

Chapter 9

Conclusion

9.1 Preface

The concluding chapter of this thesis provides a consolidated overview of the research undertaken to address the problem of traffic-induced vibrations (TIV) in complex urban environments. Through a sequence of four interrelated studies, this work establishes a signal-based framework for the analysis, quantification, classification and forecasting of ground vibrations generated by heterogeneous traffic flows.

This chapter summarizes the key findings, highlights the scientific contributions and outlines practical implications for infrastructure planning and traffic management. It also identifies limitations of the current work and presents directions for future research that can enhance the scalability, integration and policy relevance of the proposed framework.

9.2 Summary of Findings

This thesis presents a unified and experimentally validated framework for analyzing, quantifying, classifying and forecasting traffic-induced vibrations (TIV) in urban environments. The work progresses through four sequential and interdependent studies that collectively

establish a data-driven foundation for vibration-aware transportation and infrastructure planning.

The first study analyzed the influence of speed-regulating structures such as bitumen, fiber and rumble strip humps on ground vibration levels. Field measurements using tri-axial accelerometers and decomposition via Variational Mode Decomposition (VMD) revealed that hump geometry and material properties significantly affect both the magnitude and directionality of the resulting vibrations. These findings offer practical guidance for selecting appropriate hump profiles in zones where vibration control is critical, such as near hospitals or research facilities.

The second study introduced two vibration normalization indices: Passenger Car Vibration Equivalence (PCVE) and Reference Vibration Emission Level (RVEL). These indices allow for the standardized quantification of vibrational impact across vehicle types and operational speeds. It was observed that heavy vehicles operating at lower speeds could generate substantially higher vibrational loads compared to passenger cars under similar conditions. These metrics provide a planning tool for regulating vehicle speeds and designing route restrictions based on quantified vibration impact rather than vehicle count alone.

The third study developed a machine learning-based classification model for identifying vehicle types using raw ground vibration signals collected from hump-free road segments. The model, trained on features such as time-domain amplitude and duration, achieved a classification accuracy of 99.78 percent. This capability supports real-time vehicle identification, enforcement of no-heavy-vehicle zones and generating class-specific vibrational data for further analysis and planning.

The fourth study extended these insights into a predictive traffic forecasting and route optimization framework. Using classified vehicle count data and GPS-based positional inputs, traffic composition was forecasted with high temporal resolution using ARIMA,

SVM and XGBoost models. The output of this study enables route selection based on predicted traffic-induced vibration levels and travel efficiency, contributing to vibration-sensitive infrastructure protection and traffic planning.

Together, these studies form a comprehensive system that integrates physical sensing, data-driven modeling and predictive analytics. The resulting framework enables the characterization, assessment and management of traffic-induced vibrations as an explicit and actionable variable in urban planning and sustainable mobility systems.

9.3 Conclusions Mapped to Research Objectives

This doctoral research was guided by four interrelated objectives, each addressing a critical gap in the characterization, quantification, and management of traffic-induced vibrations (TIV). The studies were designed sequentially to ensure that empirical observations, theoretical interpretation, and practical applications converged into a unified vibration-aware traffic management framework.

The first objective was to empirically characterize speed hump-induced vibrations across vertical, lateral, and longitudinal directions. Field measurements with tri-axial accelerometers, analyzed using Variational Mode Decomposition (VMD), revealed that both geometry and material of humps significantly influenced vibration magnitudes and modal distributions. The findings established that smoother hump profiles, particularly bitumen-based designs, mitigated vertical and lateral vibrations more effectively, while rumble strips generated higher amplitudes suitable for strict enforcement zones. This confirmed the objective of linking geometric design with vibration-sensitive infrastructure planning.

The second objective focused on the formulation of standardized vibration emission metrics, namely Passenger Car Vibration Equivalence (PCVE) and Reference Vibration Emission Level (RVEL). These indices successfully normalized vibrational impacts across

heterogeneous vehicle types and speeds. Results demonstrated that heavy vehicles, especially at lower speeds, produced disproportionately higher PCVE and RVEL values compared to passenger cars. The metrics therefore provide regulators with quantitative tools to design vibration zoning policies, speed restrictions, and infrastructure protection strategies, meeting the goal of introducing a scalable, comparative framework for vibration quantification.

The third objective sought to develop a vibration-based vehicle classification framework. Using raw ground vibration signals, statistical and energy-based features were extracted and modeled with ensemble machine learning classifiers. The system achieved 99.78% accuracy under real-world traffic conditions, demonstrating robust differentiation between vehicle categories. This fulfilled the objective of enabling a non-intrusive, weather-resilient, and infrastructure-compatible classification method, directly addressing limitations of vision-based and intrusive sensor systems.

The fourth objective was to construct a forecasting and route optimization framework that integrates vehicle classification outputs with machine learning and GPS-based data. The developed models (ARIMA, SVM, XGBoost) accurately predicted traffic composition and enabled route evaluation based on both congestion and cumulative vibrational impact. This established the feasibility of vibration-aware traffic planning, where high-PCVE vehicles can be strategically rerouted to minimize infrastructural fatigue and improve travel-time efficiency. In doing so, the objective of operationalizing vibration forecasting into decision support was successfully met.

In summary, each objective of this research was systematically mapped to concrete findings. Together, the studies contribute an integrated framework that transforms TIV from an incidental byproduct of urban mobility into a measurable, classifiable, and controllable parameter. This framework not only advances the theoretical understanding of vibration-

vehicle-infrastructure interactions but also provides practical tools for policy formulation, sustainable planning, and resilient infrastructure management.

9.4 Practical Implications

9.4.1 Study-wise Practical Implications

1. Speed Hump Study: Design for Vibration Control

The first study demonstrated that different speed hump geometries and materials significantly influence the vibrational impact on vehicles and surrounding infrastructure. Among the profiles tested, Bitumen humps consistently produced lower vertical and lateral vibrations compared to Fiber and Rumble Strip designs. This finding supports the deployment of smoother, damped humps in areas requiring vibration-sensitive control, such as near hospitals, laboratories and educational buildings. Conversely, Fiber and Rumble Strip humps, which generate higher acceleration magnitudes, may be more appropriate for strict speed enforcement zones. The results also highlight the value of tuning hump geometry to align with the suspension response of prevalent vehicle types in specific corridors.

2. RVEL-PCVE Study: Quantification for Regulation and Policy

The second study introduced the Passenger Car Vibration Equivalence (PCVE) and Reference Vibration Emission Level (RVEL) metrics as standardized tools for quantifying the vibrational impact of various vehicle classes. These indices enable data-driven regulation, allowing authorities to design speed restrictions, route access policies, or pavement reinforcement strategies based on cumulative vibration load rather than traffic volume alone. The study revealed that heavy vehicles at lower speeds can produce the PCVE of a passenger car multiple times, validating the need for targeted vibration zoning. RVEL

values can also inform infrastructure health monitoring by quantifying cumulative exposure over time.

3. Vehicle Classification Study: Real-Time Sensing and Enforcement

The third study produced a robust and economical solution for vehicle classification using ground vibration signals from a 3D accelerometer setup. The system achieved 99.78% accuracy using XYZ SUM features and a WBS machine learning approach. This high-resolution classification enables practical implementation in smart infrastructure contexts, where intrusive or vision-based systems are infeasible. Real-time classification allows for enforcement of no-heavy-vehicle zones, dynamic tolling based on vehicle type and development of vehicle-specific traffic analytics. Moreover, the system's adaptability to 2D accelerometer setups further enhances its feasibility for low-cost deployment across urban and peri-urban networks.

4. Route Optimization Study: Forecasting and Decision Support

The fourth study showed that incorporating classified vehicle count data into GPS-based forecasting models improves the accuracy of traffic volume predictions. By integrating manual classification data with geospatial coordinates, models such as ARIMA, SVM and XGBoost were able to predict congestion and guide optimal route selection. A comparative study demonstrated measurable reductions in travel time, highlighting the practical value of vehicle-type-informed prediction. This approach offers a scalable and adaptive decision-support system for real-time traffic management, routing advisories and congestion mitigation, particularly in mid-sized and high-growth urban areas.

9.4.2 Unified Framework Applications and Integration Potential

The proposed vibration-aware traffic management framework integrates real-time sensing, signal decomposition, vehicle classification and vibration quantification into a unified, decision-oriented system. As shown in Figure 9.1, the framework systematically links field-acquired vibration data to route-level decision-making to minimize traffic-induced vibration exposure, particularly in sensitive urban zones.

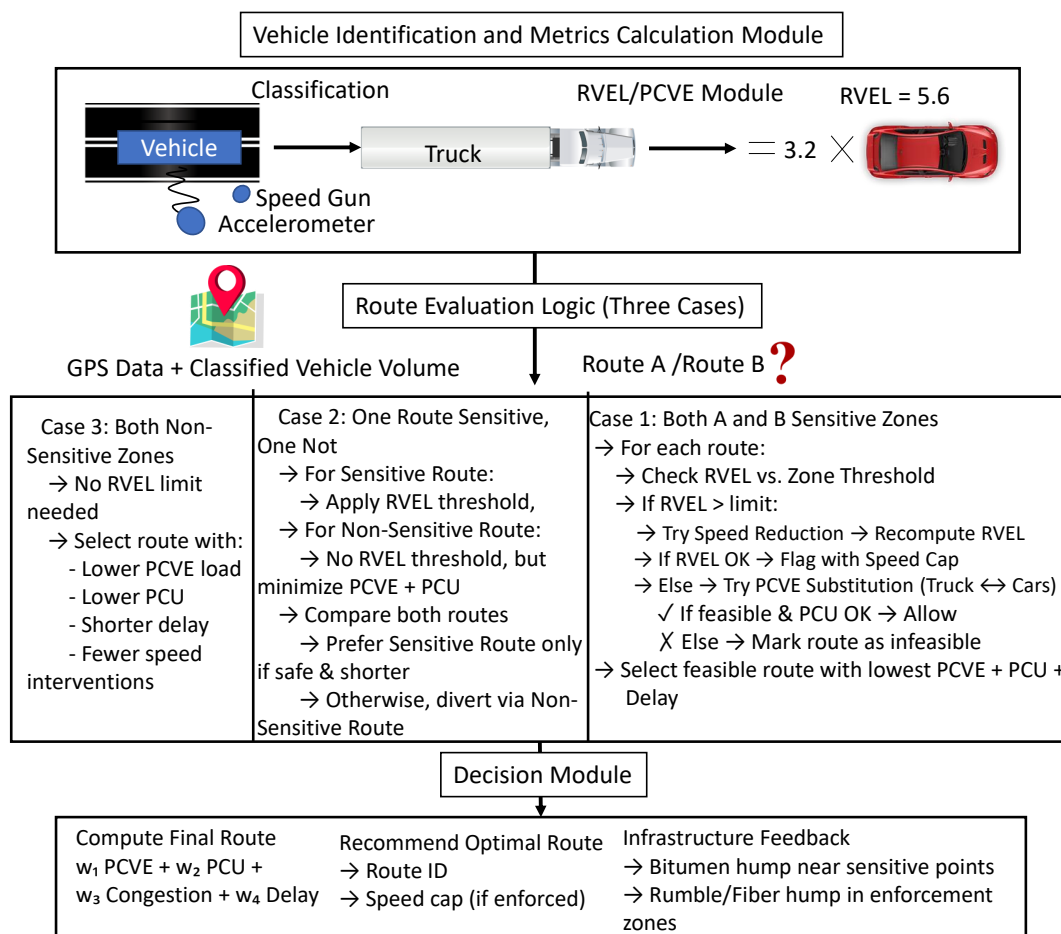


Fig. 9.1 Proposed Unified Framework for Vibration-Aware Traffic Management

Step 1: Vehicle Identification and Vibration Metric Calculation: Each vehicle is identified in real time using non-intrusive ground vibration signals captured through tri-

axial accelerometers and associated speed sensors. These signals are processed using machine learning classifiers such as Random Forest and XGBoost, which categorize the vehicle into predefined types, including trucks, buses, cars and others. Once the vehicle type is determined, its vibrational impact is quantified using two key indices. The first is the Passenger Car Vibration Equivalence (PCVE), which measures the vehicle's relative vibrational severity compared to a standard passenger car. The second is the Reference Vibration Emission Level (RVEL), which captures the absolute vibration energy emitted by the vehicle, incorporating directional and speed-dependent components. Together, PCVE and RVEL offer a comprehensive representation of each vehicle's dynamic influence on the surrounding infrastructure.

Step 2: GPS-Aided Route Identification: Upon determining vehicle type and vibration metrics, the system queries GPS data to identify feasible route alternatives (e.g., Route A and Route B). These routes are simultaneously evaluated based on traffic composition and urban sensitivity maps.

Route Evaluation Logic: Sensitivity-Based Case Handling

The decision logic operates on three routing cases based on the vibration sensitivity of the candidate routes:

- **Case 1 - Both Routes Sensitive:**

When both routes traverse vibration-sensitive zones (e.g., hospitals, heritage corridors), the system enforces strict RVEL thresholds:

- If RVEL exceeds the limit, vehicle speed reduction is attempted.
- If still violated, PCVE-based substitution is explored (e.g., one truck replaced by multiple cars).
- If all mitigation options fail, the route is marked infeasible.

The feasible route with the lowest combined PCVE, PCU and travel delay is then selected.

- **Case 2 - One Route Sensitive:**

When only one route is sensitive, it is preferred only if RVEL thresholds are met and delay remains acceptable. Otherwise, the non-sensitive route is chosen, optimized for minimal PCVE + PCU.

- **Case 3 - Both Routes Non-Sensitive:**

If neither route intersects sensitive zones, the system evaluates them using a weighted score:

$$\text{Score} = w_1 \cdot \text{PCVE} + w_2 \cdot \text{PCU} + w_3 \cdot \text{Delay}$$

where w_1, w_2, w_3 are policy-driven weights reflecting environmental, operational and mobility priorities.

This structured evaluation ensures dynamic routing that protects infrastructure while maintaining efficient traffic flow.

Step 3: Decision Module for Route and Control Actions: The final route is selected based on a multi-criteria decision model:

$$\text{Score} = w_1 \cdot \text{PCVE} + w_2 \cdot \text{PCU} + w_3 \cdot \text{Congestion} + w_4 \cdot \text{Delay}$$

where w_1-w_4 are tunable based on urban policy or zone-specific priorities. The decision module outputs:

- Optimal route recommendation
- Suggested speed limits or control actions

- Infrastructure recommendations (e.g., fiber rumble strips, modified hump design near hospitals)

Advanced Applications and Integration Potential

The unified vibration-aware framework extends beyond route optimization to enable proactive traffic governance, infrastructure resilience and urban policy enforcement. By fusing real-time vehicle classification with vibration metrics (PCVE and RVEL) and integrating these with GPS-aided route scanning and forecasting, the system anticipates vibration overloads and triggers context-specific mitigation. These include rerouting high-PCVE vehicles, enforcing time-window-based access control in sensitive zones and applying PCVE-equivalent substitutions under traffic constraints. Cumulative RVEL mapping informs maintenance prioritization for roads, bridges and subgrades exposed to chronic vibration. Vibration-aware zoning further aids in siting hospitals, labs, or heritage buildings, including in areas of seismic co-risk. The modular design supports edge-enabled smart city integration, where distributed low-power sensors and onboard analytics allow for real-time anomaly detection, policy automation and scalable, decentralized monitoring. Critically, this framework benefits both building owners and drivers, buildings experience reduced vibrational fatigue, while drivers benefit from smoother, faster and less mechanically stressful routes. Overall, this system transforms vibration from an unmanaged side effect into a controllable parameter in infrastructure, mobility and public health planning.

9.5 Theoretical Implications

While the thesis has been primarily supported by empirical data, its novelty is strengthened when interpreted through established principles of vibration and dynamics. Each of the

four studies is underpinned by theoretical concepts that extend the current understanding of traffic-induced vibrations.

In the speed hump study, the observed variations in vibration response can be interpreted through the theory of forced vibration and resonance. Hump geometry and material properties alter the excitation frequency input to the vehicle–road system, influencing resonance conditions in suspension dynamics. The systematic field evidence therefore confirms theoretical expectations and provides new insight into how hump design can be tuned for vibration-sensitive environments.

In the PCVE–RVEL study, the proposed indices are rooted in the principles of dynamic equivalence and vibration energy emission. PCVE extends the idea of reference equivalence from traffic flow theory into the vibration domain, while RVEL draws from energy-based representations of vibrational load. Together they form a theoretically consistent framework for comparing different vehicle types and speeds on a normalized basis.

In the vehicle classification study, the success of signal-based learning models is explained by system identification and modal analysis concepts. Each vehicle produces a unique vibrational signature determined by its axle configuration, suspension stiffness, and dynamic load transfer. The classification framework therefore captures underlying physical differences, aligning machine learning performance with vibration theory.

In the traffic forecasting study, the predictive models implicitly reflect the principle of superposition of dynamic loads. Variations in vehicle composition and speed create cumulative vibration fields that evolve in time, and the forecasting system operationalizes this dynamic interaction through learning-based models.

Finally, the unified framework integrates these theoretical underpinnings into a coherent structure. It extends vibration theory from individual vehicle–road interactions to system-level traffic management. By embedding PCVE and RVEL into route optimiza-

tion, the framework transforms vibration from an incidental byproduct of mobility into a quantifiable, controllable parameter for sustainable transport planning.

9.6 Contribution of the Study

This research presents a unified, scientifically grounded framework for measuring, classifying, quantifying and predicting traffic-induced vibrations (TIV) in urban environments. It contributes a detailed vibration analysis of multiple speed hump geometries under varied vehicle classes, establishing their role in passive vibration mitigation near sensitive facilities. The work further introduces two novel vibration quantification metrics, Passenger Car Vibration Equivalence (PCVE) and Reference Vibration Emission Level (RVEL), to standardize the vibrational impact of different vehicles under dynamic conditions. These indices form the basis for planning speed limits, estimating infrastructure exposure and regulating heavy vehicle flow through vibration-sensitive corridors.

Additionally, the study develops a robust and non-intrusive vehicle classification system using accelerometer-based vibration signals, achieving a classification accuracy of 99.78% using a machine learning-based stacked ensemble approach. It further integrates classified traffic data with GPS coordinates to construct a machine learning-based forecasting and route optimization model capable of predicting traffic composition and enabling vibration-aware routing. Together, these contributions form a cohesive, scalable system that supports smart infrastructure planning, real-time vehicle regulation, infrastructure fatigue monitoring and the formulation of vibration-sensitive zoning and policy mechanisms in urban transport networks.

9.7 Limitations and Future Scope

While the proposed framework demonstrates strong performance and practical potential across all four study domains, several limitations constrain its generalizability and real-time scalability. First, the speed hump vibration analysis was conducted in controlled field conditions on a limited range of pavement types and climatic conditions, which may not fully capture regional variability in soil dynamics or vehicle suspension responses. The PCVE and RVEL indices, while robust within the study context, assume consistent pavement stiffness and do not currently account for environmental variations such as temperature, moisture, or pavement aging. When extrapolating the metrics to different terrains or seasons, these factors may introduce uncertainty.

Although highly accurate under single-vehicle pass-by conditions, the vehicle classification model does not yet address the challenges of overlapping signatures under high-density traffic or simultaneous vehicle crossings. The current classification framework considers one vehicle pass-by at a time; future work should extend this to handle multiple simultaneous vehicle pass-bys using overlapped-signal decomposition and temporal feature disentanglement. Moreover, data acquisition was limited to bituminous pavements and dry-weather scenarios, necessitating validation on concrete surfaces and under varying environmental conditions. Manual vehicle labeling and classification were used to train the models, introducing subjectivity and scalability constraints. Similarly, the traffic forecasting model relied on pre-collected data and manual vehicle counts, limiting its real-time adaptability and ease of deployment in dynamically changing urban environments.

Despite these constraints, the research opens several avenues for impactful future work. One major direction is the extension of the RVEL-PCVE framework to account for compound loading scenarios, such as multi-axle vehicles, platooning and continuous high-density traffic streams. Incorporating additional contextual variables like road texture, slope, or subsoil properties can improve the accuracy and transferability of the vibration

metrics. Future versions of the classification system can integrate overlapped-signal separation and temporal correlation analysis to handle multi-vehicle scenarios and explore generalization to non-motorized and electric vehicle types.

Another critical direction involves deploying this system at scale using embedded hardware and edge processing. The framework can support roadside or vehicle-mounted deployments by adapting the sensing and classification algorithms to compact, low-power accelerometer modules with real-time processing capabilities. This enables large-scale vibration monitoring and dynamic vehicle regulation without relying on centralized computation or infrastructure-heavy setups.

From a planning and policy standpoint, future studies can explore the integration of this framework into municipal zoning laws, environmental impact assessments and road asset management platforms. Linking vibration data to pavement deterioration models, structural health indices and public health metrics would broaden the applicability of the system to multi-stressor urban resilience models. Additionally, integrating these vibration analytics with other urban data streams, such as noise, emissions, or energy use, would enable holistic, AI-driven urban planning models. Collectively, these advancements would position the proposed system not only as a technical contribution to civil and transportation engineering but as a critical component of sustainable and intelligent city infrastructures.

*“Data without rigor is noise.
Research without clarity is an undamped
vibration.”*

— Amar Deep Pandey