Self-Organized Platooning in Heterogeneous Human-Driven and Autonomous Traffic Flow: Simulation Evidence and Implications for Behavior Design

Sadman Ahmed Shanto
Department of Physics and Astronomy
Texas Tech University

Jia Li, PhD.
Department of Civil, Environmental, and Construction Engineering
Texas Tech University

December 25, 2019

Abstract

Keywords: Travel behaviors, Cellular Automata, Automated Vehicles, Mixed Traffic Flow, Platooning

1. Introduction

Our work reveals the existence of self-organized clustering (platooning) and lane formation in mixed traffic flow of autonomous vehicles (AVs) and human-driven vehicles (HVs) based on simulation experiments. We propose a parsimonious Cellular Automata model to capture the different characters of AVs and HVs as well as their interactions. AVs are endowed with opportunistic behaviors, reflected through gap seeking and awareness of neighbor vehicle types. We compare clustering and lane formation properties and mixed flow flux in three scenarios, accounting for the impact of two distinct AV behavior types and a control case of homogeneous flow. We observe that, intriguingly, even with this relatively simple model, AVs demonstrate self-organized properties in the mixed traffic flow. AVs form into clusters (i.e. platoons) and even lanes on their own in the mixed flow, without centralized control. Such phenomena seem to relate to the intrinsic incentives that AVs perceive and their ability to tell neighbor vehicle types. This finding suggests the possibility of regulating mixed AV-HV flow through distributed incentives, rather than centralized coordination. Furthermore, we also study the effect that each of these models have on the flux of the mixed traffic flow through a Fundamental Diagram Analysis. We find that the neighbor-aware opportunistic AV model results improves both the overall and individual vehicle class traffic flow due to the prominent self-organized clustering phenomenon.

2. Methodology

In our paper, we adapt the Cellular Automaton model to introduce a model of mixed traffic flow of HVs and AVs that captures two potential behaviors of AVs -*opportunistic*, and *neighbor awareness* - and the control case of HV-like behavior [2]. We distinguish between the two classes of vehicles [1][3] and the three models of AV in our simulation by assigning different behavioral parameters to each vehicle type (See Table 1).

The opportunistic model of the AV is modeled to be purely opportunistic and while satisfying the safety constraints, whereas, the neighbor aware model of the AV is such that it is both opportunistic and aware of the type of the neighboring cars. As a result, the AV can adjust its headway depending on the type of car it trails. Equations 1 to 4 shows the changes needed to implement such a model in the CA framework. In the base scenario model, the AV behaves identically to an HV.

$$v_{max} = \begin{cases} v_{aa} & \text{if } AV - AV \\ v_{ah} & \text{if } AV - HV \\ v_h & \text{if } HV \end{cases} \tag{1}$$

$$v_{aa} > v_{ah} \geq v_h \tag{2}$$

$$v'_{l'} = min(v'_{max}, d_{back}) \tag{3}$$

$$v'_j = min(min(v'_j + 1, v'_{max}), d_j) \tag{4}$$

We conduct two simulation experiments with the purpose of studying the impact of the three models of AV on the overall traffic flow and understanding any emergent patterns of collective behavior. In both the experiments, we consider a circular road with three lanes of equal length. At the beginning of each simulation, the vehicles are distributed randomly on the road with zero velocity; the vehicle type is determined stochastically upon allocation. We record various traffic-flow and clustering parameters each time step for both the experiments.

For experiment 1, we simulate the traffic flow for each of these three models for the same number of simulation time steps for three different densities corresponding to a low-occupancy, critical and high occupancy state for the road. The proportion of AV, throughout the experiment, was kept constant at 33%. In experiment 2 we again consider the three models of AV but increase the system density linearly till it reaches the jam density. We allow the simulation to run for a fixed number of time steps for each system density before incrementing it. The results from these experiments were used to test our hypothesis.

3. Results and Discussion

The summary of our results from experiment 1 is presented in Table 2, where the "cluster no." is the number of distinct clusters present at each time step, and the survival time is calculated as the number of time-steps each distinct cluster lasts in the simulation. These results prove that if AVs are aware of other AVs under ideal occupancy states - low to critical density - they would engage in collective behavior without any centralized command and display clustering phenomenon as long as they share common incentive of being opportunistic. This implies that is possible to design AV behavior that can form self-organized clusters.

Our results from experiment 2 show that the opportunistic model of AV leads to the best overall throughput, with the Fundamental Diagrams for both AV and RV showing the highest maximum flow (See Figure 1). This is not surprising, considering that AVs and HVs had a higher maximum speed allowed (See Table 1) compared to the neighbor aware model. In the case of the Base Scenario model, where both types of cars had the highest allowed maximum speed, it was still not the best performing model because it was the most stochastic. The neighbor aware model had the smallest overall maximum speed for each class, and yet it had a better throughput than the base scenario model and had a comparable performance with the opportunistic model. These findings argue that the clustering phenomenon does indeed improve traffic flow by allowing opportunistic neighbor aware AVs to seek and trail one another and maintain shorter headways leading to higher speeds for the AV class and more open space for the HV class, which they may use to travel at higher speeds.

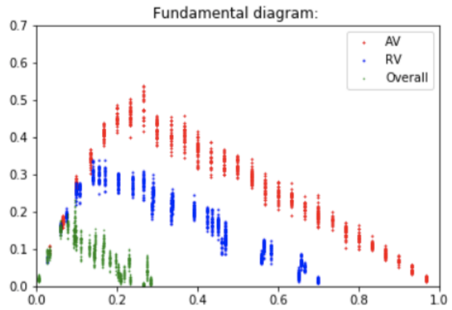
4. Conclusions

Our investigation into the behaviors of mixed traffic flow of AVs and HVs through simulation experiments to understand the relation between opportunistic behaviors of AV and formation of clusters and lanes without centralized control has led us to propose a new cellular automata model to account for potential behavior differences between AVs and HVs. We devised three models for AVs - opportunistic, neighbor vehicle type aware and HV like. Simulation experiments were conducted in two scenarios, which compare the clustering process and traffic flow performance with the three models of AV at both fixed densities and linearly increasing densities.

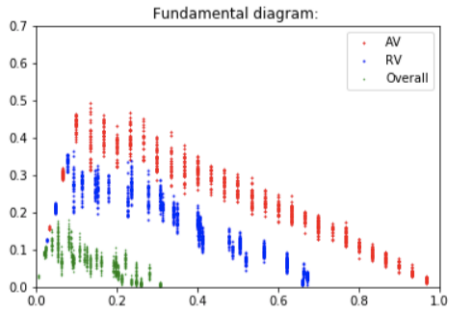
One major finding of this research, which is intriguing, is the self-organized formation of AV clusters and lanes without any centralized control. This may suggest clustering as an intrinsic property of mixed HV and AV flow. We postulate such self-organized phenomena is due to the incentives that AVs perceive to seek and partner with peer AVs. When AVs are opportunistic, such effect is reinforced, as seen in our experiment. If the postulation is confirmed to be true through further simulation or field experiments, it may suggest the possibility of regulating mixed HV-AV flow through designing or inducing decentralized incentives, instead of performing centralized coordination. Our research also compares the mixed flux in all scenarios, and the positive effect of the clustering phenomenon is confirmed.

The findings of this paper may serve as initial evidence to the self-organization in mixed flow of AVs and HVs. We recognized the proposed model is by no means realistic in the quantitative sense. In addition, as AVs haven't been launched in large scale in the real world and existing data is limited, their opportunistic behavior just represent on possibility we deem likely. In future works, as more data become available, it is desirable to model the decision-making of AVs more realistically, and further verify the finding in this paper.

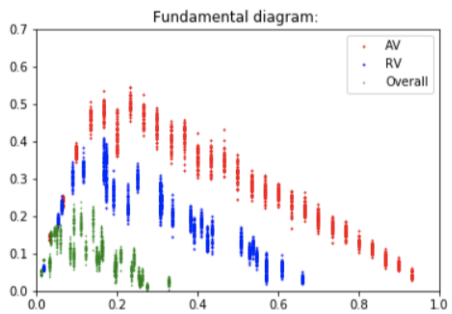
***Figures and Tables**



(a) Combined FD: Neighbor Aware Model



(b) Combined FD: Base Scenario Model



(c) Combined FD: Opportunistic Model

Figure 1: Fundamental Diagram Plots for different AV models

Parameter	Neighbor Aware	Opportunistic	Base Scenario
$p_l(HV)$	0.6	0.6	0.6
$p_l(AV)$	1	1	0.6
$p_s(HV)$	0.4	0.4	0.4
$p_s(AV)$	0	0	0.4
v_{aa}	5	5	5
v_{ah}	4	5	5
v_h	3	4	5

Table 1: Table of parameter values used in the three test cases of Experiment 1 and 2

Low Density Regime		
AV Model	cluster no.	survival time
opportunistic	1.0	6.21
neighbor aware	1.0	11.69
base model	1.0	1.13
Critical Density Regime		
AV Model	cluster no.	survival time
opportunistic	1.27	13.17
neighbor aware	1.49	28.97
base model	1.28	16.56
High Density Regime		
AV Model	cluster no.	survival time
opportunistic	4.94	1200.0
neighbor aware	4.88	1200.0
base model	5.16	1200.0

Table 2: Weighted average of parameters collected from Experiment 1

References

[1] K. Nagel. A cellular automaton model for freeway traffic. *Physical Review E*, 3(6):4655–4672, 1995.

[2] K. Nagel and M. Schreckenberg. A cellular automaton model for freeway traffic. *Journal de Physique*, 2:2221–2229, 1992.

[3] N. K. S. M. Rickert, M. and A. Latour. Two lane traffic simulations using cellular automata. *Physica A*, 3(6):4655–4672, 1995.