Analysis of Traffic Flow Characteristics in Lane-Free Traffic

Master's Thesis of Hanwen Zhang

Mentoring: Dr. Majid Rostami-Shahrbabaki
M.Sc Patrick Malcolm

Lane-free traffic (LFT) is a paradigm where there are no lane marks, and CAVs have the freedom to choose arbitrary lateral positions on the road. In this context, vehicles exert inter-vehicle forces: the rear vehicles apply ''nudging force'' forward when approaching the front vehicle, while the front vehicles exert ''repulsive force'' backward.

Research Objectives

1) Analysis of macroscopic flow dynamics for LFT.
2) Conceptualizing safety criteria for LFT.
3) Mathematical modeling considering inter-vehicle forces in LFT.

Simulation-Based Traffic Flow Analysis

Traffic simulations are conducted to gain insights into the macroscopic characteristics of traffic flow, the fundamental diagrams (FD) are as follows.

Fundamental Diagrams

Figure 1 demonstrates a $10.2\ m$ wide lane-free freeway achieving a stable peak flow at $240\ veh/km$, tripling the capacity of a traditional three-lane freeway. Figure 2 suggests that the maximum flow per width value rises with increasing freeway widths, with the $3.2\ m$ width consistently indicating the lowest values across all simulated densities.

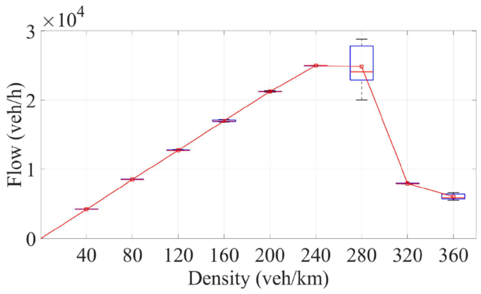

Figure 1. FD of 10.2m Wide Freeway

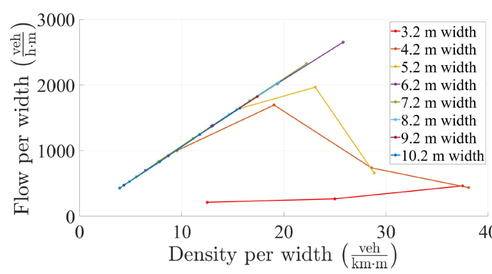

Figure 2. FD of Freeways in Various Width

Contour Plots

A contour plot is relevant for analyzing traffic flow dynamics. Figure 3 illustrates the state where vehicles accelerate from a standstill to the state close to their desired speed at $240\ veh/km$, under a $10.2\ m$ width freeway.

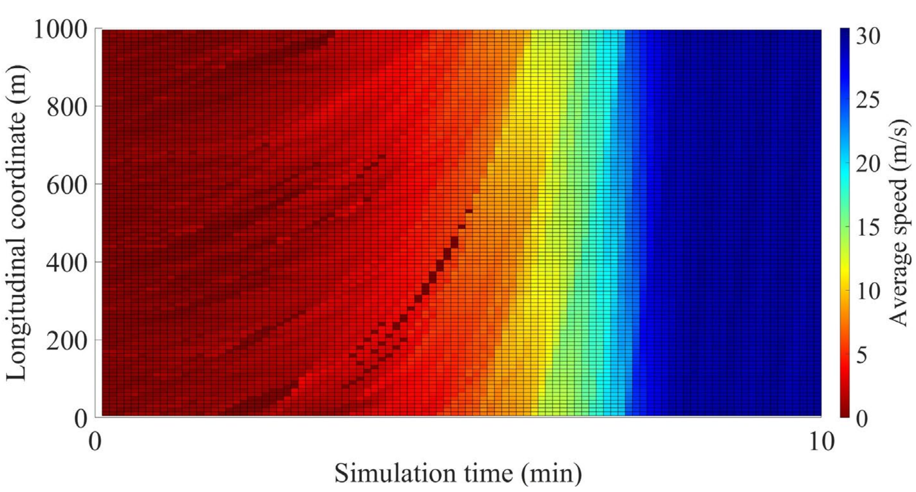

Figure 3. Speed Contour Plot of Simulation

Safety Criteria Conceptualization

Developing a Safety Criteria for LFT is crucial to assess its safety level. The industry-recognized parameter, time-to-collision (TTC), is an ideal criterion for evaluating traffic safety in the context of LFT.

Two-Dimensional Time-To-Collision

In CAV environments, sharing vehicle dynamics allows easy calculation of TTC using relative position $\vec{D}_{eff}$ and acceleration $\vec{a}_r$.

$$t_1, t_2 = \frac{-(\vec{V_r} \cdot \vec{D_{\text{eff}}}) \pm \sqrt{(\vec{V_r} \cdot \vec{D_{\text{eff}}})^2 - 2(\vec{a_r} \cdot \vec{D_{\text{eff}}})\|\vec{D_{\text{eff}}}\|^2}}{\vec{a_r} \cdot \vec{D_{\text{eff}}}}$$

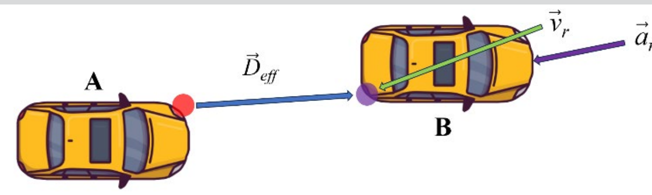

Figure 4. Relative positions and speeds and accelerations

For the t_1 and t_2, we take the smaller positive value as the final result of TTC.

Time-To-Collision Bound

TTC of a CAV at each time step k, step $k+1$, step $k+2\dots$ should not exceed the bound TTC_{min}:

$$TTC(k+2) \leq TTC_{\text{min}}$$

By incorporating this bound into the system input constraints, we ensure that the CAV maintains a TTC above TTC_{min} during operation. Additionally, the TTC bound enhances comfort by concentrating vehicle dynamics within a smaller range, as Figure 5, and causing a more uniform average time headway distribution across the width, as Figure 6 shows.

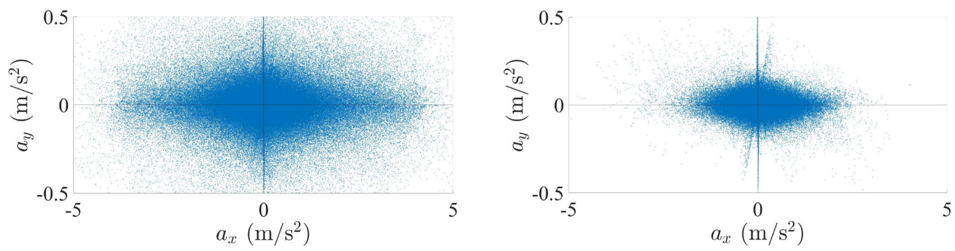

Figure 5. Acceleration distribution of scenarios without TTC bound and TTC bound 0.35s

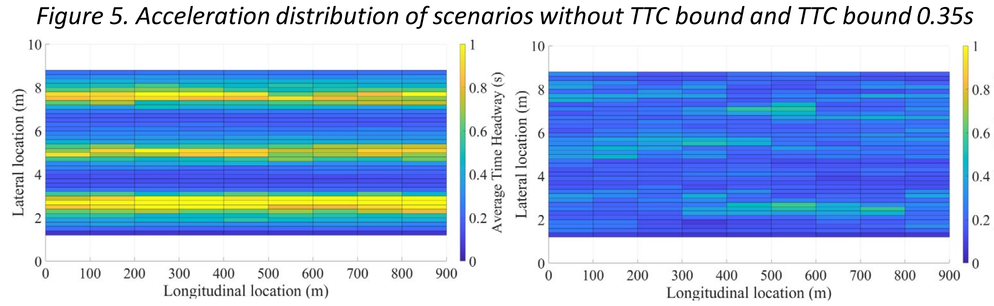

Figure 6. Average headway of scenarios without TTC bound and TTC bound 0.35s

Mathematical Modeling of Lane-Free Traffic Flow

A numerical solution was developed using the adapted LWR model, considering inter-vehicle forces in LFT. The central difference method was utilized for spatial discretization, while the CFL condition determined the simulation step length. Neumann conditions were set as boundary constraints, and the Godunov scheme was applied to solve flow. As a form of validation, a higher flow at the road's right end was introduced, and for showing the evolution of traffic flow, simulation steps $t=1$, $t=10$, $t=30$, and $t=80$, as illustrated in Figure 7.

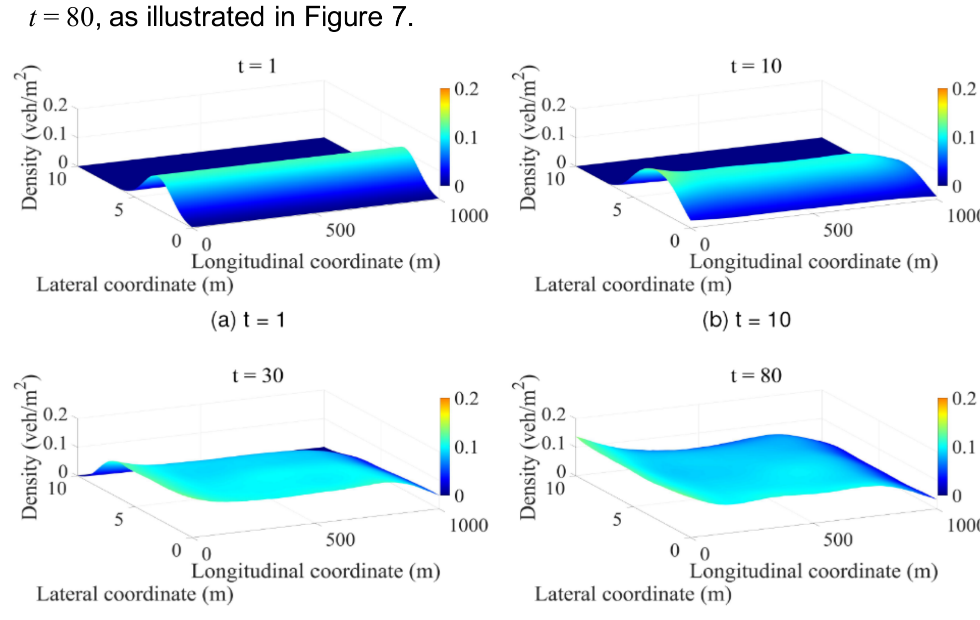

Figure 7. Traffic Flow Dynamics Over Time from Numerical Solutions

Technische Universität München
Lehrstuhl für Verkehrstechnik
Univ.-Prof. Dr.-Ing. Klaus Bogenberger