Spontaneous Platooning in Heterogeneous Traffic Flow and Implications for Decentralized Autonomous Vehicle Control

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1 Introduction

The advent of autonomous vehicles (AVs) makes it imperative to consider their interactions of human-driven vehicles (HVs), so as to understand the collective properties of heterogeneous traffic flow and design effective control strategies to regulate their interactions. Platooning, among other properties, is one of the most important character to be considered. It is known that platooning may increase the effective capacity of traffic flow (due to smaller spacing) and potentially stabilize traffic flow. According to whether a centralized mechanism exists to enable platooning, we may categorize platooning into spontaneous and coordinated ones. The focus of this study is the spontaneous platooning in heterogeneous traffic flow.

In particular, we attempt to answer the following question: if AVs can be endowed with certain behavior properties, how would these properties influence the platooning properties of heterogeneous traffic flow consisting of AVs and HVs? We develop a parsimonious Cellular Automata model to capture the interactions of two types of agents (namely HVs and AVs) and conduct simulation experiments to answer this question. Two potential decentralized properties of AVs are considered, namely neighbor awareness and opportunisticity. We compare the platooning properties of heterogeneous traffic flow 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 may form into platoons spontaneously, without centralized control. These platoons may or may not sustain depending on overall traffic density. The platoon sizes also differ when the behavior properties of AVs change. We postulate that such phenomena are related to the intrinsic incentives that AVs perceive and their ability to tell neighbor vehicle types. In addition, we also study the effect that each of these models have on the flux of the mixed traffic flow. 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.

Our study suggests the possibility of regulating mixed heterogeneous AV-HV flow through modifying individual AV's driving preferences/behaviors, instead of centralized coordination. The findings may serve as a first step towards more rigorous decentralized autonomous vehicle control design and analysis in heterogeneous traffic flow.

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2 Methodology

We develop a simulation model based on the Cellular Automata framework and conduct simulation experiments to capture the interactions of two classes of vehicles, i.e. HVs and AVs. We consider three hierarchies of AV behavioral scenarios in our model, namely *opportunistic driving*, *neighbor awareness*, and *HV-like behavior*.

HV-like behavior. In this case, AVs and HVs behave identically. This serves as the control case in our simulation experiments.

Opportunistic driving. The opportunistic property aims to capture the better sensing and maneuvering capability and more willingness of an AV to seek gaps and change lanes to improve its speed. This is captured through the parameter of lane changing probability (see Table 1).

Neighbor awareness. Neighbor awareness refers to that an AV is opportunistic, and in addition, it is aware of the type of the neighboring cars, so that it can adjust its headway depending on the type of car it trails, leveraging technologies such as CACC (Cooperative Adaptive Cruise Control).

The different behaviors are captured through behavioral parameters assigned to each agent, which are summarized in Table 1. A key difference of our model from the conventional CA models is the dependence of maximum speed on the type of vehicle it is following, as shown in (1).

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

where $v_{aa} > v_{ah} \geq v_h$ are the maximum speed in each scenario. This dependency allows us to account for the neighbor awareness mentioned above. The opportunistic behaviors are captured through lane-change probabilities. Parameter values used in the experiments are summarized in Table 1. Here $p_l(\cdot)$ refers to probability of lane-changing, and $p_s(\cdot)$ refers to probability of taking a random brake.

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

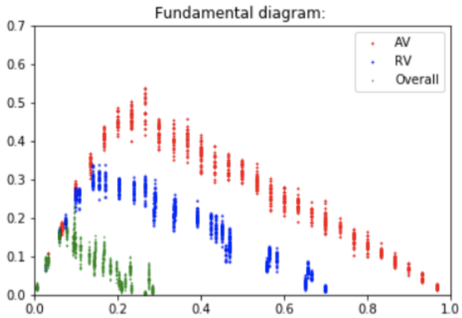
Table 1: Parameters used in simulation experiments

We conduct two simulation experiments to study the impacts of the three AV behaviors on the overall traffic flow, and in particular, the properties of platooning. 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.

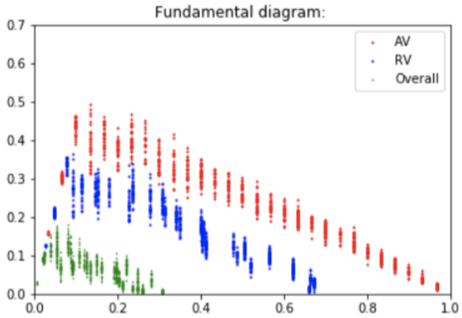
In experiment 1, we simulate each of these three models for the same number of simulation time steps at three different densities levels, corresponding respectively to low-occupancy, critical and high-occupancy state. The proportion of AV was kept constant at 33% throughout all the experiment. In experiment 2 we again consider the three behavior scenarios of AVs but increase the system density linearly till it reaches the jam density. We let the simulation run for a fixed number of time steps at each system density.

3 Results

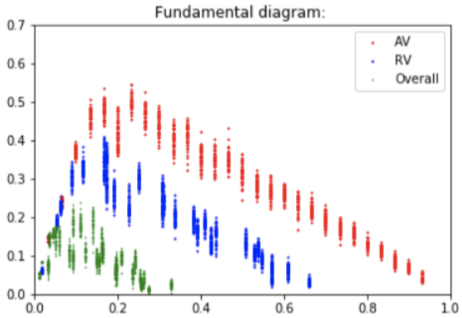
Results from experiment 2, as depicted in Figure 1, shows that the opportunistic model of AV leads to the best overall throughput, with the Fundamental Diagrams for both AV and RV showing the highest maximum flow. This is not surprising, considering that AVs and HVs had a higher maximum speed (See Table 1), compared to the neighbor aware model. In the case of the Base Scenario model, even though both types of cars had the highest allowed maximum speed, it was still not the best performing model, which may be attributed to the strong stochasticity in both lane-changing and braking.



(a) Combined FD: Neighbor Aware Model



(b) Combined FD: Base Scenario Model



(c) Combined FD: Opportunistic Model

Figure 1: Fundamental diagrams in each scenarios

Results from experiment 1 are summarized 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 organize themselves into platoons without any centralized command, as long as they are all opportunistic.

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 from Experiment 1 (We note that 1200 is the simulation time steps. Survival time of 1200 indicates that platoon structures are unchanged, due to difficulty of lane-changing and overtaking in high density.)

Overall, the neighbor-aware scenario had the smallest overall maximum speed for each class, but a better throughput than the base scenario model. The opportunistic scenario seems to outperform the other two scenarios. The experiments confirm the impacts of individual AV behaviors on platooning in heterogeneous traffic flow. These findings suggest that the platooning 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 Conclusion

One major finding of this research, which is intriguing, is the self-organized formation of AV platoons without 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 proposed model is by no means realistic in the quantitative sense, and opportunistic behaviors of AVs just represent on possibility we envision. The findings of this paper should be interpreted as a hint of self-organization in the heterogeneous flow of AVs and HVs and may serve as an initial step towards more rigorous development of decentralized control schemes.