Does Behavioral Adaptation of Human Drivers Affect Traffic Efficiency of Mixed Traffic on Priority T-Intersections?

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Extended abstract submitted for presentation at the Conference in Emerging Technologies in Transportation Systems (TRC-30)

September 02-03, 2024, Crete, Greece

April 29, 2024

Keywords: Behavioral adaptation, Mixed traffic, Gap Acceptance, Microscopic Traffic Simulation, Traffic efficiency

1 Introduction

It is well established that the presence of Automated Vehicles (AVs) will increase in traffic in the coming decades which will result in a mixed traffic condition, in which Human Driven Vehicles (HDVs) will interact with AVs in different road situations. Human drivers' behavior could be influenced by the driving styles and the recognizability of AVs, and as a result change their driving behavior (Arvin et al., 2020; Reddy et al., 2022). We refer to this change in driving behavior as *behavioral adaptation*. Behavioral adaptation could influence the nature of traffic interactions, which in result could influence traffic safety and efficiency. There is an increasing evidence of HDVs' behavioral adaptation due to interactions with AVs. Field tests have found that human drivers adopt shorter time headways when following AVs (e.g., Zhao et al., 2020). Other studies using driving simulators also observed that human drivers adopt shorter time headways when following AVs or when driving alongside AV platoons (e.g., Razmi Rad et al., 2021). Our previous study (Reddy et al., 2022), through a driving simulator experiment, studied human drivers' gap acceptance behavior at priority T-intersections in mixed traffic. We found that drivers accept larger gaps when AVs are less defensive and recognizable. Understanding the implications of this behavioral change when scaled up, at different penetration levels of AVs, on traffic efficiency is of great importance for road operators and policy makers.

This study aims to understand the effect of AVs' penetration rate, recognizability, and driving style on the efficiency of mixed traffic at priority T-intersection. Such intersections have an important effect on traffic flow, influenced primarily by drivers' gap acceptance decisions. In this context, we also aim to understand the effect of considering human drivers' behavioral adaptation on the efficiency of mixed traffic. To our knowledge, to date there has not been a microscopic traffic simulation study to investigate the effect of mixed traffic at priority intersections considering behavioral adaptation in gap acceptance behavior.

2 Methodology

Using the data from the driving simulator experiment (Reddy et al., 2022), we estimated gap acceptance models. We then set-up a simulation network of a T-intersection in SUMO, in which we implemented the estimated models and measured traffic efficiency indicators.

2.1 Driving simulator

One hundred and fourteen participants took part in the driving simulator experiment. The route that the participants drove on consisted of motorway driving, regional road driving, and three non-signalized priority T-intersections. The speed limits on these different parts of the network were 100 km/h on the motorway, 80 km/h on the regional road, and 50 km/h on the urban road. This study focuses on the three T-intersections.

Scenarios in the experiment differed in the AVs' recognizability and their driving styles. Each participant experienced four scenarios: 1) Only HDVs, 2) HDVs and non-recognizable (NR) AVs (with AV driving style), 3) HDVs and Recognizable (R) AVs (with AV driving style), and 4) HDVs and Recognizable (R) AVs (with HDV driving style). Participants were divided into two **groups** *More defensive* AVs and *Less defensive* AVs. Drivers in the group of *More defensive/ Less defensive* AVs only experienced AVs of the respective driving style in mixed traffic. All the scenarios had a 50% AV penetration rate. The **Driving behavior** of AVs and HDVs were defined by the desired speed and the desired car following time gap based on previous studies from the literature. The gaps between vehicles on the major road at the intersections were randomly drawn from a uniform distribution between 3 and 10 seconds avoiding very small or very large.

2.2 Gap acceptance modelling

To model gap acceptance, we adopted the *generalized linear model* (logistic regression) . We estimated three models to predict the probability of accepting an offered gap, using maximum likelihood estimation method: Model 1 for conventional traffic, Model 2 for *Less defensive* AV traffic, and Model 3 for *More defensive* AV traffic. Table 1 presents the model results for Model 1 only as an example.

Table 1: Estimated coefficients of the generalized linear logistic model for gap acceptance in conventional traffic (Model 1: *Conventional traffic*)

Coefficients	Estimate	Standard error	z-value	Pr (>z)
(Intercept)	-5.35	0.58	-9.22	< 0.001
Gap	0.62	0.07	8.79	< 0.001
Driving style of human driver (Ref.: Anxious and dissociative)				
Careful and distress reducing	0.64	0.29	2.18	0.029
Risky and aggressive	0.62	0.34	1.84	0.065
Order of encountering the scenario (Ref.: Scenario order 1)				
Scenario order 2	0.37	0.33	1.12	0.264
Scenario order 3	0.57	0.31	1.81	0.069
Scenario order 4	0.52	0.38	1.39	0.160
AIC	436.30			

2.3 Microsimulation set-up.

The estimated models were then implemented in microscopic traffic simulation. The designed road network is a simple priority T-intersection. The traffic on the **major road** consisted of both HDVs and AVs with a volume fixed at 600 veh/h with gaps between vehicles generated using a Poisson distribution. Generated HDVs had a distribution of desired time gaps drawn randomly from [0.5 s, 0.75 s, 1 s, 1.25 s, 1.5 s], which presents the volume distribution of HDVs with different desired time gaps on the major road at different AV penetration rates. Major and minor road vehicles followed the Intelligent Driver Model (IDM) (Treiber et al., 2000). Traffic on the **minor road** always consisted of HDVs. Their gap acceptance behavior was as per the estimated models. The traffic volume on the minor road was fixed at 200 veh/h. Different simulation conditions were defined based on AV Penetration Rate (0%, 25%, 50%, 75%), AV Driving style (*Less defensive (LessDef)* and *More defensive (MoreDef)*), and AV recognizability (Recognizable (R) and not-recognizable (NR)), and whether behavioral adaptation was considered (BA considered (BA) or not (NoBA)). To evaluate the traffic efficiency, three indicators were used: 1) Delay per vehicle on the minor road, 2) Delay per HDV on the major road, 3) Delay per AV on the major road. Each simulation condition was run with 10 different seeds, and the results were averaged per condition. Every simulation run lasted for a duration of 1 hour.

3 Results

We present the results for the minor road only as no meaningful impacts were observed for the major road.

Figure 1, as an example, presents the effect of penetration rate and considering BA. For both *MoreDef* and *LessDef AVs*, the delay increases with penetration rate, but by larger extent for *MoreDef AVs*. The effect of considering behavioral adaptation is not noticeable for *MoreDef* AVs. For *LessDef* recognizable AVs, considering BA results in larger delays.

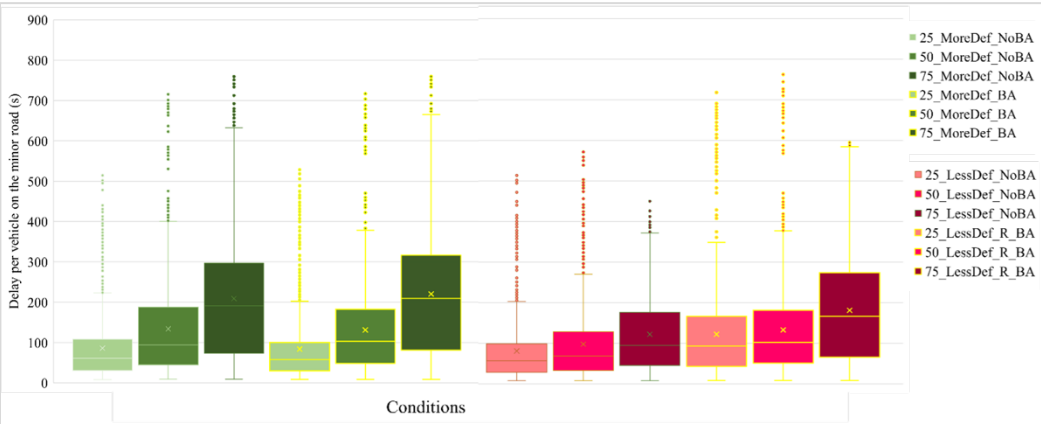

Figure 1: Effect of penetration rate and considering BA for MoreDef and LessDef AVs.

4 Discussion

For vehicles on the minor road, the delay increases with an increase of AV penetration rate on the major road. This occurs both when AVs are *More defensive* and when they are *Less defensive* (recognizable and non-recognizable). This could be because both *Less defensive* and *More defensive* AVs as defined in this study have larger desired headways than most HDVs. Therefore, vehicles on the major road are more spread (but still not with an enough big gap to merge from the minor road) and have smaller gaps between groups (platoons) of vehicles arriving at the intersection. Therefore, more vehicles on the minor road end up waiting at the stop line before an acceptable gap is available.

Recognizability significantly affected the gap acceptance behavior only in *Less defensive* AV traffic. For vehicles on the minor road, the median delay was larger when *Less defensive* AVs were recognizable compared to when being non-recognizable. This held true at all penetration rates. This is because minor road vehicles are less likely to accept a gap in front of a recognizable *Less defensive* AV. **At higher penetration rates, minor road vehicles were found to experience larger delays when AVs were *More defensive* than when AVs were *Less defensive* and non-recognizable**. The difference between the median delay per minor road vehicle increased with increasing AV penetration rate. **The effect of considering behavioral adaptation on the measured median delay for minor road vehicles is primarily noticeable when AVs are *Less defensive* and recognizable**. Considering behavioral adaptation results in an increase in median delay for minor road vehicles in recognizable *Less defensive* AV traffic, when compared to not considering behavioral adaptation. In other scenarios, the difference in median delay for minor road vehicles before and after considering behavioral adaptation is not considerable. As for the major road vehicles, the effect on their delay is much less noticeable in general.

5 Recommendations

Infrastructure to Vehicle (I2V) and Vehicle to Vehicle (V2V) communication could be designed to trigger changes in the headways of AVs when the minor road queue length exceeds by a critical margin. Policy makers and road authorities should consider whether the delays and the differences in delays between different scenarios are meaningful (or important enough).

Future research on traffic efficiency effects of mixed traffic must consider behavioral adaptation when modelling gap acceptance behavior in mixed traffic. Additionally, traffic safety indicators must be included in the analysis to gain traffic safety insights.

6 References

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Acknowledgment

This work was supported by the Applied and Technical Sciences (TTW), a subdomain of the Dutch Institute for Scientific Research (NWO) through the Project Safe and Efficient Operation of Automated and Human-Driven Vehicles in Mixed Traffic (SAMEN) under Contract 17187.