw). It focusses on this rotation and the longitudinal and lateral movement and determines the vehicle's motion around its center of gravity using Equations 9, 10 and 11.

For the yaw movement:

$$Iw_z = [a(F_x^{fR} + F_x^{fL}) \sin(\delta) + a(F_y^{fR} + F_y^{fL}) \cos(\delta) - b(F_y^{rL} + F_y^{rR}) + \frac{d}{2}(F_x^{fR} - F_x^{fL}) \cos(\delta) + \frac{d}{2}(F_x^{rR} - F_x^{rL}) + \frac{d}{2}(F_y^{fR} - F_y^{fL}) \sin(\delta)] \quad (9)$$

For the longitudinal movement:

$$v_x - v_y w_z = \frac{1}{m} [(F_x^{fR} + F_x^{fL}) \cos(\delta) - (F_y^{fR} + F_y^{fL}) \sin(\delta) + F_x^{rL} + F_x^{rR}] \quad (10)$$

For the lateral movement:

$$v_y + v_x w_z = \frac{1}{m} [(F_y^{fR} + F_y^{fL}) \cos(\delta) + (F_x^{fR} + F_x^{fL}) \sin(\delta) + F_y^{rL} + F_y^{rR}] \quad (11)$$

Where F_x and F_y values are x and y force components for the vehicle's tires, a and b are displacements of the vehicle's center of gravity during its operation, d is displacement between the left and right tires, v_x and v_y are vehicle's longitudinal and lateral velocities, w_z is vehicle yaw, δ is front wheel's steering angle, m is vehicle mass, and I is vehicle's inertia about its yaw.

2. Full Vehicle Model

The full vehicle model allows for the prediction and analysis of rotation and movement on all three axes (x, y, z) of the vehicle, resulting in a comprehensive analysis of vehicle dynamics including yaw, longitudinal and lateral motions [108]. Due to these considerations, the model features 14 degrees of freedom leading to high levels of complexity [111]. However, it gives a more comprehensive and realistic prediction of vibrations [112]. The yaw, longitudinal and lateral equations of the model are given in Equations 12, 13 and 14 respectively. It should be noted that

the model makes further considerations by determining the roll, pitch and heave components of the vehicle as a result of the yaw, lateral and longitudinal movements for a more holistic overview of vehicle vibrations.

Yaw movement:

$$I_z w_z - \Phi I_{xz} = a[F_x^{fR} \sin(\delta) + F_y^{fR} \cos(\delta) + F_x^{fL} \sin(\delta) + F_y^{fL} \cos(\delta) - b(F_y^{rL} + F_y^{rR})] \quad (12)$$

Longitudinal movement:

$$m(v_x + v_y w_z) + m_s h w_z \Phi = [F_x^{fR} \cos(\delta) - F_y^{fR} \sin(\delta) + F_x^{fL} \cos(\delta) - F_y^{fL} \sin(\delta) + F_x^{rL} + F_x^{rR}] - f_r m g \quad (13)$$

Lateral Movement:

$$m(v_y + v_x w_z) + m_s h \Phi = [F_x^{fR} \sin(\delta) + F_y^{fR} \cos(\delta) + F_x^{fL} \sin(\delta) + F_y^{fL} \cos(\delta) + F_y^{rL} + F_y^{rR}] \quad (14)$$

Where w_z is vehicle yaw rate, δ is front wheel's steering angle, I_z is sprung mass inertia yaw rate, a and b are distances from vehicle's center of gravity, Φ is roll angle of sprung mass, F_x and F_y values are x and y force components for the vehicle's tires m is the mass of the vehicle, v_x and v_y are the vehicle's speeds in the x and y directions respectively, f_r is the coefficient of rolling resistance and h is the vertical displacement between the vehicle's rolling center and the center of gravity of the sprung mass.

Together, noise and vibration models play a crucial role in assessing bus vibroacoustic performance, providing valuable insights for future vibroacoustic modeling endeavors. However, a critical assessment of these models reveals shortcomings associated with limited number of factors and the rigidity of environmental scenarios which these models can be operated. Therefore, a more comprehensive approach which addresses different environmental contexts and factors are needed for a more accurate assessment of bus vibroacoustic levels, which this study fulfills.

3. RESEARCH METHODOLOGY

3.1.Scope of Study

Montreal city is the most populous region of the Montreal Metropolitan Area. According to Canada's 2021 population census, it accommodates 1,762,949 people, which is about 41% of the metropolitan's population [113]. The city serves as the metropolitan's urban hub where most jobs and activities are concentrated, resulting in numerous trips per day [114]. To cope with the daily transit demands, the Société de Transport de Montreal (STM) offers multimodal transportation services in Montreal city and the entire island of Montreal with services covering the entire island of Montreal, as shown in Figure 3.1. Buses are the most dominant mode in the STM's multimodal system, responsible for 61.8% of the annual public transport ridership [115].

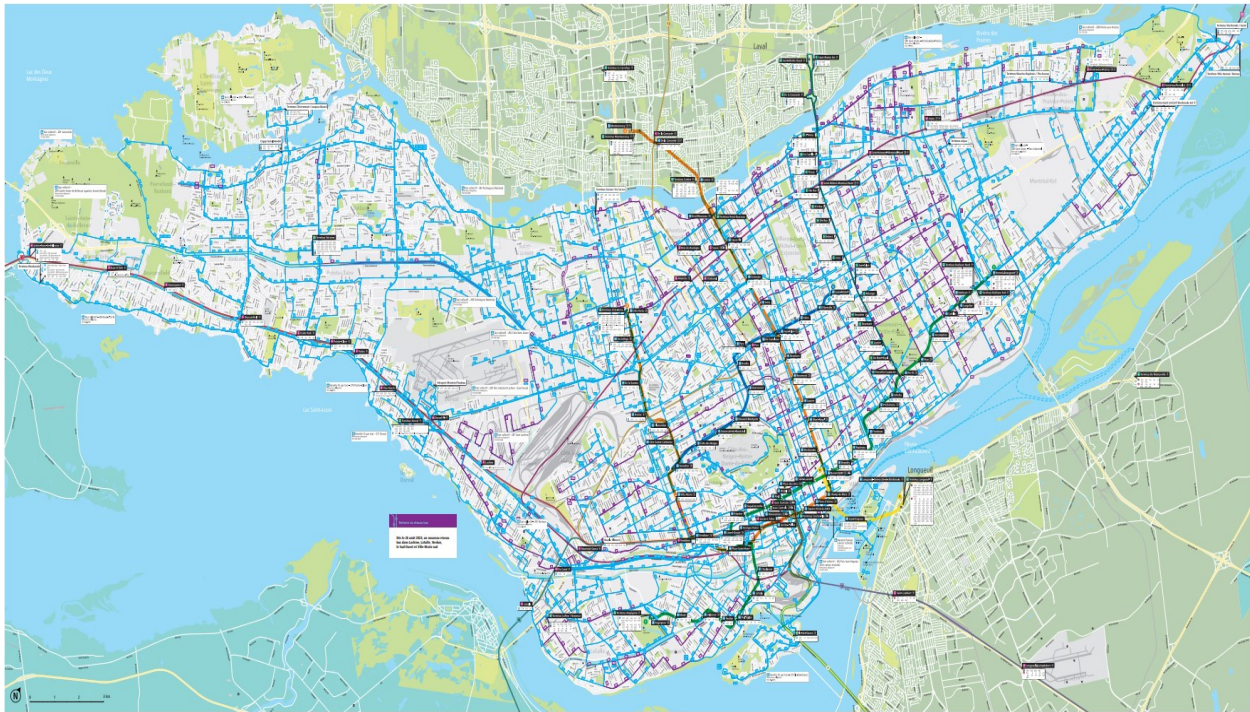


Figure 3.1. 2024 STM Transit Network Map (Bus Network in Blue and Purple)

According to [116], there are 228 designated routes in the bus network. These routes are classified under local, night, express, and shuttle lines. The local bus lines (routes 10 – 293) operate all days of the week, typically between 5am and 1am. The night bus lines (routes 350 – 382) operate from 1am to 5am the entire week. The express bus lines (routes 401 – 496) operate just like the local buses, albeit with limited stops, while the shuttle bus lines (routes 711 – 777) operate

as special purpose buses, serving major sites in the city. Together, these buses fulfill an average daily ridership of 977400 riders [117].

The STM's fleet consists of 894 conventional and 41 electric buses [10]. The conventional bus fleet procured from Nova Bus mostly consists of regular-sized buses (40 ft) and some articulated buses (62 ft) specifically models LFS (Low Floor Series) and LFS-A (Low Floor Series – Artic). On the other hand, all electric buses are regular-sized and sourced from Nova Bus and New Flyer specifically the LFSe and XE40 models respectively. The conventional buses were deployed between 2006 and 2013, while the electric buses at the time of this study were deployed in 2019 and 2020.

3.2. Bus and Rider Sampling

The conventional and electric buses sampled in this study were achieved using Cochran's sample size formula, depicted in Equation 15. This formula was utilized because of its sampling efficiency especially with smaller populations (894 for conventional and 41 for electric) considered in this study. The sample calculations involved bus population parameters (N), a 5% margin of error (e), a Z-score of 1.96 (Z) corresponding to a 95% confidence level and assumed population proportions (p) of 0.98 for conventional buses and 0.99 for electric buses. It should be noted that these population proportions were assumed to ensure a feasible and representative sample sizes for the study. Additionally, these assumptions reflect the nearly universal presence of noise and vibration in all buses, ensuring that the sample sizes remain manageable while still providing reliable and robust data.

For rider sampling, the average daily 977,400 riders provided by [117] was used in the population for the sample size, using Yamane's sample size formula, shown in Equation 16. This formula was utilized because of its simplicity and ability to efficiently generate sample sizes from large populations such as the rider populations considered in this study. It incorporated a 5% margin of error (e) alongside the rider population (N). Given this, the details of the sample size calculations are as follows:

For conventional buses,

$$n_{conventional} = \frac{Z^2 p(1-p)}{e^2} / \left(1 + \frac{\frac{Z^2 p(1-p)}{e^2} - 1}{N_{conventional}}\right) \quad (15)$$

$$n_{conventional} = \frac{(1.96)^2 * 0.98(1-0.98)}{0.05^2} / \left(1 + \frac{\frac{(1.96)^2 * 0.98(1-0.98)}{0.05^2} - 1}{894}\right)$$

$$n_{conventional} = 29.168 \approx 30 \text{ buses}$$

For electric buses,

$$n_{electric} = \frac{Z^2 p(1-p)}{e^2} / \left(1 + \frac{\frac{Z^2 p(1-p)}{e^2} - 1}{N_{electric}}\right)$$

$$n_{electric} = \frac{(1.96)^2 * 0.98(1-0.98)}{0.05^2} / \left(1 + \frac{\frac{(1.96)^2 * 0.98(1-0.98)}{0.05^2} - 1}{894}\right)$$

$$n_{electric} = 11.297 \approx 12 \text{ buses}$$

For the riders,

$$n_{riders} = \frac{N_{riders}}{1 + N_{riders} * e^2} \quad (16)$$

$$n_{riders} = \frac{977400}{1 + 977400 * (0.05^2)}$$

$$n_{riders} = 399.84 \approx 400 \text{ riders}$$

It should be noted that the study sampled 31 conventional buses instead of 30 due to the availability of an extra bus at the time of data collection, which helped improve data reliability and account for potential inconsistencies or outliers. This adjustment was not made for electric buses due to their smaller population, which limited the flexibility for additional sampling. As a result, a total of 43 buses were sampled. Furthermore, to maintain consistency in rider perception data, 430 riders were sampled, ensuring an equal distribution of 10 riders per bus for a balanced comparison.

3.3.Data Collection Instruments

In this study, a smartphone-based measurement approach was adopted. This approach was adopted considering that the use of professional-grade sound and vibration instruments were not accessible/feasible due to the scale of the observations and the fact that the researcher could not alter operations or install intrusive equipment in public buses during their routine operations. Furthermore, the method directly supported the study's aim of capturing realistic, in-service vibroacoustic conditions experienced by passengers with minimal interference to routine bus activities. In this regard, mobile sensing apps offered a cost-effective, rapid, non-intrusive, and easily replicable means of conducting noise and vibration measurements in a field environment analysis. Although limitations such as reduced measurement accuracy, device variability, and restricted frequency response were acknowledged, the approach was sufficient to address the targets of the study with all measurements were taken using the same device and controlled procedures, ensuring consistent and reliable comparisons between conventional and electric buses. The instruments adopted in this research will be presented in the subsequent sub-sections.

3.3.1 Bus Vibroacoustic Measurement Instruments

Vibroacoustic data from the sampled buses were obtained using a smartphone and vibroacoustic measurement apps. This method was chosen for its cost-effectiveness, simplicity, and speed compared to traditional sound level meters and accelerometers [118, 119, 120]. The smartphone used for the vibroacoustic measurement was the LG G6 ThinQ. This device was selected for its high sensor capabilities, specifically its acoustic overload point (AOP) of 132 dB(A) and accelerometer resolution of 0.0024 m/s^2 with a range of $\pm 78.45 \text{ m/s}^2$, as these specifications adequately cover the range of bus vibroacoustic measurements reported in the existing studies. The mobile app used for the bus vibroacoustic levels data collection was the Sound Meter Pro by Smart Tools. Co. for noise measurement and iDynamics by RPTU Kaiserslautern-Landau for vibration measurement. The Sound Meter Pro app is capable of measuring sound pressure levels in dB(A) within frequency ranges of 300 Hz and 3400Hz and in a “slow response” time-weighting manner which means it takes an average of 1 second to register changes in the noise being measured. These parameters were established in the app's details. On the other hand, the iDynamics app is capable of measuring acceleration vibrations within sample

rates of 0.5Hz to 100Hz accurately according to Reference [123]. In addition to this, both apps were selected based on their high ratings (4.6/5) on the Android Play Store and the empirical validation by existing research.

For the Sound Meter Pro, [121] investigated its uncalibrated accuracy against a calibrated Brüel & Kjær Type 2250 in an ISO 3741 compliant reverberation chamber at sound levels 50, 70, and 90 dB(A). They discovered the Sound Meter Pro app to be the best android-based app with an error of 1.93 dB(A) across the noise measurements, which is deemed within the acceptable error threshold of ± 2 dB(A) established by the American National Standards Institute (ANSI). Additionally, [122] tested this app under real-time and uncensored environmental conditions across different day and night times against an Extech 407730 Digital Sound Meter and revealed that the app's measurement fell within the ± 2 dB ANSI error range 92.9% of the time, while 31% showed the same readings as the professional sound meter level. However, it should be acknowledged that the accuracy of the results reported in Reference [122] may be limited, as the mobile application was validated against a Type 2 sound level meter, which has not been considered for high-accuracy acoustic measurements. Despite this limitation, this study nevertheless establishes a benchmark against which the improvements in the methodology of subsequent research can be objectively assessed. Given this, additional noise-based validation was conducted where the accuracy of the noise data collection instruments was established by comparing them against a calibrated B&K 2270 under controlled conditions, using a fixed sound source of 70 and 90 dB(A). These reference levels were selected because they reflect the typical noise levels of buses, as reported by [53]. The results of the accuracy tests are shown in Table 1 below.

Table 3.1: Results of Noise Data Collection Instruments Accuracy Tests

Noise Source Level (B&K 2270)	LG G6 ThinQ with Sound Meter Pro	Error
70 dB	71.6	1.6
90 dB	92.3	2.3
Average Error		+1.95 dB(A)

From Table 1, the average error of +1.95 dB falls within the ANSI-accepted ± 2 dB error range, thus making its accuracy suitable for noise measurements in the context of this research. This average error was also used to calibrate the Smart Meter Pro app. Thus, the calibration was set at -1.95 dB for the app.

On the other hand, [123], [124] and [125] utilized the iDynamics for real-life structural and traffic-induced vibrations. They concurred on the app's acceptable accuracy and suitability for first-hand analysis of vibration phenomena. It was based on these studies that the selected apps were utilized in this research.

Figure 3.2 shows the interfaces of Sound Meter Pro and iDynamics on the LG G6 ThinQ.

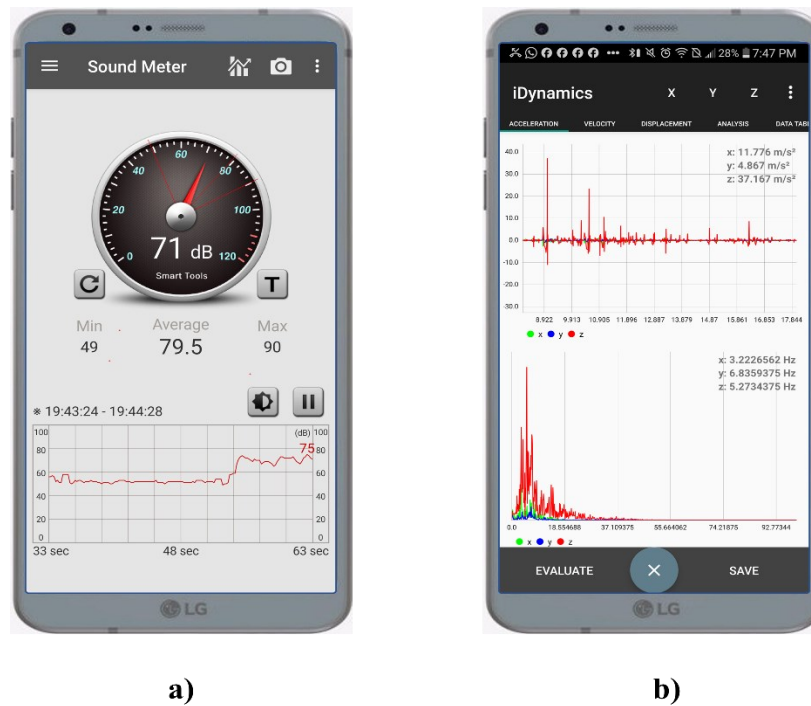


Figure 3.2: Interfaces of (a) Sound Meter Pro and (b) iDynamics on the LG G6 ThinQ.

3.3.2 Rider Perception Instrument

The data collection instrument used for obtaining rider comfort perceptions on bus noise and vibration was the interview. This instrument was utilized because of its ability for immediate feedback regarding the noise and vibrations being experienced, and its speed in soliciting the required information so that riders taking short trips can participate. The study's interview solicited

two opinions namely the riders' perceptions on the intensities of bus noise and vibration during their trips. These opinions were given on a comfort scale of 1 to 10, where 1 denoted lower noise and vibration sensitivity inferring very comfortable vibroacoustic perception and 10 denoted higher noise and vibration sensitivity inferring very uncomfortable vibroacoustic perception.

Given that the study involved human participants, the researcher undertook an ethics course (TCPS 2: Ethical Conduct for Research Involving Humans) and obtained approval for undertaking the interview from the Concordia Office of Research – Research Ethics Unit. These steps were taken to ensure utmost compliance with research ethics. The associated documents for participant invitation, consent, interview as well as the ethics certificate are attached at the Appendices of this thesis.

3.3.3 Operational Factors Data Collection Instruments

Data on bus operational dynamics were collected using an array of instruments. For road conditions, a present serviceability rating (PSR) was used. This instrument utilized a subjective five-point scale assessment where 1 represents the very poor road condition and 5, a very good road condition [126]. Additionally, data on road networks, bus occupancy and schedule (day and time) were acquired from the STM-approved Chrono app, which provided the designated bus routes as well as real-time occupancy and schedule information. Data on bus age was obtained by observing the acquisition and deployment year displayed on each bus. Lastly, average speed data was computed by dividing the total travel distance (obtained via Google Maps) by the journey duration (recorded during the bus ride).

3.4.Data Collection Process

3.4.1 Bus Vibroacoustic Data Collection Process

Bus vibroacoustic levels were recorded at the mid-section of all sampled buses to obtain representative noise and vibration measurements during operation. Noise data was collected by positioning the smartphone in the mid-section, while vibration was recorded by placing the phone on one of two seats in the same area based on their availability, as shown in Figure 3.3. The mid-section was selected to provide an unbiased evaluation of vibroacoustic levels, preventing

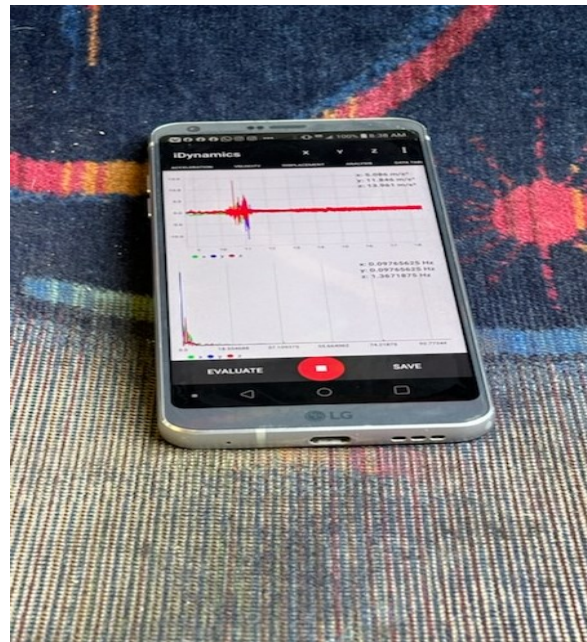
overrepresentation or underrepresentation of sources like the propulsion system, which may be too close or too far from other measurement positions. This measurement position was supported by [127], who found that noise levels are highest at the front or rear depending on the propulsion unit's position. Additionally, [128] identified greater accelerations in these areas due to suspension stiffness, further justifying the mid-section as the optimal location for vibration measurements.



a. Measurement positions considered for noise (in red) and vibration (in green)



b. Actual noise measurement



c. Actual vibration measurement

Figure 3.3: Measurement of Noise and Vibration Levels in Buses

3.4.2 Rider Comfort Perception Data Collection Process

Rider perception data was also collected in the mid-section, as illustrated in Figure 3.4. This was done to ensure that the perceptions of bus riders corresponded with the noise and vibration levels measured in the same general area. The rider data collection followed ethical

research protocols in three stages: participant invitation, consent, and interview. During the invitation stage, participants were informed of the research purpose, the researcher's identity, their rights, and the voluntary nature of participation. The consent stage documented their agreement to participate. Finally, in the interview stage, responses were gathered through brief structured questions.



Figure 3.4: Seats Considered for Rider Comfort Perception Data Collection

3.4.3 Operational Factors Data Collection Process

The data collection processes for the operational factors differed from one another. For road conditions, a Present Serviceability Rating (PSR) was assigned to the road spanning each trip taken by bus. It should be noted that a trip entailed the movement of the bus from one designated stop to the next designated stop within its predetermined route. This was done to capture variations in road conditions throughout the journey. Passenger occupancy levels, bus operation schedule and road network data were obtained from the Chrono app, with bus occupancy recorded for each trip taken. Additionally, road networks were monitored using the app and recorded accordingly. In instances where detours were taken due to construction or other circumstances, rectifications were made to reflect the actual bus route during its operations. It should be noted that for road networks, only the number of curves or bends were considered, as they have a direct effect on bus speed and subsequently vibroacoustic levels, as outlined in the literature review. Lastly, bus age was determined by identifying the acquisition and deployment year displayed on each bus to ensure accurate classification, while average speed was calculated by measuring the total travel distance using Google Maps and dividing it by the duration of each journey recorded during bus operations.

3.5.Data Analysis

3.5.1 Data Preparation

The first step in the analysis was data preparation, a necessary process to enable meaningful quantitative analysis. This stage involved converting categorical textual data into numerical codes, allowing for statistical computations and modeling. In this regard, day of bus operation factor was encoded, with "weekdays" assigned a value of "1", and "weekends" a value of "2". Similarly, bus operation times were categorized by assigning "1" to "morning", "2" to "afternoon", and "3" to "evening" periods.

The second step entailed the conversion of raw data into meaningful inputs to better achieve the aim and objectives set out in this study. Firstly, the study required the average noise and vibration levels in the buses across their journeys for data analysis. Given the Sound Meter Pro app's ability to record noise levels in this state, no data processing was involved. However, the iDynamics app fundamentally recorded vibration levels in the x, y, and z axes, thus requiring data processing to convert to a single-value acceleration vibration level. To achieve this, a resultant acceleration ($a_{resultant}$) was computed for each set of x, y and z axes measurement per bus trip, using Equation 17. This was used principally for the XGBoost bus vibration model. Following this, the RMS acceleration (a_{RMS}) was determined to establish the average vibration level per bus, using Equation 18. This was used for the development of the rider vibration perception model.

$$a_{resultant} = \sqrt{a_x^2 + a_y^2 + a_z^2} \quad (17)$$

$$a_{RMS} = \sqrt{\frac{1}{n} \sum_{i=1}^n (a_{resultant,i})^2} \quad (18)$$

Where n is the number of trips in a single journey designated to each bus.

3.5.2 Descriptive Statistical Analysis

After the data were pre-processed, descriptive statistical analysis was performed to summarize and interpret the data by establishing the trends in the data. The descriptive analysis covered a comparative overview of vibroacoustic levels and perceptions across the two bus types and different bus and operational perspectives, in alignment with the first objective.

1. Hyperparameter Tuning

To support the interpretive goals of this study (second objective, that is, uncovering the relationships and effects of operational factors on bus noise and vibration levels), the researchers employed a structured hyperparameter tuning strategy called Dual-Bound Bayesian Optimization (DBBO). Unlike traditional approaches like grid or random search that prioritize predictive accuracy, DBBO is explicitly designed to balance model complexity with explanatory clarity. At its core, the DBBO builds on the strengths of Bayesian Optimization (BO), using it as a foundation to identify the point at which core relationships in the data are sufficiently captured, without risking extreme complexity. The DBBO entails three steps namely, upper bound search, lower bound search and balanced search. Their details are presented as follows:

a. Upper Bound (Overfit Search)

This step aims to explore the maximum capacity of the model. Bayesian Optimization is applied to the high-complexity region $H_{overfit}$. This region includes configurations with deep trees, many estimators and minimal regularization etc. The goal is to find the hyperparameter configuration $h_{overfit}$ that produces the highest possible training R^2 , represented as the objective function $f(h)$. The hyperparameters from this stage capture both meaningful patterns and potential noise, establishing the model's upper complexity limit. This search is mathematically presented in Equation 19 as:

$$h_{overfit} = \arg \max_{h \in H_{overfit}} f(h) \quad (19)$$

b. Lower Bound (Underfit Search)

This step was taken to establish the minimum viable complexity required for the model to learn the meaningful structure in the data. Here, Bayesian Optimization is applied to a constrained region of hyperparameter space, $H_{underfit}$, which includes shallow trees, fewer estimators and stronger regularization etc. The objective was to identify the hyperparameter configuration $h_{underfit}$, that achieved the highest possible training R^2 , represented as the objective function $f(h)$. This marks the point below which the model begins to fail, indicating underfitting. This is shown in Equation 20.

$$h_{underfit} = \arg \max_{h \in H_{underfit}} f(h) \quad (20)$$

c. Balanced (DBBO Search)

With the overfitting and underfitting bounds defined, the final step used Bayesian Optimization within the intermediate region, $H_{balanced}$. This region excludes the overly simplistic and excessively complex configurations. The aim was to identify the hyperparameter configuration, h_{DBBO} , that maximizes training R^2 , represented as the objective function $f(h)$, to the point where additional complexity yields minimal gains in explanatory power. This threshold is formalized by the condition $\frac{\partial f(h)}{\partial complexity} \approx 0.001$, which ensured that the selected model captures the dominant relationships in the data without overfitting or risking excessive complexity. Equation 21 presents the idea behind this step.

$$h_{DBBO} = \arg \max_{h \in H_{balanced}} f(h) \text{ subject to } \frac{\partial f(h)}{\partial complexity} \approx 0.001 \quad (21)$$

Where complexity refers to the overall capacity of the model to fit data, determined by the combination of key hyperparameters, such as tree depth, number of boosting rounds, learning rate, subsampling ratios, and regularization terms. It should be noted that it is not measured as a single numerical value or derivative but rather inferred by the Bayesian Optimization from R^2 performance with respect to hyperparameter changes during its iterations.

There are a number of assumptions and limitations associated with the Dual-Bound Bayesian Optimization used in this study. Firstly, the tuning strategy assumes that the training R^2 score gives a reliable indication of how well the model has captured meaningful patterns in the data. It also assumes that when further tuning leads to only small improvements in R^2 , the model has already learned the most important relationships. For the limitations, the DBBO is intended for explanation-focused machine learning, where the goal is to understand patterns in the data, rather than for predictive tasks that require performance on unseen data. In addition, DBBO depends on clearly defined boundaries for what counts as an overly simple or overly complex model. Despite these limitations, DBBO is well suited for this study, where interpretability and relationship discovery are the primary goals.

2. Modeling

a. Development and Evaluation of XGBoost Noise and Vibration Models

XGBoost was employed to model the collected data and uncover relationships between bus vibroacoustic levels and its potential operational drivers. The choice of XGBoost was motivated by the complex, nonlinear, and potentially interacting nature of the input variables and the predicted values. This model can be defined as a tree-based ensemble learning algorithm that constructs its model in an additive manner, sequentially building decision trees that minimize the residual errors of the ensemble up to that point. The construct by XGBoost can be expressed as a sum of K regression trees. This is shown in Equation 22 as:

$$\hat{y}_i = \sum_{k=1}^K f_k(x_i), \quad f_k \in F \quad (22)$$

Where $\hat{y}_i$ is the predicted value for observation i , x_i are the independent variables, f_k is the k -th regression tree, and F is the space of all possible regression trees.

The constructed model as described in Equation 5 seeks to minimize a regularized loss function defined in Equation 23 as:

$$L(\Phi) = \sum_{i=1}^n l(y_i, \hat{y}_i) + \sum_{k=1}^K \Omega(f_k) \quad (23)$$

Where $l(y_i, \hat{y}_i)$ is the measured loss between the predicted value $\hat{y}_i$ and the true value y_i for an i -th observation, and $\Omega(f_k)$ is a regularization term that penalizes model complexity to prevent overfitting. This regularization term is defined in Equation 24 as:

$$\Omega(f_k) = \gamma T_k + \frac{1}{2} \lambda \sum_{j=1}^{T_k} \omega_j^2 \quad (24)$$

Where T_k is the number of leaves in tree k , ω_j is the weight (score) assigned to leaf j , and γ and λ are the regularization parameters controlling the cost of model complexity.

In this study, all components of the XGBoost model, including the number of trees, tree depth, learning rate, and regularization parameters, were fixed using the balanced hyperparameters identified via Dual-Bound Bayesian Optimization. The model obtained was then evaluated using R^2 and MSE as model evaluation metrics, shown in Equations 25 and 26 respectively.

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (25)$$

$$MSE = \frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2 \quad (26)$$

Where, y_i are the actual or true values, $\hat{y}_i$ are the predicted values and $\bar{y}$ is the mean of the predicted values.

To interpret the results from the XGBoost models, a suite of post hoc model interpretation techniques designed to quantify and visualize both individual feature effects and interactions were employed. The interpretation process began with traditional feature importance analysis, which ranked input variables based on their contribution to the model's structure. Additionally, the authors adopted the SHAP (Shapley Additive Explanations) framework, which provided a unified, theoretically grounded approach to decomposing the model's predictions into additive contributions from each feature. Thus, for any prediction $\hat{y}_i$, the SHAP framework expressed it, as shown in Equation 27.

$$\hat{y}_i = \psi_0 + \sum_{j=1}^M \psi_j^{(i)} \quad (27)$$

Where, ψ_0 is the model's expected output and $\psi_j^{(i)}$ is the SHAP value for feature j on instance i , representing its marginal contribution to the prediction. These values were visualized using bee swarm plots, to illustrate the global importance and directionality of each feature's impact across all observations.

Next, dependence plots were used to assess the isolated effect of individual features on the model output by plotting SHAP values against corresponding feature values. These plots revealed both linear and nonlinear relationships while implicitly capturing correlations between variables. Furthermore, SHAP interaction values were utilized to emphasize the joint contributions of feature pairs to the prediction. This allowed interpretations of how combinations of variables influence model output beyond their individual contributions. Equation 28 presents the general formula for SHAP interaction assessments.

$$\hat{y}_i = \psi_0 + \sum_{j=1}^M \sum_{k \neq j} \psi_{j,k}^{(i)} \quad (28)$$

Where, $\psi_{j,k}^{(i)}$ represents the interaction effect between features j and k for instance i . The resulting interaction values were visualized to see the importance of various interactive factors in vibroacoustic generation in buses.

b. Development and Evaluation of Ridge Regression Models for Vibroacoustic Perceptions

Following the XGBoost models, ridge regression models were developed to ascertain the predictive relationships between bus noise and vibration levels (independent variables) and rider perceptions (dependent variables). This modelling approach was chosen for its ability to deal with relatively small datasets as in this instance and improve model stability by finding a good balance between model fit and generalization. The model achieves the aforementioned advantages through its generalized equation shown in Equation 29.

$$J(\beta) = \sum_{i=1}^n (y_i - \beta_0 - \sum_{j=1}^p \beta_j x_{ij})^2 + \alpha \sum_{j=1}^p \beta_j^2 \quad (29)$$

In this function, $J(\beta)$ represents the cost function to minimize, y_i represents the observed response, β_0 is the intercept, β_j are the coefficients for the predictors x_{ij} , n is the number of observations, p is the number of predictors, and α is the regularization parameter. The first term $(\sum_{i=1}^n (y_i - \beta_0 - \sum_{j=1}^p \beta_j x_{ij})^2)$ measures the sum of squared errors (SSE), ensuring a good fit to the data, while the second term $(\alpha \sum_{j=1}^p \beta_j^2)$ imposes an L2 penalty on the magnitude of the coefficients, shrinking them to reduce overfitting and improve generalization. Additionally, the regularization parameter controls the trade-off between model fit and coefficient shrinkage. In this study, a regularization parameter of 1 was selected to enhance the model's ability to adapt to variations in data distribution for both conventional and electric buses. To ensure model validity and reliability, several statistical tests were also conducted. These included the R^2 value for the explanatory power of the model and mean squared error (MSE) for prediction accuracy.

A summary of the research methodology employed in this work is presented in Figure 3.5 below.

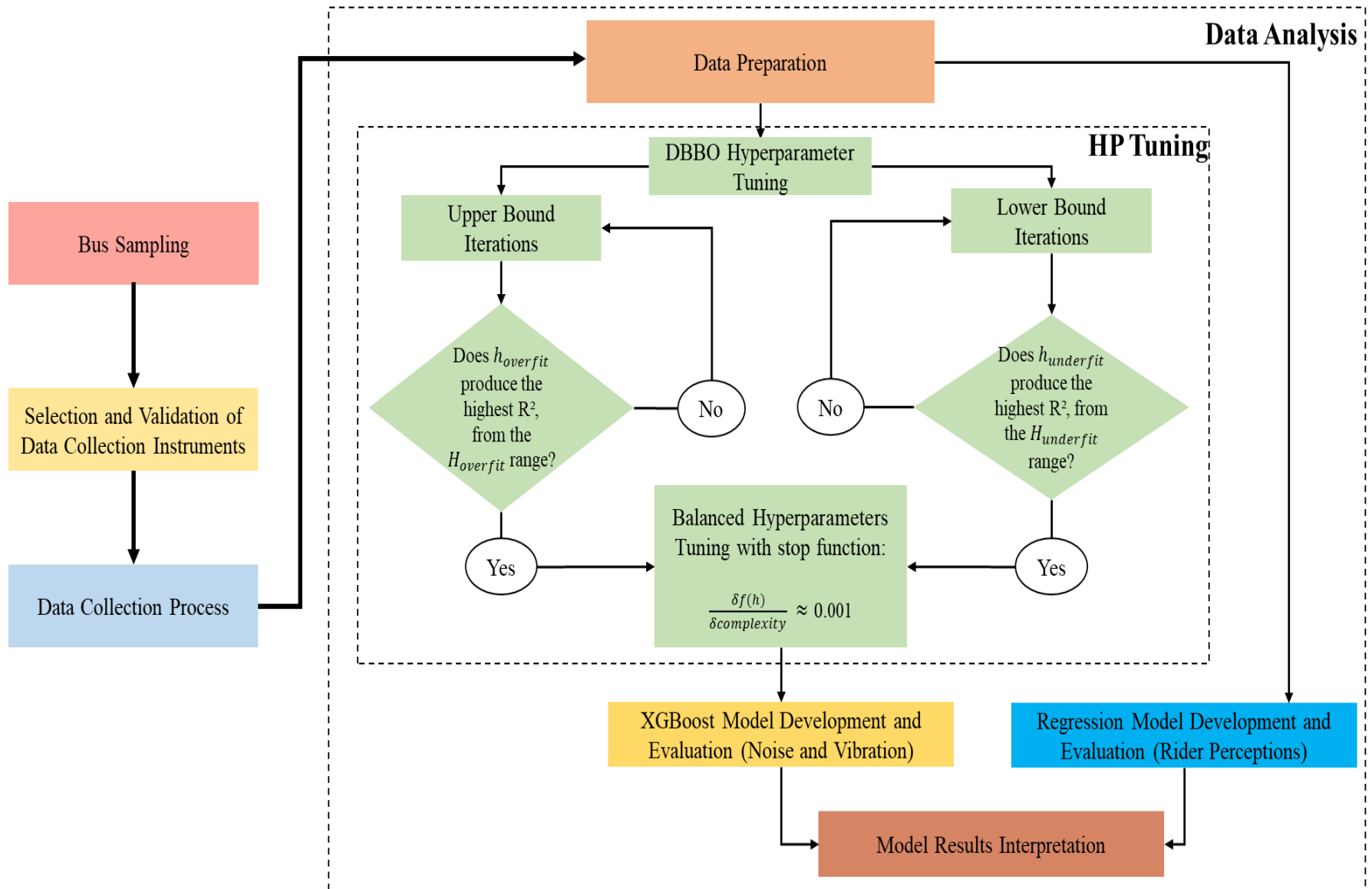


Figure 3.5: Sequential framework for the study's research methodology

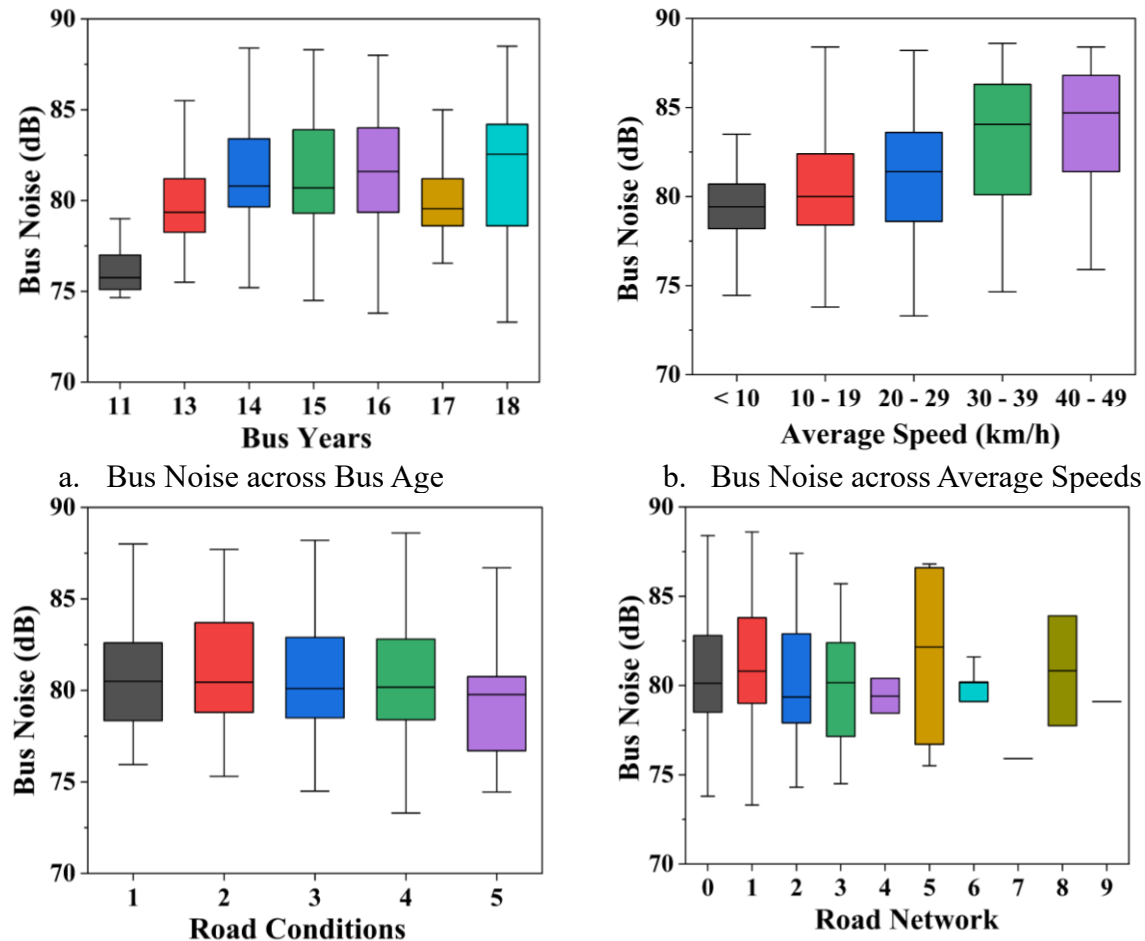
4. RESULTS AND DISCUSSIONS

4.1. Overview of Bus Noise and Vibration Levels in Montreal

This section showcases the comparative results of the noise and vibration data collected from conventional and electric buses in Montreal. The comparisons were made across the eight operational factors (bus age, average speed, road condition, road network, distance travelled, occupancy levels, day and time of operation) for the two bus types across well-known standards in the domain namely the Canadian Motor Vehicle Safety Regulation (CMVSR) (Standard 1106) which outlined a threshold of 83dB(A) [140] and the ISO 2631-1: 1997 which outlined a threshold of $\leq 0.315\text{m/s}^2$ across a sample rate of 0.5Hz to 80Hz [96]. The details are presented in the subsequent subsections.

4.1.1 Conventional Bus Noise Levels

Figure 4.1 presents conventional bus noise level trends across different operational factors.



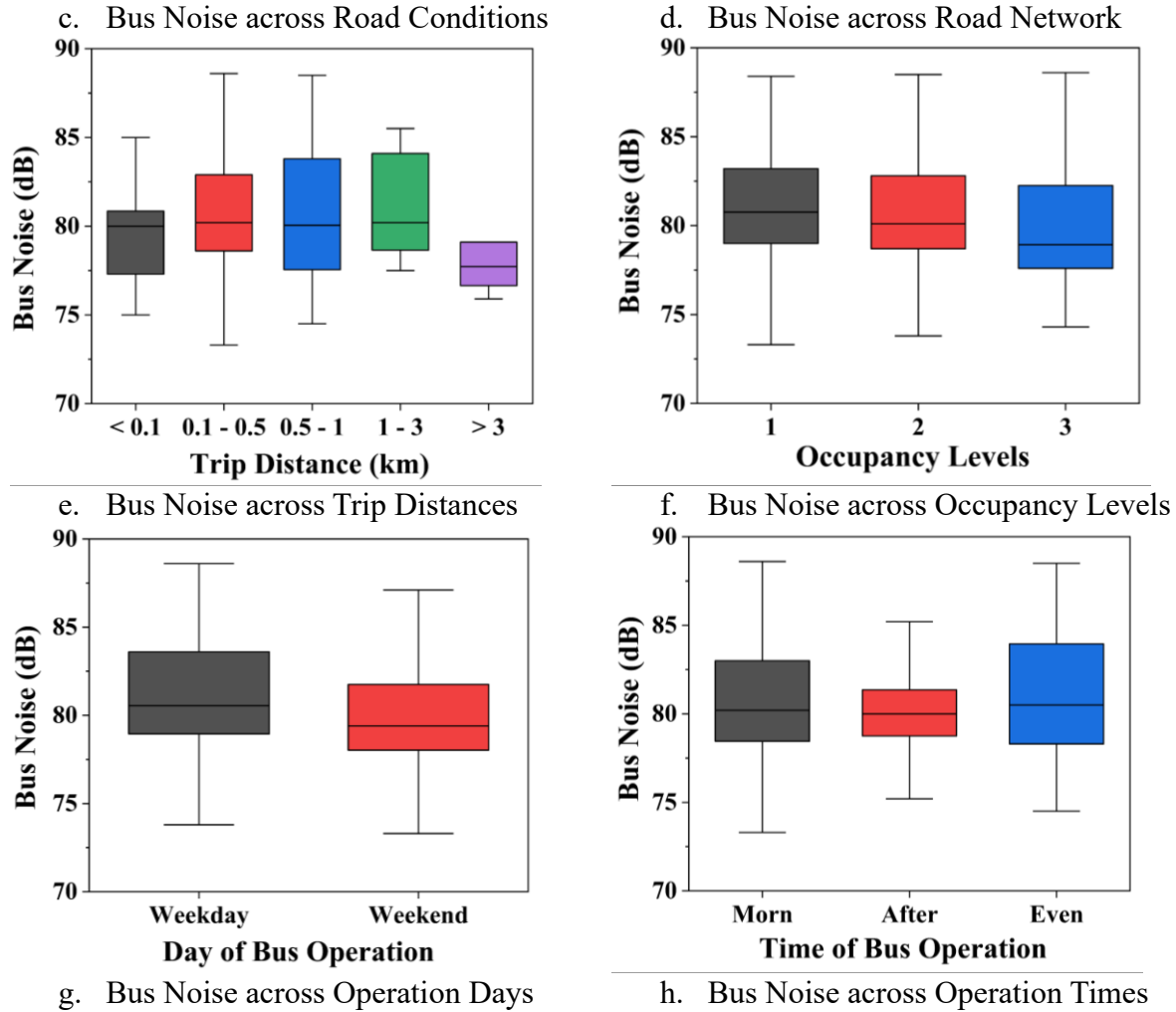


Figure 4.1: Conventional Bus Noise Levels across Different Operational Factors

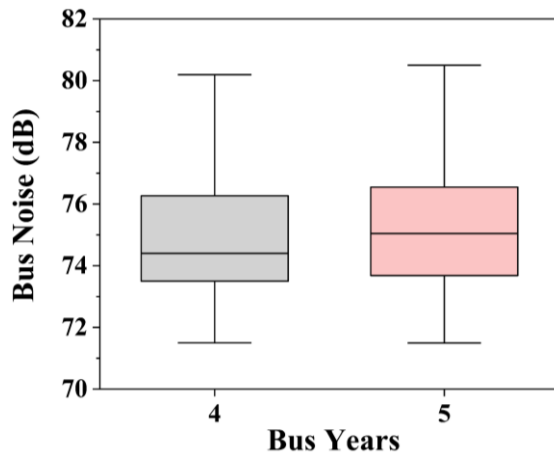
The analysis of conventional bus noise data across the varying operational factors revealed distinct trends that agree with the results of existing literature. Regarding bus age, a general trend where older buses generated more noise than younger buses was observed in this study. For instance, buses aged 11 years, the youngest in the sampled fleet, had an average bus noise level of 75.73 dB(A) while those aged 18 years, representing the oldest in the sampled fleet, registered the highest average noise level of 82.55 dB(A). This trend concurred with the findings of [32]. In comparison with the CMVSR Standard 1106 (which established a threshold of 83 dB(A)), the results infer that older buses are close to the limit set. Additionally, [54] generally attributed the trend to increasing mechanical wear in older buses compared to younger ones. Following this, the

factor of average speed showed a clear upward trend in noise levels with increasing average speeds. Specifically, buses which operated under 10 km/h had an average noise level of 79.43 dB(A), rising progressively to 84.7 dB(A) in the 40–49 km/h range. This suggests that higher speeds may amplify engine and aerodynamic noise, contributing to the overall elevated noise levels [20]. Given this, it was also seen that buses which operated at the highest average speeds exceeded the CMVSR Standard 1106. In relation to road conditions (RC), the general trend in the data showed that as road conditions improved from very poor roads (RC 1) to very good roads (RC 5), noise levels decreased, concurring with [21]. In this light, it was seen that buses on RC 1 roads produced an average noise level of 80.5 dB(A), while those on RC 5 roads recorded a lower average of 79.78 dB(A). This supports the notion that smoother, well-maintained roads reduce vibration and mechanical strain, thereby lowering the noise output of buses. Additionally, it was noted that all the average noise generated on all road conditions did not exceed the CMVSR Standard 1106 albeit that the noise generated on higher road qualities were far below the standard. Regarding the road network (RN) factor, there was no definitive general trend from the collected data. The results throughout the differing number of bends and curves produced fluctuating average noise levels which typically ranged between 80.1–82.15 dB(A), which were also below the CMVSR Standard 1106. With regards to the trip distance factor, the results showed that shorter trips generally resulted in higher noise levels. Specifically, routes under 0.5 km exhibited average noise levels of 80.1 to 80.2 dB(A), while routes exceeding 3 km had a reduced average of 77.73 dB(A). This trend can be attributed to frequent stopping and acceleration in shorter distances compared to longer distances, which contributed to the overall average bus noise levels. Additionally, compared to the CMVSR Standard 1106, all the average noise generated across the different distances was below the standard. Considering bus occupancy level, it was noticed that higher bus occupancy resulted in lower noise levels. When buses were low on Occupancy Level 1, an average noise level of 80.75 dB(A) was seen. This decreased to 80.1 dB(A) at Occupancy Level 2 and 78.93 dB(A) at Occupancy Level 3. This trend can be attributed to the fact that heavier loads may stabilize vehicle dynamics and consequently reduce the noise emission of buses. Additionally, compared to the CMVSR Standard 1106, all the average noise generated across the different occupancy levels were below the standard. With the day of operation, buses operated on weekdays had a higher average noise level of 80.55 dB(A) compared to 79.40 dB(A) on weekends. This meant that noise levels were on average, higher in weekdays than at weekends, concurring with [86]. Again, compared to the

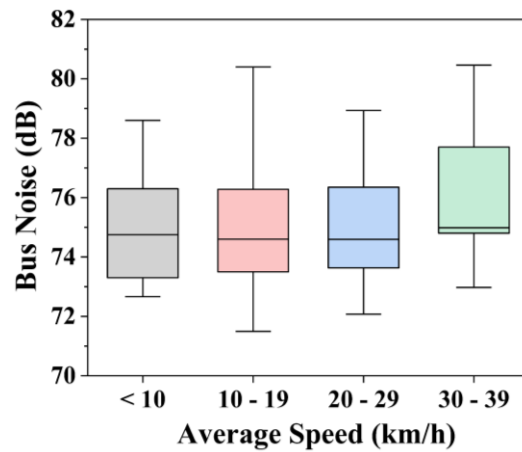
CMVSR Standard 1106, all the average noise generated across the different days of operation was below the standard. Finally, for time of operation, the general trend showed that afternoons were the least noisy with an average noise level of 80 dB(A), followed by mornings with 80.2 dB(A) and 80.5 dB(A) in the evening. This elevation in the evening hours could be attributed to prolonged operational strain on buses leading to mechanical fatigue and subsequently, higher noise levels. Once again, compared to the CMVSR Standard 1106, all the average noise generated across the different times of operation were below the standard.

4.1.2 Electric Bus Noise Levels

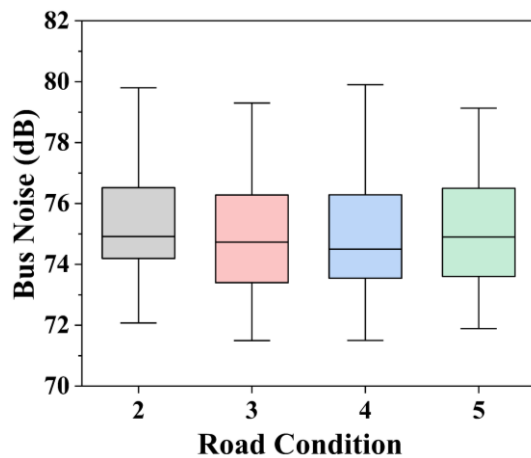
Figure 4.2 presents electric bus noise level trends across different operational factors.



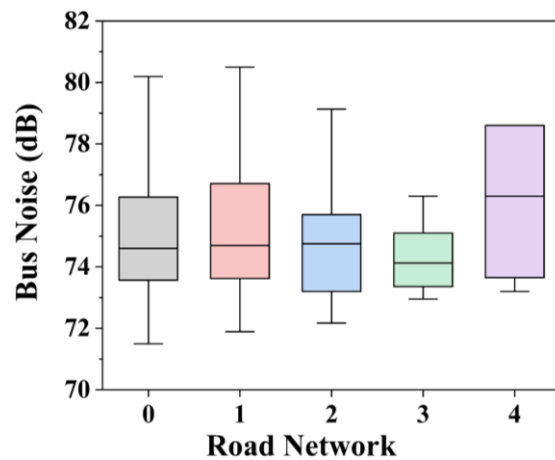
a. Bus Noise across Bus Age



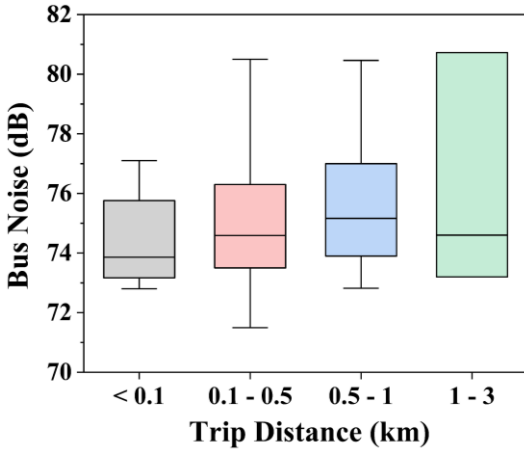
b. Bus Noise across Average Speeds



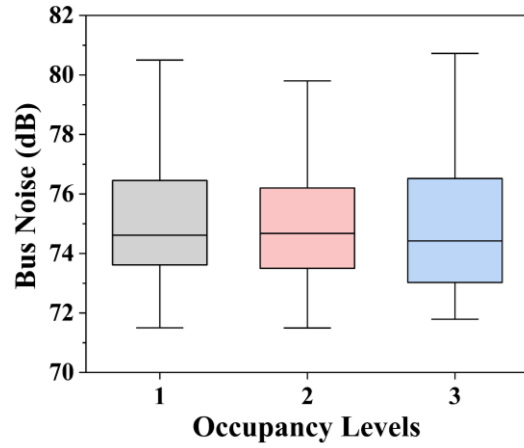
c. Bus Noise across Road Conditions



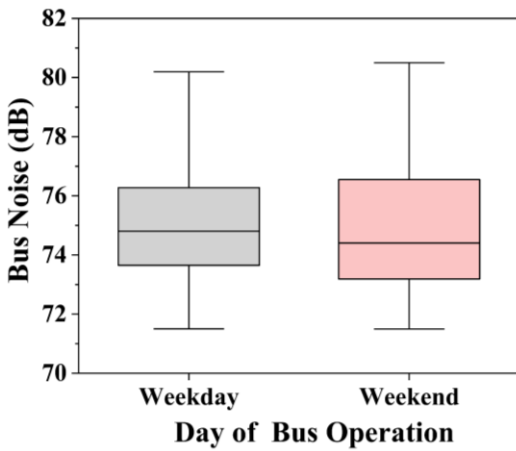
d. Bus Noise across Road Network



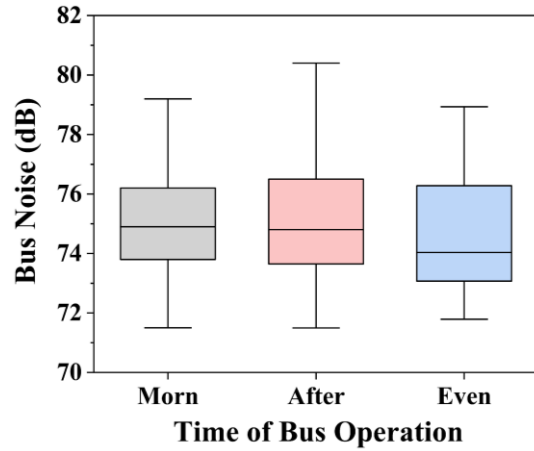
e. Bus Noise across Trip Distances



f. Bus Noise across Occupancy Levels



g. Bus Noise across Operation Days



h. Bus Noise across Operation Times

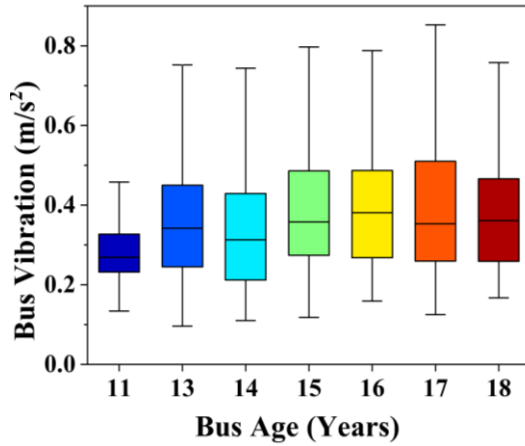
Figure 4.2: Electric Bus Noise Levels across Different Operational Factors

The analysis of the electric bus noise data in the context of the studied operational factors also showed notable patterns in line with existing work in the domain. Starting with bus age, the results showed that older electric buses emitted slightly higher noise compared to the newer ones. Specifically, buses aged 4 years (youngest in the fleet) had an average noise level of 74.4 dB(A), while those aged 5 years (oldest in the fleet) recorded a higher average of 75.05 dB(A), concurring with the assertions of [135]. Considering the factor of average speed, an overarching level trend was noticed. Buses operating below 10 km/h had an average noise level of 74.75 dB(A), which remained fairly stable through the 10.0–19.0 km/h and 20.0–29.0 km/h categories at 74.6 dB(A) and 74.59 dB(A) respectively. A marginal increase was noted in the 30.0–39.0 km/h bracket at

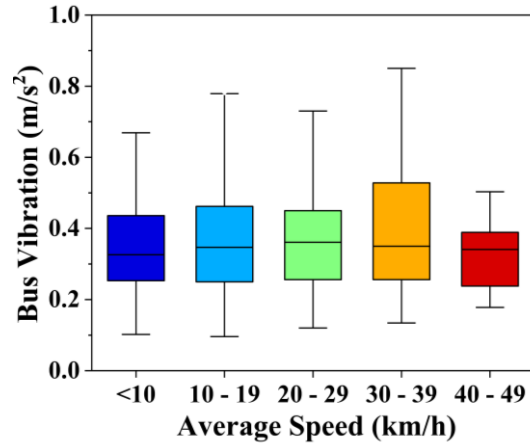
74.98 dB(A). This suggests that electric motors in general maintain consistent noise output across typical operating average speeds. Relating to road conditions (RC), the general trend showed a reduction in bus noise as road quality increased. From RC 2 to RC 4, this trend is evident with average noise levels of 74.9, 74.7 and 74.5 dB(A) respectively. However, with RC 5, the average noise increased to 74.9 dB(A). With regards to road network (RN), no distinct trend was seen just like in the conventional results. Here, the average noise levels ranged from 74.12 dB(A) to 76.04 dB(A), with some fluctuations. Road Networks with 4 bends or curves recorded the highest average of 76.04 dB(A), while RN with 3 bends or curves had the lowest at 74.12 dB(A). For trip distance, trends showed that noise levels were slightly lower on very short trips. Trips under 0.1 km had an average noise level of 73.86 dB(A), increasing slightly for distances up to 1 km (75.3 dB(A)), then stabilizing around 74.6 dB(A) for longer trips over 1 km. Considering occupancy level, the data inferred a mild inverse trend. At occupancy level 1, the average noise level was 74.6 dB, increasing slightly to 74.7 dB(A) at level 2 and then decreasing to 74.4 dB(A) at level 3. Although the differences were minimal, the trend supports the fact that increased vehicle load contributes to more stable operation and lower noise. In the context of day of operation, weekdays were seen to show higher average noise levels of 74.8 dB(A) compared to 74.4 dB(A) on weekends. This slight difference may be attributed to traffic conditions or route variations, corroborating with [86], who observed weekday traffic contributing more significantly to urban noise levels. Finally, with time of operation, the data showed that the afternoon period was slightly quieter with an average of 74.8 dB(A), followed closely by morning operations with average 74.9 dB(A), with evening showing the lowest average at 74.04 dB(A). It should be noted that with the average noise levels generated in the electric buses, regardless of the changing operational conditions or factors, none of the buses were remotely close to exceeding the CMVSR Standard 1106 threshold of 83 dB(A) thus attesting to the superior acoustic performance of electric buses in the field of operation.

4.1.3 Conventional Bus Vibration Levels

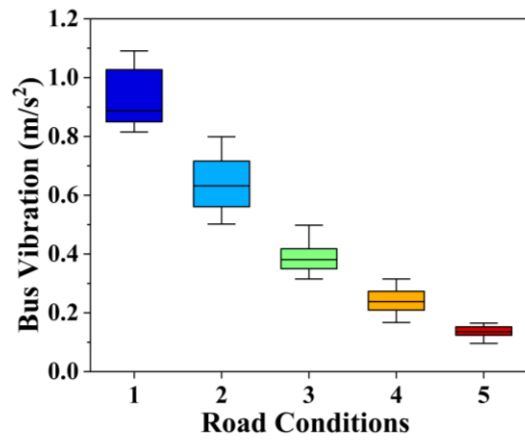
Figure 4.3 presents conventional bus vibration level trends across different operational factors.



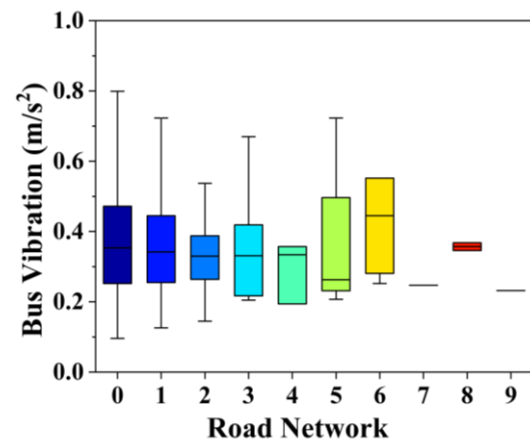
a. Bus Vibration across Bus Age



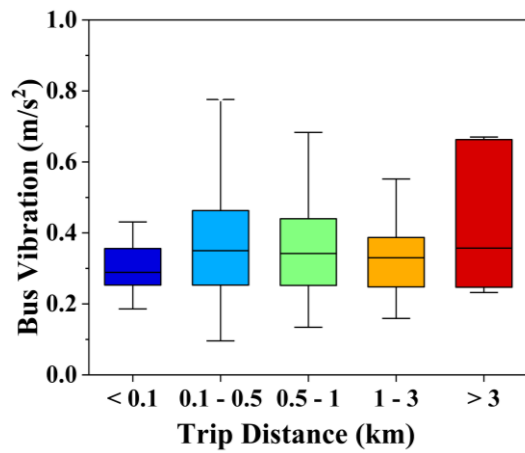
b. Bus Vibration across Average Speeds



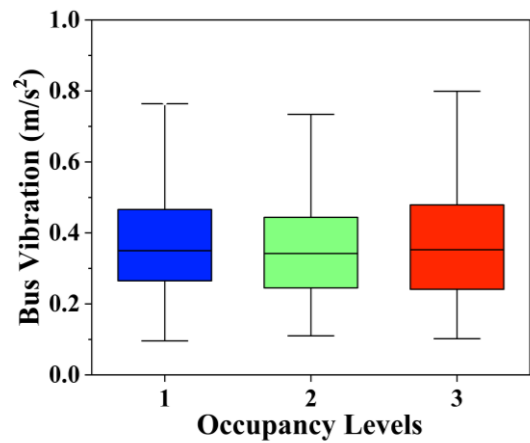
c. Bus Vibration across Road Conditions



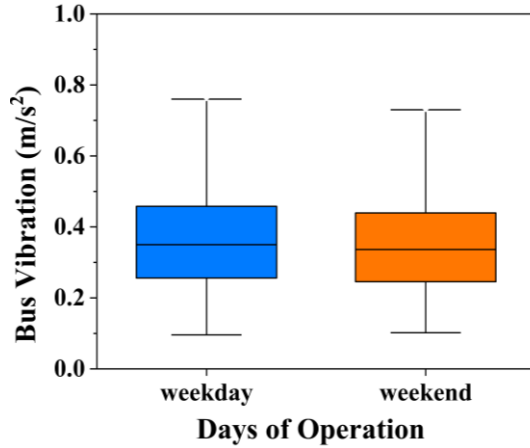
d. Bus Vibration across Road Network



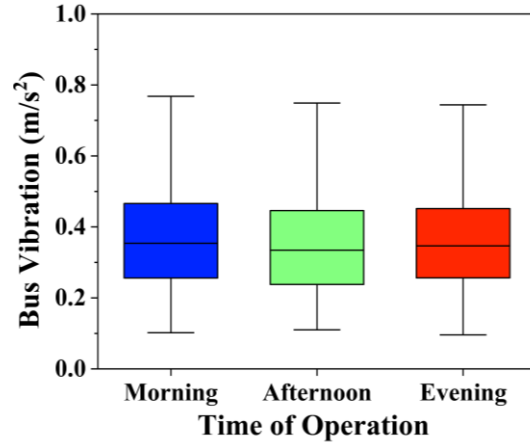
e. Bus Vibration across Trip Distances



f. Bus Vibration across Occupancy Levels



g. Bus Vibration across Operation Days



h. Bus Vibration across Operation Times

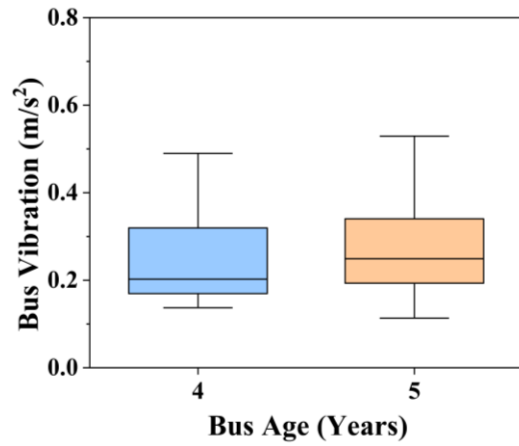
Figure 4.3: Conventional Bus Vibration Levels across Different Operational Factors

The analysis of vibration data for conventional buses across various operational factors also revealed some noteworthy patterns. In terms of bus age, a general upward trend was observed in vibration levels as bus age increased. For example, buses aged 11 years recorded an average vibration level of 0.269 m/s^2 , while those aged 15–18 years exhibited the highest average vibration levels, ranging from 0.358 to 0.381 m/s^2 . This trend aligns with findings by [32]. Furthermore, it can be noticed that buses over the ages of 15 years exceeded the ISO 2631:1 1997's $\leq 0.315 \text{ m/s}^2$ standard. Considering average speed, the data revealed a subtle upward trend with increasing speed, though with some variability. Buses traveling at speeds below 10 km/h recorded an average vibration of 0.326 m/s^2 , which rose to 0.347 m/s^2 for speeds of $10\text{--}19 \text{ km/h}$ and peaked at 0.361 m/s^2 in the $20\text{--}29 \text{ km/h}$ category. After this point, the levels slightly decreased to 0.350 m/s^2 for $30\text{--}39 \text{ km/h}$ and further to 0.331 m/s^2 for $40\text{--}49 \text{ km/h}$. This pattern suggests that while moderate increases in speed may enhance vibration due to engine load and suspension dynamics, very high or very low speeds may reduce or stabilize vibration through more consistent operating conditions. Additionally, regardless of the average speed the buses operated with, they exceeded the ISO 2631:1's standard. With regard to road condition (RC), a consistent and clear inverse relationship was identified where vibration levels decreased as road condition improved. Roads classified under RC 1, representing very poor conditions, exhibited the highest average vibration of 0.887 m/s^2 , while RC 5, denoting very good conditions, had the lowest level at 0.159 m/s^2 , generally concurring with [21]. Regarding the performance using the ISO 2631:1 benchmark, the worst road

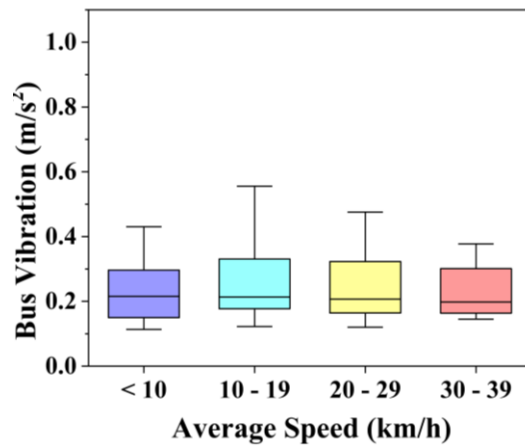
conditions exceeded the threshold of $\leq 0.315 \text{ m/s}^2$ while very good roads fell below the standard. The road network (RN) factor showed no definitive pattern, with vibration levels fluctuating across different road network classifications. For instance, RN 0 recorded a vibration level of 0.354 m/s^2 , RN 1 at 0.342 m/s^2 , RN 5 at a lower 0.263 m/s^2 , and RN 6 at a high of 0.445 m/s^2 . These inconsistencies suggest that variations in the number and severity of bends, curves, and intersections within the road network may introduce complex interactions with vibration levels, making a linear relationship difficult to establish. This makes the factor heavily dependent on the driving styles of the drivers of the buses and how they choose to approach the maneuvers of the curves or bends. In examining trip distance, a non-linear relationship was also observed. The shortest trip category ($<0.1 \text{ km}$) yielded a vibration level of 0.289 m/s^2 , which increased across medium distances of 0.35 m/s^2 ($0.1\text{--}0.5 \text{ km}$), 0.342 m/s^2 ($0.5\text{--}1 \text{ km}$), and 0.33 m/s^2 ($1\text{--}3 \text{ km}$) before spiking to 0.58 m/s^2 for trips over 3 km . This significant rise at the $>3 \text{ km}$ mark may be attributed to the possible exposure of the bus to degraded longer routes. In addition, the shortest trip distances were seen to be comfortable in terms of the ISO 2631:1 while those above that trip distance were seen to exceed the comfort threshold. In terms of occupancy, a non-linear pattern was observed. Buses with Occupancy Level 1 recorded a vibration level of 0.35 m/s^2 , which slightly decreased to 0.342 m/s^2 at Occupancy Level 2 before rising again to 0.352 m/s^2 at Occupancy Level 3. Regarding the standard-based performance of the various occupancy levels, it was seen that buses in all occupancy levels exceeded the ISO 2631:1 comfort threshold. When evaluating day of the week, buses which operated on weekdays showed slightly higher vibration levels (0.35 m/s^2) compared to weekends (0.337 m/s^2). Time of day analysis indicated a modest variation in vibration levels across the day. Morning operations recorded the highest vibration level of 0.354 m/s^2 , followed by evening at 0.346 m/s^2 and the lowest in the afternoon at 0.335 m/s^2 . This pattern may reflect peak-hour operational stress in the morning, with possible mechanical fatigue and increased road usage conditions contributing to vibration levels during the evening. Thus, regarding the standard-based performance of the various operational schedule (day and times), it was seen that buses exceeded the ISO 2631:1 comfort threshold in these cases.

4.1.4 Electric Bus Vibration Levels

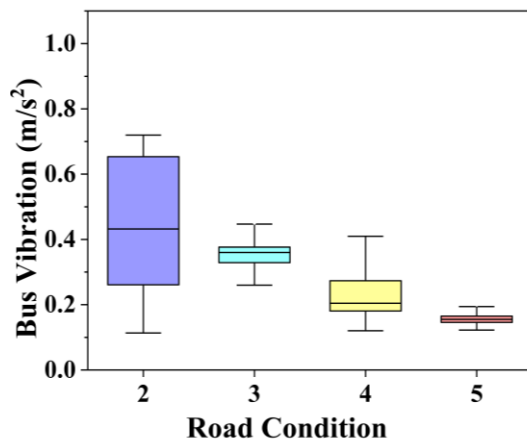
Figure 4.4 presents electric bus vibration level trends across different operational factors.



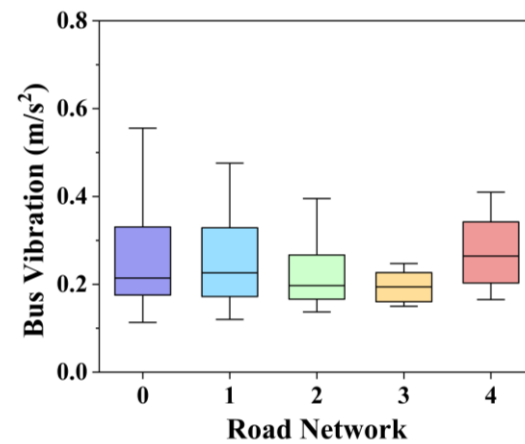
a. Bus Vibration across Bus Age



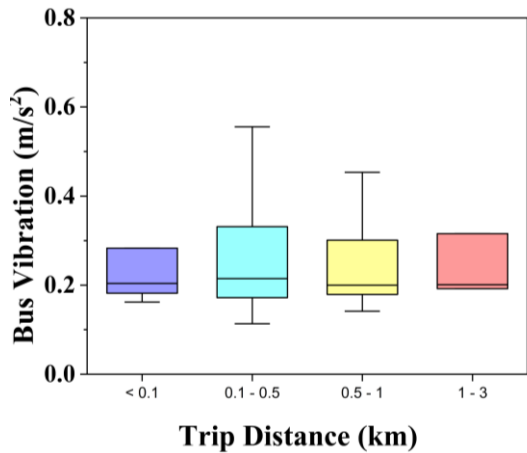
b. Bus Vibration across Average Speeds



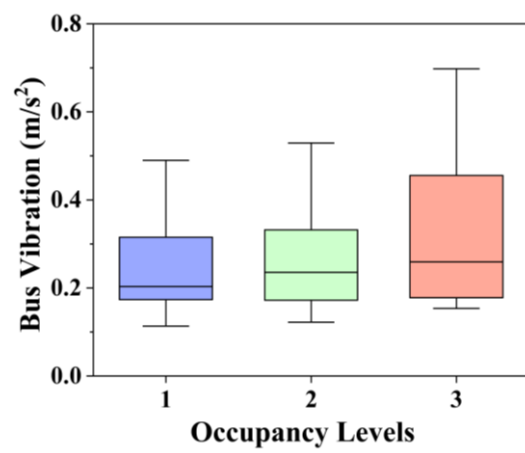
c. Bus Vibration across Road Conditions



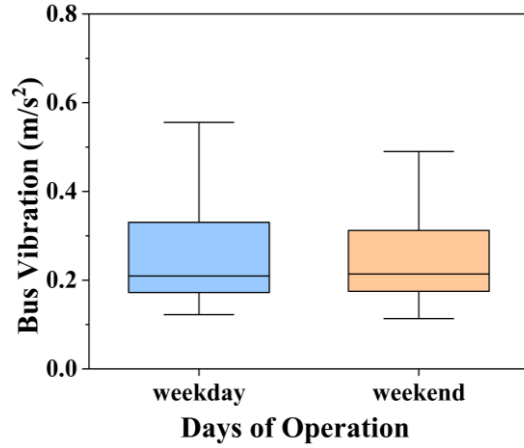
d. Bus Vibration across Road Network



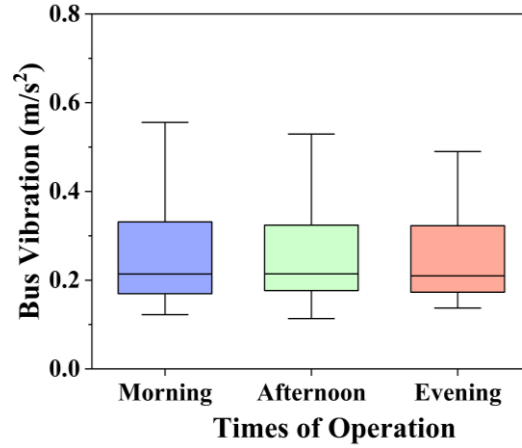
e. Bus Vibration across Trip Distances



f. Bus Vibration across Occupancy Levels



g. Bus Vibration across Operation Days



h. Bus Vibration across Operation Times

Figure 4.4: Electric Bus Vibration Levels across Different Operational Factors

The analysis of the electric bus vibration data across various operational factors revealed subtle but consistent patterns. Starting with bus age, the results indicated that older electric buses exhibited slightly higher vibration levels compared to newer models. Specifically, buses aged 4 years recorded an average vibration level of 0.202 m/s², while those aged 5 years had a higher average of 0.249 m/s². Considering average speed, the data reflected a slight downward trend in vibration as speed increased. Buses operating below 10 km/h experienced an average vibration level of 0.215 m/s². This slightly declined to 0.2134 m/s² for speeds of 10–19 km/h, followed by further reductions at 0.207 m/s² (20–29 km/h) and 0.197 m/s² (30–39 km/h). These results suggest that electric buses may exhibit more stable and smoother operation at higher speeds, likely due to efficient drivetrain mechanics and fewer gear shifts. With regard to road condition (RC), the general trend showed decreasing vibration levels as road quality improved. For instance, RC 2 showed an average vibration of 0.423 m/s², which declined to 0.360 m/s² at RC 3 and further to 0.204 m/s² at RC 4. The lowest level was recorded at RC 5 with 0.150 m/s². This trend is consistent with expectations, as better-maintained roads transmit fewer surface irregularities and thus produce less vibration [21]. Looking at the road network (RN), no distinct or linear trend was evident. Vibration levels varied across different RN classifications, with RN 0 recording 0.214 m/s² and RN 1 slightly higher at 0.226 m/s². Meanwhile, RN 2 and RN 3 had lower values of 0.197 m/s² and 0.194 m/s² respectively, while RN 4 peaked at 0.279 m/s². These fluctuations may stem from differing curvature profiles and how drivers navigate turns or elevation changes, influencing

vibration differently across segments. For trip distance, the trend suggested that mid-range trips experienced marginally higher vibrations. The shortest trips (<0.1 km) registered a vibration level of 0.204 m/s^2 . This increased slightly for distances of $0.1\text{--}0.5$ km (0.215 m/s^2), but then dropped to 0.203 m/s^2 for $0.5\text{--}1$ km and further to 0.202 m/s^2 for $1\text{--}3$ km. This suggests that very short trips might involve more stop-start motion, increase transient vibration, while longer trips benefit from more consistent movement. Considering occupancy level, the trend indicated a gradual increase in vibration with rising occupancy. At Occupancy Level 1, the vibration level was 0.203 m/s^2 . This rose to 0.235 m/s^2 at Occupancy Level 2 and peaked at 0.259 m/s^2 at Occupancy Level 3. In the context of the day of operation, weekends showed slightly higher vibration levels (0.214 m/s^2) compared to weekdays (0.209 m/s^2), disagreeing with the general notion posed by [82]. Lastly, time-of-day analysis revealed minimal variation. Morning and afternoon operations had nearly identical vibration levels of 0.214 and 0.2141 m/s^2 respectively, while the evening showed a slightly reduced level of 0.209 m/s^2 . It should be noted that with the average vibration levels generated in the electric buses, regardless of the changing operational conditions or factors, none of the buses were remotely close to exceeding the ISO 2631:1 1997 threshold of $\leq 0.315 \text{ m/s}^2$. This infers the superior vibration generation performance of electric buses in the field of operation.

4.1.5 Rider Perceptions

Figure 4.5 presents average rider perceptions for noise and vibration levels across conventional and electric buses.

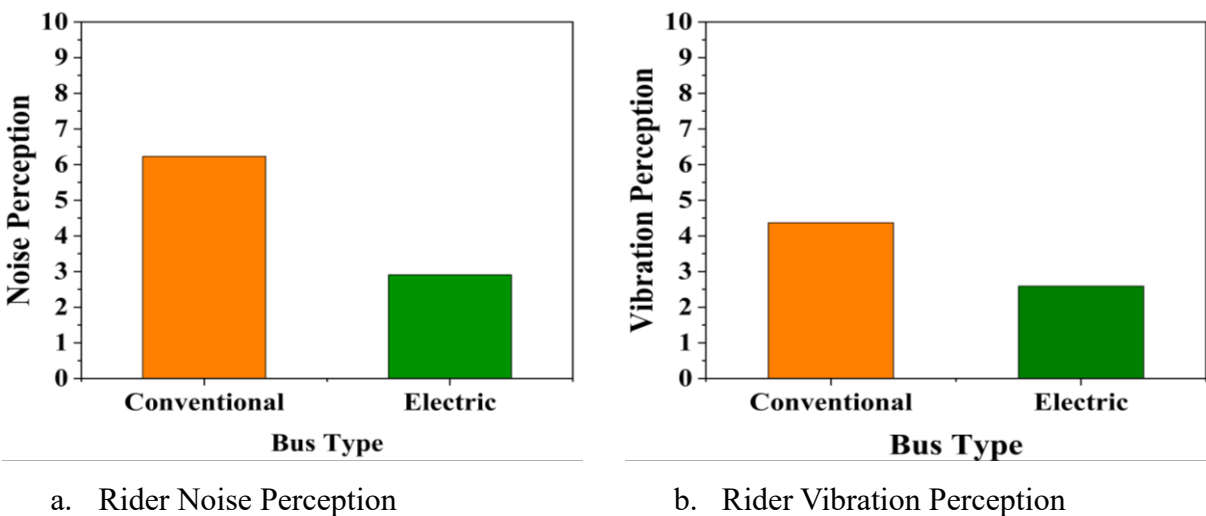


Figure 4.5: Average Rider Perceptions of Bus Noise and Vibration Levels

From Figure 4.5, the data revealed that passengers rated their average noise perception for conventional buses at 6.23, indicating a moderately high level of perceived noise discomfort. In contrast, electric buses received a significantly lower average noise perception score of 2.91, reflecting a noticeably quieter rider experience. Similarly, for vibration, conventional buses were rated at 4.37, while electric buses received a lower average score of 2.59, again suggesting improved ride comfort in electric vehicles. These perception ratings support the broader findings of existing literature which confirms that electric buses are generally associated with a more favorable vibroacoustic environment from the passenger's perspective than their conventional counterparts.

4.2.Models

4.2.1 Conventional and Electric Noise Models

1. Hyperparameter tuning

The hyperparameters used for the conventional and electric bus noise models' development were achieved using the DBBO tuning strategy. For the upper bound (overfit search), the following hyperparameters ranges, $H_{overfit}$, were used: max depth (6–12), number of estimators (200–1000), learning rate (0.01–0.3), subsample (0.7–1.0), col sample by tree (0.7–1.0), alpha regularization (0–5), and lambda regularization (0–5). These ranges promoted overfitting by allowing the model to grow deep trees with many boosting rounds and minimal regularization. The high subsample and col sample by tree values ensured access to most of the data and features at each iteration, while the low learning rate facilitates fine-grained learning, collectively enabling the model to capture not only genuine patterns but also noise in the training data. The results of the upper bounds iterations for both conventional and electric bus noise models are presented in Figure 4.6.

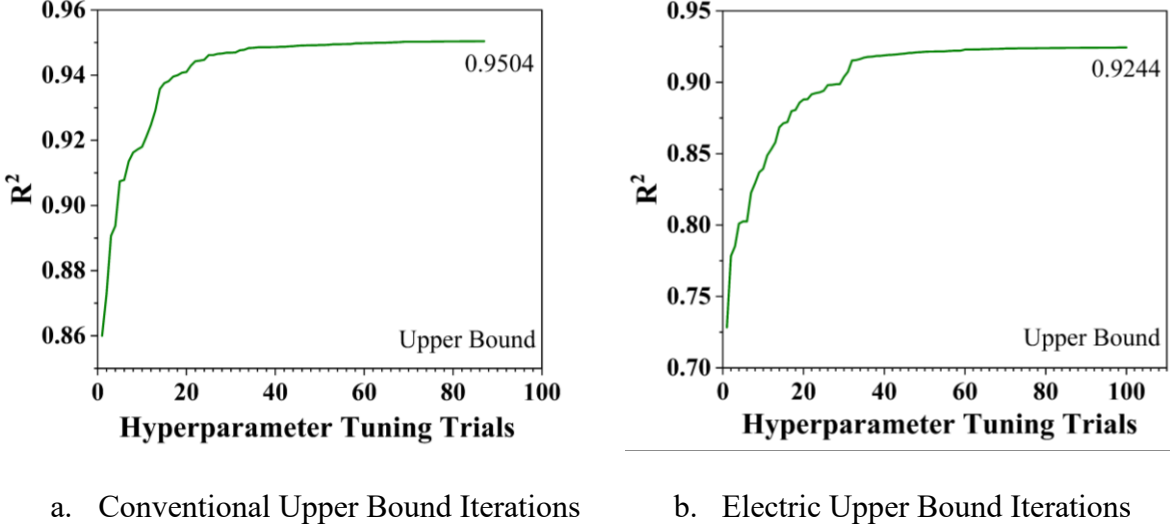
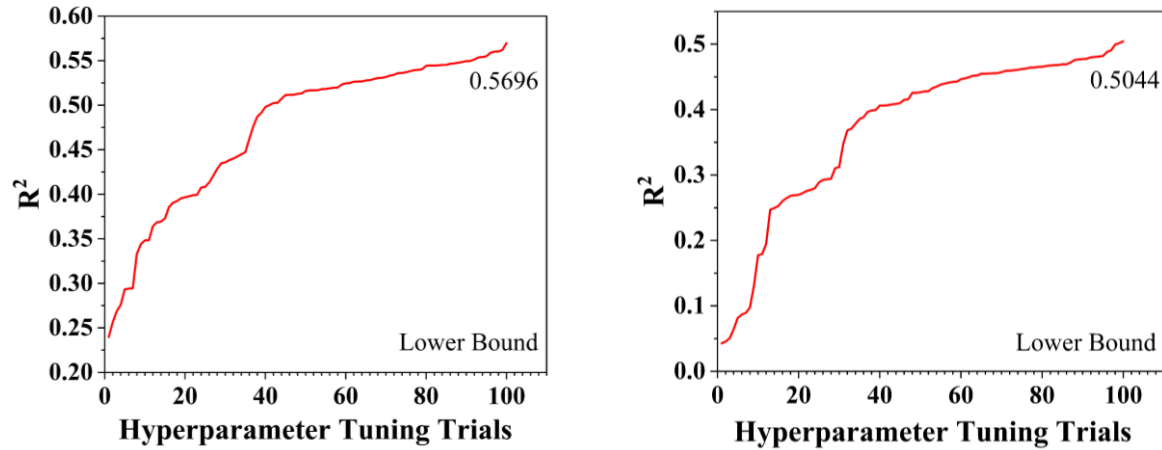


Figure 4.6: Upper Bound Iterations for Conventional and Electric Buses

The upper bound hyperparameter tuning resulted R^2 of 0.9504 and 0.9244 for the conventional and electric bus noise models respectively. For the conventional upper bound, the hyperparameters were max depth = 11, number of estimators = 649, learning rate = 0.09, subsample = 0.99, col sample by tree = 0.98, alpha regularization = 0.003, and lambda regularization = 1.85. Conversely, for the electric upper bound, the hyperparameters were max depth = 7, number of estimators = 931, learning rate = 0.18, subsample = 0.94, col sample by tree = 0.85, alpha regularization = 0.02, and lambda regularization = 2.34.

For the lower bound (underfit search), the following ranges $H_{underfit}$, were used: max depth (1–3), number of estimators (10–50), learning rate (0.2–0.6), subsample (0.1–0.7), col sample by tree (0.1–0.7), alpha regularization (0–1), and lambda regularization (0–1). These constraints reduced the model’s learning capacity by limiting tree depth and the number of estimators, increasing the learning rate, and reducing the proportion of data and features used per iteration. As a result, the iterated models lacked sufficient capacity to capture complex relationships in the data, leading to underfitting. The results of the lower bounds for both conventional and electric bus noise models are presented in Figure 4.7.



a. Conventional Lower Bound Iterations

b. Electric Lower Bound Iterations

Figure 4.7: Lower Bound Iterations for Conventional and Electric Buses

The lower bound hyperparameter tuning resulted R^2 of 0.5696 and 0.5044 for the conventional and electric bus noise models respectively. For the conventional lower bound, the hyperparameters were max depth = 3, number of estimators = 48, learning rate = 0.58, subsample = 0.64, col sample by tree = 0.68, alpha regularization = 0.5, and lambda regularization = 0.02. Conversely, for the electric lower bound, the hyperparameters were max depth = 3, number of estimators = 47, learning rate = 0.56, subsample = 0.66, col sample by tree = 0.67, alpha regularization = 0.09, and lambda regularization = 0.27.

Using these ranges the balanced hyperparameters for the conventional bus noise model was found as: max depth = 4, number of estimators = 180, learning rate = 0.40, subsample = 0.76, col sample by tree = 0.89, alpha regularization = 0.25, and lambda regularization = 0.40. For the electric bus noise model, the hyperparameters were max depth = 4, number of estimators = 687, learning rate = 0.21, subsample = 0.70, col sample by tree = 0.81, alpha regularization = 0.05, and lambda regularization = 1.57. These hyperparameters were used to generate the XGBoost models.

2. Model Performance Results

Using the obtained parameters, the conventional and electric bus noise models were generated. The models had the following properties shown in Table 4.1.

Table 4.1: Bus Noise Model Performance

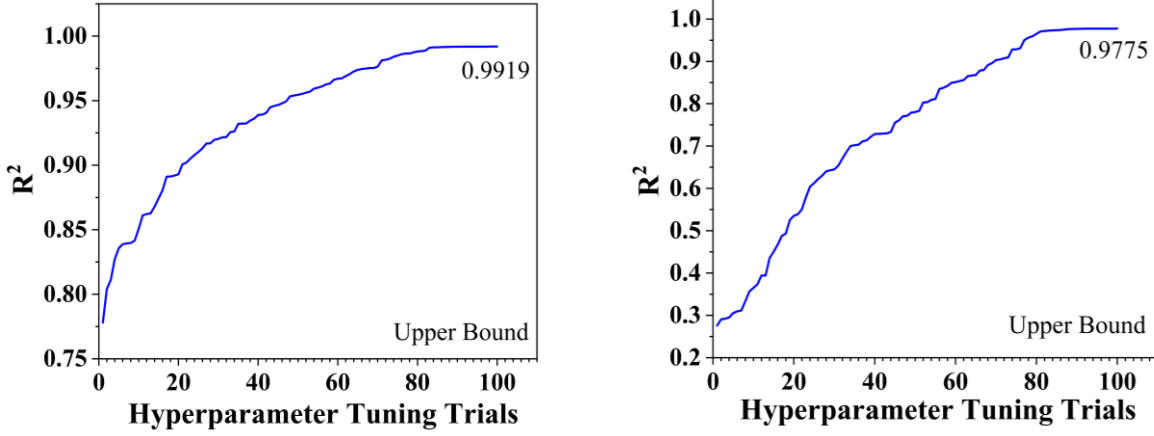
Model Name	Parameters	
	R^2	MSE (dB ²)
Conventional Bus Noise	0.8456	1.4724
Electric Bus Noise	0.8758	0.4761

From the models' output, the conventional bus noise model had an R^2 of 0.8456, meaning it explained 84.56% of the variation in noise levels. Furthermore, its MSE of 1.4724 dB² indicated relatively larger prediction errors, reflecting greater variability and complexity in noise patterns for conventional buses. In contrast, the electric bus noise model achieved a higher R^2 of 0.8758, explaining 87.58% of the variation in noise levels, with a lower MSE of 0.4761 dB², reflecting more accurate and consistent predictions.

4.2.2 Conventional and Electric Vibration Models

1. Hyperparameter tuning

For the vibration models, the same set of hyperparameters applied in the bus noise models was adopted. Accordingly, for the upper bound configuration (overfitting-focused search), the following hyperparameter ranges, denoted as $H_{overfit}$, were used: max depth (6–12), number of estimators (200–1000), learning rate (0.01–0.3), subsample (0.7–1.0), column sample by tree (0.7–1.0), alpha regularization (0–5), and lambda regularization (0–5). As previously outlined, these ranges were intentionally selected to encourage overfitting by enabling deeper trees, more boosting rounds, and limited regularization. The outcomes from the upper bound iterations for both conventional and electric bus vibration models are illustrated in Figure 4.8.



a. Conventional Upper Bound Iterations

b. Electric Upper Bound Iterations

Figure 4.8: Upper Bound Iterations for Conventional and Electric Buses

The upper bound hyperparameter tuning resulted R^2 of 0.9919 and 0.9591 for the conventional and electric bus noise models respectively. For the conventional upper bound, the hyperparameters were max depth = 12, number of estimators = 919, learning rate = 0.199, subsample = 0.964, col sample by tree = 0.746, alpha regularization = 0.001, and lambda regularization = 3.447. Conversely, for the electric upper bound, the hyperparameters were max depth = 12, number of estimators = 679, learning rate = 0.165, subsample = 0.967, col sample by tree = 0.854, alpha regularization = 0.001, and lambda regularization = 0.885.

For the lower bound configuration (underfitting-focused search), the same hyperparameter ranges, $H_{underfit}$, previously applied during the tuning of the bus noise models were utilized: max depth (1–3), number of estimators (10–50), learning rate (0.2–0.6), subsample (0.1–0.7), column sample by tree (0.1–0.7), alpha regularization (0–1), and lambda regularization (0–1). As discussed earlier, these restrictive settings limited the model's capacity by constraining tree depth and estimator count, increasing the learning rate, and reducing both the training data and feature subset per iteration. Consequently, the models were unable to capture more complex patterns in the data, resulting in underfitting. The outcomes of the lower bound iterations for both conventional and electric bus vibration models are shown in Figure 4.9.

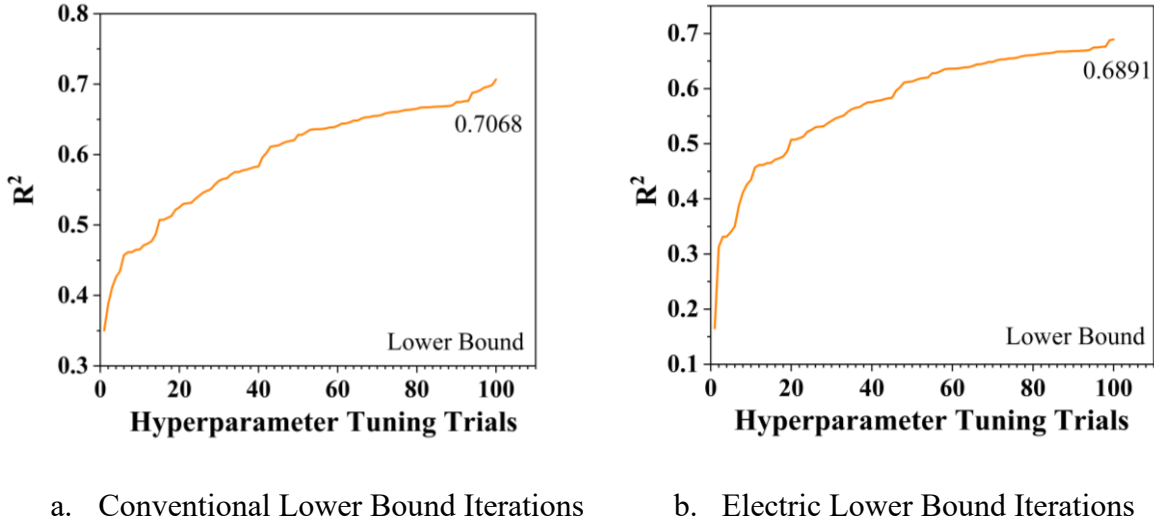


Figure 4.9: Lower Bound Iterations for Conventional and Electric Buses

The lower bound hyperparameter tuning resulted R^2 of 0.7086 and 0.6891 for the conventional and electric bus noise models respectively. For the conventional lower bound, the hyperparameters were max depth = 3, number of estimators = 49, learning rate = 0.511, subsample = 0.662, col sample by tree = 0.692, alpha regularization = 0.044, and lambda regularization = 0.921. Conversely, for the electric lower bound, the hyperparameters were max depth = 3, number of estimators = 49, learning rate = 0.559, subsample = 0.643, col sample by tree = 0.602, alpha regularization = 0.029, and lambda regularization = 0.508.

Using these ranges the balanced hyperparameters for the conventional bus conventional model was found as: max depth = 3, number of estimators = 495, learning rate = 0.333, subsample = 0.832, col sample by tree = 0.713, alpha regularization = 0.040, and lambda regularization = 0.958. For the electric bus vibration model, the hyperparameters were max depth = 3, number of estimators = 653, learning rate = 0.51, subsample = 0.88, col sample by tree = 0.769, alpha regularization = 0.006, and lambda regularization = 0.509. These hyperparameters were used to generate the conventional and electric bus vibration XGBoost models.

2. Model Performance Results

Using the obtained parameters, the conventional and electric bus vibration models were generated. The models had the following properties shown in Table 4.2.

Table 4.2: Bus Vibration Model Performance

Model Name	Parameters	
	R^2	MSE (dB ²)
Conventional Bus Vibration	0.9590	0.0012
Electric Bus Vibration	0.9094	0.0013

From the models' output, the conventional bus vibration model had an R^2 of 0.9590, meaning it explained 95.90% of the variation in noise levels. Furthermore, its MSE of 0.0012 dB² indicated extremely lower prediction errors, and higher accuracy. In contrast, the electric bus vibration model achieved a lower R^2 of 0.9094, explaining 90.94% of the variation in vibration levels, with an MSE of 0.0013 dB², also reflecting higher accurate and consistent predictions.

4.2.3 Noise Perception Model

The bus noise ridge regression models utilized average bus noise perception (np) as the dependent variable and average bus noise level ($\bar{L}$) as the independent variable. The regression equations of the developed models are presented in Equations 30 and 31 respectively for conventional and electric buses.

$$np_c = 0.723 (\bar{L}_c) - 52.48 \quad (30)$$

$$np_e = 0.350 (\bar{L}_e) - 24.09 \quad (31)$$

The conventional bus noise perception model attained an R^2 of 0.919, indicating that 91.9% of the dataset's variability could be accounted for by the independent factor considered in the model. Furthermore, the model exhibited small MSE of 0.16. On the other hand, the electric bus noise perception model had an R^2 of 0.897, indicating that 89.7% of the dataset's variability could be accounted for by the independent factor considered in the model. Additionally, the model had an MSE of 0.10 respectively, attesting to the model's accuracy.

4.2.4 Vibration Perception Model

The bus noise ridge regression models utilized average bus vibration perception (vp) as the dependent variable and average bus vibration level ($\bar{a}$) as the independent variable. The regression

equations of the developed models are presented in Equations 32 and 33 respectively for conventional and electric buses.

$$vp_c = 0.612 (\overline{a_c}) + 4.40 \quad (32)$$

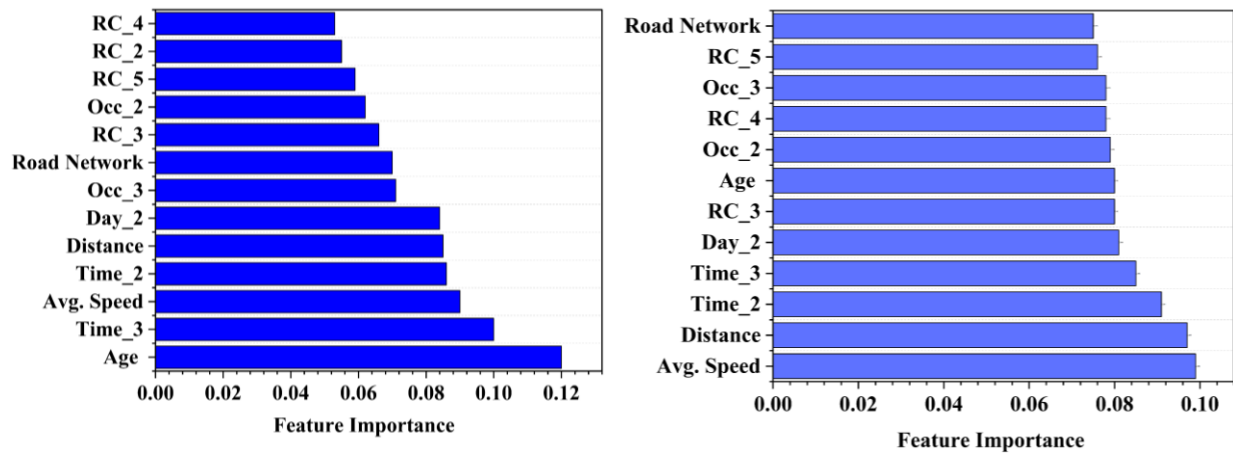
$$vp_e = 0.032 (\overline{a_e}) + 3.245 \quad (33)$$

The developed conventional bus vibration perception model attained an R^2 of 0.859, indicating that 85.9% of dataset's variability could be accounted for by the independent factor considered in the model. Furthermore, the model exhibited small MSE of 0.20, attesting to the model's accuracy. On the other hand, the electric bus noise perception model had an R^2 of 0.887, indicating that 88.7% of dataset's variability could be accounted for by the independent factor considered in the model. Additionally, the model had an MSE of 0.04 respectively, showcasing higher model prediction accuracy.

4.3.Factor Importance

4.3.1 Conventional and Electric Noise

Figure 4.10 presents the operational factor importance rankings extracted from the noise models' training. The rankings highlight the factors deemed important by the models in their process of predicting noise in both buses.



a. Conventional Model Factor Importance

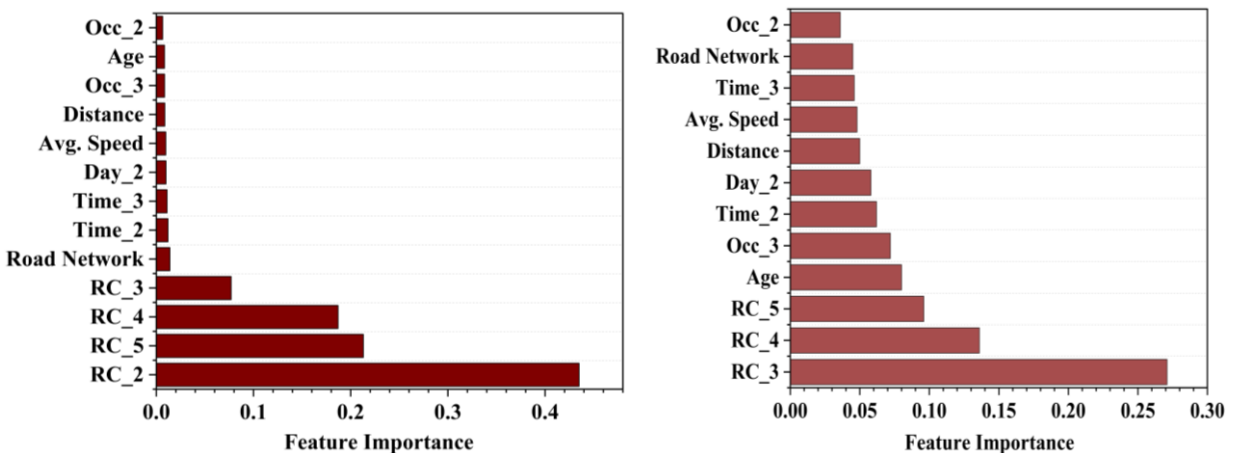
b. Electric Model Factor Importance

Figure 4.10: Operational Factor Rankings for Conventional and Electric Buses

From the results, it is clearly seen that both conventional and electric bus noise levels share the same important operational factors, although they are ranked differently. For the conventional bus noise model, bus-related factors like bus age emerged as the most influential. Additionally, other factors like time of bus operation, specifically evenings and afternoons, along with average speed and trip distance also ranked highly. This reflects the impact of situational and environmental factors on shaping the noise generated by conventional buses during their operations. Notably, day of operation (specifically weekends), occupancy levels and various road condition categories were also deemed important, highlighting the multi-facet nature of noise generation in conventional buses. In contrast, the electric bus model placed greater emphasis on average speed and distance as its most important factors. Additionally, factors like time and day of operation (specifically, evenings, afternoons and weekends) were also identified as important in electric bus noise generation. However, bus-related factors like bus age and occupancy were less dominant, while factors like road network came out as the least dominant. Overall, while both models rely on similar features, their differing emphasis reflects the underlying mechanical and operational distinctions between conventional and electric buses.

4.3.2 Conventional and Electric Vibration

Figure 4.11 presents the operational factor importance rankings extracted from the vibration models' training. The rankings highlight the factors deemed important by the models in their process of predicting vibration in both buses.



a. Conventional Model Factor Importance b. Electric Model Factor Importance

Figure 4.11: Operational Factor Rankings for Conventional and Electric Buses

From the results, it is evident that both conventional and electric bus vibration levels are influenced by similar operational factors, though with distinct rankings and emphasis. For the conventional bus vibration model, road condition was the most influential factor, with extreme conditions such as very good (RC 5) and poor (RC 2) showing high importance, followed by good (RC 4) and average (RC 3) conditions. This suggests that the physical quality of the roads significantly affects vibration levels in conventional buses. In contrast, other factors such as time of operation, particularly during afternoons and evenings, day of operation (weekends), and vehicle-related parameters like average speed, distance, occupancy levels, and bus age had relatively low influences. This points to a vibration pattern in conventional buses that is more sensitive to road quality than to dynamic or usage-related characteristics.

In comparison, the electric bus vibration model presented a broader distribution of influential factors. Road condition still played a key role, particularly RC 3, RC 4, and RC 5, but bus age, occupancy (especially high levels), and temporal factors such as afternoons (Time 2) and weekends (Day 2) also held significant weight. Additionally, distance and average speed were moderately influential, indicating that both operational context and road quality shape vibration in electric buses. Lesser importance was given to road network and average occupancy levels (Occ 2), suggesting these factors contribute minimally. Overall, while both models draw upon similar variables, conventional bus vibrations are driven more by extremes in road conditions, whereas electric bus vibrations reflect a more balanced sensitivity to vehicle use patterns, age, and occupancy, in addition to road quality.

4.4. Relational Impacts of Operational Factors on Bus Vibroacoustic Levels

1.1.1 4.4.1 Conventional Bus Noise

The relational impacts of the identified importance factors were established using the SHAP summary plots. Figure 4.12 presents the summary plot for the conventional bus noise model.

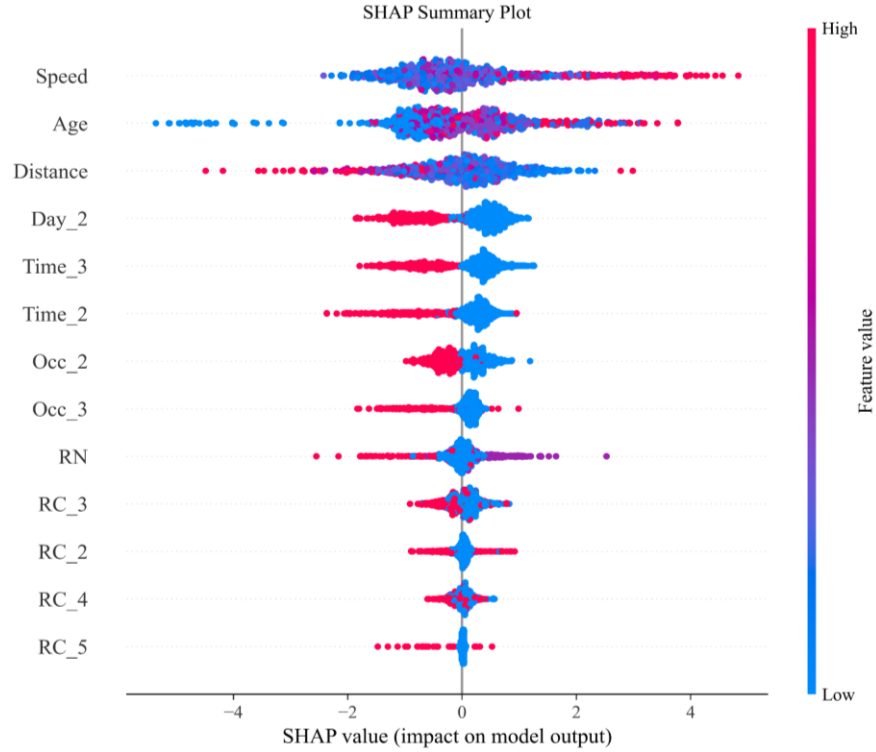


Figure 4.12: SHAP Summary Plot for Important Conventional Bus Noise Generation Features

In the conventional bus noise model, all operational factors exhibited distinct relationships with bus noise generation. Notably, age (Age) and average speed (Speed) showed a positive correlation with noise levels, indicating that older buses and higher operating speeds contributed to increased noise. This aligns with expectations, as mechanical wear and elevated engine load over time typically result in louder vehicle operation. In contrast, all other evaluated factors, including trip distance (Distance), weekend operations (Day 2), time of day such as afternoon (Time 2) and evening (Time 3), average occupancy levels (Occ 2), high occupancy levels (Occ 3), road network type (RN), average road conditions (RC 3), and very good road conditions (RC 5), demonstrated negative correlations with bus noise. This suggests that as the quality or magnitude of these features increased, bus noise levels tended to decrease. Only two factors, namely bad road conditions (RC 2) and good road conditions (RC 4) showed relatively neutral effects, indicating minimal or inconsistent influence on noise generation patterns.

4.4.2 Electric Bus Noise

The relational impacts of the identified importance factors were established using the SHAP summary plots. Figure 4.13 presents the summary plot for the electric bus noise model.

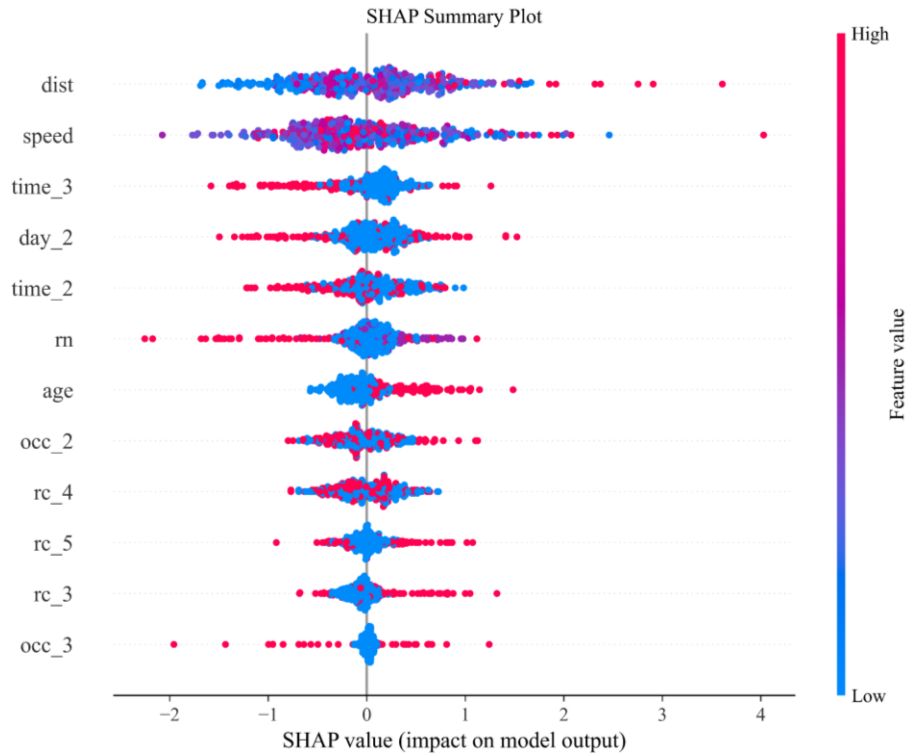


Figure 4.13: SHAP Summary Plot for Important Electric Bus Noise Generation Features

The electric bus model also exhibited distinct relational behaviors. Although bus age (Age) continued to have a positive impact, suggesting that component degradation occurs even in electric systems over time, several other factors behaved differently. Average speed (Speed), high occupancy levels (Occ 3), and good road conditions (RC 4) showed largely neutral effects on noise generation, reflecting the inherent quietness of electric drivetrains across varying speeds and loads. Trip distance (Distance), however, had a positive relationship with noise levels, indicating that longer journeys may amplify operational noise, possibly due to prolonged motor activity or ancillary system use. Consistent with the conventional model, afternoon (Time 2), evening (Time 3), and weekend operations (Day 2) showed negative correlations with bus noise, likely a result of smoother traffic flow or less aggressive driving conditions during these periods. Interestingly, average (RC 3) and very good (RC 5) road conditions, as well as average occupancy levels (Occ 2), had positive effects on noise generation in electric buses. This may be attributed to the lower baseline noise of electric vehicles, which can make subtler mechanical, or cabin sounds more noticeable in smoother, quieter operating environments. Additionally, the road network factor

(RN) demonstrated a negative relationship, suggesting that routes with more curves and turns, often associated with lower speeds, may reduce overall noise output.

4.4.3 Conventional Bus Vibration

The relational impacts of the identified importance factors were established using the SHAP summary plots. Figure 4.14 presents the summary plot for the conventional bus vibration model.

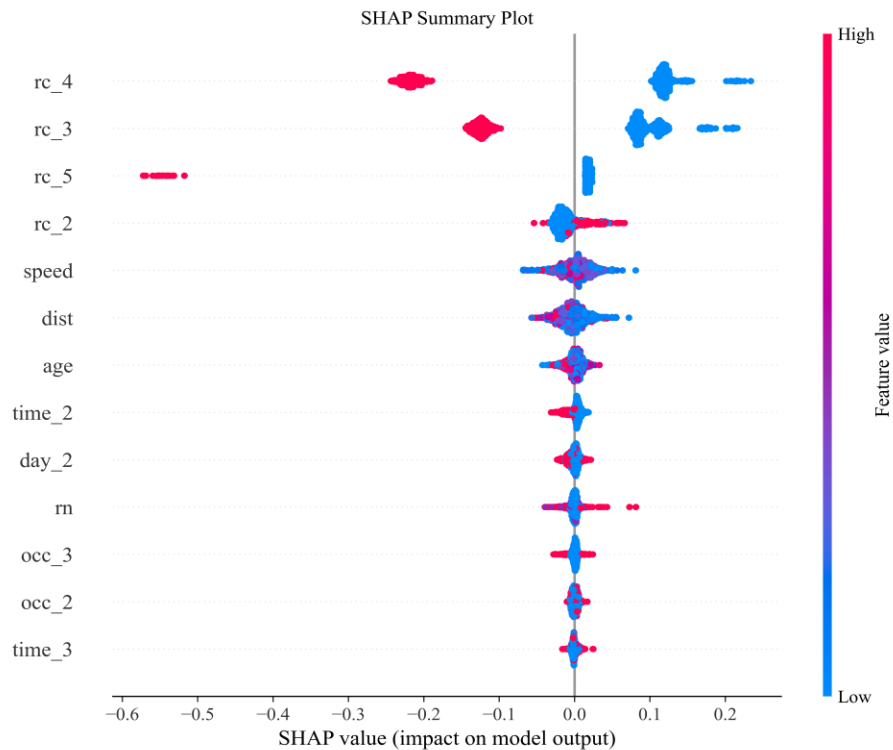


Figure 4.14: SHAP Summary Plot for Important Conventional Bus Vibration Generation Features

In the conventional bus vibration model, all operational factors displayed distinct relationships with vibration levels. Most notably, road condition categories RC 5 (very good), RC 4 (good), and RC 3 (average) exhibited negative correlations with vibration, indicating that better or moderately maintained roads were associated with reduced bus vibration. Among these, RC 5 had the strongest negative impact, followed by RC 4 and then RC 3, emphasizing that improved infrastructure plays a key role in dampening vibrations. In contrast, poor road conditions (RC 2) demonstrated a positive relationship, suggesting that buses operating on such roads experienced

increased vibration levels, likely due to the rough or deteriorated surface. Other factors also revealed nuanced impacts. Distance travelled (trip distance) had a slightly negative effect, implying that longer trips may expose buses to a variety of road segments, which could include smoother stretches that offset rough patches, thus, resulting in an overall reduction in average vibration levels. Bus age showed a slightly positive effect, indicating that older vehicles tend to generate more vibration, potentially due to structural wear and reduced suspension efficiency over time. Temporal and occupancy-related variables showed mixed relationships. Afternoon operations (Time 2) had a negative correlation with vibration, while evening operations (Time 3) and average occupancy levels (Occ 2) displayed positive contributions, suggesting that higher passenger presence and later service hours may increase vehicle load or road exposure, thereby amplifying vibration. Meanwhile, weekend operations (Day 2) and high occupancy levels (Occ 3) had largely neutral effects. Finally, road network characteristics (e.g., curves and bends) had a positive correlation with vibration levels, indicating that routes with more complex or irregular geometries contributed to increased vibration during operation. Overall, the results underscore the multi-dimensional nature of vibration in conventional buses, with strong influences from road quality and vehicle condition, and more subtle but relevant effects from operational context and passenger load patterns.

4.4.4 Electric Bus Vibration

The relational impacts of the identified importance factors were established using the SHAP summary plots. Figure 4.15 presents the summary plot for the electric bus vibration model.

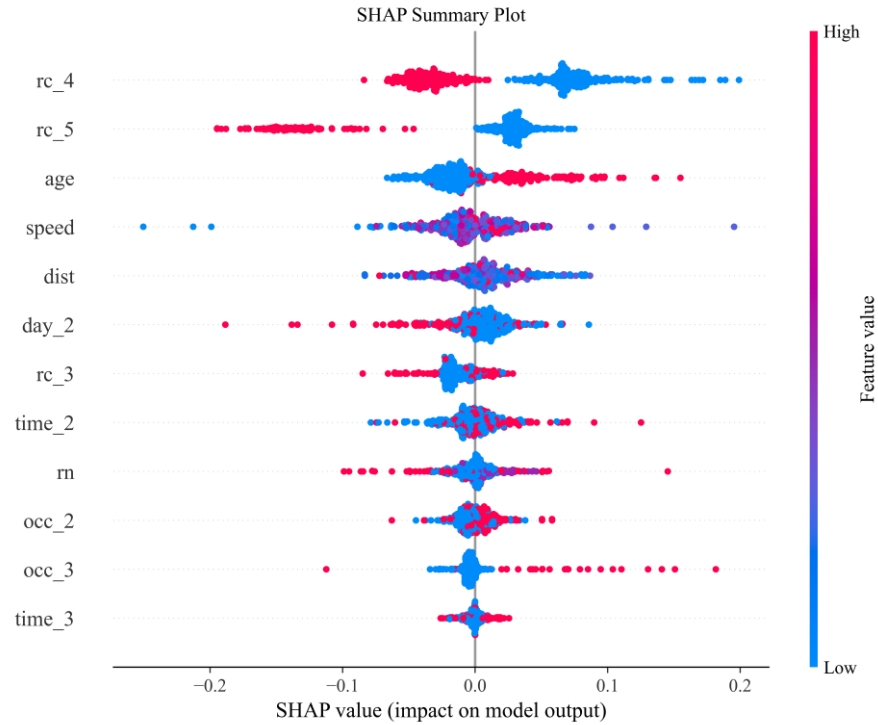


Figure 4.15: SHAP Summary Plot for Important Electric Bus Vibration Generation Features

In the electric bus vibration model, all operational factors exhibited distinct relationships with vibration generation, with some demonstrating more pronounced effects. Among the most impactful were road condition categories RC 4 (good) and RC 5 (very good), both of which showed strong negative correlations with vibration levels. RC 5, in particular, had the most substantial negative impact, suggesting that well-maintained road surfaces significantly reduce vibration in electric buses. Additionally, RC 3 (average condition) also showed a negative relationship, though its effect was comparatively weaker. In contrast, bus age emerged as a strong positive contributor, indicating that older electric buses experience greater vibration. This is likely due to accumulated wear on components such as suspension systems or mounting structures, even in the absence of combustion-related vibrations. Several other factors demonstrated positive relationships with vibration. These include afternoon operations (Time 2), evening operations (Time 3), and occupancy levels, particularly high occupancy (Occ 3), followed by average occupancy (Occ 2). These findings suggest that increased passenger load and later operational hours may contribute to heightened vehicle stress or shifting dynamics, thereby amplifying vibrations during service. On the other hand, weekend operations (Day 2) showed a negative effect, potentially reflecting less

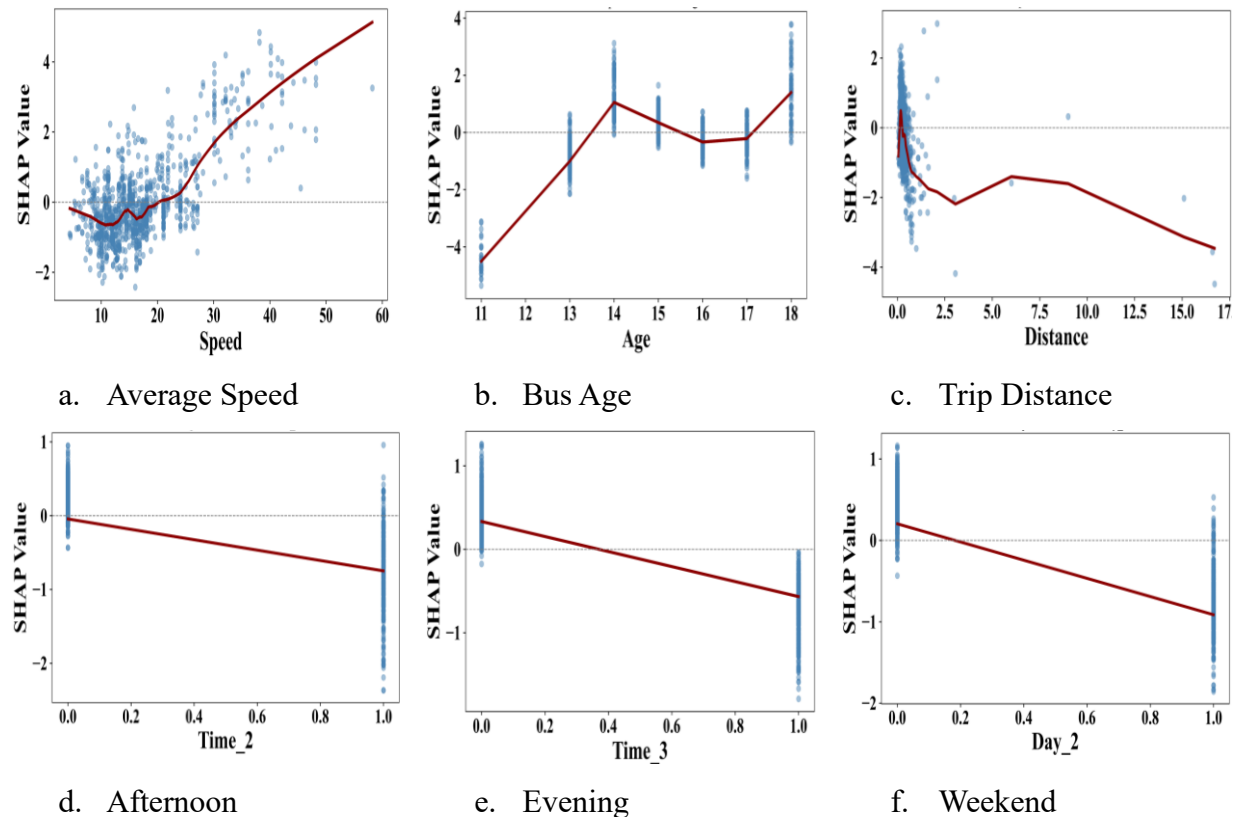
congested or smoother traffic conditions that allow for more stable driving behavior. Meanwhile, average speed, distance traveled, and road network characteristics exhibited neutral effects, indicating limited or inconsistent contributions to vibration levels within electric buses. Overall, these results highlight that while electric buses are generally less susceptible to vibration from drivetrain components, they remain sensitive to road surface quality, vehicle age, and operational loading conditions.

4.5. Isolated Contributive Effects of Operational Factors to Bus Vibroacoustic Levels

The isolated effects analysis brings to light the independent contributions of various operational and contextual features on conventional bus noise levels. By isolating each variable's impact through SHAP values, this approach disentangles complex interactions to provide clearer insights into the drivers of noise and vibration emissions in buses.

4.5.1 Isolated Effects of Operational Factors on Bus Conventional Noise

Figure 4.16 presents the isolated effects for operational factors in conventional bus noise.



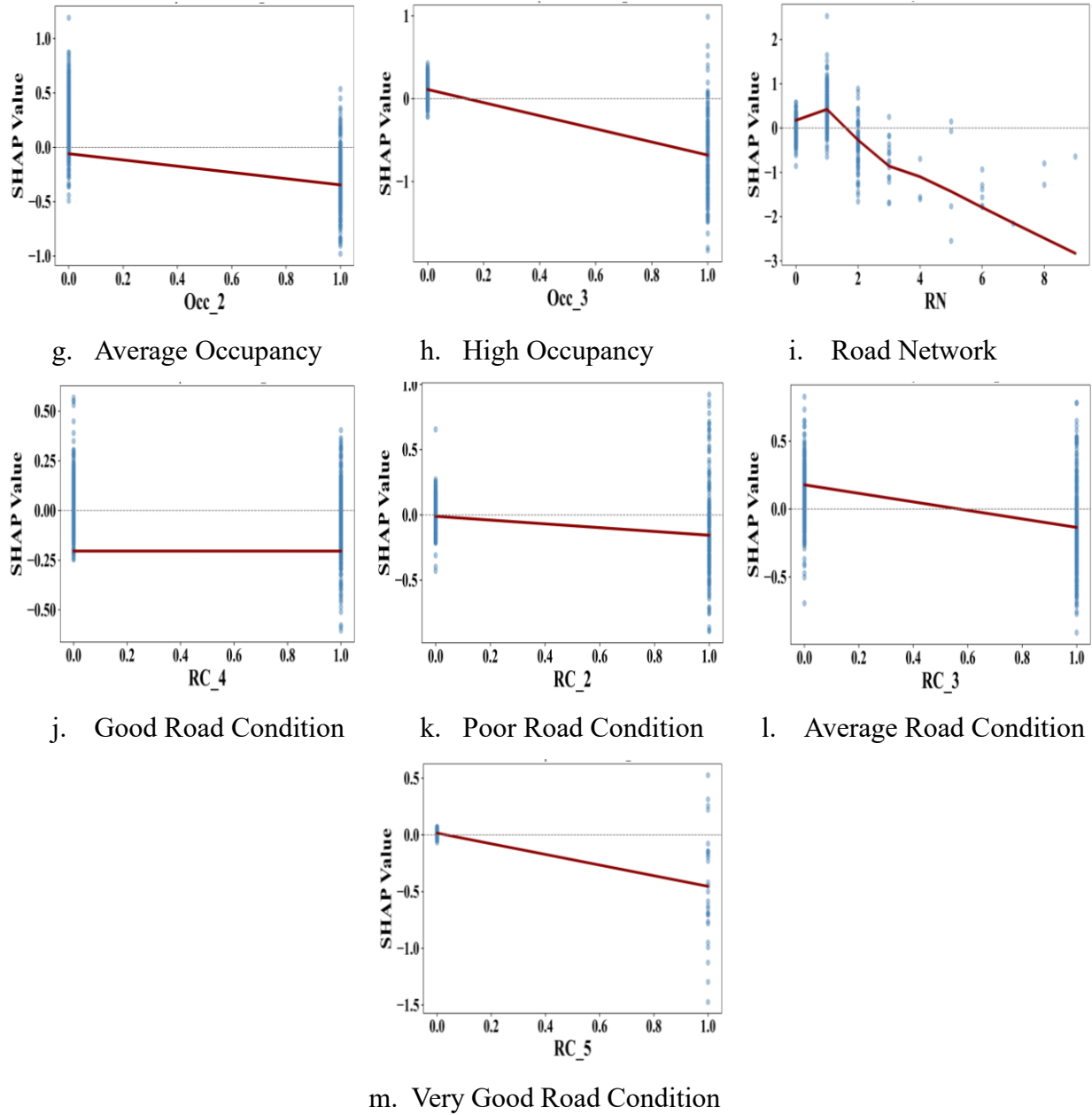


Figure 4.16: Isolated Effects of Operational Factors on Conventional Bus Noise Generation

The analysis revealed that at lower speeds (0–20 km/h), buses tended to exhibit a net negative contribution to noise generation, fluctuating modestly between 0 and -1 dB(A). This suggests that in congested traffic conditions which cause multiple stop-and-go scenarios and lowering average speeds, noise generation in conventional buses are reduced. However, a subtle inflection appeared around the 20–25 km/h range, beyond which noise contributions began to increase slightly (up to 0.05 dB(A)), and then rose more sharply with speed. At speeds above 25 km/h, a sharp increase in noise output was observed, with SHAP values reaching up to 5 dB(A).

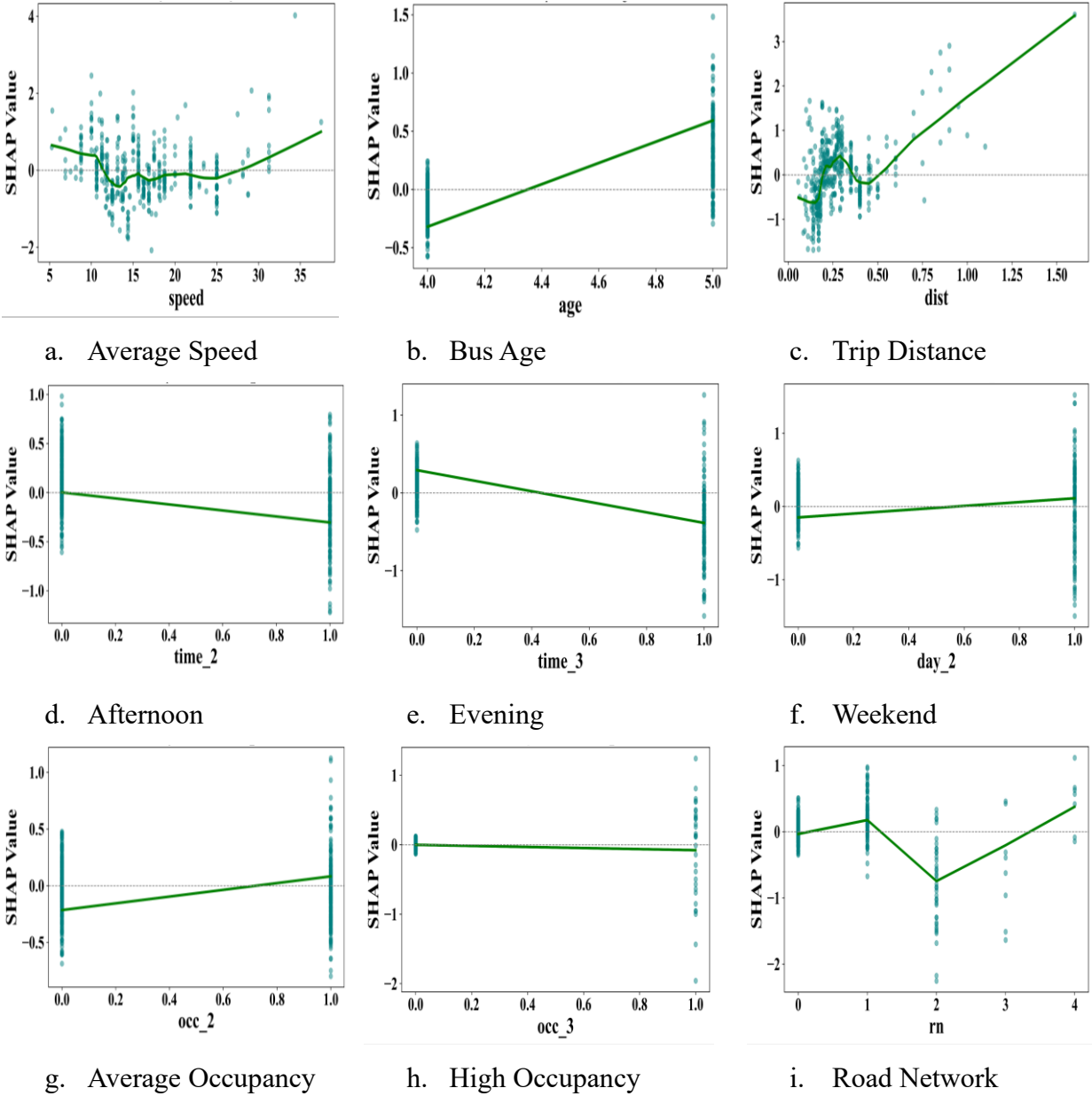
This indicates that higher speeds significantly amplify noise levels. The age of the bus also played a substantial role. Buses aged 13 years or less showed strong negative contributions, with noise levels reduced by 1 to 4.2 dB. This suggests that newer or moderately aged vehicles are acoustically more efficient. In contrast, buses older than 13 years showed a positive or fluctuating contribution, ranging from -0.1 dB(A) to +1.8 dB(A). This highlights that deterioration in engine and structural conditions is a factor in elevated noise emissions. Trip distance similarly influenced acoustic output. Shorter trips (0–1 km) tended to yield minimal negative contributions (0 to -1 dB(A)), while longer distances were associated with greater reductions in noise. Buses covering more than 1 km demonstrated increasingly negative contributions, reaching up to -3.5 dB(A). This suggests that optimized engine operation and reduced acceleration-deceleration cycles over extended journeys help lower noise levels.

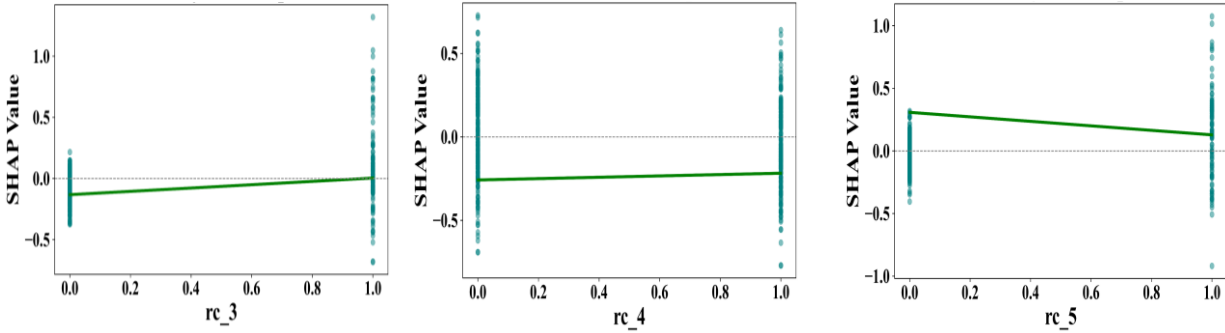
For situational contexts, the analysis revealed that buses operating in the afternoon (Time 2) and evening (Time 3) both exhibited negative noise contributions, averaging -0.7 dB and -0.6 dB(A), respectively. These patterns suggest that smoother traffic flows and less stop-and-go behavior compared to peak morning periods contribute to reduced noise. Furthermore, operation during weekends (Day 2) was associated with a reduction in noise output of approximately -0.9 dB(A) compared to weekdays. This suggests that the quieter temporal conditions of weekends, often characterized by lower congestion and traffic density, could facilitate this effect. Additionally, passenger level, expressed through occupancy categories, also correlated with noise behavior. Buses with average occupancy (Occupancy 2) contributed an average of -0.4 dB(A) to noise levels, while those with high occupancy (Occupancy 3) were associated with a slightly stronger negative effect of -0.6 dB(A). This suggests that increased load may dampen noise through vehicle dynamics stabilization. The road network configuration, particularly the number of bends or curves, significantly shaped noise outcomes. Buses traveling on routes with 0–1 curve showed positive contributions to noise, ranging from 0.1 to 0.4 dB(A). However, as route complexity increased beyond two bends or curves, the contribution became strongly negative, with values declining to -2.8 dB. This suggests that reduced speeds and smoother, more controlled driving behavior necessitated by roads with many bends or curves help lower noise levels. Lastly, road conditions further modulated acoustic performance. Surprisingly, good road surfaces (Condition 4) did not outperform others, showing contributions similar to the overall average of -0.2 dB(A). Buses on bad (Condition 2) and average (Condition 3) roads yielded slightly lower

contributions of -0.10 dB and -0.15 dB(A), respectively. However, very good road conditions (Condition 5) resulted in a more substantial negative effect of -0.45 dB(A). This implies that optimal road quality enables more stable and quieter bus operation.

4.5.2 Isolated Effects of Operational Factors on Electric Bus Noise

Figure 4.17 presents the isolated effects for operational factors in electric bus noise.





j. Average Road Condition k. Good Road Condition l. Very Good Road Condition

Figure 4.17: Isolated Effects of Operational Factors on Electric Bus Noise Generation

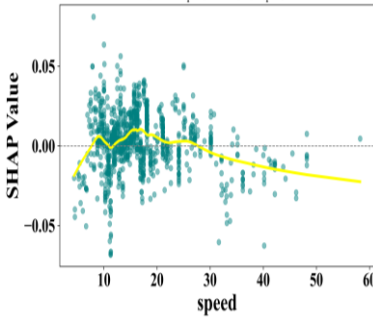
The results showed that average speed had a nuanced relationship with electric bus noise generation. At very low speeds (<10 km/h), buses showed a positive contribution to noise levels, with SHAP values ranging from 0.5 to 0.6 dB(A). This suggests that stop-and-go conditions, causing multiple instances of acceleration, elevate sound levels in electric vehicles. However, between 10–28 km/h, there was a notable dip, where the contributions became negative and fluctuated modestly within a band of 0 to -0.4 dB(A), possibly reflecting efficient cruising and silent operational capabilities. Beyond 28 km/h, the contribution trend shifted again, with positive values increasing linearly up to 1 dB(A). This indicates that higher speeds in electric buses, despite their quieter propulsion systems, still incur rising noise effects, likely from road–tire interaction. The role of bus age in electric fleets did not differ from their conventional counterparts. Older electric buses exhibited positive contributions to noise at around 0.6 dB(A), while newer vehicles contributed negatively, approximately -0.4 dB(A). These patterns may reflect drivetrain wear and component degradation in aging electric buses. Trip distance also yielded a variable acoustic profile. For short distances (0–0.2 km), noise contributions were negative, ranging from -0.5 to 0 dB. Between 0.2–0.4 km, the effect reversed to a positive trend (up to 0.3 dB(A)), before dipping again between 0.4–0.5 km to a small negative range (-0.1 to 0 dB(A)). Beyond 0.5 km, a clear linear trend emerged: as distance increased, so did noise contributions, resulting in values as high as 3.5 dB(A). This suggests that prolonged operation, even in electric vehicles, may result in noise buildup due to sustained mechanical activity or environmental amplification.

For situational contexts, the analysis revealed that buses operating in the afternoon (Time 2) and evening (Time 3) led to negative contributions to noise output of -0.35 dB(A) and -0.4 dB(A), respectively. This suggests that lower congestion levels or smoother driving patterns during

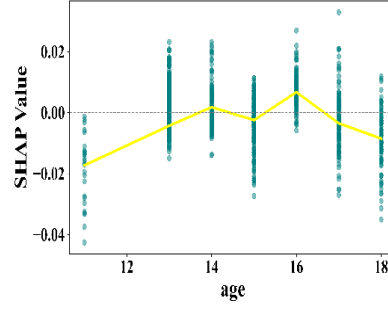
off-peak periods reduce noise. In contrast, weekend operations (Day 2) showed a positive average contribution of approximately 0.15 dB(A). While modest, this may reflect variations in traffic composition or road usage patterns on weekends, potentially involving more start–stop motion due to mixed-use roadways or less predictable vehicle spacing. The effects of occupancy levels were relatively minor but directionally informative. Buses with average occupancy (Occupancy 2) tended to contribute positively to noise output by around 0.1 dB(A), whereas high occupancy (Occupancy 3) corresponded to a slight negative contribution of -0.05 dB(A). These differences, though subtle, may suggest improved vehicle efficiency and smoother operation under full loads, or conversely, increased mechanical strain under average loads. The road network layout, especially the number of bends or curves, showed a mixed pattern. On roads with 0 to 1 curve, electric buses exhibited positive contributions to noise, ranging from 0 to 0.2 dB(A). Notably, a sharp negative contribution of -0.8 dB(A) was observed for exactly 2 curves, suggesting an inflection point of operational adaptation. Beyond this, contributions fluctuated but tended toward mild positive effects in the range of -0.3 to 0.4 dB(A). This suggests that the complexity of the route may indirectly shape acoustic dynamics through its influence on speed and maneuvering. Lastly, road condition also modulated noise outcomes in nuanced ways. Average-quality roads (RC 3) exhibited a neutral effect on noise output of 0 dB, while good roads (RC 4) showed slightly fewer negative contributions of -0.2 dB(A) compared to the general average of -0.25 dB(A). Very good roads (RC 5) surprisingly registered a positive contribution of 0.15 dB(A); however, this was lower than the general trend for other roads, which reached up to 0.3 dB(A). These results suggest that although very smooth surfaces reduce certain types of mechanical noise, they may also facilitate behaviors, such as higher speeds, that offset these acoustic gains.

4.5.3 Isolated Effects of Operational Factors on Conventional Bus Vibration

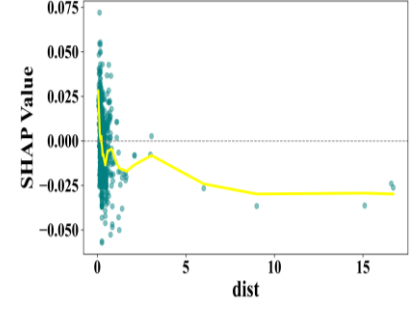
Figure 4.18 presents the isolated effects for operational factors in conventional bus vibration.



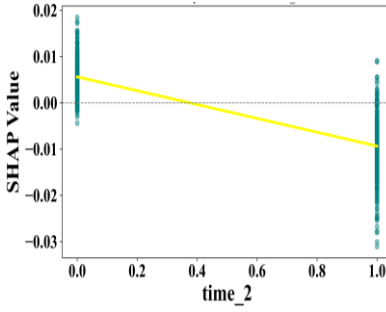
a. Average Speed



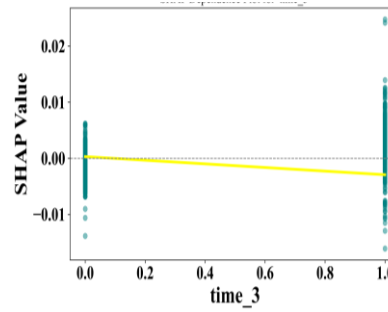
b. Bus Age



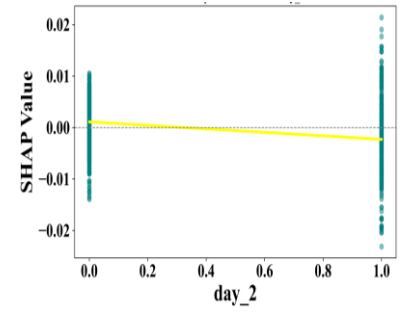
c. Trip Distance



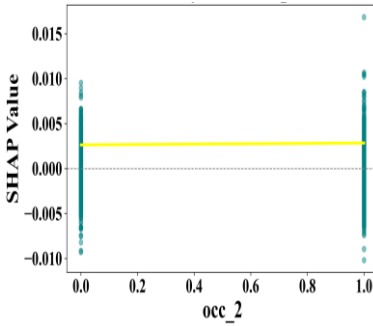
d. Afternoon



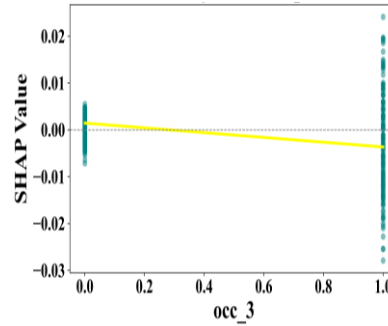
e. Evening



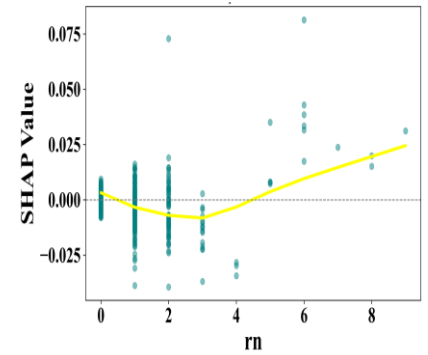
f. Weekend



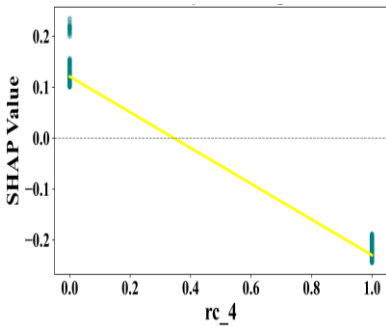
g. Average Occupancy



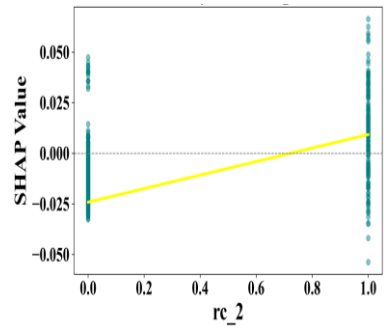
h. High Occupancy



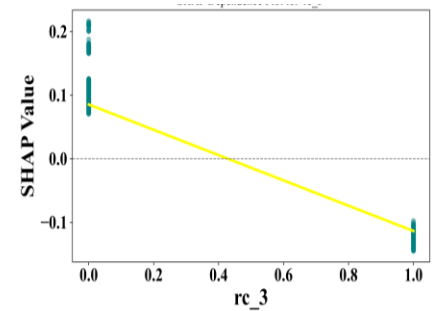
i. Road Network



j. Good Road Condition



k. Poor Road Condition



l. Average Road Condition

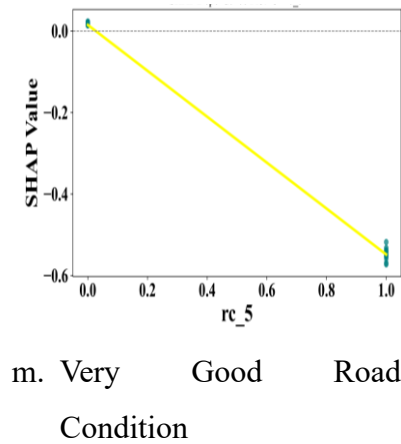


Figure 4.18: Isolated Effects of Operational Factors on Conventional Bus Vibration Generation

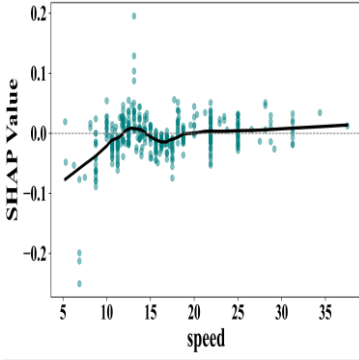
The analysis revealed patterns in how isolated operational factors influence vibration levels in conventional buses. Average speed displayed a non-linear relationship with vibration. At lower speeds (below 10 km/h), vibration contributions were consistently negative, ranging from -0.02 to 0 m/s². As speed increased from 10 to 28 km/h, contributions shifted to a predominantly positive range (0 to 0.015 m/s²), suggesting that moderate speeds may intensify vibration due to increased drivetrain and road interface activity. However, beyond 28 km/h, vibration contributions again became increasingly negative, reaching as low as -0.02 m/s². This trend implies that higher, more stable cruising speeds may help dampen vibration. This may be likely due to smoother motion and less frequent acceleration or deceleration cycles. Trip distance also showed distinct dynamics. At very short distances (<1 km), vibration contributions varied though the majority were positive, peaking around 0.026 m/s². Negative contributions in this range fell to -0.013 m/s². Beyond 1 km, the contributions shifted consistently negative and stabilized after 8 km to around -0.025 m/s². This suggests that longer trips may smooth out road and traffic-related variations, resulting in overall lower average vibration levels. Time-of-day effects were also apparent. Buses operating in the afternoon (Time 2) demonstrated more significant reductions in vibration, with -0.012 m/s². Evening operations (Time 3) had milder negative effects (-0.003 m/s²), and weekend service (Day 2) showed even smaller reductions (-0.002 m/s²). These findings may reflect smoother driving conditions and reduced stop-and-go behavior during non-peak periods. The age of the bus played a nuanced role. Vehicles aged below 14 years generally contributed negatively to vibration, with reductions reaching up to -0.019 m/s². Between 14 and 16 years, the effect became mixed, oscillating between mild positive and negative values (from -0.002 to +0.008 m/s²). Beyond 16

years, the contributions shifted consistently negative again, reaching down to -0.01 m/s^2 . This may indicate more cautious handling of older vehicles, resulting in lower vibration generation. Occupancy patterns also affected vibration outcomes. Buses with average occupancy levels (Occ 2) showed a slight positive contribution ($+0.003 \text{ m/s}^2$), similar to the overall effect of other occupancy states. In contrast, buses with high occupancy levels (Occ 3) demonstrated negative contributions, with reductions up to -0.004 m/s^2 . This suggested that heavier passenger loads might help stabilize vehicle motion and dampen vibration through improved balance or suspension compression. The road network design significantly influenced vibration as well. Routes with no curves or bends resulted in positive contributions ($+0.003 \text{ m/s}^2$), while routes with 1 to 3 bends showed increasingly negative contributions, reaching -0.011 m/s^2 . Interestingly, once the number of bends exceeded three, vibration contributions shifted positive again and rose steadily, peaking at around $+0.025 \text{ m/s}^2$. This suggests that moderately complex routes impose driving behaviors (e.g., braking and steering adjustments) that reduce vibration, while highly complex routes may overwhelm these dampening effects due to continuous maneuvering and acceleration-deceleration actions. Road condition emerged as one of the most decisive factors. Buses operating on good road surfaces (RC 4) showed large negative effects, with vibration contributions dropping up to -0.23 m/s^2 , while very good road conditions (RC 5) led to even greater reductions, reaching -0.57 m/s^2 . In contrast, poor road conditions (RC 2) showed positive effects ($+0.011 \text{ m/s}^2$), implying that rough or deteriorated roads amplify vibration levels. Average road conditions (RC 3) also resulted in a reduction of around -0.12 m/s^2 .

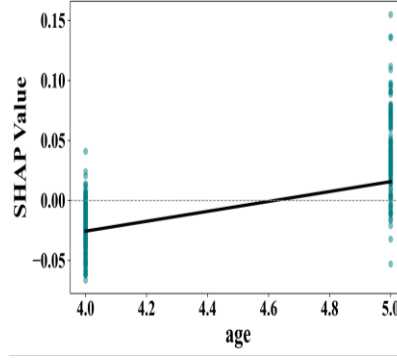
Overall, these patterns suggest that conventional bus vibration is shaped by a delicate interplay between vehicle condition, operational setting, and road environment. While certain factors like very good road surfaces, moderate distances, and afternoon operation clearly dampen vibration, others such as poor roads, intermediate speeds, and short trips tend to intensify it.

4.5.4 Isolated Effects of Operational Factors on Electric Bus Vibration

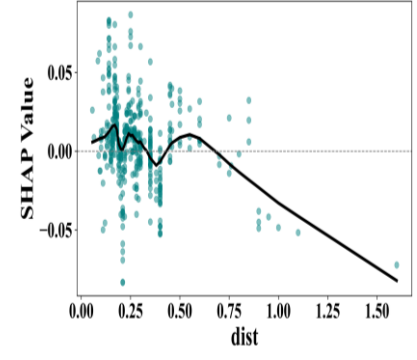
Figure 4.19 presents the isolated effects for operational factors in electric bus vibration.



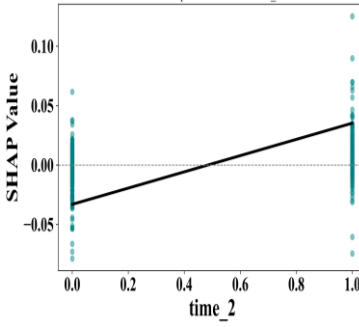
a. Average Speed



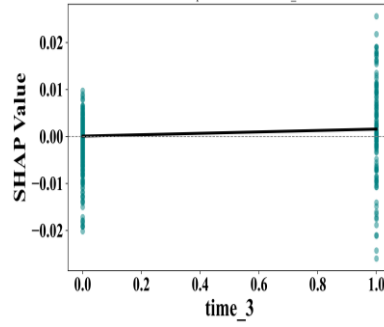
b. Bus Age



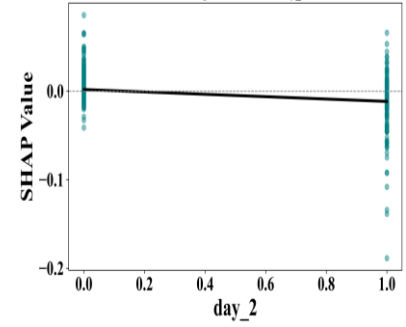
c. Trip Distance



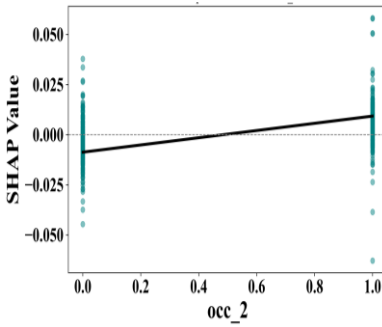
d. Afternoon



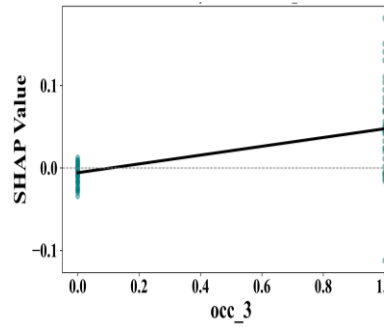
e. Evening



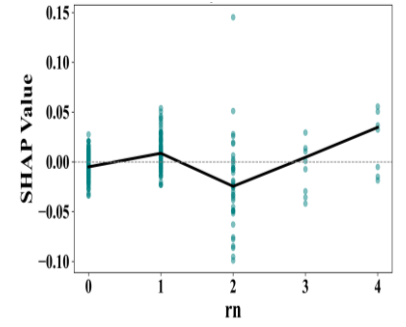
f. Weekend



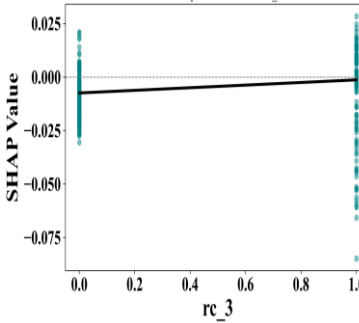
g. Average Occupancy



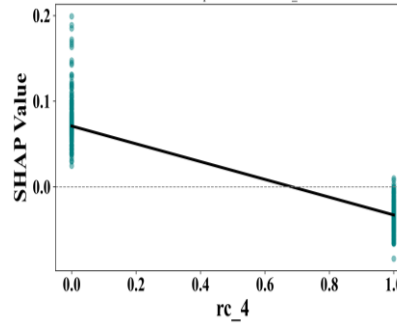
h. High Occupancy



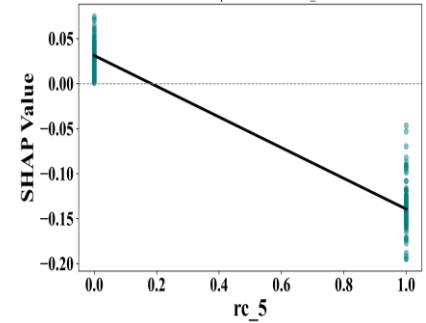
i. Road Network



j. Average Road Condition



k. Good Road Condition



l. Very Good Road Condition

Figure 4.19: Isolated Effects of Operational Factors on Electric Bus Vibration Generation

The analysis of electric bus vibration highlighted several distinct patterns in the isolated contributions of operational factors. Average speed demonstrated a segmented trend. At speeds below 12 km/h, vibration contributions were negative, reaching up to -0.008 m/s^2 , suggesting smoother operation in low-speed conditions. In the range of 12–15 km/h, contributions shifted slightly positive, peaking at 0.001 m/s^2 . A subsequent dip occurred between 15–20 km/h, where negative effects reappeared, reaching -0.0015 m/s^2 . Beyond 20 km/h, vibration contributions steadily increased again, becoming positive and reaching a peak of 0.0015 m/s^2 . This indicates that moderate to higher speeds may incrementally increase vibration levels, while very low and mid-range speeds can help suppress it. The relationship between distance traveled and vibration also revealed dynamic variation. For distances up to 0.4 km, contributions oscillated between positive and negative, with positive effects dominating. The negative effects in this range reached -0.001 m/s^2 , while positive contributions peaked at 0.02 m/s^2 . From 0.4 to 0.7 km, vibration remained positive, with a maximum of 0.017 m/s^2 . However, after 0.7 km, a sharp shift to negative contributions was observed, which continued to intensify with increasing distance. These reductions reached -0.09 m/s^2 . This pattern suggests that short travel distances may introduce more dynamic motion, whereas longer distances allow for more stabilized conditions, reducing vibration output. Moreover, evening operations (Time 3) resulted in a positive contribution of $+0.002 \text{ m/s}^2$. Afternoon operations (Time 2) produced the strongest positive effect, contributing up to $+0.047 \text{ m/s}^2$. This indicates that buses operating in the afternoon may experience conditions such as increased load or stop-start behavior that heighten vibration levels. For day-of-week effects, buses operating during weekends (Day 2) showed negative contributions of -0.015 m/s^2 . This is likely reflected in lighter traffic and smoother ride profiles during weekends. Road condition had significant and varied impacts. Buses operating on average road surfaces (RC 3) experienced slight negative contributions of -0.0001 m/s^2 . Good road conditions (RC 4) led to more substantial negative contributions of -0.04 m/s^2 , whereas the most significant reduction in vibration came from very good road conditions (RC 5), where contributions dropped to -0.14 m/s^2 . Bus age showed a discontinuous relationship with vibration. At 4 years, buses experienced negative effects reaching -0.025 m/s^2 , while at 5 years, contributions became positive, reaching $+0.018 \text{ m/s}^2$. This transition suggests a shift point in vehicle wear and dynamics that could affect vibration patterns, with newer buses exhibiting stronger vibration dampening prowess. Occupancy levels also played a notable role. Average occupancy (Occ 2) contributed positively at 0.0124 m/s^2 . In comparison, high

occupancy (Occ 3) yielded a more substantial positive contribution of $+0.047 \text{ m/s}^2$. This indicates that heavier passenger loads may lead to increased vibrational responses, likely through greater structural stress or dynamic shifting. The influence of road network geometry followed a nonlinear trend. On routes with no bends, vibration contributions were negative, at -0.007 m/s^2 . At 1 bend, a shift to positive contribution occurred, reaching 0.009 m/s^2 . The most significant negative effect was observed at 2 bends, where vibration dropped to -0.025 m/s^2 . Beyond this point (more than 2 bends), positive contributions resumed, steadily increasing to reach 0.045 m/s^2 . This suggests that light route complexity may reduce vibration through moderated driving, while excessive curvature reintroduces vibration through continuous steering and suspension loading.

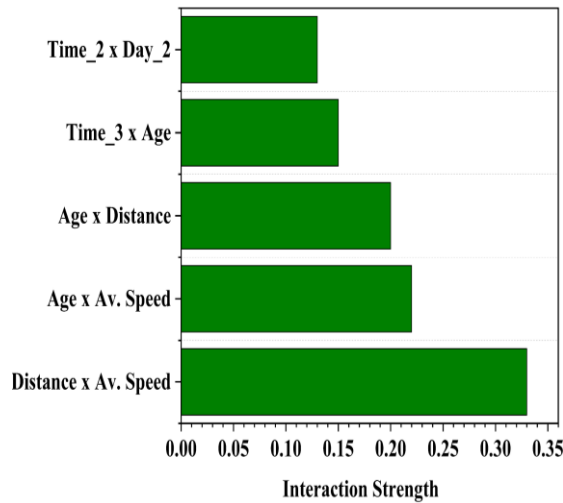
In summary, vibration in electric buses is influenced by a wide array of factors, with road condition, trip distance, occupancy, and time of operation having particularly pronounced effects. Very good road conditions (RC 5) and longer trip distances significantly reduce vibration, while high occupancy levels, afternoon operations, and routes with multiple curves increase it.

4.6.Interactive Effects

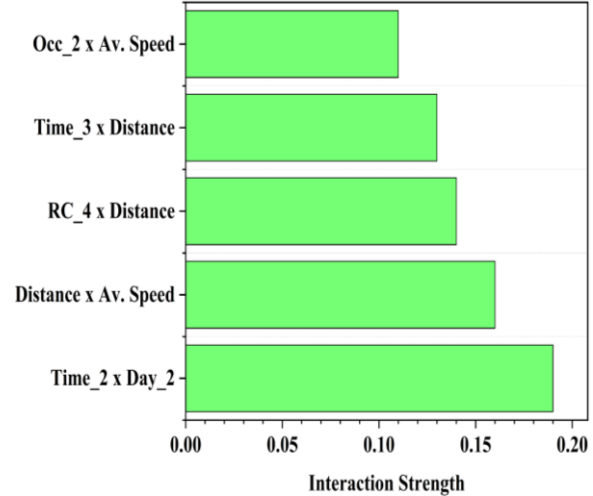
The SHAP interaction analysis reveals how combinations of features, rather than individual effects alone, shape bus vibroacoustic emissions. These interactions highlight factorial combinations with the most influential effects on bus vibroacoustic generations in buses.

4.6.1 Conventional and Electric Noise

Figure 4.20 presents the strongest interactive effects for both conventional and electric bus noise generation.



a. Conventional



b. Electric

Figure 4.20: Interactive Effects of Operational Factors in Bus Noise Generation

For conventional buses, the strongest interaction observed was between distance and average speed, with an interaction strength of 0.33. This suggests that the effect of speed on noise is highly dependent on how far the bus travels, indicating that longer trips at higher speeds are likely to amplify noise. Similarly, the interactions between age and average speed, with a strength of 0.22, and age and distance, with a strength of 0.20, point to older buses being more sensitive to operational intensity. This implies that aged vehicles generate disproportionately more noise when operated over long distances or at higher speeds.

Situational contexts also played a meaningful role. The interaction between evenings (Time 3) and age, with a strength of 0.15, may indicate that older buses operating under evening conditions, potentially characterized by lighter traffic, exhibit different acoustic behavior. Additionally, the interaction between afternoon (Time 2) and weekend (Day 2), with a strength of 0.13, suggests that noise patterns during weekend afternoons may deviate from weekday norms, possibly due to unique traffic dynamics on weekends. For electric buses, the dominant interaction was also situational: the interaction between afternoon (Time 2) and weekend (Day 2) had a strength of 0.19. This reflects how time-of-day effects on noise are shaped by the operational context of the day, likely due to differing traffic loads on weekends. The interaction between distance and average speed, with a strength of 0.16, was also present in conventional buses but with lower intensity. This suggests that even in electric buses, average speed over longer trips still modulates noise, though to a lesser degree. Unique to electric buses was the interaction between

good road condition (RC 4) and distance, with a strength of 0.14. This suggests that on better roads, the distance traveled has a stronger effect on noise, potentially due to higher achievable speeds. Likewise, the interaction between evening (Time 3) and distance, with a strength of 0.13, implies that longer trips in the evening may influence acoustic patterns differently. Lastly, the interaction between average occupancy (Occupancy 2) and average speed, with a strength of 0.11, highlights that passenger load modifies how speed affects noise, perhaps due to variations in vehicle weight and load dynamics.

Overall, conventional buses showed stronger interactions among core mechanical and temporal features, reflecting the greater sensitivity of combustion systems to compound operational noise. Electric buses, in contrast, exhibited weaker but more distributed interactions, with an emphasis on contextual and infrastructure-related factors. This aligns with their quieter and more stable acoustic profile. These patterns underscore that while electric buses are quieter overall, strategic combinations of operational features still influence their noise behavior in meaningful ways.

4.6.2 Conventional and Electric Vibration

Figure 4.21 presents the strongest interactive effects for both conventional and electric bus vibration generation.

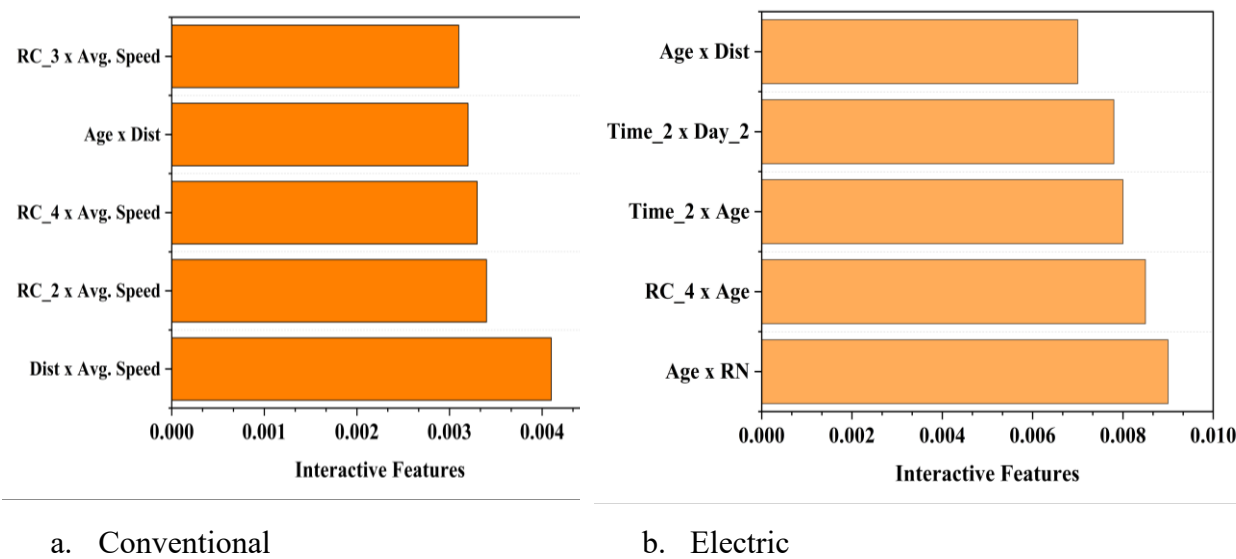


Figure 4.21: Interactive Effects of Operational Factors in Bus Vibration Generation

For conventional buses, the most prominent interaction was observed between distance and average speed, with an interaction strength of 0.0041. This suggests that vibration levels in conventional buses are influenced by the way speed and distance compound. Here, longer trips at sustained speeds likely result in elevated vibration due to prolonged mechanical activity and road exposure. Other key interactions included RC 2 and average speed (0.0034) and RC 4 and average speed (0.0033), indicating that the effect of road condition on vibration is closely tied to how fast the bus is traveling. These interactions suggest that both poor and good roads can amplify or dampen vibration depending on the operational speed. Mechanical factors also demonstrated relevant pairwise dynamics. For instance, the interaction between bus age and distance had a strength of 0.0032, implying that older buses are more susceptible to vibration buildup over longer journeys, possibly due to reduced suspension effectiveness or structural wear. Additionally, the interaction between road condition and afternoon operation (RC x Time 2), with a strength of 0.0031, highlights the effect of situational conditions. This interaction suggests that specific time-of-day and infrastructure combinations can alter vibration behavior, possibly due to traffic flow or driver response to road conditions during daytime hours.

In contrast, electric buses showed a different pattern. The dominant interactions revolved around bus age, highlighting its central influence on vibration in electric vehicles. The most significant was between bus age and road network, with a strength of 0.009, indicating that the effect of road geometry on vibration is highly dependent on vehicle age. Thus, older electric buses may be more sensitive to curves or bends. Other notable interactions included RC 4 and bus age (0.0085) and Time 2 and bus age (0.008), further reinforcing that the aging of electric vehicles alters how they respond to both infrastructure quality and daily operational cycles. Situational and compound effects were also evident in electric buses. The interaction between afternoon operations (Time 2) and weekends (Day 2) reached a strength of 0.0078, suggesting that time-of-day impacts on vibration are modulated by the day of operation (specifically the weekend in this case), where traffic patterns and driving behaviors could uniquely affect ride smoothness. Finally, the interaction between bus age and distance (0.007) appeared in both vehicle types, representing a common thread where aging fleets become more vibration-prone during longer trips.

Overall, conventional buses displayed stronger interactions involving average speed, pointing to their heightened sensitivity to mechanical and performance-related dynamics.

Meanwhile, electric buses exhibited a more distributed interaction profile, with bus age emerging as the most recurring interacting feature. The shared interaction of age and distance across both vehicle types suggests a universal effect of aging on how trip length influences vibration. These findings underscore that while electric buses maintain a more stable vibration baseline, their ride quality is still shaped by the interplay of operational context, infrastructure, and vehicle condition.

5. POLICY IMPLICATIONS

5.1. Conventional and Electric Bus Noise

The findings from this study decisively establish the pivotal role that operational factors play in shaping noise emissions from both conventional and electric buses. Across both propulsion types, variables such as average speed, trip distance, and vehicle age consistently emerged as the most influential determinants of acoustic performance. Although their specific effects vary between vehicle types, their overall impact is unequivocal. These insights point to an urgent need for transit agencies and urban transport planners to proactively monitor and strategically manage these operational conditions. Doing so is essential for maintaining transit systems that are environmentally responsible and tolerable.

Importantly, the strong statistical link between measured noise levels and rider perception further validates these findings. The developed perception models for both conventional and electric buses demonstrated that rider-reported noise experience is highly predictable based on actual acoustic measurements. For conventional buses, over 91% of variability in noise perception could be explained by the model, while for electric buses, nearly 90% was accounted for. This indicates that changes in bus noise due to operational factors are measurable and are directly felt and registered by passengers, reinforcing the urgency of targeted noise mitigation strategies.

In this view, several targeted policy directives emerge from this analysis. First, managing vehicle speed and fleet age must be prioritized as foundational measures in bus transit noise reduction. For conventional buses, reducing operating speeds to *no more than 20 km/h* can substantially lower their noise output during their operations in urban zones. On the other hand, electric buses benefit from operating within a *higher yet moderate speed range of 10–28 km/h*. This helps balance their efficiency and acoustic performance. To ensure compliance with these average speed thresholds, transit agencies can implement GPS-based geofencing and real-time speed monitoring systems. Regarding the factor of age, the results unanimously showed that lower noise levels in both bus types were associated with younger buses. To this effect, conventional buses being operated must be *maintained below 13 years of age*, to ensure superior acoustic performance. For electric buses, the exact threshold could not be established because the buses sampled were all relatively young. However, the results also showed that younger buses were significantly better. Hence, transit agencies should set their procurement strategies to purchase

younger buses at all times to avoid the acoustic penalties associated with mechanical degradation. Additionally, fleet renewal schedules should phase out older vehicles starting with those assigned to noise-sensitive routes.

Second, scheduling strategies must integrate situational factors such as time of day, day of week, and occupancy levels. Buses operating during off-peak hours, particularly in the afternoon and evening, were consistently associated with reduced noise. Accordingly, high-frequency services should be prioritized during these quieter periods, especially in densely populated areas. Furthermore, higher occupancy levels correlated with reduced noise emissions. In this regard, agencies should leverage demand-responsive scheduling, passenger load monitoring, and dynamic pricing to maximize passenger efficiency while maintaining service comfort.

Third, environmental and infrastructural conditions including trip length, road surface quality, and route network design represent crucial levers for noise control. For conventional buses, *longer trips exceeding 1 km promote smoother driving* behavior and reduce start-stop acoustic peaks arising from numerous accelerations and decelerations. In contrast, electric buses benefit from limiting continuous high-speed operation on long routes by introducing strategic layover intervals or alternating vehicle assignments. These intervals can be positioned at *maximum trip distances of 0.5 km*, to ensure that electric buses keep their acoustic superiority. For road conditions (road surface quality), urban planners must focus on ensuring that *both bus types travel on good or very good road conditions (RC 4 or 5)* to help reduce road induced noise during their operations. Finally, route planning should also prioritize *corridors with two or more bends per road section*. This will inherently moderate speed and encourage smoother driving, reducing noise in both bus types.

Equally important are the interaction effects identified in this study, which underscore the complexity of bus noise generation. The influence of one factor such as average speed cannot be fully understood without considering how it interacts with others like trip distance or road condition. This complexity demands that transit agencies abandon single perspective fixes in favor of integrated, system-based strategies. For example, *roads in top condition might require complementary speed moderation in both buses to sustain acoustic benefits*. Thus, effective noise mitigation must account for the compounding and modulating effects of multiple operational and environmental variables simultaneously.

Ultimately, achieving a quieter and more sustainable urban transit system requires more than fleet electrification. It demands deliberate, data-driven management of how buses are deployed, when they operate, and where they travel. This includes specific policies such as restricting speed limits, retiring older vehicles, scheduling buses for off-peak times, optimizing occupancy, and redesigning route infrastructure with both acoustic and operational efficiency in mind. These findings offer a robust foundation for transit authorities to design and implement smarter, context-sensitive policies, ones that align service efficiency with environmental protection and public health priorities.

5.2. Conventional and Electric Bus Vibration

The findings from this study decisively establish the pivotal role that operational factors play in shaping vibration levels in both conventional and electric buses. Although both propulsion types share several key variables such as road condition, trip distance, average speed, vehicle age, and occupancy, their specific effects and patterns differ in meaningful ways. These differences highlight how the mechanical and operational characteristics of combustion-based and electric drive-trains interact differently with their operating environments. For transit operators and planners, these insights reinforce the importance of data-driven strategies aimed at improving ride quality, reducing mechanical strain, and enhancing passenger comfort.

These objective measurements of vibration were shown to align closely with how passengers perceive ride quality. The developed regression models revealed that vibration perception in both conventional and electric buses is strongly predicted by actual vibration levels. In conventional buses, over 85% of rider perception variance was explained by measured vibration, while in electric buses, this rose to about 89%. These results confirm that technical improvements in vibration control translate directly into more favorable passenger experiences.

Several actionable policy directions emerge from this vibration analysis. First, road condition was found to be the most influential factor for both bus types, but particularly for conventional buses. In this case, *operating on very good (RC 5) or good roads (RC 4) resulted in substantial reductions in vibration*. Electric buses also benefited from *high-quality road surfaces specifically with RC 5*, reinforcing the value of good infrastructure in maintaining electric vehicle ride quality.

Second, vehicle speed and trip distance showed complex, nonlinear effects that demand nuanced management. In conventional buses, *very low speeds (<10 km/h) and higher speeds (>28 km/h) dampened vibration generation*. This pattern suggests that average speed control can serve as a practical lever for minimizing vibration. For electric buses, *lower speeds (<12 km/h) were beneficial, while higher speeds (>20 km/h) gradually increased vibration*. Accordingly, transit agencies should apply GPS-based speed management systems to optimize speed profiles according to propulsion type. Trip distance also played an important role. In conventional buses, *trips longer than 1 km consistently reduced vibration*. Electric buses, however, *benefited most from distances greater than 0.7 km*, with lower distances leading to higher vibration generation. To mitigate this, transit agencies should consider introducing stops on electric bus routes exceeding 0.7 km and 1 km for conventional buses to preserve ride comfort over time.

Third, temporal and situational scheduling must be strategically incorporated. For conventional buses, operating in the afternoon (Time 2) and evening (Time 3) reduced vibration. Electric buses showed the opposite trend: afternoon operations resulted in the strongest positive contribution possibly due to higher loads or operational stress during these periods. Additionally, weekend operations (Day 2) were associated with slight reductions in vibration for both bus types, reinforcing the benefit of lighter traffic conditions.

Fourth, bus age and occupancy levels significantly influenced vibration patterns. For conventional buses, *those younger than 14 years contributed significantly to vibration reduction* while buses older than 16 years also showed a return to negative effects possibly as a result of more cautious driving. In contrast, electric buses exhibited a sharp distinction: 4-year-old vehicles had negative contributions but at 5 years, vibration increased significantly suggesting that older buses were more susceptible to vibration generation. These findings reinforce the need for targeted fleet renewal strategies. Older conventional buses, especially beyond 16 years, should be reassigned to less vibration-sensitive routes. For electric buses, the availability of existing buses does not allow for proper recommendations.

Passenger occupancy also showed clear effects. Conventional buses *with high occupancy* demonstrated negative contributions. Electric buses, in contrast, showed increasing positive contributions with both average and high occupancy situations. This difference highlights the importance of load balancing, especially in electric buses due to their sensitive nature.

Fifth, road network complexity also influenced vibration in both systems, albeit differently. For conventional buses, *routes with 1 to 3 bends dampened vibration*. In electric buses, *the best reduced effects occurred at 2 bends*. These results suggest that moderate route complexity supports smoother driving and reduced vibration, while highly curved or overly straight roads can worsen the ride. Route planning policies should therefore *aim for 1–3 bends per road section* where feasible.

Finally, the interaction effects revealed critical synergies among operational variables that are often overlooked. In conventional buses, the strongest interaction was between distance and average speed, followed by road condition 2 and average speed. These illustrate how vibration is not simply a function of speed or road condition alone, but their combination. For instance, even good roads can induce vibration if buses travel too fast. Additional interactions such as bus age $\times$ distance show that temporal and usage factors further modulate these dynamics and thus should be considered when introducing policy recommendations. On the other hand, electric buses showed a different pattern. Bus age emerged as the dominant interacting factor, appearing across multiple combinations like age $\times$ road network, RC 4 $\times$ age, and Time 2 $\times$ age. These indicate that age amplifies the effect of both infrastructure and scheduling variables. Additionally, the interaction, age $\times$ distance, was present in both vehicle types, making it a universal point of attention for transit agencies. Together, these results emphasize that vibration management cannot rely on one-dimensional interventions. Policies must account for the interdependent nature of speed, road condition, vehicle age, and scheduling. Roads in excellent condition will only deliver comfort benefits if paired with appropriate speed regulation and vehicle assignment.

Ultimately, achieving a smoother, more comfortable, and efficient urban transit system requires more than electric vehicle adoption. It demands strategic deployment, timing, and infrastructure alignment. Transit agencies must enforce speed limits, retire or repurpose aging buses, schedule operations with temporal vibration effects in mind, manage passenger loads, and engineer route layouts for both structural efficiency and rider comfort. These findings provide a comprehensive framework for vibration-conscious transit planning with commuter experience in mind.

6. CONCLUSIONS

6.1. Research Summary

In summary, this study investigated on a comparative basis the vibroacoustic performance of conventional and electric buses in Montreal. It sought to establish the existing vibroacoustic differences between the two bus types, explore how various operational factors affect bus vibroacoustic levels and suggest policy guidelines to maintain optimal vibroacoustic performance and rider comfort. In achieving this, the study utilized a quantitative research methodology, which incorporated bus vibroacoustic data collection using Sound Meter Pro and iDynamics apps, structured interviews for rider comfort perceptions and data analysis techniques like descriptive statistics, XGBoost modelling, ridge regression modelling, and Shapley Additive Explanations.

The study discovered that electric buses generally produced less noise and vibration than their conventional counterparts, although their vibroacoustic advantage varied under different operational conditions. Additionally, operational factors like bus age, road surface conditions and average speed significantly impacted bus vibroacoustic levels, with older buses, rougher roads and higher speeds leading to higher bus noise and vibration. Also, the models provided insights into how these factors, vibroacoustic levels and rider perceptions interact. This allowed for suggestions to be made which when adopted, have the potential to optimize bus assignments, rider comfort and sustainability. Together, the study and its findings contribute to improving public transit systems by identifying key vibroacoustic determinants and offering actionable strategies for mitigation.

6.2. Contributions of the Study

The study's main contributions are presented as follows:

1. First comparative benchmark study on bus vibroacoustic levels in Montreal.

Prior to this study, there was no comprehensive investigation into the vibroacoustic performances of Montreal's conventional and electric buses. This lack of comparative analysis caused transit agencies not to understand the operational vibroacoustic properties of their buses. To address this gap, this study measured the average noise and vibration levels of the buses under their diverse operational conditions. The findings showed that Montreal's electric buses

outperformed the conventional buses from a vibroacoustic standpoint across all conditions. These findings present an empirical basis on which Montreal's transit agencies can use to support the transition from conventional to electric buses.

2. Identification of Key Operational factors affecting bus vibroacoustic levels

Existing research in this domain has largely focused on the impact and contributions of vehicle mechanics like propulsion and powertrain on bus vibroacoustic levels. However, these studies lacked insights into how multiple operational factors interact to influence bus vibroacoustic levels. This study filled that gap by assessing the significance between seven operational factors on bus vibroacoustic levels. The results identified bus age, road surface conditions and average speed as the most critical operational factors affecting bus noise and vibration. The insights from the results can aid transit agencies and researchers by providing them with specific operational factors which can be targeted in mitigation strategies to improve the vibroacoustic performances of buses.

3. A multifactorial analysis of the Impacts of Operational Factors on Bus Vibroacoustic Levels

Previous studies had examined the impact of diverse operational factors on bus vibroacoustic levels in isolation. This research introduced an integrated approach by incorporating eight operational factors into a single study. Through the regression models, the study highlighted the overall relationships, isolated effects and relational impacts of these factors on bus vibroacoustic levels. The findings demonstrated that factors like bus age, road surface conditions and average speed etc. dynamically interacted to influence bus vibroacoustic levels. The quantitative insights from the results will enable transit agencies and researchers to understand the dynamic interactions of these factors and tailor mitigation strategies to curb their individual effects.

4. Establishment of result-oriented policy implications

Despite the existence of bus vibroacoustic regulations and standards, there had been no policy implications to help achieve these regulations by considering bus operational conditions, and vibroacoustic performance backed by rider comfort perceptions. To remedy this, the study established results-oriented policy implications that provided actionable guidelines for operations. These guidelines can assist transit authorities and researchers in making informed decisions about

vibroacoustic performance improvements, which can lead to better rider satisfaction, and more sustainable public transport operations.

6.3.Limitations of the Study

The limitations of the study are presented as follows:

1. The study used a relatively small sample size of 31 conventional buses and 12 electric buses, which may not fully represent the overall vibroacoustic performance of Montreal's bus fleet.
2. The use of mobile apps and rider interviews for data collection might have introduced variability and potential biases due to app inaccuracies compared to industry-grade equipment, as well as psychological influences and demographic differences among riders.
3. The study focused on a few prominent operational factors influencing bus noise and vibration, omitting other potentially significant factors such as traffic density, driving skills, and maintenance, which may also impact noise and vibration levels.
4. The study did not focus on capturing the effects of the interactions between the operational factors and their combined effects in noise and vibration generation in conventional and electric buses.
5. Lastly, the comparative analysis made in this study did consider the two bus types during their (actual) routine operations and not necessarily under the same or similar operating conditions, such as identical routes, passenger loads, traffic patterns, or environmental factors, which may have influenced the observed noise and vibration differences.

6.4.Suggestions for Future Research

The study suggests the following points for future research in this domain

1. Future studies should aim to expand the sample size and improve the generalizability of findings by conducting similar studies with larger and more diverse bus types like hybrids etc. This would allow for a more complete and robust analysis of bus vibroacoustic performance. Additionally, cross-city and international comparative studies could help

validate these findings in different transit environments and offer a holistic understanding into bus vibroacoustic trends across urban settings.

2. Future studies can also focus on expanding the scope of influencing factors would provide a more holistic understanding of bus vibroacoustic performance. Investigating these additional parameters could lead to the development of more comprehensive predictive models and optimized policy frameworks that better address real-world transit challenges.
3. Additionally, future studies should assess the integration of the policy implications into real-world transit planning and decision-making processes. This includes assessing economic viability, regulatory adoption, and operational impacts, with pilot programs validating its effects on passenger comfort, environmental noise reduction, and transit efficiency.
4. Lastly, future studies can bridge the gap between vehicle mechanics and operational factors by exploring real-time adaptive noise and vibration control systems in public buses. Specifically, researchers can focus on the integration of smart sensors to monitor and report on various mechanical vibroacoustic sources and their contributions across various real-world operational conditions. These sensors could provide real-time data to support adaptive and dynamic strategies for mitigating noise and vibration during bus operations.
5. Future studies could expand the experiment settings and explore controlled (hypothetical) conditions assessing both bus types in the same routes, under similar passenger loads, and across comparable traffic and environmental settings. This would allow for a controlled assessment of their vibroacoustic differences in addition to the field study results obtained in this research.

REFERENCES

- [1] UN-Habitat, SDG Indicator 11.2.1 Training Module: Public Transport System, United Nations Human Settlement Programme (UN-Habitat), Nairobi, 2018, pp. 23. Available: https://unhabitat.org/sites/default/files/2020/06/indicator_11.2.1_training_module_public_transport_system.pdf
- [2] P. Miller, A. G. De Barros, L. Kattan, and S. C. Wirasinghe, “Public Transportation and Sustainability: A Review,” *KSCE Journal of Civil Engineering*, vol. 20, no. 3, pp. 1076–1083, 2016, Doi: <https://doi.org/10.1007/s12205-016-0705-0>
- [3] C. Narboneta and K. Teknomo, “A Study of Metro Manila’s Public Transportation Sector: Implementing a Multimodal Public Transportation Route Planner,” *Asian Transport Studies*, vol. 4, no. 2, pp. 460–477, 2016. Doi: <https://doi.org/10.11175/eastsats.4.460>
- [4] Canadian Urban Transit Association, The Economic Impact of Transit Investment in Canada, Urban Mobility Issue Paper, no. 50, pp. 1–4, 2019. Available: https://cutaactu.ca/wp-content/uploads/2021/01/final_issue_paper_50_cuta_v2.pdf [Accessed: Aug. 26, 2024].
- [5] M. Hamed and W. Effat, “A GIS-based Approach for the Screening Assessment of Noise and Vibration Impacts from Transit Projects,” *Journal of Environmental Management*, vol. 84, no. 3, pp. 305–313, 2007, doi: <https://doi.org/10.1016/j.jenvman.2006.06.010>
- [6] Transport Canada, Transportation in Canada: Overview Report, 2018. Available: https://tc.canada.ca/sites/default/files/migrated/transportation_in_canada_2018.pdf [Accessed: Jun. 16, 2024].
- [7] M. Ollier, At the Crossroads of Sustainable Transportation and Social Inclusion: The potential of Public Transit to Create Inclusive and Equitable Cities, Samuel Centre for Social Connectedness, 2018. Available: <https://www.socialconnectedness.org/wp-content/uploads/2019/06/At-The-Crossroads-of-Sustainable-Transportation-and-Social-Inclusion-2.pdf> [Accessed: May 18, 2024].
- [8] American Public Transportation Association, Public Transportation Ridership Report: Second Quarter 2020, APTA, Washington DC, USA, 2020, pp. 1–40.

- [9] V. Chakour, "An Econometric Analysis of Public Transport in Montreal," M.S. thesis, McGill Univ., Montreal, QC, Canada, 2013. Available: <https://escholarship.mcgill.ca/concern/theses/7w62fc62f> [Accessed: Oct. 20, 2023].
- [10] Société de transport de Montréal, A year of exceptional achievements and challenges, STM Annual Report, 2020, pp. 30. Available: <https://www.stm.info/fr/a-propos/informations-entreprise-et-financieres/rapport-annuel-2020> [Accessed: Oct. 22, 2023].
- [11] Exo, Annual Report (2022), Exo, 2022, pp. 1–40. Retrieved from: Exo - Publications on Oct. 28, 2023.
- [12] International Association of Public Transport, "Urban Public Transport in the 21st Century: Statistics Brief," Advancing Public Transport, UITP, 2017, pp. 1–8. Available: https://cms.uitp.org/wp/wp-content/uploads/2020/08/UITP_Statistic-Brief_national-PT-stats.pdf [Accessed: Dec. 20, 2023]
- [13] M. Orczyk and F. Tomaszewski, "Measurement and analysis of acoustic phenomena occurring in public transport buses based on surveys and field study," IOP Conference Series: Earth and Environmental Science, vol. 642, no. 1, 012019, 2021. <https://doi.org/10.1088/1755-1315/642/1/012019>.
- [14] L. Ravensbergen, J. Varickanickal, K. B. Neewbold, and M. Mohamed, "A Mixed-Methods Investigation of Older Adults' Public Transit Use and Travel Satisfaction," Travel Behavior and Society, vol. 32, 100577, pp. 1–9, 2023. DOI: <https://doi.org/10.1016/j.tbs.2023.100577>.
- [15] Y. Qiu, L. Zheng, Y. Du, and S. Jiang, "Performance evaluation of transit signal priorities on bus transit corridor based on data envelopment analysis," International Journal of Transportation Science and Technology, vol. 9, no. 1, pp. 1–13, 2020. DOI: <https://doi.org/10.1016/j.ijtst.2020.03.004>
- [16] J. Guo, Y. Susilo, C. Antoniou, and A. P. Brenden, "Influence of Individual Perceptions on the Decisions to Adopt Automated Bus Services," Sustainability, vol. 12, 6484, pp. 1–13, 2020. DOI: <https://doi.org/10.3390/su12166484>
- [17] C. M. K. L. Yao, A. K. Ma, S. L. Cushing, and Y. W. Lin, "Noise exposure while commuting in Toronto – A study of personal and public transportation in Toronto," Journal of Otolaryngology – Head and Neck Surgery, vol. 46, no. 62, pp. 1-8, 2017. Doi: <https://doi.org/10.1186/s40463-017-0239-6>

- [18] C. Bianca-Mihaela and P. Blaga, "Investigating Noise Sources for a Heavy Vehicle," *International Journal of Current Advanced Research*, vol. 12, no. 8, pp. 2450–2454, 2023. DOI: <http://dx.doi.org/10.24327/ijcar.2023.2454.1533>.
- [19] S. Misanovic, D. Taranovic, M. Maljkovic, and B. Milicic, "Measurement noise level of E-Bus HIGER KLQ6125GEV3 on the polygon," *IOP Conference Series: Material Science and Engineering*, vol. 1271, 012018, pp. 1-6, 2022. Doi: <http://dx.doi.org/10.1088/1757-899X/1271/1/012018>
- [20] J. Nygren, S. Boij, R. Rumpler, and C. J. O'Reilly, "Vehicle-Specific Noise Exposure Cost: Noise Impact Allocation Methodology for Microscopic Traffic Simulations," *Transportation Research Part D*, vol. 118, 103712, pp. 1–17, 2023. Doi: <https://doi.org/10.1016/j.trd.2023.103712>
- [21] I.Khan, K. S. Khattak, Z. H. Khan, and T. A. Gulliver, "Impact of road pavement condition on vehicle free flow speed, vibration and in-vehicle noise," *Science, Engineering and Technology*, vol. 3, no. 1, pp. 1-8, 2023. Doi: <https://doi.org/10.54327/set2023/v3.i1.48>
- [22] K. Flaris, K. Gkritza, P. A. Singleton, A. R. H. Graul, and Z. Song, "Riders' Perceptions towards Transit Bus Electrification: Evidence from Salt Lake City, Utah," *Transportation Research Part D: Transport and Environment*, vol. 117, 103642, 2023. DOI: <https://doi.org/10.1016/j.trd.2023.103642>.
- [23] F. Laib, A. Braun, and W. Rid, "Modelling noise reductions using electric buses in urban traffic: A case study from Stuttgart, Germany," *Transportation Research Procedia*, vol. 37, pp. 377-384, 2019. <https://doi.org/10.1016/j.trpro.2018.12.206>.
- [24] H. Yang, C. Lin, and W. Li, "Study on vibration and noise characteristics of pure electric bus," *4th International Conference on Computer Engineering, Information Science and Application Technology*, pp. 186-193, 2020.
- [25] Z. Damijan, D. Iwanski, and G. Dahlke, "Investigation of the Vibroacoustic Climate Inside the Bus Solaris Urbino 12 Used in Public Transport Systems," *Acta Physica Polonica A*, vol. 121, no. 1, pp. 32–37, 2012. Doi: <https://doi.org/10.12693/APhysPolA.121.A-32>
- [26] S. Li, Y. Su, and C. Shen, "Noise analysis and control on motor starting and accelerating of electric bus," *Journal of Vibration Engineering & Technologies*, vol. 6, pp. 93–99, 2018. Doi: <https://doi.org/10.1007/s42417-018-0019-2>

- [27] X. Hua, A. Thomas, and K. Shultis, "Recent Progress in Battery Electric Vehicle Noise, Vibration and Harshness," *Scientific Progress*, vol. 104, no. 1, pp. 1-11, 2021. Doi: <https://doi.org/10.1177/00368504211005224>
- [28] M. Zeng, B. Tan, F. Ding, et al., "An experimental investigation of resonance sources and vibration transmission for a pure electric bus," *Proceedings of the IMechE Part D: Journal of Automobile Engineering*, vol. 234, no. 4, pp. 1–13, 2019. Doi: <https://doi.org/10.1177/0954407019879258>
- [29] Health Canada, *Guidance for Evaluating Human Health Impacts in Environmental Assessment: Noise*, Health Canada Publication, no. 160331, pp. 1–54, 2017.
- [30] K. Shaaban and A. Abouzaid, "Measuring Traffic Noise for Different Types of Vehicles," *Intermountain Engineering, Technology and Computing*, pp. 1–6, 2023. Doi: <https://doi.org/10.1109/IETC57902.2023.10152062>
- [31] R. Burdzik and L. Konieczny, "Vibrations Issues in Passenger Car," *Transport Problems*, vol. 9, no. 3, pp. 83–90, 2014.
- [32] R. Rahmani, M. Aliabadi, R. Golmohammadi, M. Babamiri, and M. Farhadian, "Evaluation of cognitive performance of city bus drivers with respect to noise and vibration exposure," *Acoustics Australia*, vol. 49, pp. 529-539, 2021. Doi: <https://doi.org/10.1007/s40857-021-00248-z>
- [33] H. B. Huang, X. R. Huang, W. P. Ding, T. C. Lim, and M. L. Yang, "Identification of vehicle interior noise sources based on wavelet transform and partial coherence analysis," *Mechanical Systems and Signal Processing*, vol. 109, pp. 247-267, 2018. DOI: <https://doi.org/10.1016/j.ymssp.2018.02.045>.
- [34] A. Ghosh and S. Chatterjee, "An overview on various sources of vibration in electric vehicles and their identification techniques," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 45, no. 1, pp. 1-15, 2023. Doi: <https://doi.org/10.1007/s40430-023-04318-3>
- [35] B.K. Swain and S. Goswami, "Acoustic Environment in the Bus: An Empirical Study," *Journal of Pollution*, vol. 4, no. 2, pp. 327–333, 2018. Doi: <https://doi.org/10.22059/poll.2017.243519.329>
- [36] S. K. Shanmugarajah and M. S. D. Wijesinghe, "Noise Level Inside Sri-Lanka Transport Board Buses and Hearing Impairment of Long and Short Distance Bus Drivers of Ampara

- and Batticaloa Districts, Sri Lanka,” *Indian Journal of Community Medicine*, vol. 47, pp. 280–284, 2022. DOI: https://doi.org/10.4103/ijcm.ijcm_768_21
- [37] E. O. Okokon, T. Yli-Tuomi, A. W. Turunen, P. Taimisto, A. Pennanen, I. Vouitsis, Z. Samaras, M. Voogt, M. Keuken, and T. Lanki, “Particulates and noise exposure during bicycle, bus and car commuting: A study in three European cities,” *Environmental Research*, vol. 154, pp. 181–189, 2017. DOI: <https://doi.org/10.1016/j.envres.2016.12.012>.
- [38] L. Zhang, S. Zhou, M. P. Kwan, F. Chen, and Y. Dai, “The Threshold Effects of Bus Micro-Environmental Exposures on Passengers’ Momentary Mood,” *Transportation Research Part D*, vol. 84, 102379, pp. 1–15, 2020. DOI: <https://doi.org/10.1016/j.trd.2020.102379>.
- [39] P. Nassiri, H. Ebrahimi, M. R. Monazzam, A. Rahimi, and P. J. Shalkouhi, “Passenger Noise and Whole-Body Vibration Exposure – A Comparative Field Study of Commercial Buses,” *Journal of Low Frequency Noise, Vibration and Active Control*, vol. 33, no. 2, pp. 207–220, 2014. Doi: <https://doi.org/10.1260/0263-0923.33.2.207>
- [40] K. Ravindra, T. Singh, J. P. Tripathy, S. Mor, S. Munjal, B. Patro, and N. Panda, “Assessment of noise pollution in and around a sensitive zone in the North India and its non-auditory impacts,” *Science of the Total Environment*, pp. 981-987, 2016. Doi: <https://doi.org/10.1016/j.scitotenv.2016.05.070>
- [41] A. Gupta, S. Sharma, and S. Narayan, “Vehicle noise and vibration,” in *Combustion Engines: An Introduction to their Design, Performance and Selection*, vol. 8, pp. 103-119, 2016. DOI: <https://doi.org/10.1002/9781119284543.ch8>.
- [42] M. Brink, S. Mathieu, and S. Rüttener, “Lowering urban speed limits to 30 km/h reduces noise annoyance and shifts exposure-response relationships: Evidence from a field study in Zurich,” *Environmental International*, vol. 170, 107651, pp. 1-10, 2022. DOI: <https://doi.org/10.1016/j.envint.2022.107651>
- [43] E. Hammer, S. Egger, T. Saurer, and E. Buhlmann, “Traffic Noise Emission Modelling at Lower Speeds,” in *23rd International Congress on Sound and Vibration*, Athens, Greece, pp. 1–10, 2016.
- [44] D. Belakova, A. Seile, S. Kukle, and T. Plamus, “Non-wovens as sound reducers,” *Latvian Journal of Physics and Technical Sciences*, vol. N2, pp. 64-76, 2018. Doi: <https://doi.org/10.2478/lpts-2018-0014>

- [45] L. Pedrosa, M. L. Matos, and J. Baptista, "Occupational noise in urban buses – A short review," in SHO2016, pp. 1-3, 2016. Available: <https://repositorio-aberto.up.pt/bitstream/10216/148076/2/146602.pdf>
- [46] A.R. Mohanty and S. Fatima, "An Overview of Automobile Noise and Vibration Control," Noise and Vibration Worldwide, pp. 10–19, 2014. Doi: <https://doi.org/10.1260/0957-4565.44.6.10>
- [47] M. E. Altinsoy, "Identification of quality attributes of automotive idle sounds and whole-body vibrations," International Journal of Vehicle Noise and Vibration, vol. 9, no. 3, pp. 1-21, 2013.
- [48] H. Nishinaka and N. Matsuoka, "Noise, vibration and harshness analysis technique using a full vehicle model," SEI Technical Review, vol. 88, pp. 122-126, 2019.
- [49] T. Skrucany, B. Šarkan, T. Figlus, F. Synák, and J. Vrábel, "Measuring noise emitted by moving vehicles," MATEC Web of Conferences, vol. 107, 00072, pp. 1-8, 2017. Doi: <https://doi.org/10.1051/matecconf/201710700072>
- [50] S. R. Mahajan and R. D. Rajopadhye, "Transportation noise and vibration – sources, prediction and control," International Journal of Soft Computing and Engineering, vol. 3, no. 5, pp. 151-153, 2013.
- [51] Y. Cao, D. Wang, T. Zhao, X. Liu, et al., "Electric Vehicle Interior Noise Contribution Analysis," SAE Technical Paper 2016-01-1296, 2016. DOI: <https://doi.org/10.4271/2016-01-1296>, pp. 1-7. Doi: <https://doi.org/10.4271/2016-01-1296>
- [52] M. Frost and S. Ison, "Comparison of noise impacts from urban transport," Proceedings of the Institution of Civil Engineers, Transport, vol. 160, no. 4, pp. 165-172, 2007. Doi: <https://doi.org/10.1680/tran.2007.160.4.165>
- [53] R. Ahamed, A. Muktadir, and T. Ahmed, "Application of regression models to assess bus interior noise in Dhaka City," International Journal of Environment Studies, vol. 76, no. 6, pp. 940-952, 2019. Doi: <https://doi.org/10.1080/00207233.2019.1644035>
- [54] B. S. Portela and P. H. T. Zannin, "Analysis of factors that influence noise levels inside urban buses," Journal of Scientific and Industrial Research, vol. 69, pp. 684-687, 2010.
- [55] S. Boren, L. Nurhadi, and H. Ny, "Preferences of electric buses in public transport: Conclusions from real life testing in eight Swedish municipalities," International Journal

- of Environmental, Chemical, Ecological, Geological and Geophysical Engineering, vol. 10, no. 3, pp. 255-264, 2016. Doi: <https://doi.org/10.5281/zenodo.1112119>
- [56] N. Sladkov, "Impact of electrification of vehicles on noise pollution in cities," Environmental Management and Physical Planning, University of Stockholm, pp. 1-22, 2024.
- [57] S. Boren, "Electric Buses' Sustainability Effects, Noise, Energy Use and Costs," International Journal of Sustainable Transportation, vol. 14, no. 12, pp. 956–971, 2019. DOI: <https://doi.org/10.1080/15568318.2019.1666324>.
- [58] S. M. J. Fadaki, M. H. Abbasi, and S. R. Esmailzadeh, "Study of electric buses and their impact on the environment in urban networks," in Conference of Civil Engineering, Architecture and Urbanism of the Islamic Countries, pp. 1-14, 2018.
- [59] X. C. Wang and J. A. González, "Assessing feasibility of electric buses in small and medium-sized communities," International Journal of Sustainable Transportation, vol. 7, no. 6, pp. 431-448, 2013. DOI: <https://doi.org/10.1080/15568318.2012.667864>
- [60] T. Sakamoto, M. Tanaka, K. Sekine, M. Morita, T. Shima, A. Korenori, and A. Yoshiike, "Reviews on countermeasure to safety risk associated with quietness of hybrid or electric vehicles in Japan," in Inter.noise, Lisbon, pp. 8, 2010.
- [61] J. Lelong and R. Michelet, "Passenger cars. Power unit and tyre-road noise, driving behaviour: what are the stakes?" in Inter.noise, The Hague, Netherlands, 2001.
- [62] J. Jabben, E. Verheijen, and C. Potma, "Noise reduction by electric vehicles in Netherlands," in Internoise and Noise-Con Congress and Conference Proceedings, Institute of Noise Control Engineering, pp. 6958-6965, 2012.
- [63] H. Campello-Vicente, R. Peral-Orts, N. Campillo-Davo, and E. Velasco-Sanchez, "The effect of electric vehicles on urban noise maps," Journal of Applied Acoustics, vol. 116, pp. 59-64, 2016. Doi: <https://doi.org/10.1016/j.apacoust.2016.09.018>
- [64] D. Sekulic, V. Dedovic, S. Rusov, S. Salinic, and A. Obradovic, "Analysis of vibration effects on the comfort of intercity bus users by oscillatory model with ten degrees of freedom," Journal of Applied Mathematical Modelling, vol. 37, pp. 8629-8644, 2013. Doi: <https://doi.org/10.1016/j.apm.2013.03.060>

- [65] G. Coquel and C. Fillol, "Analysis of ground-borne noise and vibration levels generated by buses," *Procedia Engineering*, vol. 199, pp. 2699-2704, 2017. Doi: <https://doi.org/10.1016/j.proeng.2017.09.564>
- [66] Z. Damijan, "Investigation of the vibroacoustic climate inside the buses Solaris Urbino 18 used in public transport systems," *Molecular and Quantum Acoustics*, vol. 29, pp. 33-44, 2008.
- [67] H. Zhao, L. Guo, and X. Zeng, "Evaluation of Bus Vibration Comfort Based on Passenger Crowdsourcing Mode," *Mathematical Problems in Engineering*, vol. 2016, 2132454, pp. 1–10, 2016. DOI: <http://dx.doi.org/10.1155/2016/2132454>.
- [68] M. El Sayed, S. Habashy, and M. El Adawy, "Whole-body vibration measurement and assessment for Cairo subway (Metro), car and bus passengers," *International Journal of Electronics, Communication & Instrumentation Engineering Research and Development (IJECIERD)*, vol. 3, no. 1, pp. 185-202, 2013. Doi: <http://dx.doi.org/10.5120/8773-2704>
- [69] O. Thamsuwan, R. P. Blood, R. P. Ching, L. Boyle, and P. W. Johnson, "Whole body vibration exposures in bus drivers: A comparison between a high-floor coach and a low-floor city bus," *International Journal of Industrial Ergonomics*, vol. 43, pp. 9-17, 2013. Doi: <https://doi.org/10.1016/j.ergon.2012.10.003>
- [70] P. M. G. Jonsson, P. W. Rynell, M. Hagberg, and P. W. Johnson, "Comparison of whole-body vibration exposures in buses: effects and interactions of bus and seat design," *Ergonomics*, 2014. DOI: <http://dx.doi.org/10.1080/00140139.2014.961568>
- [71] Z. Damijan, "Investigation of the vibroacoustic climate inside the buses MAN SG242 used in public transport systems," *Acta Physica Polonica A*, vol. 118, no. 1, pp. 27-30, 2010.
- [72] P. Mitchell, "Speed and road traffic noise: The role that lower speeds could play in cutting noise from traffic," *UK Noise Association Report*, pp. 1-20, 2009.
- [73] Z. Lan, M. Yuan, S. Shao, and F. Li, "Noise Emission Models of Electric Vehicles Considering Speed, Acceleration, and Motion State," *International Journal of Environmental Research and Public Health*, vol. 20, 3531, pp. 1–15, 2023. DOI: <https://doi.org/10.3390/ijerph20043531>.
- [74] D. Flor, D. Pena, L. Pena, V. A. De Sousa, and A. Martins, "Characterization of noise level inside a vehicle under different conditions," *MDPI Sensors*, vol. 20, 2471, pp. 1-19, 2020. Doi: <https://doi.org/10.3390/s20092471>

- [75] K. Qian, Z. Hou, and D. Sun, "Sound quality estimation of electric vehicles based on GA-BP artificial neural networks," *MDPI Applied Sciences*, vol. 10, 5567, pp. 1-15, 2020. Doi: <https://doi.org/10.3390/app10165567>
- [76] O. Hunaidi, "Traffic vibrations in buildings," *National Research Council of Canada, Construction Technology Update*, vol. 39, pp. 1-6, 2000.
- [77] X. Wang, Z. Cheng, and N. Ma, "Road recognition based on vehicle vibration signal and comfortable speed strategy formulation using ISA algorithm," *Sensors*, vol. 22, 6682, pp. 1-21, 2022. Doi: <https://doi.org/10.3390/s22176682>
- [78] M. N. Harduke and R. R. Malagi, "Automobile noise and vibration-sources, prediction and control," *Indian Journal of Science and Resources*, vol. 12, no. 1, pp. 1-6, 2015.
- [79] N. U. Khan, S. Ahmad, M. M. Janjua, and A. Mennad, "The design of vibration nomograph for the vehicle vibrations affecting man," in *2022 Advances in Science and Engineering Technology International Conferences (ASET)*, pp. 1-7, IEEE, 2022. DOI: <https://doi.org/10.1109/ASET53988.2022.9735120>.
- [80] M. Lamb and V. Rouillard, "On the parameters that influence road vehicles vibration levels," *Packaging Technology and Science*, vol. 34, no. 9, pp. 525-540, 2021. Doi: <https://doi.org/10.1002/pts.2592>
- [81] A. Vaitkus, D. Cygas, V. Vorobjovas, et al., "Traffic/road noise mitigation under modified asphalt pavements," *Transportation Research Procedia*, vol. 14, pp. 2698-2703, 2016. Doi: <https://doi.org/10.1016/j.trpro.2016.05.446>
- [82] T. Nguyen, N. NguyenDinh, B. Lechner, and Y. D. Wong, "Insight into the lateral ride discomfort thresholds of young-adult bus passengers at multiple postures: Case of Singapore," in *World Conference on Transport Research Society*, pp. 1-23, 2019. Doi: <https://doi.org/10.1016/j.cstp.2019.07.002>
- [83] A.L. Montenegro, G. Rey-Gozalo, J. P. Arenas, and E. Suarez, "Streets classification models by urban features for road traffic noise estimation," *Science of the Environment*, vol. 932, 173005, pp. 1-14, 2024. Doi: <https://doi.org/10.1016/j.scitotenv.2024.173005>
- [84] X. Lu, J. Kang, P. Zhu, J. Cai, F. Guo, and Y. Zhang, "Influence of urban road characteristics on traffic noise," *Transportation Research Part D: Transport and Environment*, vol. 75, pp. 136-155, 2019. Doi: <https://doi.org/10.1016/j.trd.2019.08.026>

- [85] J. Lambert, J. Lelong, and C. Philipps-Bertin, ENNAH - European Network on Noise and Health, 178 p., 2013.
- [86] T. H. Oiamo, H. Davies, D. Rainham, and C. Rinner, “Environmental noise study in the city of Toronto,” pp. 1-31, 2017.
- [87] Y. A. Farghaly, F. A. A. Hemeida, and S. Salah, “Noise utilization as an approach for reducing energy consumption in street lighting,” PLoS ONE, vol. 14, no. 7, pp. 1-20, 2019. Doi: <https://doi.org/10.1371/journal.pone.0219373>
- [88] CTA and OmniTrans, Noise and vibration technical study: West Valley Connector Project, CTA and OmniTrans, pp. 1-192, 2018.
- [89] E. R. Dugundji, A. Paez, T. A. Arentze, and J. L. Walker, “Transportation and social interactions,” Transportation Research Part A, vol. 45, pp. 239-247, 2011. Doi: <https://doi.org/10.1016/j.tra.2011.01.001>
- [90] X. Zhou, Y. Liu, M. Luo, S. Zheng, R. Yang, and X. Zhang, “Overall and thermal comfort under different temperature, noise, and vibration exposures,” Indoor Air, vol. 32, e12915, pp. 1–16, 2022. DOI: <https://doi.org/10.1111/ina.12915>.
- [91] Wang and Zacharias, “Noise, odor and passenger density in perceived crowding in public transport,” Transportation Research Part A: Policy and Practice, 2020. Doi: <https://doi.org/10.1016/j.tra.2020.03.013>
- [92] M. Festa, F. Stalter, A. Tavornmas, and F. Gauterin, “Human response to vehicle vibrations and acoustics during transient road excitations,” Vibration, vol. 4, pp. 357-368, 2021. DOI: <https://doi.org/10.3390/vibration4020023>.
- [93] National Institute for Occupational Safety and Health, Occupational noise exposure: Criteria, 1998. Available: <https://pubhtml5.com/gfen/flgi/basic/> [Accessed: Jun 14, 2024]
- [94] Canadian Centre for Occupational Health and Safety (CCOHS), Noise - Occupational exposure limits in Canada, 2023. Available: https://epe.lac-bac.gc.ca/100/205/301/tbs/reports_plans_priorities/2013-2014e/ccohs.ca/oshanswers/phys_agents/exposure_can.html [Accessed: Aug. 26, 2024].
- [95] S. N. Gerges, “Noise control policy in Brazil and South America,” The Journal of the Acoustical Society of America, vol. 131, no. 4_Supplement, p. 3328, 2012. Doi: <https://doi.org/10.1121/1.4708455>

- [96] International Standard Organization, ISO 2631-1: Mechanical vibration and shock evaluation of human exposure to whole-body vibration, International Standard Organization, pp. 1-31, 1997.
- [97] F. Nadri, M. R. Monazzam, N. Khanjani, M. R. Ghotbi, A. Rajabizade, and H. Nadri, "An investigation on occupational noise exposure in Kerman metropolitan bus drivers," *International Journal of Occupational Hygiene*, vol. 4, no. 1, pp. 1-5, 2012.
- [98] A.Lacerda, A. Ribas, J. Mendes, and P. Andrade, "Noise Level and its Perception by Commuters in Urban Buses of Curitiba," *Canadian Acoustics*, vol. 32, no. 4, pp. 53-59, 2004.
- [99] G. Mohammadi, "Noise exposure inside of the Kerman urban buses: Measurements, drivers and passengers' attitudes," *Iranian Journal of Health, Safety and Environment*, vol. 2, no. 1, pp. 224-228, 2014.
- [100] A.F. Azenan and J. Azlis-Sani, "Effects of Vibration on Intrastate Bus Drivers," *IOP Conference Series: Journal of Physics Conference Series*, vol. 1049, 012094, pp. 1-7, 2017. DOI: <https://doi.org/10.1088/1742-6596/1049/1/01/2094>
- [101] J. Consuegra, B. Torres, K. Garcia, and A. Oscar, "Vibratory Analysis of a Public Bus and Evaluation of Health Comfort and Perception," in *XXVII Encontro da Sociedade Brasileira de Acustica*, pp. 1-11, 2018. DOI: 10.17648/sobrac-87165.
- [102] D. Eager, M. I. Hossain, A. L. Lindqvist, and S. Zhou, "City Bus Seat Vibration Analysis using 6-axis Accelerometer and Gyroscope Sensors," *Nature Scientific Reports*, vol. 14, 29865, pp. 1-20, 2024. DOI: <https://doi.org/10.1038/s41598-024-80804-5>.
- [103] K. Abdur-Rouf and K. Shaaban, "Development of prediction models of transportation noise for roundabouts and signalized intersections," *Transportation Research Part D: Transport and Environment*, vol. 103, 103174, pp. 1-13, 2022.
- [104] F. Ibili, E. K. Adanu, C. A. Adams, S. A. Andam-Akorful, S. S. Turay, and S. A. Ajayi, "Traffic noise models and noise guidelines: A review," *Noise and Vibration Worldwide*, pp. 1-15, 2021. DOI: <https://doi.org/10.1177/09574565211052693>.
- [105] N. Sylvestre-Williams and R. Ramakrishnan, "Error bounds, uncertainties and confidence limits of outdoor sound propagation," *Canadian Acoustics*, vol. 34, no. 3, pp. 42-43, 2006.

- [106] T. Suksaard, P. Sukasem, S. M. Tabucanon, et al., “Road traffic noise prediction model in Thailand,” *Journal of Applied Acoustics*, vol. 58, pp. 123-130, 1999. Doi: [https://doi.org/10.1016/S0003-682X\(98\)00069-3](https://doi.org/10.1016/S0003-682X(98)00069-3)
- [107] W. Patthanaissaranukool, K. Bunnakrid, and T. Sihabut, “Applying mathematical modeling to predict road traffic noise in Phuket Province, Thailand,” *International Journal of GEOMATE*, vol. 17, no. 62, pp. 133-139, 2019.
- [108] W. Chen, H. Xiao, L. Liu, J. W. Zu, and H. Zhou, “Integrated control of vehicle system dynamics: Theory and experiment,” in *Advances in Mechatronics*, H. Martinez-Alfaro, Ed. Rijeka: InTech, pp. 1-28, 2011. Available: <http://www.intechopen.com/books/advances-in-mechatronics/integrated-control-of-vehicle-system-dynamics-theory-and-experiment> [Accessed: Aug. 21, 2024].
- [109] A. Aboazoum, “Modeling and simulation of a vehicle dynamics system,” *Nexus: Journal of Innovative Studies of Engineering Science*, vol. 1, no. 1, pp. 41-46, 2022.
- [110] R. N. Jazar, “Vehicle planar dynamics,” in *Advanced Vehicle Dynamics*, Springer, pp. 115-213, 2019. DOI: https://doi.org/10.1007/978-3-030-13062-6_2.
- [111] M. Belrzaeg, A. A. Ahmed, A. Q. Almabrouk, M. M. Khaleel, A. A. Ahmed, and M. Almkhtar, “Vehicle dynamics and tire models: An overview,” *World Journal of Advanced Research and Reviews*, vol. 12, no. 1, pp. 331-348, 2021. DOI: <https://doi.org/10.30574/wjarr.2021.12.1.0524>
- [112] A. Bhuyan and M. Rababah, “Passive suspension modelling and analysis of a full-car model,” *International Journal of Advanced Science and Engineering Technology*, vol. 3, no. 2, pp. 250-261, 2013.
- [113] Statistics Canada, “Table 98-10-0003-01: Population and dwelling counts: Census metropolitan areas, census agglomerations and census subdivisions (municipalities),” 2022. Available: <https://doi.org/10.25318/9810000301-eng> [Accessed: Aug. 28, 2024].
- [114] Board of Trade of Metropolitan Montreal, “Public transit: At the heart of Montréal’s economic development,” 2010. Available: http://www.btmmt.qc.ca/Study_Public_Transit [Accessed: Aug. 28, 2024].
- [115] City Transit, “Annual Public Transit Ridership: Montreal,” *International Association of Public Transit (UITP)*, 2020. Available: <https://citytransit.uitp.org/montreal/public-transport-ridership> [Accessed: Aug. 28, 2024].

- [116] STM, “Annual Report 2023,” 2023. Available: <https://www.stm.info/fr/a-propos/informations-entreprise-et-financieres/rapport-annuel-2023/rapport-dactivite>. [Accessed: Aug. 28, 2024].
- [117] American Public Transportation Association, “APTA Transit Ridership Report: First Quarter 2019,” APTA, pp. 1–36, Washington DC, USA, 2019.
- [118] W. Zamora, C. T. Calafate, J. C. Cano, and P. Manzoni, “Accurate Ambient Noise Assessment Using Smartphones,” *Sensors*, vol. 17, 917, pp. 1-18, 2017. Doi: <https://doi.org/10.3390/s17040917>
- [119] A.L. Padilla-Ortiz, F. A. Machuca-Tzili, and D. Ibarra-Zarate, “Smartphones, a Tool for Noise Monitoring and Noise Mapping,” *International Journal of Environmental Science and Technology*, vol. 20, pp. 3521–3536, 2023. Doi: <https://doi.org/10.1007/s13762-022-04240-6>
- [120] P. Paramo-Balsa, J. M. Roldan-Fernandez, F. Gonzalez-Longatt, and M. Burgos-Payan, “Measurement of the Speed of Induction Motors Based on Vibration with a Smartphone,” *Applied Sciences*, vol. 12, 3371, pp. 1–19, 2022. DOI: <https://doi.org/10.3390/app12073371>.
- [121] E. Murphy and E. A. King, “Testing the Accuracy of Smartphones and Sound Level Meter Applications for Measuring Environmental Noise,” *Applied Acoustics*, vol. 106, pp. 16–22, 2016. Doi: <https://doi.org/10.1016/j.apacoust.2015.12.012>
- [122] T. I. Ibekwe, D. O. Folorunsho, E. A. Dahilo, M. M. N. Gbujie, and O. G. Nwaorgu, “Evaluation of Mobile Smartphones app as a Screening Tool for Environmental Noise Monitoring,” *Journal of Occupation and Environmental Hygiene*, vol. 13, no. 2, pp. 31–36, 2016. Doi: <https://doi.org/10.1080/15459624.2015.1093134>
- [123] A. Feldbusch, H. Sadgeh-Azar, and P. Agne, “Vibration Analysis Using Mobile Devices (Smartphones or Tablets),” *Journal of Procedia Engineering*, vol. 199, pp. 2790–2795, 2017. Doi: <https://doi.org/10.1016/j.proeng.2017.09.543>
- [124] H. M. Shiferaw, “Measuring Traffic Induced Vibration using Smartphone Sensors for a Firsthand Structural Health Monitoring,” *Scientific African*, vol. 11, e00703, pp. 1–10, 2021. Doi: <https://doi.org/10.1016/j.sciaf.2021.e00703>
- [125] J. T. Hassani and R. Teixeira, “A Mobile Phone Application Designed for Bridge Structural Assessments,” *Journal of Physics: Conference Series*, vol. 2647, 252008, pp. 1–10, 2024.

- [126] U.S. Department of Transportation and Federal Highway Administration, Present Serviceability Rating Computation from Reported Distresses, FHWA-HRT-21-041, pp. 1–42, 2021.
- [127] M. Orczyk, “Evaluation of the Distribution of Sound Levels in a Public Transport Bus During the Ride and at Standstill,” in *Challenges of Urban Mobility, Transport Companies and Systems 2018*, pp. 77–87, 2019. Doi: https://doi.org/10.1007/978-3-030-17743-0_7
- [128] G. Wang, J. Zhang, and X. Kong, “Study on Passenger Comfort Based on Human-Bus-Road Coupled Vibration,” *Applied Sciences*, vol. 10, 3254, pp. 1–22, 2020. Doi: <https://doi.org/10.3390/app10093254>
- [129] M. R. Phillips, C. C. Wykoff, L. Thabane, et al., “The clinician’s guide to p values, confidence intervals, and magnitude of effects,” *Eye*, vol. 36, pp. 341–342, 2022. DOI: <https://doi.org/10.1038/s41433-021-01863-w>.
- [130] N. Shrestha, “Detecting Multicollinearity in Regression Analysis,” *American Journal of Applied Mathematics and Statistics*, vol. 8, no. 2, pp. 39–42, 2020. DOI: <https://doi.org/10.12691/ajams-8-2-1>
- [131] J. Masri, M. Amer, S. Salman, and M. Ismail, “A Survey of Modern Vehicle Noise, Vibration and Harshness: A State-of-the-Art,” *Aim Shams Engineering Journal*, vol. 15, 102957, pp. 1–20, 2024. DOI: <https://doi.org/10.1016/j.asej.2024.102957>.
- [132] M. Wrótny, J. Bohatkiewicz, and J. Bohatkiewicz-Czaicka, “Influence of using low-noise pavements on residents’ perception of road noise protection,” *Transportation Research Part D*, vol. 113, 103531, pp. 1–10, 2022. DOI: <https://doi.org/10.1016/j.trd.2022.103531>
- [133] L. A. Ellingsen, et al., “Life cycle assessment of battery electric buses,” *Transportation Research Part D*, vol. 112, 103498, pp. 1–10, 2022. DOI: <https://doi.org/10.1016/j.trd.2022.103498>
- [134] P. Regulski, “Assessment of life cycle of city buses with diesel and electric drive in the operation phase,” *Combustion Engines*, vol. XXXX, pp. 3–7, 2023. DOI: <https://doi.org/10.19206/CE-162108>
- [135] P. H. T. Zannin, F. B. Diniz, C. Giovanini, and J. A. C. Ferreira, “Interior noise profiles of buses in Curitiba,” *Transportation Research Part D*, vol. 8, pp. 243–247, 2003. DOI: [https://doi.org/10.1016/S1361-9209\(03\)00019-1](https://doi.org/10.1016/S1361-9209(03)00019-1)

- [136] F. Alanazi, “Electric Vehicles: Benefits, Challenges, and Potential Solutions for Widespread Adaptation,” *Applied Sciences*, vol. 13, 6016, pp. 1–20, 2023. DOI: <https://doi.org/10.3390/app13106016>.
- [137] C. Deubel, S. Ernst, and G. Prokop, “Objective evaluation methods of vehicle ride comfort—A literature review,” *Journal of Sound and Vibration*, vol. 548, 117515, pp. 1–22, 2023. DOI: <https://doi.org/10.1016/j.jsv.2022.117515>.
- [138] S. Mohammadi and A. Ohadi, “A novel approach to design quiet tires, based on multi-objective minimization of generated noise,” *Applied Acoustics*, vol. 175, 107825, pp. 1–18, 2021. DOI: <https://doi.org/10.1016/j.apacoust.2020.107825>.
- [139] Kernytskyy, Y. Yakovenko, O. Horbay, M. Ryviuk, R. Humenyuk, Y. Sholudko, Y. Voichyshyn, Ł. Mazur, P. Osiński, K. Rusakov, et al., “Development of Comfort and Safety Performance of Passenger Seats in Large City Buses,” *Energies*, vol. 14, 7471, pp. 1–13, 2021. DOI: <https://doi.org/10.3390/en14227471>
- [140] Transport Canada Motor Vehicle Safety (2005). Test Method 1106: Noise Emission Tests. Transport Canada, 1 – 15.

APPENDIX A: VERBAL INVITATION SCRIPT



Thesis: A Comparative Analysis of Noise and Vibration Levels in Conventional and Electric Buses in Montreal

Researcher: Emmanuel Davies

Supervisor: Dr. Fuzhan Nasiri

Hello.

I am Emmanuel Davies, a building engineering master's student at Concordia University.

I am currently conducting research on noise and vibration levels in conventional and electric public buses in Montreal and I would like you to participate in this study.

The purpose of the study is to compare the noise and vibration generated in the buses and perceived by riders such as yourself.

I would like to point out that your participation is totally voluntary, and that all information collected will not infringe on your privacy.

There are no personal benefits, incentives, risks and consequences to your decision to participate or not. Your decision will be respected accordingly.

Would you be interested in participating?

APPENDIX B: VERBAL CONSENT SCRIPT AND INTERVIEW GUIDE



A. PURPOSE

The purpose of the study is to compare the noise and vibration generated in the buses and perceived by riders during the buses' commute.

B. PROCEDURES

If you agree to participate in the study, you will be asked to answer two questions covering your perceptions of the noise and vibration levels in the bus during its commute.

In total, participating in this study will typically last between 3 – 5 minutes.

C. RISKS AND BENEFITS

Participating in this study will not put you in any risk.

Furthermore, there are no personal benefits or incentives associated with participating in the research.

D. CONFIDENTIALITY

I will gather the following information as part of this research: Your ranked perception of noise levels and vibration levels in the bus during its commute.

I will be the only person with access to the information provided and it will solely be used for the purposes of the research described earlier on.

The information gathered will be anonymous. That means that it will not be possible to make a link between you and the information you provide.

The information provided will be protected through the encryption of digital files and the disposal of all written documentation after the creation of digital files.

I intend to publish the results of the research, and it will not be possible to identify you in the published results.

The remaining files of the information collected will be discarded 2 years after the completion of the study.

F. CONDITIONS OF PARTICIPATION

You do not have to participate in this research. It is purely your decision. If you do participate, you can stop at any time. There will be no consequences for not participating, withdrawing from the data collection process or asking us to withhold any given information.

There will be no compensation for participation.

G. PARTICIPANT'S DECLARATION

To declare your participation, I would like you to respond in the affirmative to the following question.

Would you like to participate in the research study?

Furthermore, to document your verbal consent, I would like you to sign a consent documentation. This documentation will serve as witness to your consent to participating in the study.



Introduction

Thank you for agreeing to take part in this study.

The study seeks to compare the noise and vibration generated and perceived in conventional and electric public buses in Montreal.

On this basis, the interview consists of only two questions. The questions will capture your perceptions of the noise and vibration in the bus during its commute.

Before we begin, I would also like to remind you that you have the right to withdraw from the interview at any point in time without any consequences.

The questions are as follows:

Questions

1. On a scale of 1 – 10, how would you rate the noise level on the bus? Take 1 to be the lowest level and 10 to be the highest level.
2. On a scale of 1 – 10, how would you rate the vibration level in the bus? Take 1 to be the lowest level and 10 to be the highest level.

Conclusion

Do you have any questions about the research or the interview?

Thank you for your time and participation.

APPENDIX C: ETHICS CERTIFICATE



CERTIFICATION OF ETHICAL ACCEPTABILITY FOR RESEARCH INVOLVING HUMAN SUBJECTS

Name of Applicant: Emmanuel Davies

Department: Gina Cody School of Engineering and Computer
Science \ Building, Civil and Environmental
Engineering

Agency: N/A

Title of Project: Comparative Analysis of Noise and Vibration Levels in
Conventional and Electric Public Buses in Montreal

Certification Number: 30020171

Valid From: June 20, 2024 To: June 19, 2025

The members of the University Human Research Ethics Committee have examined the application for a grant to support the above-named project, and consider the experimental procedures, as outlined by the applicant, to be acceptable on ethical grounds for research involving human subjects.

A handwritten signature in black ink, reading "Richard DeMont".

Dr. Richard DeMont, Chair, University Human Research Ethics Committee