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MODELING AUTONOMOUS VEHICLE-TARGETED AGGRESSIVE MERGING BEHAVIORS IN MIXED TRAFFIC ENVIRONMENT

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ABSTRACT

Promising advances in Autonomous Vehicle (AV) technology have fueled industry and research fields to dedicate significant effort to the study of the integration of AVs into the traffic network. This study focuses on the transition phase between all Human Driven Vehicles (HDVs) in the network to all AVs, where these different vehicle types coexist in a mixed traffic environment. This paper investigates the potential impacts of aggressive merging behaviors by human drivers on traffic performance in a mixed environment. For this, three vehicle types – AVs, HDVs, and Aggressive HDVs (AHDVs) – are modeled in an open-source microscopic traffic simulation model, SUMO. In the developed simulation, the AHDVs are modeled to emulate aggressive merging behaviors in front of AVs at a merge section of a freeway exit ramp. Several experiments are used to study the impact of such behavior. Results show travel time gains by AHDVs at the expense of AVs and HDVs.

1 INTRODUCTION

Recent advancements in the development and deployment of Autonomous Vehicles (AVs) bring closer to reality the likelihood of a mixed fleet on the roadway, containing AVs and Human Driven Vehicles (HDVs). To understand the traffic stability found within a mixed fleet environment, it is important to develop algorithms to model potential changes to driving behaviors when AVs and HDVs interact. Several studies suggest that human drivers will exhibit aggressive driving behavior targeted towards Autonomous Vehicles (AVs), such as displaying hostile verbal or hand gestures, tailgating, and sharp merging behaviors (Lee et al. 2018; Randazzo 2018; Hamilton 2020). To begin the exploration of aggressive HDV behaviors toward AVs, this study models the impact on merging at an exit-ramp location.

2 BACKGROUND

Typically, studies of mixed traffic environments (i.e., both AV and HDV in the traffic stream) focus on modeling driver behavior modifications with an assumption of cooperative actions between vehicles (Aria et al. 2016; Rahman and Abdel-Aty 2018; Stanek et al. 2017; Zhou et al. 2017). With such cooperative interaction assumptions, studies often overlook the impact on traffic performance of potential aggressive HDV behavior directed toward AVs (Aria et al. 2016; Rahman and Abdel-Aty 2018; Stanek et al. 2017). However, significant uncertainty exists in the actual HDV behaviors that will be directed toward AVs. Some studies suggest that human drivers may take advantage of conservative AV behaviors (Rothenbucher et al. 2016; Muller et al. 2017). Hence, it is crucial to model different types of interaction behaviors between AVs and HDVs. This study aims to fill this gap by modeling and investigating the potential traffic performance impacts of the presence of aggressive human driver merging behaviors targeted at AVs, in a mixed fleet environment.

In addition to uncertain HDV behavior, a challenge commonly experienced in modeling AV behavior is a lack of standardization in driver (where the AV acts as the "driver") behavior parameters, such as acceptable gaps for merging and the level of cooperativeness with merging vehicles (Zhou et al. 2017; Hedlund 2015; General Motors; National Academies of Sciences 2017). Researchers often overcome this modeling challenge by tweaking current human driver models to model AVs, without extensive modifications (Stanek et al. 2017; Muller et al. 2017; National Highway Transportation Safety Administration 2017; Nishimura et al. 2019; Wagner 2016).

Studies on the interaction of AVs and HDVs show large variations in customized lane-changing rules and criteria assigned to create cooperative AV characteristics. These rules often limit or eliminate aggressive interactions by using cooperative behaviors between neighboring vehicles and removing aggressive motivations for lane changing behaviors (Stanek et al. 2017; Lopez et al. 2018; Zhou et al. 2017; Wagner 2016; Hua et al. 2020; Liu et al. 2018). Even in the studies that allowed aggressive behaviors of the HDVs, these aggressive behaviors are exerted in an unbiased manner toward vehicle types (Nishimura et al. 2019; Hedlund 2015). The model developed in this study implements customized lane-changing rules on top of the existing car following and lane-changing models, while displaying AHDVs' aggressive behaviors only toward AVs.

3 STUDY OVERVIEW

The objective of this effort is to develop a rule-based and deterministic model of aggressive merging behaviors displayed by a subset of human driven vehicles (AHDVs) toward AVs, in a mixed AV-HDV environment. For the analysis, a freeway exit ramp is utilized as the example study location (Figure 1); however, the results are applicable to other merging situations. This study does not try to provide evidence for or against the use of AVs; rather, the study develops the tools to facilitate modeling of AV-HDV interactions as the vehicle fleet transitions from pure HDV to higher percentages of AVs.

The potential impact of merging behaviors on traffic performance is explored in a microscopic simulation environment in this study. Three classes of vehicles are considered – AVs, HDVs, and AHDVs. AHDVs represent human driven vehicles with aggressive merging behavior characteristics. AHDVs differ from HDVs as they seek to minimize the travel time through queue-jumping and aggressive lane changes.

For this study, located at a freeway exit ramp, the assumed goal of the AHDVs is to travel the maximum downstream distance on the mainline lanes in the freeway exit area, so as to minimize the travel on the slower-moving deceleration lane and, thereby, minimize their travel time. To accomplish this, AHDVs target and merge in front of the farthest reachable AV on the deceleration lane. This implies an AHDV will force a merge in front of an AV, even where this results in a small to non-existent gap between the AHDV and the AV, potentially forcing sharp braking by the AV. It is also assumed that such aggressive behavior is only displayed in interactions with AVs. Where an AV is not present, the AHDV will utilize "normal" merging behavior (same as HDVs), merging in front of a nearby HDV in a non-aggressive manner, not seeking maximum downstream advancement.

A simulation model that emulates aggressive merging behaviors of AHDVs at a freeway exit-ramp merge section in a mixed traffic environment is developed using the open source traffic simulation package "Simulation of Urban MObility" (SUMO) (Lopez et al. 2018; Simulation of Urban Mobility 2022). The simulated network consists of a two-lane freeway with a deceleration lane near the freeway exit. AHDVs travel on the higher speed mainline lanes targeting AVs in the deceleration lane for their merge maneuver while HDVs travel on both lanes mixed with AHDVs and AVs. Using simulation experiments, the impacts of the AHDVs' aggressive behaviors in a mixed traffic environment (AVs, HDVs, and AHDVs) on different network traffic performance measures, such as travel time, is demonstrated.

3.1 Network Layout

Figure 1 shows the modeled network layout and lane speed. It consists of two through lanes with a 600 ft. deceleration lane to an exit ramp. The aggressive merge behavior occurs in the area near the freeway exit ramp, i.e., the merging zone. The two-lane freeway extends for one mile upstream of the beginning of the merge zone, allowing for sufficient space for vehicles to queue during congestion without spilling out of the network. The outflow from the ramp is controlled by a simple two-phase pre-timed traffic signal, with the splits and cycle length set dependent on the modeled scenario; they are specified in each experiment. The ramp junction with the cross street is 1,500 ft. downstream from the ramp gore.

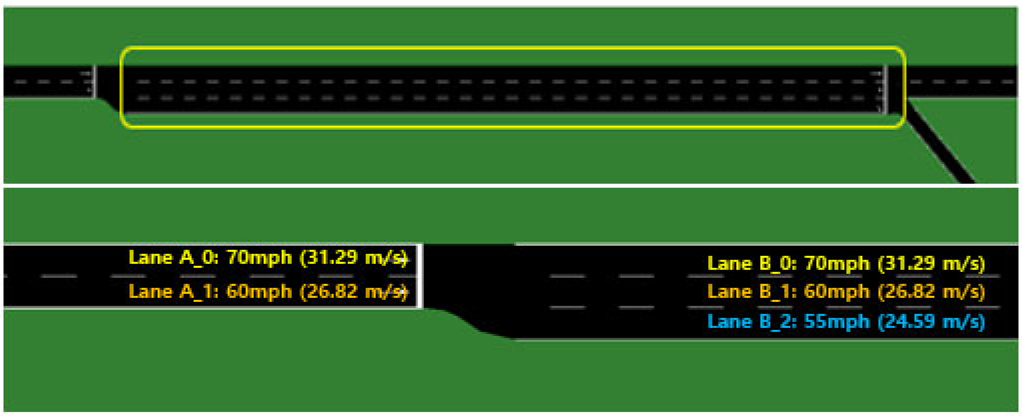

Figure 1: Roadway layout on merging zone, highlighted in yellow with speed by lane.

3.2 Vehicle Classification and Characteristics

To study the interactions between the different vehicle types, three vehicle classes are defined based on driving behaviors. The Krauss and LC2013 models were used for AVs' and HDVs' car following and lane changing, respectively (Simulation of Urban Mobility 2022). Heterogeneity in the traffic flow is introduced through the use of a normally distributed [1 ,0.1] speed factor within each vehicle type. For each individual vehicle, the vehicle type maximum desired speed is multiplied by the speed factor, providing the vehicles' upper bound on desired speed. The three vehicle classes are:

1. AVs exhibit cooperative driving behaviors, i.e., AVs slow to extend the leading gap, allowing merging vehicles to more easily enter their lane. When AVs exit the freeway, they will change lanes at the start of the deceleration lane. The AV behavior is fully controlled by SUMO.
2. AHDVs travel on a high-speed lane only (Lane B_1) until they merge into the deceleration lane. These vehicles exhibit aggressive merge behavior toward AVs by accepting smaller gaps (minimum half-vehicle in length to begin a merge) in front of the AV compared to a merge in front of an HDV. AHDVs will always seek to merge in front of the farthest reachable downstream AV in the deceleration lane. When making an aggressive merge, the AHDV behavior is controlled during runtime through the Traffic Control Interface (TraCI), which allows customized control over the vehicle during runtime. When an AV is not reachable, the AHDV merge behavior will be non-aggressive and controlled by SUMO.
3. HDVs exhibit the same cooperative driving behaviors as AVs, but are not targeted by AHDVs. The HDV behavior is fully controlled by SUMO.

3.3 Aggressive Merge Behavior Model

The AHDVs' aggressive merge behaviors consist of customizing two key behaviors – target selection behavior and lane changing behavior. The default SUMO car following models describe the human-to-human interactions. It is noted that adjusting the SUMO gap acceptance parameters, such as tau and minGap, did not allow for the desired AHDV aggressive behavior toward AVs, i.e., AHDV's bumper-to-bumper merge. Thus, the aggressive behaviors were modeled by supplementing the existing Krauss car following model with these behaviors, rather than adjusting the model parameters.

3.3.1 Target Selection Behavior Process

The objective of the target selection behavior is to identify the optimal target vehicle, which in this study is considered the AV furthest downstream in the deceleration lane. When queueing occurs on the deceleration lane (Lane B_2), this targeting behavior allows AHDVs to travel on the higher-speed adjacent lane (Lane B_1) until merging in front of target vehicles in the deceleration lane, thus allowing AHDVs to queue-jump. To implement this behavior:

- The AHDVs' choose an initial target that is the closest AV on the target lane.
- After a target is selected, the AHDVs adjust their speed to overtake the AV, within the constraints of the speed of the leading vehicle in the same lane (if one is present) or the lane speed.
- Once the AHDV is in the vicinity (to be defined subsequently) of the target vehicle, the AHDV will check if the next downstream AV is reachable prior to the end of the deceleration lane.
- By repeating this process, the AHDV will merge in front of the farthest reachable downstream AV. As every AHDV targets the farthest AV, this behavior often results in multiple AHDVs merging in front of the same AV as shown in Figure 2.

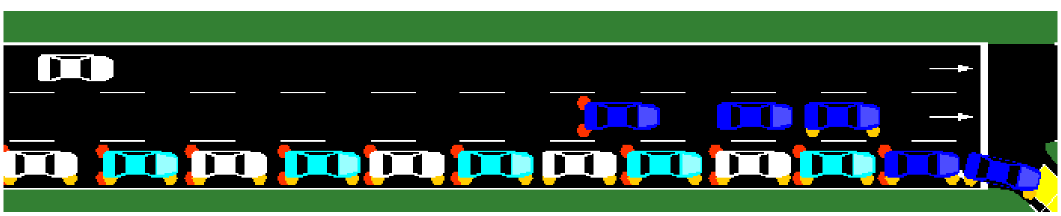

Figure 2: Aggressive merge behavior of AHDVs towards AVs (AHDVs – deep blue vehicles, AVs – light blue vehicles, and HDVs – white vehicles).

If an AHDV's target AV becomes no longer reachable due to a speed change or other interference in the AHDV lane, the AHDV will seek to merge in front of an HDV. However, the merge in front of the HDV will not exhibit aggressive behaviors and will be fully controlled by SUMO. Should SUMO be unable to successfully complete the merge and an AV from upstream on the deceleration lane begins to overtake the AHDV (which may occur when congestion results in a lower speed on the mainline lane than that on the deceleration lane), the AHDV will return to its aggressive behavior and merge in front of the approaching AV.

There are three essential computations used to model the targeting behavior – *position check, can-catch,* and *merge position check*. These three functions are executed every time step to update the target vehicle based on the position and speed changes in AHDVs and their target vehicles.

Position Check. To merge into the deceleration lane, the AHDV must decrease to the speed of the vehicle in front of the target AV, as the target AV and its leading vehicle represent the lagging and leading vehicles, respectively, for the gap that will be entered by the AHDV. The objective of *position check* is to determine if the AHDV has reached the position where it must decide whether to target the next downstream AV or keep the current target vehicle and start braking to prepare for the merge.

Can Catch. The objective of the *can catch* function is to determine if the AHDV can reach the front of the target vehicle, to allow for a merge, before the deceleration lane's end point. This is determined by evaluating the current position and speed conditions and comparing the travel time of the AHDV and target vehicles to the end of the lane. *Can catch* is applied at every time step to confirm that the current target vehicle may still be reached, allowing for potential changing conditions due to congestion. In addition, *position check* may call *can catch* to evaluate if the AHDV will switch from its current target to the next downstream AV.

Merge Position. This function checks whether an AHDV is within the position to initiate an aggressive merge. *Merge Position* returns true and an AHDV executes the merge process if its front bumper is anywhere between the center of the target vehicle and the head of the leading vehicle to the target vehicle.

3.3.2 AHDV's Target Selection Process in Aggressive Merge

The target selection process is undertaken every time step. The following steps are the general procedure.

1. Vehicle ID list is updated to include all vehicle IDs currently in the merging zone. Vehicles entering the merging zone are added and vehicles that have merged into the deceleration lane are removed.
2. When an AHDV first arrives at the upstream start of the merging zone, the deceleration lane condition is reviewed.
   a. If the deceleration lane is empty, the AHDV changes the lane without any further consideration.
   b. If the deceleration lane is not empty, the AHDV checks for the presence of an AV.
   c. If there is no AV, the AHDV continues to search for any AV while allowing SUMO to execute a merge whenever it is possible. This process continues until either SUMO executes the merge or the AHDV finds an AV in the traffic.
   d. If there is more than one AV in the deceleration lane, AHDV initially identifies the nearest downstream AV.
3. Next, using the *can catch* function, the merge feasibility of the AHDV with the nearest AV is checked. If the AHDV cannot merge in front of the nearest AV, it indicates that there is no AV that the AHDV can overtake. The process returns to Step 2c.
4. If the AHDV can overtake the nearest AV, the position of the AHDV is checked (using the *position check* function) to determine whether the AHDV is ready to search for the next AV downstream. If the AHDV is not in such position, it continues to travel until being checked again in the next time step.
5. If the AHDV is in such position, the next AV downstream is identified and checked for the merge feasibility using the *can catch* function
6. If the AHDV can overtake the next AV downstream, the target AV is updated. If not, the current target AV is maintained.
7. In every time step, the *can catch* function is used to determine if the AHDV can still overtake the current target AV.
8. If the AHDV can no longer overtake the current target AV, the AHDV first searches to check whether there is a nearby reachable AV downstream. If there is one, the AHDV updates its target.
9. If there is no reachable downstream AV, the AHDV searches for the nearest reachable AV upstream and updates its target. If there is no such AV, the process returns to Step 2c.

The process continues until all AHDVs have been checked for target selection. Then, the simulation time advance is triggered.

3.3.3 Lane Changing

After the target selection process is complete and the AHDV is positioned next to the target AV, the lane change process is initiated. AHDVs merge in front of the target AV as soon as the AHDV's rear bumper crosses the front bumper of the AV, forcing the AV to decelerate sharply to meet its' desired spacing. For this aggressive merge the TraCI *moveTo* command is utilized that manually moves the position of a vehicle by the specified coordinate shift in SUMO. The *moveTo* command allows the simulation to bypass the need for the vehicle to satisfy any gap requirements. This command was used to create a high level of aggressive behavior that could not be achieved by reduced gap acceptance parameters. This aggressive approach relies on the AVs' ability to quickly slow for merging vehicles. This bumper-to-bumper merging behavior, though not verified with field data, simulates the highest level of expected aggressive behavior. The research in this study can be further extended in the future by introducing different levels of aggressive merging behavior and testing the impacts thereof. Additionally, inclusion of stochasticity in the aggressive behavior, based on field observations, should be explored to improve the realism of the simulation. For example, stochasticity could be introduced in the behavior model by varying AHDVs' target selection process. Rather than targeting the farthest reachable AV, some percentages of AHDVs could target the second or third farthest reachable AV.

3.3.4 Merging Process in SUMO-Controlled Merge

When vehicles are merged by SUMO, the *'lcCooperativeSpeed'* parameter is set to 1 for the cooperative characteristic in AVs and HDVs. Setting this parameter to 1 allows the neighboring vehicles to slow down cooperatively for merging vehicles. When the algorithm requests SUMO control for the merging process for an AHDV, the neighboring vehicle (an HDV, as an aggressive merge would be undertaken for an AV) starts slowing down cooperatively to create a sufficient gap for the AHDV to merge. However, when TraCI is utilized to implement an aggressive merge, the AVs do not exhibit this cooperative behavior, as they are unaware the AHDV will merge until it begins to encroach into the AV lane. Only upon an AHDV's encroachment will the AV begin to slow.

Thus, a SUMO-controlled merge requires a sufficient gap before a lane change is performed, whereas aggressive merges (using the *moveTo* command) are not affected by the gap availability. This results in the SUMO-controlled merge often requiring a longer time period for a merge, requiring slowing of the merging vehicle to find a suitable gap to complete.

4 EXPERIMENT

The objective of this experiment is to investigate the impact of aggressive merging behavior under conditions where AHDVs are distributed throughout the traffic stream, for two traffic-demand levels.

4.1 Experiment Setup

Traffic volume is balanced in the mainline lanes entering the merge zone. All exiting vehicles enter the merge zone already positioned in lane A_1 (Figure **1**). Thus, all vehicles in the left most lane A_0 are through vehicles only, while vehicles on lane A_1 consist of both through and exit vehicles. In this experiment, 35 % of the traffic is assumed to exit, thus 70 % of the lane A_1 vehicle were assigned as exit vehicles, consisting of AVs, HDVs, and AHDVs (percentages described subsequently). All exit vehicles except for the AHDVs shift over to the deceleration lane B_2 when they reach the merging zone, at the start of the deceleration lane. The AHDVs continue to travel on lane B_1 and make a lane change to B_2 by either an aggressive merge or a SUMO-controlled merge, as defined previously.

Two levels of traffic demand were considered in this experiment – high traffic-demand (1,200 vehicles/hour/lane) and low traffic-demand (600 vehicles/hour/lane). For each traffic demand level, five different AV penetration ratios, i.e., 10 %, 20 %, 30 %, 40 %, and 50 %, were modeled. In addition, for those vehicles not assigned as AV, five different AHDV penetration rates were modeled, i.e., 0 %, 25 %, 50 %, 75 %, and 100 %. This results in a total of 50 different scenarios. Ten replicate runs were completed for each scenario, resulting in a total of 500 simulation runs.

In this experiment, 50 seconds of green time and 70 seconds of red time are used for both the lower traffic-demand and higher traffic-demand conditions at the ramp intersection with the roadway. This results in no queue spillback to the deceleration lane in the low traffic-demand case, but there was queueing on the deceleration lane in the high traffic-demand case. The base case (AHDV 0 %) consists of only AV and HDV.

4.2 Results

Figure 3 and Figure 4 show the average travel-time of exit vehicles by vehicle type in each scenario. Note that the y-axis scales are different in the two figures to accommodate the wider range of travel-times in Figure 4.

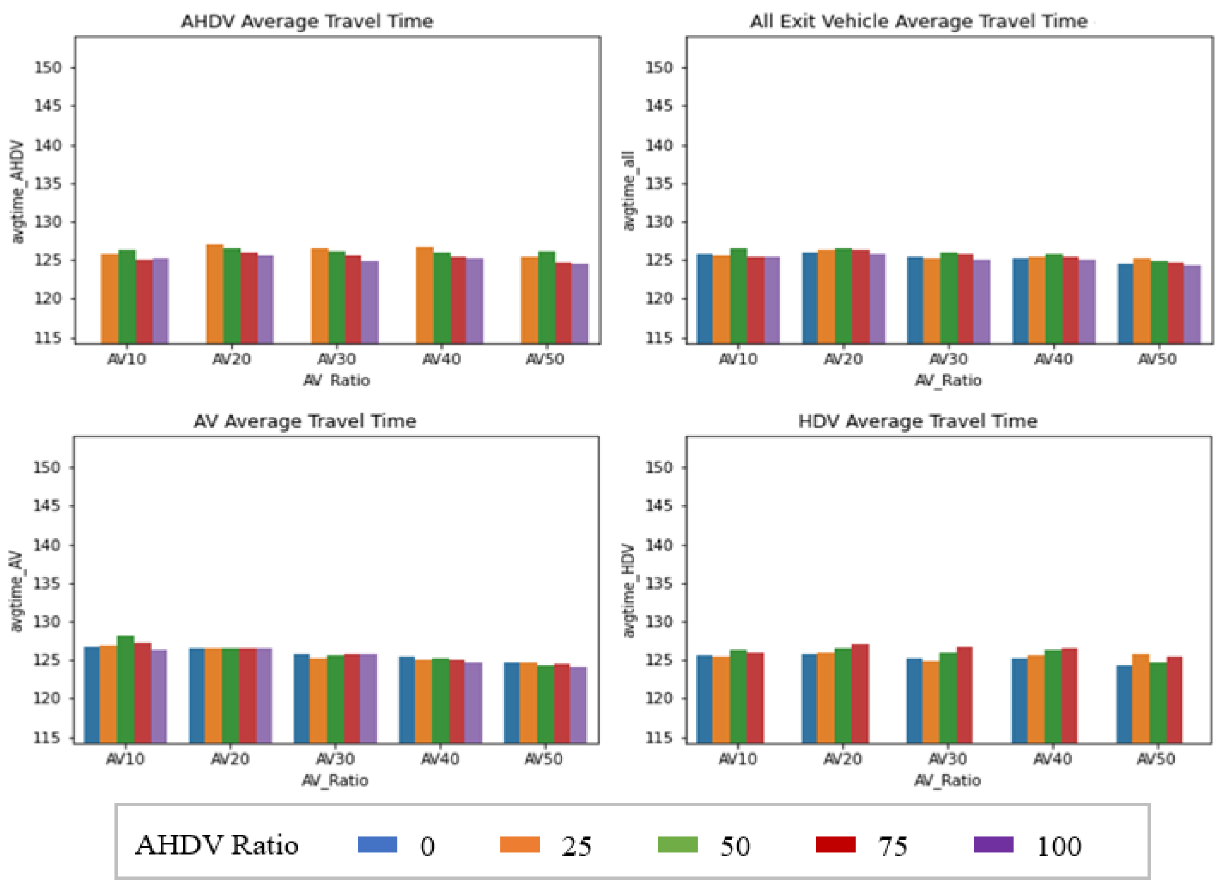

Figure 3: Experiment 1, average travel time by vehicle type in low traffic-demand condition.

A paired t-test on the travel-times of the AHDVs compared to the travel times of the AVs and HDVs was conducted (table of results not shown for brevity). It was found that the AHDVs' lower travel times are statistically significant under high congestion, where the aggressive behaviors were frequently displayed. In low congestion, the aggressive behaviors were not as frequently displayed, since the larger distances between the vehicles often prevented AHDVs from catching an AV. The paired t-test results showed that the AHDVs' travel times were not significantly different than the other vehicle types in low congestion.

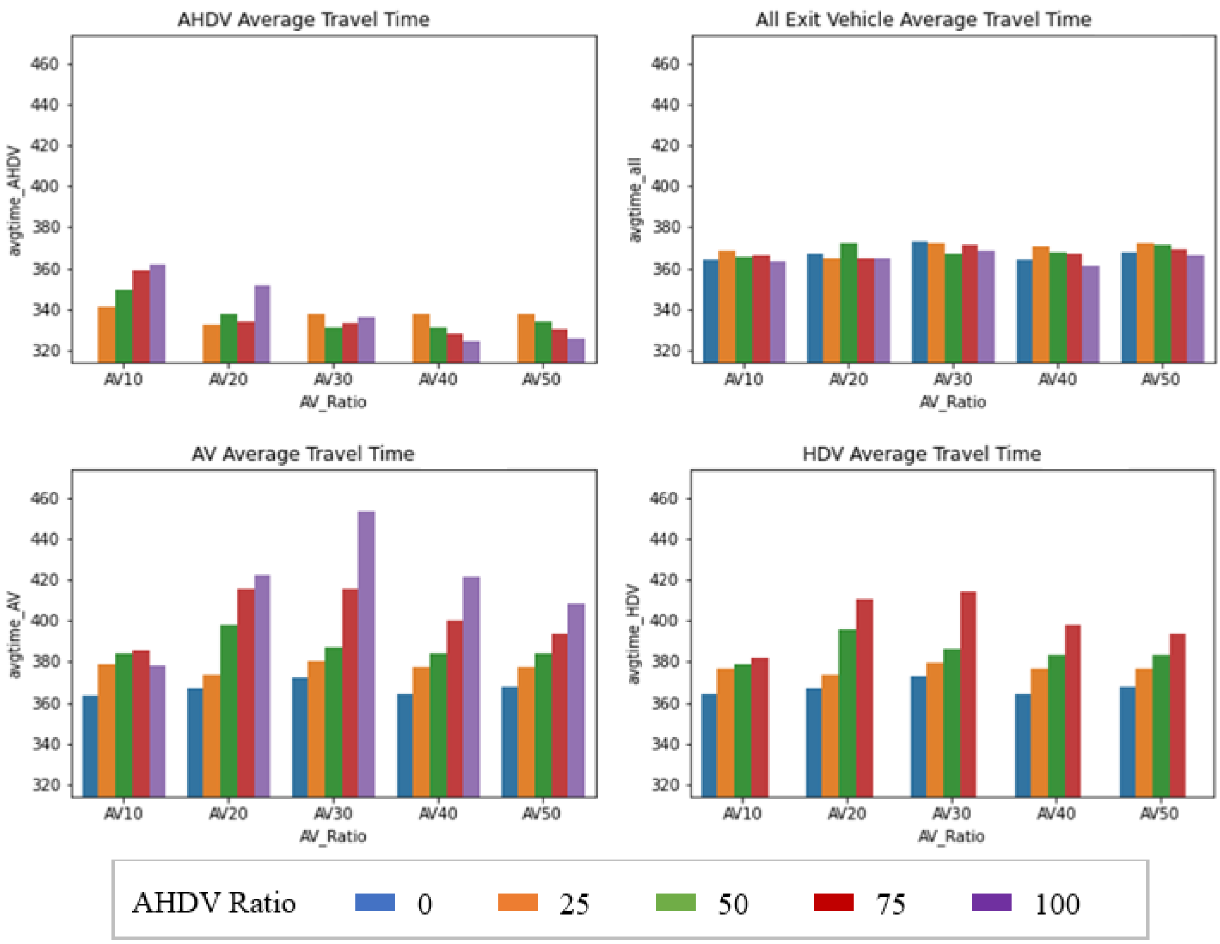

Figure 4: Experiment 2, average travel time by vehicle type in high traffic-demand condition.

4.3 Discussion

The travel times of exit vehicles in the low traffic-demand scenarios as shown in Figure 3 were not significantly impacted by the aggressive merges, with no clear trends apparent. The travel times between vehicle types or AV penetration rates never differ by more than a few seconds. Since there is no queue formed on the deceleration lane in low traffic-demand, most AHDVs performed lane changes to the deceleration lane immediately, since the deceleration lane was empty. In a few cases where AHDVs performed aggressive merges, the impacts of the aggressive merges may have been muted because of the existence of large headways between the vehicles. As a result, the paired t-test in low traffic-demand conditions showed that the AHDVs had no significant difference in travel-time compared to the AVs and the HDVs in most scenarios.

In high traffic-demand conditions, where queuing tended to occur on the deceleration lane, the AHDVs' travel times are significantly lower than the travel-times of the AVs and HDVs, in all scenarios with aggressive merges. In these scenarios the AHDVs sought to advance further downstream in the mainline lane, "jumping" the deceleration lane queue and cutting in front of a downstream AV closer to the exit gore. However, the overall average travel times remained relatively constant, implying that as the AHDVs were able to improve their travel time, the AVs and HDVs suffered increased travel time, showing trade-off effects. This result highlights that the AHDVs benefit at the expense of the AVs and HDVs. While the HDV travel times did not increase to the same extent as the AV, they did see travel time increases, even though they were never "targeted" by the AHDV. The HDV travel-time increase results from HDVs in the deceleration following AVs that are targeted. Such impacts as these, due to varying merging behaviors in mixed environments, can be quantified and studied to suggest improved traffic control and safety strategies.

It is also seen that the AHDV travel times show (Figure 4) an increasing trend at the lower AV ratios (10 % and 20 %). However, the trend reverses when the AV ratios were high (30 % – 50 %). The reason for this behavior is that when there is a smaller number of AVs to target, more AHDVs performed non-aggressive merges, which requires a longer time to complete. As the availability of target AVs increased with higher AV ratios, more AHDVs successfully completed aggressive merges by targeting AVs. It was also observed during the simulation run that multiple AHDVs could target the same AV on the deceleration lane, forcing the target AV, as well as the following traffic, to come to a complete stop.

5 CONCLUSION

This paper develops a rule-based, deterministic model for aggressive merging behavior in human drivers toward AVs in a mixed traffic environment. The model is constructed using the open-source microscopic traffic simulation model SUMO. The existing literature review suggests that the general outlook regarding the introduction of AVs into the traffic fleet is that they will lead to enhanced roadway performance and safety. However, these studies had a common assumption – autonomous vehicles and human roadway users will have cooperative interactions. This paper asks the question "what happens if the interactions are not always cooperative between autonomous vehicles and human drivers". Opportunistic and aggressive behaviors already witnessed in congested traffic near work zones or exit lanes, and anecdotal evidence of aggressive behavior toward level-2 autonomous vehicles, indicate that the potential impacts of aggressive behavior modeled in the study should be considered in the transition period where HDVs and AVs will operate together on the roadways. Within the experiment it was seen that the adverse effects were more significant in high congestion conditions, when there is a queue on the deceleration lane. AHDVs achieved lower travel-times through aggressive behaviors, which in return had adverse effects on the AVs' and the HDVs' travel-times as a trade-off effect of the AHDVs' aggressive behaviors. The impacts of AHDVs' aggressive merges were muted by the larger headways between vehicles in low congestion, where there is little to no queuing on the deceleration lane.

The findings of this study suggest that, in a mixed traffic environment, there may be adverse impacts on non-aggressive vehicle travel times in the presence of human drivers with aggressive behaviors, especially in congested conditions. Thus, when the potential benefits of the AV are most needed, i.e., at or near capacity, it is possible that human interaction may negate many of the potential savings. However, an underlying assumption of this study is that human drivers can easily identify the AVs. Thus, future AV design and regulations should consider the findings from this study to weigh whether the AVs' having an easily distinguishable appearance would be beneficial. In addition, the findings of this study suggest that vehicle-type-specific operation strategies may need to be considered to mitigate the impacts shown.

While it is the goal of this effort to provide a meaningful data point to the range of potential driver behavior characteristics and subsequently operational outcomes, there are certainly limitations to this study. Firstly, this study is limited to a freeway exit-ramp deceleration lane merge zone. While the authors believe that insights gained from this study are transferrable to other situations, additional research and testing should be conducted for different roadway and traffic scenarios. Secondly, this study focuses on the operational impacts of the interactions. There is likely to be safety impacts of such interactions, for example a HDV following an AV that is employing emergency braking for collision avoidance might not be able to react in time, which could lead to a rear-end collision. Safety impacts were not evaluated in this study. Thirdly, there is lack of field data validation. As the interaction between AVs and human driven vehicles is rare, some may argue non-existent or at least still "novel", it is impossible to validate the behavioral assumptions made. This same limitation exists for all mixed fleet studies. Lastly, the aggressive behavior is modeled here as deterministic, that is, either a vehicle is aggressive or it is not, and all aggressive vehicles utilize the same gap acceptance and lane changing parameters. In future research, to overcome this limitation, uncertainty may be introduced into the behavioral models, reflecting a range of potential driver behaviors.

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REFERENCES

Aria, E., J. Olstam, and C. Schwietering. 2016. "Investigation of Autonomous Vehicle Effects on Driver's Behavior and Traffic Performance". *Transportation Research Procedia* 15:761–770.

General Motors. 2023. *General Motors Promotes DSRC for Connected Vehicle (V2X) Technology Development in China*. https://news.gm.com.cn/en/home/newsroom.detail.html/Pages/news/cn/en/2015/Nov/1124_v2x.html#:~:text=SHANGHAI%20%E2%80%93%20General%20Motors%2C%20the%20first,of%20its%20V2X%20communication%20protocol, accessed 10th January.

Hamilton, I. A. 2019. *Uber Says People Are Bullying Its Self-Driving Cars with Rude Gestures and Road Rage.* Business Insider. https://www.businessinsider.com/uber-people-bullying-self-driving-cars-2019-6, accessed 10th January 2020.

Hedlund, J. 2015. *Autonomous Vehicles Meet Human Drivers: Traffic Safety Issues for States*. Governors Highway Safety Association, https://www.ghsa.org/resources/spotlight-av17, accessed10th January 2020.

Hua, X., W. Yu, W. Wang, and W. Xie. 2020. "Influence of Lane Policies on Freeway Traffic Mixed with Manual and Connected and Autonomous Vehicles". *Journal of Advanced Transportation* 3968625.

Lee, S., C. Oh., and S. Hong. 2018. "Exploring Lane Change Safety Issues for Manually Driven Vehicles in Vehicle Platooning Environment". *IET Intelligent Transport Systems* 12(9): 1142–1147.

Liu, H., X. Kan, S. E. Shladover, X.Y. Lu, and R.E. Ferlis. 2018. "Impact of Cooperative Adaptive Cruise Control on Multilane Freeway Merge Capacity". *Journal of Intelligent Transportation Systems* 22(3):263–275.

Lopez, P.A., M. Behrisch, L. Bieker-Walz, J. Erdmann, Y.P. Flotterod, R. Hillbrich, L. Lucken, J. Rummel, P. Wagner, and E. Wiebner. 2018. "Microscopic Traffic Simulation using SUMO". In *21st International Conference on Intelligent Transportation Systems (ITSC),* November 4th–7th, Hawaii, USA, 2575–2582.

Muller, L., C. Emmenegger, and M. Risto. 2016. "The Social Behavior of Autonomous Vehicles". In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing,* September 12th–16th, New York, USA, 686–689.

National Academies of Sciences. 2017. "Strategies to Advance Automated and Connected Vehicles, Briefing Document". NCHRP Research Report 845. Transportation Research Board.

National Highway Transportation Safety Administration. 2017. "Automated Driving Systems 2.0, a Vision for Safety". US Department of Transportation.

Nishimura, Y., A. Fujita, A. Hiromori, H. Yamaguchi, T, Higashino, A. Suwa, H. Urayama, S. Takeshima, and M. Takai. 2019. "A Study on Behavior of Autonomous Vehicles Cooperating with Manually-Driven Vehicles". In *IEEE International Conference on Pervasive Computing and Communications (PerCom)*, March 11th–15th, Kyoto, Japan, 212–219.

Rahman, M.S. and M. Abdel-Aty. 2018. "Longitudinal Safety Evaluation of Connected Vehicles' Platooning on Expressways". *Accident Analysis Prevention* 117:381–391.

Randazzo, R. 2018. *A Slashed Tire, a Pointed Gun, Bullies on the Road: Why Do Waymo Self-Driving Cars Get So Much Hate?* USA Today. https://www.usatoday.com/story/money/cars/2018/12/13/waymo-self-driving-vehicles-face-harassment-road-rage-phoenix-area/2288833002/, accessed 10th January 2020.

Rothenbucher, D., J. Li, D. Sirkin, B. Mok, and W. Ju. 2016. "Ghost Driver: A Field Study Investigating the Interaction Between Pedestrians and Driverless Vehicles". In 25th *IEEE International Workshop on Robot and Human Communication (ROMAN),* August 26th–31st, New York, USA; 795–802:

Simulation of Urban Mobility. 2022. *Definition of Vehicles.* https://sumo.dlr.de/docs/Definition_of_Vehicles%2C_Vehicle_Types%2C_and_Routes.html#vehicle_type_distributions, accessed 26th August.

Stanek, D., E. Huang, R.T. Milam, and Y. Wang. 2017. "Measuring Autonomous Vehicle Impacts on Congested Networks Using Simulation". In *Transportation Research Board 97th Annual Meeting*, January 7th–11th, Washington DC, USA.

Wagner, P. 2016. *Autonomous Driving.* Berlin: Springer.

Zhou, M., X. Qu, and S. Jin. 2017. "On the Impact of Cooperative Autonomous Vehicles in Improving Freeway Merging: A Modified Intelligent Driver Model-Based Approach". In *IEEE Transactions on Intelligent Transportation Systems* 18(6):1422–1428.

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