Effects of Mixed Traffic on Fundamental Diagrams at Unsignalized Intersections

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Abstract

This report examines the effect of mixed traffic, specifically the variation in robot vehicle (RV) penetration rates, on the fundamental diagrams at unsignalized intersections. Through a series of simulations across four distinct intersections, the relationship between traffic flow characteristics were analyzed. The RV penetration rates were varied from 0% to 100% in increments of 25%. The study reveals that while the presence of RVs influences traffic dynamics, the impact on flow and speed is not uniform across different levels of RV penetration. The fundamental diagrams indicate that intersections may experience an increase in capacity with varying levels of RVs, but this trend does not consistently hold as RV penetration approaches 100%. The variability observed across intersections suggests that local factors possibly influence the traffic flow characteristics. These findings highlight the complexity of integrating RVs into the existing traffic system and underscore the need for intersection-specific traffic management strategies to accommodate the transition towards increased RV presence.

1. Introduction

Our transportation systems are on the verge of a significant transformation with the introduction of robot vehicles (RVs). These vehicles differ in their driving behavior compared to human drivers, potentially impacting traffic flow in new ways (James et al. (2018)). Fundamental diagrams (FDs), which depict the relationship between traffic flow, density, and speed, serve as a cornerstone for understanding these dynamics (Greenberg (1959), Daganzo (1997)). Traditional FDs, however, are based on human-driven vehicle behaviors, raising questions about their applicability in mixed traffic scenarios that include RVs.

Recent advancements in RV technology, particularly features like Adaptive Cruise Control (ACC), have introduced new vehicle behaviors into the traffic stream. These behaviors differ fundamentally from those of human drivers, due to the precise, prescriptive, and fast-responding nature of RV control systems. As RV penetration rates increase, understanding how these technologies impact traffic flow characteristics becomes crucial for traffic management and infrastructure planning.

Empirical studies and theoretical models have begun to explore the impacts of RVs on traffic flow. For instance, Shi & Li (2021) conducted field experiments with commercial RVs to construct FDs for RV traffic, revealing that while the shortest RV headway setting can significantly improve road capacity, other settings may decrease it compared to human-driven traffic. Similarly, Makridis et al. (2024) proposed a method to derive FDs from platoon vehicle trajectories, highlighting the potential for ACC systems to enhance capacity and the distinct behaviors of human drivers compared to partially automated vehicles.

Helbing et al. (2007) conducted research on the transitions from laminar to stop-and-go and turbulent flows in high-density scenarios, such as crowd movements during disasters, which can offer insights into similar transitions in vehicular traffic. These studies highlight the importance of understanding the conditions that lead to such transitions, which can have implications for traffic safety and efficiency as well.

In addition to empirical studies, simulation-based research has been instrumental in understanding traffic flow dynamics. The research by Shang & Stern (2021) introduces a numerical method to estimate the composite FD for mixed human-piloted and automated traffic flow, providing insights into macroscopic traffic behavior at different RV market penetration rates. Furthermore, Lu et al. (2018) investigated the impacts of RVs on the urban Macroscopic Fundamental Diagram (MFD) through traffic simulation, emphasizing the need to reassess traffic dynamics and control methodologies in light of RV integration. Their findings suggest that while RVs can improve traffic efficiency, particularly at high penetration rates, the benefits are less pronounced at lower levels of RV integration.

This report aims to extend the current understanding of mixed traffic impacts on fundamental diagrams at unsignalized intersections. By analyzing fundamental diagrams obtained from simulations across four intersections with varying RV penetration rates, we seek to identify patterns and draw conclusions about the effects of mixed traffic on traffic flow characteristics. This analysis is crucial for developing effective traffic management strategies and infrastructure designs that can accommodate the transition towards increased RV presence in urban traffic systems.

2. Method

2.1 Traffic Flow Variables

The variables which are the building blocks of the fundamental diagrams are speed, density, and flow:

- **Speed (V):** The average speed of vehicles passing through a segment of the road network during a specified time interval.
- **Density (k):** The number of vehicles occupying a given length of a lane or roadway at a particular instant in time, typically expressed as vehicles per kilometer.
- **Flow (Q):** The rate at which vehicles pass a reference point on the road, usually expressed as vehicles per hour.

The relationship among these variables are given by the following equation:

$$Q = k.V \tag{1}$$

2.2 Mixed Traffic Control

The control and coordination of vehicles in mixed traffic environment was accomplished following the approach proposed by Wang et al. (2023). The authors present a decentralized multi-agent reinforcement learning approach to handle mixed traffic at unsignalized intersections. Each RV uses a deep reinforcement learning policy to decide whether to stop or go at the intersection entrance, based on observing the surrounding traffic conditions. The policy is trained with a novel conflict-aware reward function that considers both traffic efficiency and potential conflicts between vehicles inside the intersection. A fail-safe coordination mechanism is implemented to eliminate conflicts between RVs at the intersection entrance.

2.3 Data Collection and Processing

The data for this study was collected using the Simulation of Urban MObility (SUMO) platform (Behrisch et al. (2011)), a highly versatile tool for simulating vehicular traffic. The network with the four intersections referenced in Wang et al. (2023) was used and reconstructed in SUMO for simulation purpose[1]. Simulations were run for each unsignalized intersection, with RV penetration rates varying from 0% to 100% in increments of 25%. Each simulation was executed three times to ensure the robustness of the data. The raw simulation data was processed to calculate the average speed, density, and flow for each intersection and RV penetration rate using the SUMO API[2]. The data points obtained from the simulations were approximated with polynomial curve fitting to construct the fundamental diagrams. The diagrams were then analyzed to identify any trends or patterns across the different RV penetration rates.

[1] https://coloradosprings.gov/

[2] https://sumo.dlr.de/docs/Tutorials/FundamentalDiagram.html

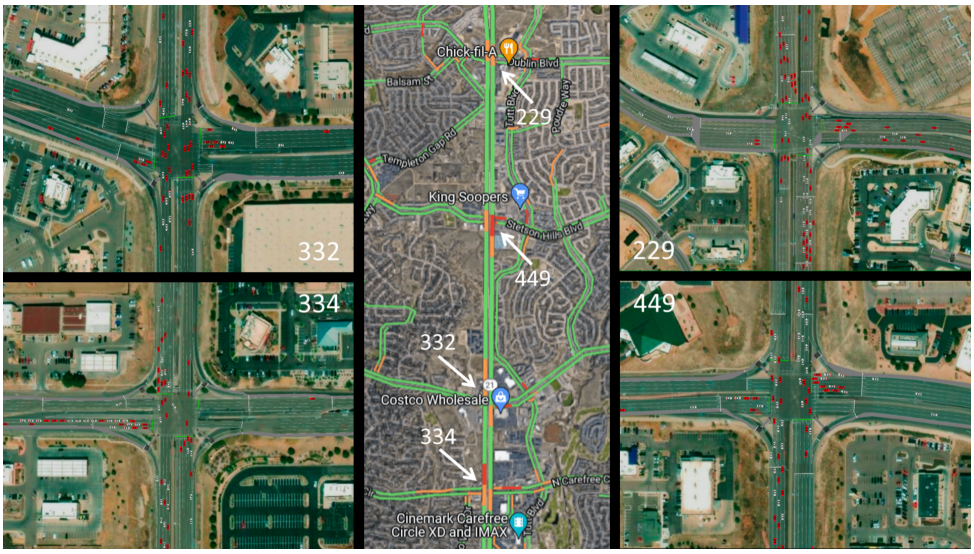

Figure 1: The four intersections in our study.

3. Simulation Results

The main results of the simulations are shown in Figure 2 and Table 1.

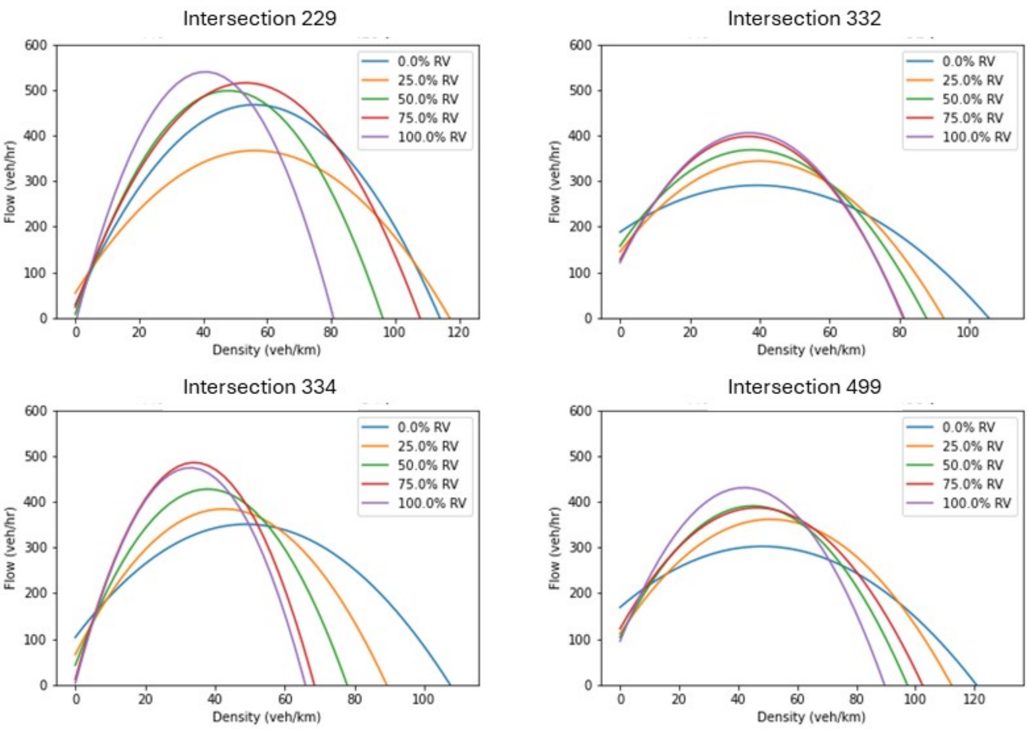

Figure 2: Fundamental diagrams for the four intersections with different RV penetration rates.

Based on the fundamental diagrams provided for the four intersections (Intersection 229, Intersection 332, Intersection 334, and Intersection 499), we can make the following observations:

1. **Capacity and Congestion:** Each diagram shows a typical flow-density relationship where the flow increases with density up to a certain point (k_{crit}), representing

Table 1: Polynomial Curve Fitting results ($Q = a.k^2 + b.k + c$)

		RV penetration rate				
		0%	**25%**	**50%**	**75%**	**100%**
Intersection 229	$\boldsymbol{a}$	-0.1393	-0.0989	-0.2139	-0.1734	-0.3352
	$\boldsymbol{b}$	15.6328	11.1185	20.4725	18.4663	27.2215
	$\boldsymbol{c}$	28.9790	54.4617	8.2439	23.5990	-13.05
	$\boldsymbol{k_{crit}}$	56	56	47	53	40
	$\boldsymbol{Q_{max}}$	467	366	498	515	539
Intersection 332	$\boldsymbol{a}$	-6.6169e-02	-1.2396e-01	-1.4762e-01	-0.2004	-0.2083
	$\boldsymbol{b}$	5.2102	9.9307	1.1160e01	14.7409	15.4011
	$\boldsymbol{c}$	1.8808e02	1.4503e02	1.5746e02	126.8757	121.0471
	$\boldsymbol{k_{crit}}$	40	40	38	35	35
	$\boldsymbol{Q_{max}}$	290	343	368	397	405
Intersection 334	$\boldsymbol{a}$	-1.0274e-01	-0.1759	-0.2673	-0.4086	-0.4345
	$\boldsymbol{b}$	1.0076e01	14.9598	20.2782	27.8169	28.6025
	$\boldsymbol{c}$	1.0347e02	65.9486	42.7053	11.8798	3.2201
	$\boldsymbol{k_{crit}}$	49	42	38	33	33
	$\boldsymbol{Q_{max}}$	350	384	427	485	473
Intersection 499	$\boldsymbol{a}$	-5.7432e-02	-9.6184e-02	-0.1421	-0.1230	-0.1901
	$\boldsymbol{b}$	5.5317	9.8022	12.7652	11.4029	15.9693
	$\boldsymbol{c}$	1.6902e02	1.1164e02	104.0837	122.3450	95.1565
	$\boldsymbol{k_{crit}}$	47	50	45	45	42
	$\boldsymbol{Q_{max}}$	302	361	390	386	430

the capacity (Q_{max}) of the intersection. Beyond this point, the flow decreases as density continues to increase, indicating congestion.

2. **RV Penetration Impact:** The curves for different RV penetration rates (0%, 25%, 50%, 75%, and 100%) show that the flow generally increases with density up to the capacity limit. However, the peak flow (capacity) and the density at which this peak occurs vary slightly with different RV penetration rates.

3. **Curve Shape:** The shape of the curves is similar across all intersections, suggesting that the fundamental relationship between flow and density is consistent, but the specific values for capacity and the onset of congestion differ.

4. **Variability:** There is variability in the flow-density relationship across the intersections, which could be due to differences in intersection design, traffic control

measures, or other local factors affecting traffic flow.

General conclusions that can be made from these diagrams are:

- There is a positive correlation between flow and density up to the capacity limit for all intersections and RV penetration rates.
- The presence of RVs affects the flow-density relationship, but the impact varies across different levels of RV penetration and may not be linear.
- The capacity and onset of congestion are influenced by the level of RV penetration, but the exact nature of this influence requires further analysis.
- The variability observed across intersections suggests that local factors play a significant role in traffic dynamics, and a one-size-fits-all approach may not be suitable for traffic management strategies at unsignalized intersections.

These observations can inform traffic engineers and planners about the potential impacts of RVs on traffic flow and help guide the development of strategies for managing mixed traffic conditions.

4. Conclusions

The objective of this study was to investigate the effects of increasing RV penetration rates on the fundamental diagrams of traffic flow at unsignalized intersections. While the analysis did not yield any clear or consistent patterns, the process highlighted the challenges and complexities involved in modeling and understanding mixed traffic systems. Further research and refinements to the simulation framework or traffic models may be necessary to uncover potential patterns or relationships.

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