Abstract

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Traffic operating under heterogeneous and weakly lane-disciplined conditions exhibit complex collective behavior arising from nonlinear vehicle interactions, mixed vehicle classes, and continuous adjustments in both longitudinal and lateral directions. Such disordered traffic environments pose significant challenges to conventional macroscopic traffic flow models, which were primarily developed for lane-based and highly regulated traffic streams. In these settings, vehicles do not remain confined to fixed lanes and frequently utilize available road space laterally, resulting in spatiotemporal traffic patterns that cannot be adequately described by classical one-dimensional formulations.

Macroscopic traffic models describe traffic as a continuum and characterize its evolution using aggregate variables such as density, speed, and flow. While first-order models based on conservation laws have been successful in explaining basic traffic phenomena, they are unable to represent several important features of real traffic, including, traffic hysteresis, capacity drop and instabilities. Higher-order macroscopic models were introduced to overcome some of these limitations by incorporating additional dynamic equations. However, most existing models remain restricted to one-dimensional motion and therefore fail to capture the lateral interactions that are intrinsic to disordered traffic flow. Motivated by these limitations, this thesis develops a higher-order, two-dimensional macroscopic framework for modeling disordered traffic. The proposed approach explicitly incorporates both longitudinal and lateral vehicle dynamics along with the repulsive forces from the road boundary, enabling a more realistic representation of traffic behavior in lane-free environments. The thesis combines theoretical model development with numerical analysis and simulation studies to investigate the emergence of complex traffic phenomena under disordered traffic conditions. The work presented in this thesis is organized into three main parts as discussed in the sections below.

The first major contribution of this thesis is the formulation of a two-dimensional macroscopic traffic flow model developed for disordered traffic conditions. Unlike conventional one-dimensional models, the proposed framework allows vehicle motion in both longitudinal and lateral directions, reflecting the continuous repositioning behavior observed in disordered traffic streams. Hence, in this study, the one-dimensional continuity equation is first extended to a two-dimensional form, ensuring mass conservation while accommodating lateral vehicle movement. Subsequently, acceleration equations are proposed separately in the longitudinal and lateral directions to fully describe macroscopic higher-order traffic flow models, which can be formulated using microscopic theoretical frameworks. Longitudinal dynamics are derived from underlying microscopic dynamics, such as the Full Velocity Difference Model (FVDM), which accounts for self-driven behavior and vehicle interactions, with the addition of repulsive road boundary effects, enabling the representation of non-equilibrium traffic states and complex traffic patterns. The lateral dynamics equations are derived using the gradient of longitudinal interaction in the lateral direction, the gradient of road repulsive force in the lateral direction, and lateral desired speed, which describe how vehicles redistribute across the road width in response to local traffic conditions, interaction forces, and boundary constraints. By coupling the longitudinal and lateral components within a unified continuum framework, the proposed model captures key characteristics of disordered traffic, including space-sharing behavior, lane indiscipline, and the influence of road geometry. This formulation represents a significant extension of existing macroscopic models and provides a foundation for analyzing traffic as a genuinely two-dimensional collective system.

The second major contribution of the thesis is therefore the development of a numerical solution framework tailored to the two-dimensional higher-order model. Appropriate numerical schemes are designed to solve the longitudinal and lateral dynamics while preserving stability, accuracy, and physical consistency. The longitudinal equations are discretized using Upwind scheme to respect the directional propagation of traffic information, whereas the lateral dynamics are addressed using Lax Friedrichs scheme that handle diffusion and interaction effects. Special attention is given to the treatment of road boundaries to ensure realistic no-flux conditions and conservation of vehicle mass. The numerical framework is tested under various initial and boundary conditions to assess its robustness and stability. Stability criteria are examined to ensure reliable long-term simulations, and the interaction between longitudinal and lateral dynamics is carefully analyzed. This numerical infrastructure enables the systematic investigation of complex traffic behavior that cannot be captured using one-dimensional models.

The third part of the thesis focuses on extensive numerical experiments designed to evaluate the performance and predictive capability of the proposed model. Simulations are conducted using a wide range of initial density distributions to study the evolution of traffic under different congestion patterns and spatial configurations. The results demonstrate the model's ability to reproduce key features of disordered traffic, such as lateral redistribution of vehicles, formation and propagation of congestion patterns, and interaction-driven density evolution. The combined longitudinal–lateral simulations highlight how lateral movement influences the development and dissipation of traffic congestion over time.

Overall, this thesis advances the macroscopic modeling of disordered traffic by introducing a two-dimensional continuum framework that bridges the gap between traditional traffic flow theory and real-world disordered traffic behavior. By integrating longitudinal and lateral dynamics within a single modeling and numerical framework, the work provides deeper insight into the collective mechanisms governing lane-free traffic systems.

High-resolution vehicle trajectory data have already been collected from urban arterial roads in Chennai, India, using unmanned aerial vehicles. This unique dataset provides detailed spatiotemporal information on vehicle movements under heterogeneous, lane-free traffic conditions. In future studies, this data will be used to calibrate and validate the proposed two-dimensional macroscopic model and to estimate the associated model parameters governing longitudinal and lateral vehicle dynamics.