Behavior Design for Heterogeneous Traffic Flow of Autonomous and Human-driven Vehicles
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We investigate spontaneous platoon formation in heterogeneous traffic flow consisting of human-driven (HDVs) and autonomous vehicles (AVs) in different behavior scenarios through simulation experiments. Our study reveals that platoons may form spontaneously, and platooning properties are associated with the behaviors of AVs. We conduct the simulation experiments through a parsimonious Cellular Automata model (we develop a software for this purpose), which captures the different characters of AVs and HDVs as well as their interactions. AVs are endowed with neighbor awareness and opportunistic behavior. We observe that, intriguingly, even with this relatively simple model, AVs form into platoons without centralized control.

We conduct two simulation experiments with the following constraints imposed by the uniformity of the two classes. Traditional CA rules described in Fig 1 were implemented to encapsulate such behavior in addition to the following:

\[ V_{\text{AV}} = V_{\text{AV}} - AV \text{- AV, } V_{\text{AV}} = V_{\text{AV}} - AV \text{- HDV, } V_{\text{HDV}} = V_{\text{HDV}} - AV \text{- HDV} \]

Simulating traffic flow.

**Autonomous Vehicles Behavior Design:**
In our project, we adapt the Nagel-Schreckenberg Cellular Automaton model to introduce a model of mixed traffic flow of AVs and HDVs that captures three potential behaviors of AVs - opportunistic, neighbor-awareness and baseline behavior. We distinguish between the two class of vehicles in our simulation by assigning different behavioral parameters - braking probability, lane changing probability, maximum speed - and methods - traversal velocity functions - to each vehicle type and behavior.

**Opportunistic model:** AVs require well defined instructions in the form of algorithms and optimization functions to make decisions while driving. This level of algorithmic control on the decision making of AVs imply that such vehicles can achieve idealized traffic flow parameters that cannot be achieved by HDVs which behave erratically. This type of erratic behavior does not apply to AVs, who make their decisions of accelerating/decelerating and lane changing solely based on safety and opportunity.

\[ P(\text{braking}) = 0.5 \times (\text{distance to vehicle front} < 2 \text{ meters}) \]

**NeighborAwareness:** AVs can communicate with each other and the surrounding using V2X technology. We hypothesize that these "neighbor aware" AVs would behave differently depending on the type of vehicle they are trailing. An AV trailing another AV can maintain a shorter headway due to their inter-connectivity and, hence, can maintain a higher speed. Such phenomenon would not be seen if the leading vehicle is a HDV.

**Baseline Model:** In this model AVs behave exactly like an HDV, with their behavior being indistinguishable from one another. Traditional CA rules described in Fig 1 were implemented to encapsulate such behavior in addition to the following constraints imposed by the uniformity of the two classes.

**Simulation Experiments:** We conduct two simulation experiments with the purpose of studying the impact of the five AV behaviors on the overall traffic flow and better understand any emergent patterns of collective behavior. In both the experiments, we consider a circular road with three lanes (periodic boundary conditions) with each lane comprising of 100 cells. The vehicle objects follow their respective set of behavior rules. For each simulation, the road starts from empty state. N Vehicles are then distributed randomly on the road with zero initial velocity; the vehicle type is determined stochastically upon allocation, following a binomial distribution with the probability of a vehicle being an AV (i.e. percentage of AVs) being 30%.

**For the first experiment,** we simulate the traffic flow for each of these models for the same number of simulation time steps (1200) for three different densities 0.08, 0.2 and 0.6. These values are normalized such that a state density of 1 represents jam density.

**For the second experiment,** we increase our system density linearly until it reaches the jam density. We allow the simulation to run for a fixed number of time steps (100) for each system density before incrementing it.

**Self-Organization Phenomenon:** Upon observation of several different simulation cases, we discovered that AVs under certain models and situations displayed strong self-organized phenomena. There were two types of self-organized events that were most prominent: AVs moving closely together but in different lanes and AVs moving closely together in the same lane. We hypothesize that the formation of clusters is natural due to the opportunistic nature of AVs, modeled through both its gap seeking and braking behavior. We study the effects of such self-organization on overall traffic flow and how different AV behaviors affect such phenomenon.

**Simulation and Analysis Software:**
We have developed a GUI software capable of simulating different heterogenous traffic flow scenarios with different AV behaviors. To create our model, we used principles of OOP with the main objects being two - Abstract Data Structures - Road and Car. The software allows the user to track different key parameters of traffic flow and later graph record of these parameters. This data is sent to an analysis part of the software to generate various plots and statistics for the user. This software is written entirely in Python3.

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**Exp 1:**

**Hytonic Dynamics Under Constant Traffic Densities:**
These results verify our initial hypothesis behind the clustering phenomenon neighbor aware and opportunistic AV agents benefit the most from trailing other AVs (due to smaller headways) resulting in collective behavior that lead to strong and prominent clustering phenomena. It further proves that clustering is not a random phenomenon but is unique to systems involving opportunistic intelligent agents that are capable of recognition. In context of our experiment, it means 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 phenomena if they share common incentive of being opportunistic. This implies that it is possible to design AV behavior that can form self-organized clusters.

**Exp 2:**

**Equilibrium Relation and Dynamics Under Varying Traffic Densities:**
In this experiment, we compare the traffic flow parameters of the five AV behaviors against the baseline model of AV behavior. We hypothesize that AVs will display a different behavior depending on the type of vehicle they are trailing. AVs following another AV will display a shorter headway due to the inter-connectivity between AVs and can maintain a higher speed as compared to HDVs.

**Fig 11:**
Overall Change Rates

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 HDV class, which they may use to travel at higher speeds. Such AV behavior also leads to interesting lane change dynamics, where the movement of AVs with respect to HVs mimic those of shepherd dogs herding sheep. The AVs keep the HVs in check by forming prominent self-organized clusters which prevent the HVs from changing lanes.

**Fig 12:**
Mean no. of clusters (High Density)