ABSTRACT

Road traffic crashes are one of the leading causes of death and injury worldwide, with low and middle-income countries carrying a disproportionate share of the burden. India, with only a small fraction of the world's vehicle population but nearly 11 per cent of global road fatalities, represents a prominent example of this disparity. Traditional crash-based safety analysis methods are reactive, relying on reported crashes that often suffer from underreporting, poor data quality, and long delays before patterns emerge and corrective measures are implemented. Surrogate Safety Measures (SSMs), which evaluate near-crash events and risky interactions, offer a more proactive approach. However, most existing SSMs were designed for lane-based, homogeneous traffic and are not well-suited to the highly heterogeneous, area-based traffic common in India and other countries with similar conditions.

This thesis develops an integrated framework for proactive road safety assessment that addresses these challenges by combining high-resolution traffic data, driver perception, and models of self-organising behaviour. Empirical data were collected through Unmanned Aerial Vehicles (UAVs), which provide detailed vehicle trajectories in complex traffic conditions. A new method was proposed for identifying interacting vehicle pairs in two-dimensional traffic, going beyond traditional leader-follower assumptions. The study also introduces the concept of the Virtual Perceived Boundary (VPB), a dynamic, context-sensitive envelope that reflects how drivers perceive the safe space around their vehicles. Unlike fixed vehicle dimensions, the VPB adjusts in real time according to vehicle type, speed, traffic density, and individual driving style, making safety analysis more reflective of drivers' behaviour.

Building on this, a novel composite risk index, the Motorised-Vulnerable Road User Risk Index (MVRI), was created to evaluate lateral conflicts involving motorised vulnerable road users (M-VRUs), who face the highest risk in mixed traffic. Statistical models, such as ordered logit and mixed ordered logit, were applied to classify interaction severity levels, with results showing the advantage of behaviourally informed measures over conventional approaches. At the microscopic modelling level, the thesis adapts a Self-Propelled Particle framework to represent vehicle-level speed and heading responses under local interactions in heterogeneous, area-based traffic. The model parameters are calibrated using observed UAV trajectories and optimisation techniques. Its performance is evaluated through vehicle-level velocity and heading prediction errors.

The present implementation is a trajectory-update model rather than a complete traffic-stream simulator. It predicts an individual vehicle's movement response using its observed state and surrounding interaction conditions. Its extension to a multi-agent simulation framework capable of generating complete synthetic trajectory datasets is identified as future work. Such an extension may eventually support trajectory-based surrogate safety analysis where sufficient empirical trajectory data are unavailable. Calibration using optimisation techniques ensured close alignment with observed data, while validation confirmed the robustness of the approach.

The results demonstrate that integrating driver perception and collective behaviour into safety analysis improves conflict detection and provides a more realistic understanding of traffic flow stability. The research highlights that crashes are not isolated events but the outcome of complex interactions shaped by behaviour and context. By embedding behavioural and system-level insights into safety models, the thesis offers a pathway to more effective interventions. The findings hold direct implications for infrastructure design, traffic management, simulation calibration, and policy development. Collectively, the studies establish a methodological sequence from validated microscopic trajectories and two-dimensional interaction identification to empirical spacing representation and conflict-risk estimation, while the SPP analysis provides a related foundation for future trajectory simulation.