

Abstract

Urban infrastructure in rapidly developing regions is increasingly stressed by rising vehicular volumes, environmental degradation and structural aging. Among the associated challenges, traffic-induced vibrations (TIV) remain under-investigated despite being highly impactful. Their effects are especially severe in heterogeneous traffic environments, where mixed vehicle fleets, irregular speed control and unplanned geometric features amplify ground-borne vibrations. Sensitive facilities such as hospitals, laboratories, heritage structures and archives are particularly vulnerable, yet conventional urban planning frameworks rarely include vibration as a measurable design or regulatory parameter. This thesis addresses that gap by repositioning vibration as an operational variable within traffic engineering and urban mobility planning.

The central objective of this research is to create an integrated framework for the characterization, standardization, classification and control of traffic-induced vibrations under real-world mixed traffic conditions. Unlike existing approaches that treat vibrations as incidental by-products, this work establishes vibration as a parameter that can guide routing, speed regulation, zoning and infrastructure design.

The thesis makes four distinct contributions. First, it introduces two standardized vibration indices, Passenger Car Vibration Equivalence (PCVE) and Reference Vibration Emission Level (RVEL), as the first vibration-based analogues to the Passenger Car Unit (PCU). Second, it provides an empirical characterization of hump-induced vibrations using Variational Mode Decomposition (VMD) in Indian traffic, offering material and geometry-specific design recommendations for speed-control devices. Third, it develops a high-accuracy, non-intrusive vehicle classification model using ground vibrations that achieves 99.78% accuracy with ensemble learning, presenting a cost-effective and privacy-respecting alternative to camera or axle-based systems. Finally, it proposes a GPS-

augmented traffic forecasting and route optimization framework that integrates classified vehicle data with machine learning models to overcome the limitations of conventional GPS-based congestion monitoring.

The research follows a multi-stage methodology that combines empirical field experiments, signal decomposition, feature engineering and predictive modeling. In the first stage, tri-axial accelerometers were deployed on road segments featuring bitumen humps, fiber-reinforced humps and rumble strips. More than 500 vehicle traversals were recorded, spanning two-wheelers, three-wheelers, passenger cars, light commercial vehicles, buses and multi-axle trucks. VMD and band-pass filtering were applied to isolate dominant modes in the longitudinal, lateral and vertical directions. Features such as RMS, peak amplitude, energy, skewness, kurtosis and dominant frequency were extracted. Results showed that bitumen humps produced smoother, lower-energy vibrations, while fiber-reinforced humps and rumble strips generated up to 40% higher high-frequency content. These findings provide practical guidance: bitumen humps are better suited near vibration-sensitive zones, while fiber humps and rumble strips are more effective in enforcement-priority corridors.

In the second stage, vibration metric standardization was performed on smooth pavement sections. Over 9,257 single-vehicle pass-by events were recorded using tri-axial accelerometers and LIDAR speed guns across 11 vehicle categories. Frequency-domain and adaptive windowing methods were applied to extract directional vibration features. Two indices, PCVE and RVEL, were formulated to standardize vibrational impacts. PCVE quantifies a vehicle's vibration relative to a reference car at the same speed, while RVEL provides speed- and vehicle-specific thresholds through regression models. A Python-based software tool was also developed to operationalize these metrics in real time. Results confirmed that heavy vehicles, particularly multi-axle trucks, generate disproportionately

high vibration emissions, emphasizing the importance of speed regulation and zoning in sensitive areas.

The third stage develops a vibration-based vehicle classification model using signals from hump-free pavements. Energy-based features such as RMS, peak amplitude and summed squared accelerations were extracted. A stacked ensemble model combining Random Forest and XGBoost achieved 99.78% accuracy across eight vehicle types. The system was validated over 50 runs and under varied weather conditions, demonstrating consistent robustness. Even with reduced sensor setups, such as 2D accelerometers, the model maintained high accuracy, indicating strong potential for cost-effective and scalable deployment at toll booths, parking facilities and logistics hubs.

The final stage integrates vehicle classification data with GPS trajectories to develop a forecasting and routing framework. Machine learning models including ARIMA, SVM and XGBoost were trained on vehicle-wise traffic counts, achieving more than 95% forecasting accuracy. Unlike traditional GPS systems that equate passenger density with congestion, this approach incorporates vehicle type and vibration emissions, providing a more realistic view of traffic loads. Field trials in Varanasi showed that users guided by the GPS-augmented system experienced 15% lower travel times and 17% lower travel costs, proving its value in real-world scenarios.

Taken together, these four studies establish a unified vibration-aware traffic management framework. It enables real-time vehicle classification, standardized vibration quantification, predictive forecasting and vibration-sensitive route optimization, while also providing design recommendations for speed-control structures. The methodological novelties, including the introduction of PCVE and RVEL, the development of a near-perfect vibration-based classifier and the first GPS-augmented forecasting system to incorporate vibration impacts, make this the first comprehensive framework of its kind.

The framework has broad applications in urban planning, intelligent transportation systems and infrastructure protection. It can support zoning regulations around vibration-sensitive facilities, guide the design of speed-control structures near critical installations, enhance toll and traffic monitoring systems through non-intrusive vehicle classification, and optimize route guidance by integrating vibration costs into traffic forecasts. These applications demonstrate the operational relevance of embedding vibration into mobility planning, with direct benefits for safety, efficiency and resilience in rapidly urbanizing regions.