Chapter 1

Introduction

1.1 Background

India's rapid urbanization has profoundly reshaped its spatial, demographic and infrastructural fabric, placing critical structural and operational pressures on urban mobility and infrastructure systems. Metropolitan cities such as Delhi, Mumbai, Bengaluru and Chennai are witnessing sharp increases in population density, vehicular ownership and infrastructure stress. As per estimates by the Ministry of Housing and Urban Affairs (MoHUA) and the International Institute for Population Sciences (IIPS), India's urban population increased from approximately 286 million in 2001 to about 488 million in 2020, with the UN-Habitat World Cities Report 2022 projecting a rise beyond 675 million by 2035 [1–3]. This demographic surge has not been met with proportional infrastructure growth, resulting in severe transportation bottlenecks, rising congestion levels and heightened exposure to traffic-induced environmental stressors, including air pollution, noise and ground-borne vibrations (TIV). These conditions are further aggravated by non-uniform road development and inadequate design margins in urban corridors, emphasizing the urgent need for integrated, vibration-sensitive planning approaches.

Quantitatively, this imbalance is stark. According to PRS Legislative Research, India's road network expanded by 39% since the early 2000s, while the number of registered vehicles surged by over 158% during the same period [4]. The total road length increased from approximately 0.4 million kilometers in the 1950s to more than 5.5 million kilometers by 2015. However, the structural quality, load-bearing capacity and maintenance of these roadways have not scaled accordingly, particularly in Tier II and Tier III cities. This asymmetry has led to the overloading of urban corridors, degraded pavement conditions and intensified vehicle-road interaction dynamics, key contributors to mechanical vibrations transmitted through the ground.

India's high dependency on road-based transportation further exacerbates the problem. While countries such as China and the United States carry only 30% and 37% of transport via roads, respectively, India transports more than 60% of its freight and passenger load on roadways [5]. This road-centric model results in high axle repetitions per lane and concentrated stress cycles, especially on arterial and sub-arterial roads in congested urban settings. The continuous passage of diverse vehicle classes over imperfect pavements and geometrically abrupt features induces vertical and lateral ground vibrations, which propagate into adjacent substructures and built environments.

Unlike many developed countries with homogeneous and lane-disciplined traffic systems, Indian urban roads present highly heterogeneous traffic streams. These include a broad spectrum of vehicle types, from two-wheelers, three-wheelers, passenger cars and LCVs, to buses, trucks, e-rickshaws and non-motorized traffic sharing limited carriageway space without formal segregation. This lack of structural separation, combined with non-lane-based, opportunistic maneuvering behavior such as zigzag driving and irregular overtaking, results in chaotic vehicle dynamics. Sudden braking, unregulated lane shifts, uneven load distributions and variable speeds collectively generate complex and non-stationary vibrational responses at the pavement vehicle interface [6, 7]. Traditional models fail to characterize these conditions, necessitating advanced traffic and vibration modeling frameworks rooted in empirical field data and dynamic signal analysis.

Urban congestion is one of the most prominent consequences of this unregulated growth [8, 9]. Overloaded intersections, suboptimal signal phasing, poor driver compliance and insufficient infrastructure lead to severe delays and traffic spillovers. This congestion contributes not only to economic inefficiency and emissions but also to elevated ground vibrations due to intensified braking and acceleration cycles. Vehicles operating under stop-and-go conditions induce transient, high-frequency vibrations, particularly harmful to nearby infrastructure with low dynamic tolerance. Critically, smoother traffic enabled by route optimization reduces these events, thereby passively mitigating vibration levels. Hence, traffic planning tools considering vehicle types and congestion levels can serve a dual purpose, improving throughput and reducing vibration exposure.

In parallel, the environmental and societal consequences of escalating traffic congestion are profound [10]. Excessive vehicular density and prolonged idling contribute significantly to urban air pollution, with transportation sources emitting high levels of particulate matter ($PM_{2.5}$, PM_{10}), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO) and volatile organic compounds (VOCs). According to the Central Pollution Control Board (CPCB) and the International Council on Clean Transportation (ICCT), the transportation sector accounts for nearly 20–35% of ambient air pollution in India's major cities [11]. Simultaneously, traffic-generated noise pollution frequently exceeds permissible thresholds, impairing auditory health and increasing the risk of cardiovascular disease. Chronic exposure to traffic congestion has also been linked to elevated stress levels, anxiety, sleep disturbances and hypertension among urban residents [12]. Moreover, congestion-induced time losses directly translate into decreased productivity, increased fuel consumption and rising socio-economic costs. These multifaceted impacts underscore the urgency of designing holistic traffic management strategies that address congestion and its secondary effects on health, environment and infrastructure integrity.

Speed-control measures such as humps, rumble strips and raised pedestrian crossings are widely used in India to regulate vehicular speed. However, their placement often lacks technical standardization and context-sensitive planning. Rigid hump materials, excessive heights, or abrupt geometries frequently result in sharp vertical accelerations and impulsive ground excitations when heavy vehicles traverse them [13]. In the absence of geometric design tailored to the expected vehicle mix and traffic volume, such features act as unintended vibration sources, affecting sensitive zones including hospitals, educational campuses and historical precincts. However, in many Indian urban contexts, the selection of hump profiles and materials lacks technical standardization or consideration of traffic characteristics such as vehicle type or peak hour load. There is a need for context-sensitive hump design that balances traffic calming with potential vibration impacts, especially near sensitive zones such as hospitals, educational institutions and heritage sites.

From an infrastructure degradation perspective, chronic exposure to traffic-induced vibrations leads to cumulative damage, especially in buildings not designed for dynamic excitations. Vibrations propagate through subsoil layers depending on stiffness, stratification and damping characteristics, often resulting in amplification or resonance at specific structural frequencies. This is particularly critical for heritage buildings with unreinforced masonry, poorly connected joints, or high slenderness ratios [14]. Existing vibration standards such as ISO 2631-1 [15] and BS 6472 [16] provide exposure thresholds but do not adequately account for frequency-specific responses in varying soil and structural conditions typical of Indian cities.

The ability to control and manage TIV depends critically on accurate, real-time identification of vehicle types contributing to vibration emissions. Conventional classification systems based on axle-load sensors or video analytics often face practical limitations in Indian urban settings due to high infrastructure costs, environmental sensitivity and complex maintenance requirements [17]. These challenges are further exacerbated in heterogeneous and mixed-traffic environments, where occlusion, variable lighting and informal vehicle behavior compromise the performance of vision-based systems. As a result, there is a growing interest in alternative, non-intrusive, data-driven classification approaches that can reliably capture vehicle-road interaction dynamics across varied operating conditions.

Following vehicle identification, quantifying vibrational impact from different vehicle types is essential for effective infrastructure planning and regulatory intervention. While the Passenger Car Unit (PCU) is widely used in traffic flow modeling to standardize vehicle impacts, there is currently no established equivalent for characterizing vibration emissions across vehicle classes. To address this gap, the development of vibration-based comparative indices, analogous to PCU, has been conceptually proposed. Hypothetical metrics such as Passenger Car Vibration Equivalence (PCVE) and Reference Vibration Emission Level (RVEL) can potentially normalize the vibrational footprint of various vehicle types over different speed and surface conditions. When integrated with real-time traffic analytics, such indices could inform vibration-sensitive route planning, zoning policies and speed regulation frameworks, especially in structurally vulnerable or sensitive urban zones.

Addressing TIV in Indian cities requires an integrated multidisciplinary framework combining empirical ground vibration measurements, advanced signal analysis, real-time traffic classification and forecasting models. Additionally, the framework should account for geometric elements such as speed-control devices (e.g., humps, rumble strips), whose designs often act as unintended sources of impulsive vibrations. Such a holistic approach would support vibration-aware traffic management, infrastructure planning and sustainable urban policy. The subsequent sections examine the physical mechanisms of TIV, existing research limitations and the motivation for a methodological framework suitable for heterogeneous urban environments.

1.2 Traffic-Induced Vibrations (TIV): Mechanisms, Impacts and System-Level Perspectives

While the background highlights the broader urban dynamics and the need for integrated solutions, a foundational understanding of the physical mechanisms and effects of TIV is critical for addressing its urban implications. Traffic-induced vibrations (TIV) have emerged as a critical yet often underestimated environmental phenomenon in rapidly urbanizing cities, particularly within the context of heterogeneous and congested traffic systems. Unlike more perceptible forms of environmental degradation, such as air and noise pollution [18], TIV is characterized by its subtler physical manifestation and cumulative impact. It remains mainly unmonitored in existing urban frameworks, despite its demonstrated influence on structural degradation, human well-being and infrastructure serviceability in vibration-sensitive zones [19, 20].

Mechanistically, TIV originates from complex dynamic interactions between moving vehicles and the roadway structure. As vehicles traverse the pavement, they impart transient and cyclic loads that generate elastic and inelastic responses within the surface and the underlying soil layers [21]. Vehicle-specific parameters heavily modulate these interactions, including axle configuration, gross weight, suspension characteristics and operational speed. Heavy vehicles such as multi-axle trucks, buses and freight carriers produce significantly higher amplitude and lower-frequency vibrations. In contrast, lighter vehicles contribute to higher-frequency but lower-energy excitations [22]. Significantly, the presence of surface irregularities such as potholes, patch joints, geometric transitions and speed control measures like humps and rumble strips amplifies these responses by introducing discontinuities in force transmission [23, 24].

In real-world urban contexts, particularly in Indian cities, such amplification is further exacerbated by inconsistent pavement maintenance, non-standardized hump design and unpredictable vehicle behaviors due to mixed traffic conditions [25]. These issues are especially pronounced in Tier-II and Tier-III cities, where rapid urban growth has outpaced infrastructure regulation. As a result, vibration waveforms transmitted from roadways propagate into subgrades, foundations and adjacent structures through surface and body wave mechanisms, with spatial reach and severity influenced by soil stiffness, damping properties and structural resonances [26].

From a structural standpoint, the effects of TIV are cumulative and manifest as long-term degradation. Repeated vibratory excitation contributes to fatigue damage, loss of material integrity and micro-crack evolution, particularly in masonry or lightly reinforced concrete structures not designed for dynamic loads. Heritage buildings, old residential blocks, educational institutions and low-rise commercial facilities are especially vulnerable due to poor dynamic resistance and the absence of seismic or vibrational design considerations. Studies have documented modal drift, dynamic amplification and serviceability loss in structures within high-traffic corridors exposed to persistent vehicular vibration [14, 19]. These degradation mechanisms are susceptible to the frequency content of ground vibrations, further underscoring the importance of spectral analysis in vibration studies.

Beyond structural concerns, TIV has notable implications for functionality and quality of life. Ground-borne vibrations are known to interfere with the performance of vibration-sensitive equipment in hospitals, research laboratories and data centers. In such environments, even sub-millimeter ground displacements can degrade the accuracy of medical diagnostics, precision testing and scientific instrumentation [27]. Moreover, prolonged human exposure to vibration stimuli has been associated with psychological stress, sleep disturbance, reduced productivity and in some cases, cardiovascular risks [20].

Despite these diverse and documented effects, India's current urban and infrastructure policies lack dedicated regulatory mechanisms to assess, monitor, or mitigate TIV. Most existing standards, such as ISO 2631-1 [15] and BS 6472 [16], provide generalized guidelines for human exposure and structural response to vibration. However, as these codes are designed for broad applicability, they do not directly account for site-specific factors such as soil properties, traffic heterogeneity, and urban land-use conditions. It is therefore the responsibility of practitioners to correctly interpret and apply these guidelines within the context of local geotechnical and environmental conditions.

Recent advances in urban traffic sensing, vehicle classification and predictive modeling have opened new pathways to more effective TIV management. By integrating classified vehicle flow data with localized vibration forecasting and intelligent infrastructure planning, urban authorities can proactively identify high-risk corridors, enforce zoning protections and implement vehicle rerouting in vibration-sensitive areas. Furthermore, the emergence of comparative vibration metrics, such as the Passenger Car Vibration Equivalence (PCVE) and the Reference Vibration Emission (RVEL), allows for standardized quantification of vibrational impacts across vehicle types and road conditions, providing a robust basis for regulatory intervention and design optimization.

This section has established the physical drivers, structural and social impacts and system-level complexities associated with traffic-induced vibrations in heterogeneous urban settings. It has also highlighted the limitations of current regulatory standards and underscored the need for integrated approaches that combine vehicle classification, vibration quantification and predictive traffic control. The following section systematically identifies the methodological and policy gaps that constrain existing solutions and sets the stage for a unified framework capable of addressing TIV through real-time sensing, spectral analytics and planning-aware mitigation strategies.

1.3 Critical Gaps and Limitations of Existing Approaches

Despite growing recognition of traffic-induced vibrations (TIV) as a significant environmental and infrastructural concern, the current frameworks for assessing, predicting and mitigating TIV remain fragmented, non-contextual and vastly inadequate for complex urban settings such as those in India. These limitations are especially pronounced in environments characterized by heterogeneous traffic flow, inconsistent pavement quality and informal speed-regulating measures. Despite established knowledge of TIV mechanisms and their consequences, real-world mitigation efforts remain ineffective due to several methodological and institutional limitations.

Firstly, the existing international vibration standards, including ISO 2631-1 [15] and BS 6472 [16], were primarily developed under assumptions of homogeneous traffic flow, smooth pavement conditions and standardized infrastructure. These standards provide generalized exposure limits for human comfort and structural safety but fail to capture the stochastic and amplified vibration patterns typical of mixed urban traffic operating over discontinuous road geometries. Their applicability becomes questionable in Indian contexts, where unplanned speed humps, deteriorated road segments and abrupt elevation changes act as localized sources of transient, high-energy vibrations that propagate into adjacent structures.

Secondly, most vibration prediction models rely on deterministic or semi-empirical formulations assuming steady-state vehicle motion over idealized pavement profiles [28]. These models typically exclude the effects of traffic-induced load variability, unsignalized intersections and impulsive excitation caused by repeated braking or acceleration events. The inability of such frameworks to simulate dynamic vehicle-pavement interactions, especially across speed-controlling elements like humps, leads to substantial deviations between predicted and observed vibration levels. Moreover, there exists a lack of standardized procedures for incorporating real-time surface irregularities and speed hump geometries into vibration modeling protocols, despite their well-documented influence on vibration amplification.

Thirdly, vehicle classification systems, essential for source identification in TIV studies, remain dependent on either manual counts, intrusive axle-load sensors, or image-based detection algorithms [29]. These approaches are often impractical in dense urban settings due to high costs, environmental sensitivity and maintenance overhead. More critically, they fail to capture the dynamic interaction characteristics that govern vibration generation. The potential of tri-axial ground vibration signals as a robust, non-intrusive data source for classification remains underexplored in current literature. There is an absence of scalable, machine-learning-driven frameworks that leverage these signals to distinguish between vehicle types based on their vibrational signatures under field conditions.

Fourthly, existing route optimization systems predominantly rely on GPS-based trajectory data to estimate congestion and travel time [30]. These tools, however, treat all GPS signals equally, ignoring vehicle type, occupancy and vibration potential. As a result, a truck and a bus are indistinguishable despite vastly different spatial and vibrational footprints. Such models fail to incorporate classified traffic volume or zone-specific sensitivity, often routing high-vibration vehicles through heritage areas, hospitals, or labs. The absence of vibration-aware routing based on vehicle class and road sensitivity restricts effective traffic management in vibration-critical corridors.

Fifthly, existing urban traffic frameworks lack universally accepted, vibration-specific comparative indices for regulatory and planning applications. While traffic flow theory adopts standardized measures such as Passenger Car Units (PCU) to normalize space and time occupancy, no equivalent standard exists for characterizing the vibration impact of different vehicle classes. This absence of a reference vibration metric prevents quantitative comparison, limiting the development of vibration-based policies, speed regulation and infrastructure zoning guidelines. Without such metrics, enforcing design or operational modifications in areas prone to chronic vibration exposure becomes difficult.

Lastly, a systemic regulatory gap persists in formally recognizing TIV as a critical planning and infrastructure parameter. National urban transport policies and municipal development codes currently do not mandate the assessment of vibrational impacts during road planning, infrastructure retrofitting, or zoning policy design. As a result, vibration mitigation is rarely embedded into traffic design workflows, even in proximity to vibration-sensitive facilities. The lack of institutional mandates constrains the adoption of vibration-sensitive infrastructure planning practices across Indian cities.

In summary, critical limitations persist across five domains: (i) inadequacy of existing vibration exposure standards under mixed-traffic and irregular roadway conditions, (ii) oversimplification in vibration prediction models lacking vehicle-road interaction realism, (iii) lack of scalable, non-intrusive vehicle classification frameworks utilizing vibration signals, (iv) reliance on GPS-based routing systems that ignore vehicle-specific vibration emission profiles and (v) non-availability of standardized comparative vibration indices for regulatory use. These deficiencies necessitate the development of an integrated, multidisciplinary framework that fuses empirical vibration data, advanced signal decomposition, machine-learning-based classification and context-aware forecasting. The subsequent sections outline the methodological structure adopted in this research to systematically address these interconnected challenges.

1.4 Need for an Integrated Multidisciplinary Framework

Addressing traffic-induced vibrations (TIV) in complex, heterogeneous urban environments, particularly those in India, requires a departure from fragmented, single-domain approaches toward a unified, multidisciplinary framework [31]. Existing practices developed under assumptions of homogeneous traffic and consistent infrastructure fail to account for the stochastic dynamics, variable surface conditions and infrastructural vulnerabilities characteristic of Indian road networks. Effective mitigation of TIV thus mandates the integration of civil engineering, signal processing, machine learning and traffic modeling within a context-aware, data-driven framework.

At the core of this integrated strategy lies the empirical quantification of ground-borne vibrations under realistic traffic conditions. High-resolution tri-axial vibration signals acquired from urban corridors provide essential insight into the directionality, intensity and frequency content of traffic-induced vibration events. These measurements capture the interplay between vehicle characteristics, pavement geometry and structural boundaries, particularly in response to surface discontinuities such as humps or degraded pavement sections without relying on controlled or laboratory conditions.

Advanced signal decomposition methods are essential for analyzing complex vibration responses, particularly when assessing the influence of speed-control structures such as humps. Techniques like Variational Mode Decomposition (VMD) [32] isolate frequency bands associated with different vehicle-pavement interactions, allowing characterization of vibration amplification under varying geometries and speeds. These insights are critical for infrastructure-responsive speed hump design and form the analytical foundation for quantifying vibrational severity in uncontrolled urban environments.

This research further extends the framework by introducing a non-intrusive, vibration-based vehicle classification system. Conventional classification tools such as axle-count sensors or video analytics are intrusive or environmentally constrained [33]. In contrast, the approach adopted here leverages machine learning to classify vehicle types using features extracted from ground vibration signatures, enabling scalable and weather-independent identification in mixed traffic.

Beyond classification, the framework incorporates predictive traffic volume modeling based on historically classified vehicle count data. Unlike traditional GPS-only models that overlook vehicle heterogeneity [34], the proposed forecasting approach emphasizes vehicle-specific flow and its relationship to future congestion and vibrational load. This enables proactive planning by predicting when and where high-vibration vehicle types may dominate the flow and allows for rerouting or regulatory intervention.

A key innovation within this framework is the introduction of comparative vibration indices, namely, Passenger Car Vibration Equivalence (PCVE) and Reference Vibration Emission Level (RVEL). These metrics standardize the vibrational footprint of different vehicle classes across speeds and road conditions, analogous to PCU in traffic engineering [35]. This enables urban planners to evaluate the cumulative vibrational impact of traffic flows and enforce zoning or routing regulations for vibration-sensitive areas.

Importantly, this framework aligns with broader urban sustainability goals by linking TIV to public health, livability and infrastructure resilience. Prolonged exposure to low-level vibrations affects structural durability and human well-being. Thus, integrating TIV considerations into policy, traffic control and infrastructure planning is a technical necessity and a public health imperative.

The proposed multidisciplinary framework bridges empirical vibration monitoring, signal decomposition, vehicle classification and forecasting within a unified system. It equips urban planners and engineers with tools to make informed, vibration-aware decisions for traffic management, infrastructure design and urban zoning, especially critical for cities with heterogeneous traffic, fragile infrastructure and limited regulatory controls. The following section outlines the specific objectives and scope of this research built upon this integrated framework.

1.5 Research Objectives and Scope of the Doctoral Research

This doctoral research aims to develop an empirically grounded and operationally scalable framework for the characterization, classification and governance of traffic-induced vibrations (TIV) in urban environments. The framework synthesizes field-based vibration sensing, signal decomposition, vehicle classification and forecasting techniques to address critical limitations in existing standards, predictive models and regulatory mechanisms. The specific research objectives are delineated as follows:

1. **To empirically characterize and evaluate the design implications of speed hump-induced ground vibrations across multidirectional components (X, Y, Z)** using triaxial accelerometers under real-world traffic conditions. The study applies Variational Mode Decomposition (VMD) to extract dominant modal characteristics and assesses how variations in hump material and geometry influence vibration profiles, supporting data-driven design recommendations.

2. **To formulate and validate standardized vibration emission metrics**, namely, *Passenger Car Vibration Equivalence (PCVE)* and *Reference Vibration Emission Level (RVEL)*, for comparative evaluation of vibrational impacts across vehicle categories and operational speeds. Among these, PCVE serves as a vibration-based analogue to the Passenger Car Unit (PCU) used in traffic engineering. At the same time, RVEL defines vehicle and speed-specific reference thresholds for emission-level regulation and zoning guidance.

3. **To develop a vibration-based vehicle classification framework** that leverages statistical and energy-based features derived from tri-axial vibration signals, enabling non-intrusive, weather-resilient identification of vehicle types. The classification

system is designed to operate under real-world conditions, using ensemble machine learning models to overcome limitations of vision-based and sensor-intrusive techniques.

4. **To construct a forecasting and route optimization framework** by integrating classified vehicle count data with time-series and machine learning models (ARIMA, SVM, XGBoost), augmented with GPS-based trajectory data. The goal is to enhance travel-time efficiency in congested urban corridors, indirectly supporting vibration mitigation by promoting smoother vehicle flow.

The scope of this research encompasses the following key components:

- **Field Vibration Data Collection:** Installation of tri-axial accelerometers at selected urban corridors, including those with speed-control devices such as humps and rumble strips, to capture authentic directional vibration signals under varying traffic and surface conditions.

- **Advanced Signal Processing and Frequency-Based Decomposition:** Application of Variational Mode Decomposition (VMD) to analyze vibration characteristics induced by geometric discontinuities such as speed humps, enabling frequency-resolved assessment of energy distribution and modal contributions.

- **Vibration Emission Metric Development and Normalization:** Formulation of standardized indices, Passenger Car Vibration Equivalence (PCVE) and Reference Vibration Emission Level (RVEL), to compare vehicle-induced vibrations across different vehicle types and speeds.

- **Vibration-Based Vehicle Classification:** Development of a non-intrusive machine learning framework using statistical and energy-based features extracted from ground vibration signals allows accurate vehicle category identification in real-time under mixed-traffic conditions.

- **Traffic Forecasting and GPS-Augmented Route Optimization:** Integration of classified vehicle count data with time-series and machine learning models (ARIMA, SVM, XGBoost), supported by GPS-based trajectory inputs, to enable congestion-aware, travel-time optimized routing.

- **Unified Framework Deployment for Vibration-Aware Governance:** Integrating field sensing, PCVE/RVEL metrics, vibration-based vehicle classification and GPS-augmented traffic forecasting into an operational system for real-time vibration monitoring, impact-sensitive traffic rerouting and risk-informed infrastructure governance.

This cohesive methodological structure establishes a robust foundation for vibration-sensitive transportation planning, supporting infrastructure-responsive design, real-time vehicle classification and data-informed regulatory decision-making for managing traffic-induced ground vibrations via data-driven infrastructure design and evidence-based regulatory interventions in urban environments.

1.6 Significance and Novel Contributions

This doctoral research proposes and validates a comprehensive, field-integrated framework for the assessment, classification and proactive management of traffic-induced vibrations (TIV) in heterogeneous urban settings. The study is situated within the complex context of Indian roadways, where mixed-traffic conditions, irregular surface geometries and infrastructural vulnerabilities complicate the assessment and mitigation of ground-borne vibrations. While previous studies have examined TIV phenomena in isolation, this work unifies empirical data collection, signal analysis, machine learning and predictive traffic modeling into a coherent system capable of informing real-time decision-making.

The significance of this research lies in its capacity to bridge the domains of vibration science, traffic engineering and data-driven urban management. Existing approaches in traffic planning often overlook the vibrational implications of vehicle movement and vibration studies seldom integrate vehicle-specific data or traffic forecasting. This thesis addresses these gaps by developing a unified methodology that enables the monitoring, classification and prediction of traffic-induced ground vibrations using real-world datasets and scalable computational models.

The major contributions of the research are outlined as follows:

- **Empirical Characterization and Design Guidance for Speed Humps:** A detailed in-situ experimental investigation was conducted using tri-axial accelerometers across urban corridors equipped with speed control devices constructed from bitumen, fiber composites and rumble strips. Vibration responses from multiple vehicle categories were analyzed using Variational Mode Decomposition (VMD) to extract dominant frequency bands, energy profiles and modal amplitudes. The findings demonstrate material- and geometry-dependent variations in vibration intensity and provide evidence-based recommendations for selecting speed hump types in vibration-sensitive and enforcement-priority zones.

- **Standardization of Vibration Quantification Metrics:** Two novel vibration-based metrics were developed: Passenger Car Vibration Equivalence (PCVE), which serves as a normalized unit for comparing the vibration contributions of various vehicle types and Reference Vibration Emission Level (RVEL), which defines expected emission levels based on vehicle type and speed. These metrics enable objective evaluation and zoning regulations sensitive to vibration intensity.

- **Machine Learning-Based Vehicle Classification Using Vibration Data:** A vibration-based vehicle classification system was developed using statistical and energy-domain features extracted from tri-axial ground vibration signals. Ensemble learning models were trained and validated for the reliable identification of vehicle categories under field conditions. This non-intrusive system overcomes the environmental and infrastructural limitations of image-based and axle-load sensor methods.

- **Forecasting Framework for Traffic Volume and Flow Composition:** The study introduces a forecasting model based on classified vehicle volume counts and augmented GPS-based trajectory inputs. By integrating ARIMA, SVM and XGBoost models, the framework predicts short-term traffic flow patterns across urban corridors. While travel-time optimization is the primary goal, smoother vehicle movements inherently reduce impulsive vibration events.

- **Integrated Framework for Vibration-Aware Traffic Management:** A unified, modular framework was developed that seamlessly integrates tri-axial vibration sensing, PCVE and RVEL-based quantification, machine learning-driven vehicle classification and predictive traffic forecasting into an operational architecture. The system enables real-time vibration-aware route optimization, dynamic zoning of vibration-sensitive corridors and infrastructure risk mitigation. It supports regulatory enforcement by translating empirical vibration signals into actionable traffic control and planning decisions, thereby bridging the gap between field measurements and urban governance.

By combining empirical fieldwork with computational intelligence and transportation analytics, this research offers a new paradigm for managing the vibrational impacts of urban road traffic. It provides planners, engineers and policymakers with a technically rigorous toolkit for sustainable, vibration-conscious infrastructure development and transportation regulation.

1.7 Structure of the Thesis

This thesis is structured into nine technically cohesive chapters. Each chapter addresses a critical component in developing a comprehensive, field-validated framework for analyzing, quantifying, classifying and forecasting traffic-induced vibrations (TIV) in urban transport systems.

- **Chapter 1: Introduction** Defines the research problem, contextualizes the importance of TIV in infrastructure planning and articulates the multi-objective goals of this doctoral investigation, establishing its interdisciplinary scope.

- **Chapter 2: Literature Review** Critically evaluates previous work related to vibration generation, speed hump impacts, signal decomposition methodologies, vehicle classification from vibration signals and limitations of GPS-based traffic prediction. A synthesis of gaps is used to frame the research agenda.

- **Chapter 3: Methodology** Outlines the complete methodological framework covering vibration sensing, signal preprocessing, Variational Mode Decomposition (VMD), machine learning for classification and the development of standardized vibration indices (PCVE and RVEL) along with forecasting strategies.

- **Chapter 4: Study Design and Data Collection** Describes the experimental protocols adopted across four primary studies. It outlines sensor placement, traffic composition, geometric configurations and vehicle category variations under which vibration data were collected.

- **Chapter 5: Empirical Characterization and VMD-Based Analysis of Speed Hump-Induced Vibrations** Presents a detailed empirical study on vehicle vibrations across Fiber, Bitumen and Rumble Strip profiles. VMD is employed to extract multimodal frequency features and the results inform the optimization of hump design based on vehicle type and road use context.

- **Chapter 6: Standardization of Vibration Metrics Using PCVE and RVEL** Introduces two novel metrics: Reference Vibration Emission Level (RVEL) and Passenger Car Vibration Equivalence (PCVE), for quantifying different vehicles' absolute and relative vibrational impacts. Statistical models and a software tool were developed for real-time evaluation.
- **Chapter 7: Vibration-Based Vehicle Classification Using Machine Learning Techniques** Proposes and validates a high-accuracy vehicle classification system using statistical, spectral and energy-based features extracted from tri-axial ground vibration signals. The system achieves 99.78% accuracy through stacked ensemble classifiers.
- **Chapter 8: Traffic Forecasting and Route Optimization Using Classified Vehicle Data and GPS Augmentation** Presents a hybrid machine learning framework that integrates classified vehicle counts with GPS trajectory inputs and forecasting models (ARIMA, SVM, XGBoost) to develop congestion-aware, vibration-sensitive routing solutions. Results from real-world trials validate its effectiveness.
- **Chapter 9: Conclusions** Summarizes the core findings, practical implications and scientific contributions of the thesis. It also outlines limitations and proposes future work toward intelligent, vibration-aware transportation systems.

The next chapter presents a comprehensive literature review on traffic-induced vibrations, vehicle classification techniques and signal-based forecasting models to identify critical gaps and position the current research within the broader academic context.