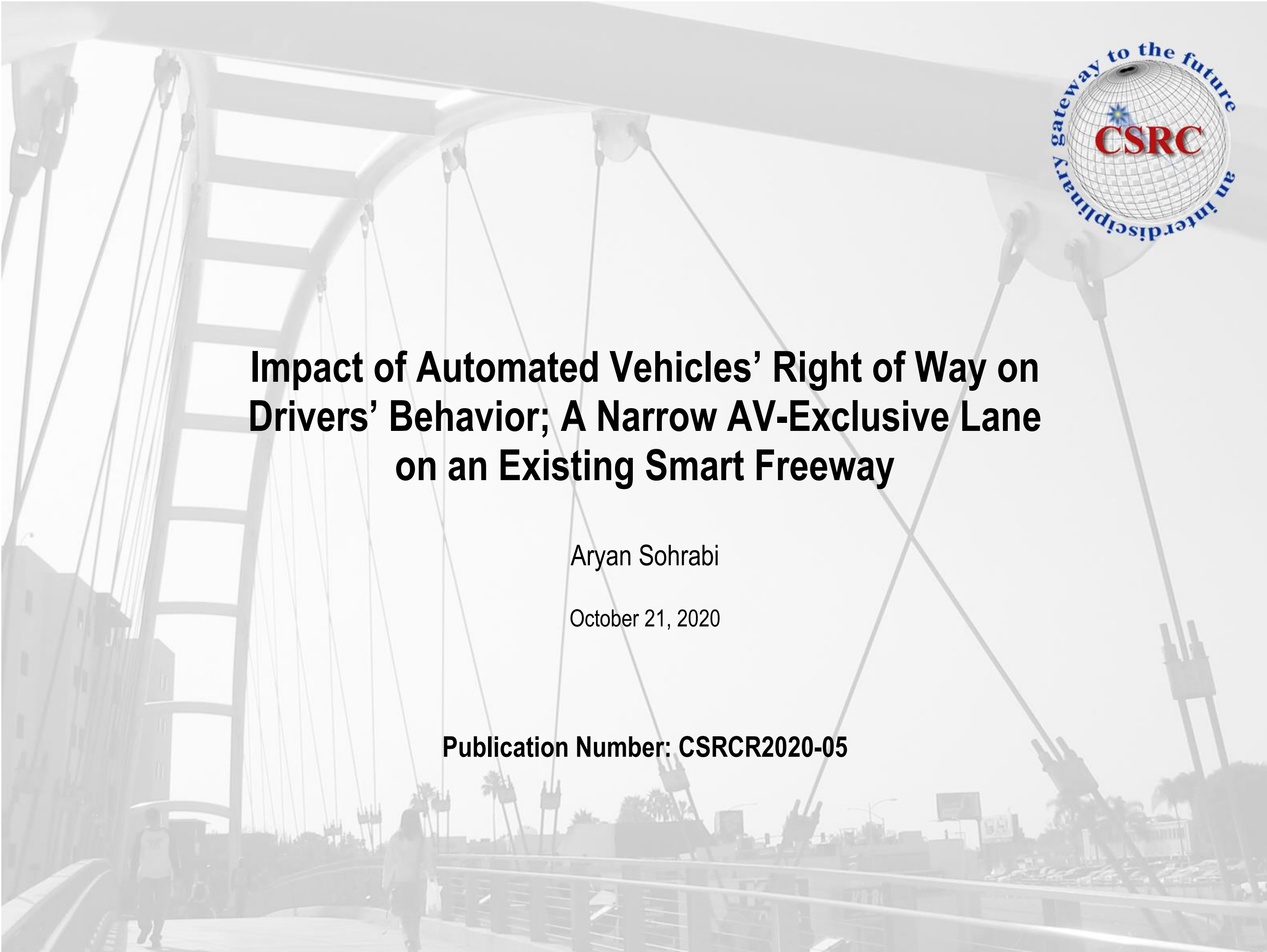

Impact of Automated Vehicles' Right of Way on Drivers' Behavior; A Narrow AV-Exclusive Lane on an Existing Smart Freeway

Aryan Sohrabi

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Fall 2020

Approval Page

Title: Impact of Automated Vehicles' Right of Way on Drivers' Behavior; A Narrow AV-Exclusive Lane on an Existing Smart Freeway

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1. ABSTRACT

This study looks at how the presence of a narrow lane (9ft) dedicated to Automated Vehicles (AVs) on a smart freeway would affect the behavior of drivers in the adjacent lane to the right. For this purpose, a driving simulation environment was designed mimicking the Interstate 15 smart corridor in San Diego. The experimental group drove next to the 9ft narrow lane while the control group drove next to a regular 12ft AV lane. Behavior of drivers was analyzed by measuring the mean lane position, mean speed, and the mental effort. In addition to AV lane width, AV headway, gender, and right lane traffic were taken into consideration in the experimental design to investigate interaction effects. The analysis results did not indicate a significant difference in speed or mental effort between driver groups. However, several groups were found to have significant differences between their lane positioning. Although the overall effect of AV lane width was not significant on lane positioning, there were some significant differences caused by the interaction effects between lane width and driver gender as well as lane width and right lane traffic presence. In all the groups with significant difference between their lane positioning, there were no cases where AV lane width was the only difference between the groups suggesting that the significant difference was caused by other factors differing between the groups. However, the trend observed amongst groups with significant difference between their lane positioning was that groups next to the 12ft lane had better lane centering compared to groups next to the 9ft lane. The analysis also showed that while in general female drivers tended to drive further away from the 9ft lane and performed worse in terms of lane centering, they performed better than male drivers when right lane traffic was present.

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4. INTRODUCTION AND BACKGROUND

Potential advantages of Automated Vehicles (AVs) have made them desirable for the future of transportation. Among these advantages are improvements in safety, traffic operation, parking, as well as economic benefits. AVs are predicted to substantially reduce traffic collisions caused by human error such as delayed reaction time, tailgating, rubbernecking, and other forms of distracted or aggressive driving. In addition, allowing for reduced safety gaps and higher speeds will result in increased roadway capacity and will minimize traffic congestion. Another important property of AVs is that they can move in platoons while maintaining a short time-headway which is beneficial for reducing highway congestion. This is accomplished by longitudinal control of vehicles and making use of vehicle-to-vehicle communication. Economically, AVs could result in reduced costs of vehicle insurance and improve fuel economy of the car.

Although a fully automated transportation system will not be implemented in the near future, mixed traffic conditions including vehicles with different automation levels interacting with each other will soon be the state of roadway traffic. This has caused the road infrastructure designers to think about new configurations to maximize the efficiency of traffic flow. To this effect, there are propositions of having narrower lanes exclusive to AVs in order to allow more lanes to fit into the freeways. AV's ability of latitudinal control and lane centering makes them suitable for such conditions. However, there are still several questions to be addressed for implementing AV-exclusive facilities.

The purpose of this study is to expand the knowledge base in terms of safety and operational impacts of narrower freeway lanes of AVs in a mixed (AVs and human-driven vehicles) traffic condition. This work investigates implications of a narrow AV-exclusive reversible lane on I-15 Express Lanes (EL) and answers the question that how the narrow AV-exclusive lane impacts the drivers who are driving on the regular EL adjacent to the narrow AV lane. The goal of the project is accomplished using a carefully designed driving simulator scenarios mimicking San Diego's I-15 Smart Corridor.

The Interstate 15 (I-15) EL, between State Route 163 (SR-163) and Via Rancho Parkway, currently provides 4 HOV and toll-paying FasTrak lanes. Caltrans is seeking more efficient ways to handle more traffic at the ELs from the main lanes, especially during rush hours or during major accidents when ELs are open to all traffic. In the available width between the fixed concrete barriers that separate the EL facility from the regular lanes, it would be possible to add a narrow (9-ft) reversible lane to be used only by AVs. In both the NB and SB directions of the EL, there would be two 12-ft wide lanes for HOV and FasTrak vehicles. With the new configuration, the questions are whether drivers who drive on the regular ELs adjacent to the proposed AV-exclusive lane change their driving behavior and how this narrow AV-exclusive lane affects mobility and safety on the regular ELs.

According to AASHTO Policy on Geometric Design, the lane width impacts comfort of driving, operational characteristics (e.g., capacity), and likelihood of certain type of crashes. Conventionally, lane widths of 9 to 12 ft are common with 12 ft lane mainly used on high-volume and high-speed roadways (*A Policy on Geometric Design of Highways and Streets, 7th Edition*, 2018). Adjacent obstructions and restricted lateral clearance affect level of service calculations through lane width and lateral clearance adjustment factors in the free flow speed equation. According to Highway Capacity Manual, narrower lane width is associated with greater reduction in free flow speed (*Highway Capacity Manual, Sixth Edition: A Guide for Multimodal Mobility Analysis*, 2016). Although there have been studies related to lane width impact on driving behavior and roadway safety and mobility in traditional roadways with no AV considerations (for examples see (Brewer, 2012; Dixon et al., 2016; Frank Gross et al., 2009; Lee et al., 2015; Potts et al., 2007)), to the best of the authors' knowledge there are no studies related to driving behavior in presence of AV-exclusive lanes. This study aims at filling this knowledge gap in the AV research.

The specific objectives of this study are as follows:

- Identify traffic implications that AV operation on AV-exclusive lanes has on performance of drivers on adjacent lanes to a narrow AV-exclusive lane compared to a regular sized AV-exclusive lane.
- Design and model a research platform in a driving simulator environment mimicking reconfiguration of San Diego I-15 smart corridor to accommodate and leverage AV technology
- Enable transport authorities to make more informed decisions on the development of new lane width standards and roadway reconfiguration for AV technology.

The remaining sections of this report include "literature review" summarizing behavioral and crash studies related to lane width as well as AV simulator research, "methodology" explaining the simulator and experimental design, variables, and participants, and "analysis and results" focusing on the results of statistical analysis and findings, followed by "discussion and conclusion".

5. LITERATURE REVIEW

Despite AV's potential benefits, there are multiple concerns that arise when considering the introduction of AVs. The first set of concerns are issues such as over-reliance on automation, possible loss of situation awareness, and loss of the skills needed to perform the automated functions manually. While these concerns are towards automated vehicles, behavioral adaptation of regular vehicles are also important. Along these lines, the purpose of this literature survey is to gain an understanding about the effects of lane width and AV platoon headway on non-AV drivers. Since the literature is limited for these specific conditions, we considered general studies on lane width and simulator studies related to AVs.

5.1. Behavioral studies related to lane widths

Behavioral studies on lane width have investigated measures such as speed and lateral position for different lane widths. Different results can be seen across the literature in this regard with majority showing speed increase in wider lanes. Liu et al. (Liu et al., 2016) tested the effects of lane width, lane position and edge shoulder width on driving behavior for a three-lane underground urban expressway. Driving speed, lane deviation, and subjective perception of driving behavior were collected as performance measures. For five different lane widths (2.85 m (9.35 ft), 3.00 m (9.84 ft), 3.25 m (10.66 ft), 3.50 m (11.48 ft), and 3.75 m (12.30 ft)), the results showed that lane width had significant effects on driving speed. Average driving speed increased from 60.01 km/h (37.29 miles/h) in the narrowest lane to 88.05 km/h (54.71 miles/h) in the widest lane. Another observation was that as the lane got wider, drivers tended to stay in the middle of the lane. In another study, Dixon et al. (Dixon et al., 2016) gathered both behavioral and crash data and identified an increase of about 2.2 mph (3.54 km/h) in speed for a 12 ft (3.66 m) lane compared with an 11 ft (3.35 m) lane.

A different result was reached by Rosey et al. (Rosey et al., 2009), who investigated the validity of simulator studies on lane width by comparing one case to a field study. The two cases of lane width were 3.5 m (11.48 ft) and 3 m (9.84 ft) chosen in reference to a previous field study. The comparison showed that, as in the field study, reducing the lane width had no impact on speeds but did induce the participants to drive closer to the center of the road. In a similar work, Mecheri et al. (Mecheri et al., 2017) concluded that in-lane position was affected differently by lane narrowing, depending on the traffic situation. In the absence of oncoming traffic, lane narrowing gave rise to significant shifts in the car’s distance from the lane’s center toward the edge line, whereas this distance remained similar across lane widths during traffic periods.

5.2. Crash studies related to lane widths

There has been a good amount of research conducted on lane width’s effect on safety measured using crash data. In most cases reduction of lane width has been done for congestion control. A study estimated various crash modification factors (CMFs) for different ranges of lane width based on the results of the generalized nonlinear models (GNMs). It was found that the crash rate was highest for 12 ft (3.66 m) lane and lower for the lane width less than or greater than 12 ft. The CMFs estimated using GNMs reflected that crashes are less likely to occur for narrower lanes if the lane width is less than 12 ft whereas crashes are less likely to occur for wider lanes if the lane width is greater than 12 ft. However, the effect of interaction between lane width and speed limit was significant. The estimated CMFs show that crashes are less likely to occur for lane widths less than 12 ft than the lane widths greater than 12 ft if the speed limit is higher than or equal to 40 mph (64.37 km/h). It was also found that crashes at higher severity levels are less likely to occur for lane widths greater or less than 12 ft compared to 12 ft lane (Lee et al., 2015).

Another study looked at a case in Shanghai where several cross-section reconstructions projects took place to increase the capacity of urban expressways. Three datasets corresponding to undersized (average lane width ≤ 3.25 m (10.66 ft)), standard-sized (average lane width ~ 3.45 m (11.32 ft)), and oversized lanes (average lane width ≥ 3.75 m (12.30 ft)) were collected for the development of CMFs. The scale in this study is different from (Lee et al., 2015) as the oversized lane width corresponds to medium size lane width in (Lee et al., 2015). Also, the three different lengths are closer to each other than the other study with difference of 0.5m (1.6 ft) between the widest and narrowest lane widths. They established different models of involved-vehicle number (two-vehicle crash and multi-vehicle crash) and traffic condition (congested-flow crash and non-congested-flow crash), and CMFs were developed respectively. The results showed that standard-sized lanes experienced the lowest crash frequency in all kinds of crash. The crash frequency of undersized lanes and oversized lanes would increase 190% and 134% compared with standard-sized lanes in total crash (Wu & Sun, 2015).

Meanwhile, Potts et al. (Potts et al., 2007) found no general indication that the use of lanes narrower than 3.6 m (12 ft) on urban and suburban arterials increases crash frequencies.

Yet another result was found by Wood et al. (Wood et al., 2015); using ten years of mid-block crash data on urban arterials and collectors from four cities in Nebraska, they estimated CMFs for various lane widths and crash types. Lane widths that were analyzed were 9 ft (2.74 m), 10 ft (3.05 m), 11 ft (3.35 m), and 12 ft (3.66 m). Roadways with 10 ft travel lanes were found to experience the highest crash frequency relative to other lane widths. Meanwhile, roads with 9 ft travel lanes were found to experience the lowest relative crash frequency. CMFs for target crash types (sideswipe same-direction and sideswipe opposite-direction) were found to be consistent with the values used in the Highway Safety Manual (HSM). Similarly, using the same ten-year crash data, Elhenawy et al. (Elhenawy et al., 2019) found the highest crash rate on 10 ft lanes. However, they noted the second highest crash rate on 9 ft lanes. It should be pointed out that crash rates can be defined differently and thus it could lead to a potential bias when comparing different studies. For example, Elhenawy et al. (Elhenawy et al., 2019) adopted an equation to calculate crash rate, which accounts for yearly crash counts, road segment length, AADT, number of lane, and a tuning parameter for the exposure measure. Dixon et al. (Dixon et al., 2016) also found a different result; the safety analysis determined a crash difference between 12ft and 11ft lanes on a freeway with 12ft lanes showing safety improvement over 11ft lanes. In addition to the effect of lane width, crash reductions were associated with each additional lane, increased left shoulder widths, and increased right shoulder widths.

Congestion on urban freeways often creates a need to increase freeway capacity by adding an additional lane. Although adding a lane by widening the existing roadbed is often difficult and expensive, converting all or part of the shoulder to a travel lane is a practical solution. However, the safety implications of this operational decision needs to be considered.

In one study an observational before-and-after evaluation with the empirical Bayes method was done to examine the safety effects of projects involving narrower lanes or shoulder conversions on existing urban freeways in California with four or five lanes in one direction of travel. The evaluation found that projects converting four lanes to five lanes resulted in increases of 10% to 11% in accident frequency. Projects converting five lanes to six lanes resulted in smaller increases in accident frequency (Bauer et al., 2004).

Another study on the safety of shoulder running considered the relationship of traffic flow parameters such as volume, density, and speed to safety. Their results suggested that as flow increased, the crash rate initially remained constant until a certain critical threshold combination of speed and density was reached. Once this threshold was exceeded, the crash rate raised rapidly. It was suggested that this rapid rise in crash rate was caused by an increase in density without a notable reduction in speed and the resultant small headways that made it difficult for drivers to compensate for error. Their model suggested that during hard shoulder running, crash rates declined because of the lower traffic volume or density per lane and that the safety benefits of a reduced volume or density per lane outweighed the adverse effects of the lack of provision of a full shoulder (Kononov et al., 2012).

5.3. Simulator studies related to AVs

It is also important to know what simulator studies have been conducted on automated vehicles. In this section, we examine studies on both automated and regular vehicles. A large portion of the literature on automated vehicles is on situation awareness of the drivers. For example, Young and Stanton (Young & Stanton, 2007) studied the effect of automated longitudinal control on the brake reaction time of the drivers and striking increase in reaction times were found for these automated conditions. Similarly, Gold et al. (Gold et al., 2015) investigated how the experience of automated driving will change trust in automation and the attitude of the driver towards automation. A questionnaire before and after the driving simulator experience was used to assess trust in automation, safety gain, intention to use, and other constructs. Also, the gaze behavior of the participants was recorded in order to measure a change of trust by a change in scanning behavior. Results indicated that the driving experience increased self-reported trust in automation and led to a decrease in other measured constructs like safety gain. Older participants rated the vehicle automation more positively than younger drivers. Horizontal gaze behavior could not be confirmed as a metric for measuring trust in automation, although this measure behaved as expected and analogous to the self-reported level of trust. Another study on situation awareness has investigated the behavior of drivers that are required to take over control of highly automated vehicles from a distracted state. From the study results, they were able to narrow down a minimum amount of time in which drivers can take over the control of vehicle safely and comfortably from the automated system in the presence of a road hazard (Mok et al., 2015).

de Waard et al. (de Waard et al., 1999) also investigated overreliance on the automated system, which was tested in an emergency condition where the automated system failed to function properly and the driver actively had to take over speed control. Three Automated Highway System (AHS) conditions were tested: driving in a platoon of cars at 1 sec and at 0.25 sec time headway and driving as a platoon leader. The results showed lower physiological and subjectively experienced levels of activation and mental effort in conditions of automated driving. In the emergency situation, only half of the participants took over control. This condition received the highest risk ratings, followed by automated driving at 0.25 sec time headway. When driving automatically, most drivers preferred the longer time headway of 1 sec to vehicles in front.

In contrast to the studies mentioned so far, which have focused on situation awareness in highly automated environments, de Vos et al. (de Vos et al., 1998) focused on the acceptance of tight margins in lateral direction in case of an Automatic Vehicle Guidance (AVG) system implemented on the left lane of a motorway. The subjects drove a route once in an automated mode and once steering the car themselves. The lane had varying width, partly physically separated from the manual traffic lanes by means of a barrier and partly directly adjacent to the normal manual traffic lanes. The results showed that the comfort level in an AVG system is not affected by a physical separation between the AVG lane and the manual lanes, nor by the speed driven within the AVG lane. The width of an AVG lane does affect comfort. A moderate reduction of lane width does not have a great impact on comfort. It was however found that, when the lane width approached the vehicle width, comfort was distinctly reduced. In manual driving, not only reduced lane width but also a barrier was found to be a discomfort factor. In order to cope with the narrow lane condition subjects reduced their speed and shifted their course away from the barrier. Steering effort was increased in the tight lane conditions.

While the previous studies simulated an automated vehicle environment, there has also been simulator studies on the behavior of regular vehicles in mixed traffic situations. A similar study to our proposed research has investigated behavior of drivers next to AVs with varying headways. This study examined whether a contagion effect would occur among the drivers of regular vehicles from the short time head way held in AV platoon. The result showed that participants adapted their driving behavior by displaying a significant shorter average and minimum THW (time headway) while driving next to an AV platoon holding short THWs than when THW was large. They also spent more time keeping a THW below a safety threshold of 1s (Gouy et al., 2014).

Meanwhile, Larburu et al. (Larburu et al., 2010) studied safe and reliable platooning systems with increased levels of automation. Similar to Gouy et al (Gouy et al., 2014), they analyzed subjective opinions of non-platoon users while driving near different sizes of platoons, but also, subjective and objective information of platoon users. The results showed that in general (around 75%), people felt uncomfortable when intra-platoon gap length was less than 16 m, and people felt unsafe under 7 m. 91% of all participants thought that 90 kph (55.92 miles/hour) was a very comfortable speed for platoons. During every transition from normal driving to automated driving and vice versa, 95% said that information to the driver was absolutely necessary and 86% said that an acknowledgment from the driver before starting the maneuvers was required. In the case of driving next to platoons, around 73% of the participants felt that driving near a platoon of five cars and one leading truck is the same as normal driving and they did not see any problems to do different maneuvers. The percentage of participants that felt the same was reduced to 55% for medium length platoon with fifteen cars and one leading truck and further reduced to only 36% for longer platoons.

6. METHODOLOGY

6.1. Driving simulator

The driving simulator used in this study is a DriveSafety RS-250 simulator located at SDSU Smart Transportation Analytics Research (SDSU-STAR) Lab (see Figure 1). It is an automatic transmission vehicle which has a steering wheel, brake and acceleration pedals, blinkers, a shifter, an emergency brake, and other less relevant accessories. The car panel has a speedometer that shows the speed during the drive. The simulation is fixed-base and the driver of the simulator does not experience simulated movements. The simulated environment is visible through three front display television screens. The audio of the simulated environment is projected through two small speakers on either side of the driver. The vehicle and the screens are controlled by four computers; one for each screen and one main component that controls the other three and communicates with a PC that has the information about the scenarios.

Figure 1. SDSU Smart Transportation Analytics Research (SDSU-STAR) Lab driving simulator

6.2. Scenario design

The scenarios were built through the HyperDrive software using custom made tiles for mimicking the I-15 smart corridor lane reconfiguration in San Diego. The speed limit was considered 65 mph as it is the designated speed limit on the I-15 corridor. There are four different scenarios for this study, and all are structured as follows (see Figure 2). Each begins with a two-lane freeway tile and then split into a custom made three lane tile. After 5 miles, the custom-made tile merges back into a two-lane tile. It then splits one more time into a three-lane tile and merges back again into a two-lane tile after 5 miles for a final time. The first 5-mile section is referred to as the first section (section 1) and the second 5-mile section as the second section (section 2). Within each section, there is an area where the collected data were used for analysis. It should also be noted that initially, stationary cars were placed in the beginning of section 1 and 2 with a distance between them that replicated an assigned AV headway for each section. Using triggers, the stationary cars in each section start moving when the participant enters that section. To fill in the space left by the moving traffic, new cars were generated from a source near the beginning of the section once the traffic has started moving. Also, data collected in the beginning and end of the sections were excluded from the analysis. The beginning portion was taken out to allow for adaptation of the participant to the new section setup and minimize the unwanted effect of environment change on dependent variables of the study. The ending portion was also taken out to eliminate the effect of lane change from 3 to 2. The drivers start in the left lane of the first two-lane tile and maintain their lane into the middle lane of the three-lane tile. The left most lane on section 1 and 2 is AV-exclusive lane occupied by AV vehicles. Therefore, in all the scenarios participants are driving on the adjacent lane to the AV-exclusive lane. At the end of section 1, they maintain their lane into the left lane of the two-lane tile, and they repeat this process one more time for section 2 (i.e., driving adjacent to the AV-exclusive lane).

Figure 3 shows the specific scenario design of the four scenarios of the study; there are two test (scenario 1 and 2) and two control (scenario 3 and 4) scenarios. The lane width configuration is different in the test and control scenarios as the purpose of the study is to evaluate the 9ft and 12 ft AV-exclusive lanes. The test scenarios have a 9ft lane on the left (AV-exclusive lane) and 12ft lanes in the center and right. The control scenarios have 12ft lanes all across including the AV-exclusive lane. Traffic exists and moves on the AV-excusive lane with headway of 1sec in section 1 and a headway of 3sec in section 2 for scenario 1. Scenario 2 has the headways reversed for the two sections (3sec headway in section 1 and 1sec headway in section 2) and has a traffic in the right lane moving with 1sec headway. Scenarios 3 and 4 are similar to 1 and 2 respectively with the exception that the left lane (Av-exclusive lane) is 12ft wide. Toward the end of each section, specific segment workload of the participant was assessed using the Ratings Scale of Mental Effort (RSME) scores. Figure 4, Figure 5, Figure 6, and Figure 7 show some snapshots of the design for scenario 1 to 4 in the simulator screen. All Scenarios were pilot tested prior to data collection.

Table 1 summarizes the experimental design matrix. The study uses a 2 (AV-exclusive lane width) x 2 (AVs headway) x 2 (Presence of traffic in the right lane) mixed-factors design (see Table 1). Participants were randomly assigned to two groups of "participant group 1" and "participant group 2". Participants in group 1 drove scenario 1 and 2 (test scenarios), and group 2 drove scenario 3 and 4 (control scenarios). Within each group of participants, the scenarios were randomly assigned.

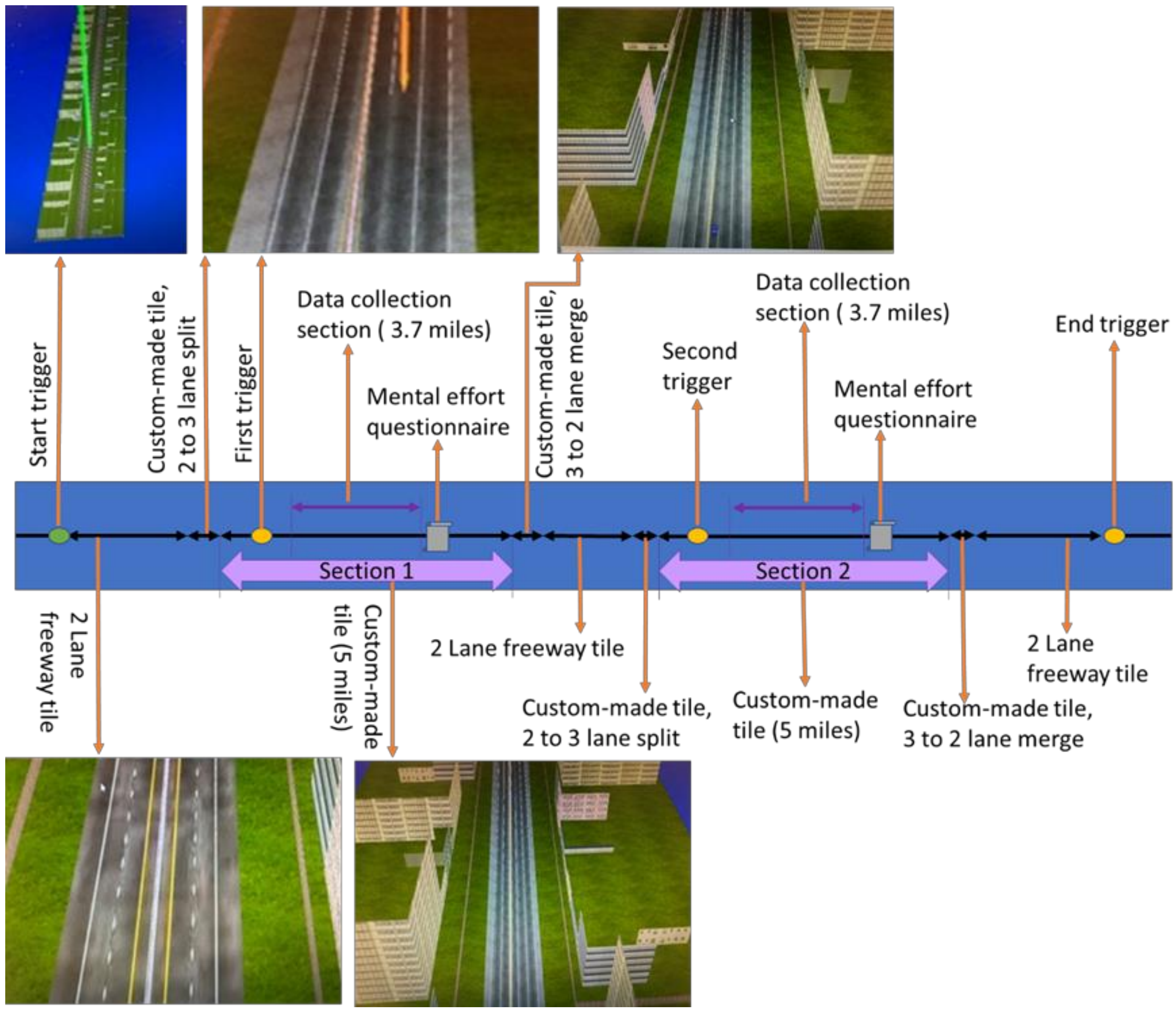

Figure 2. Overview of the design for the 4 scenarios

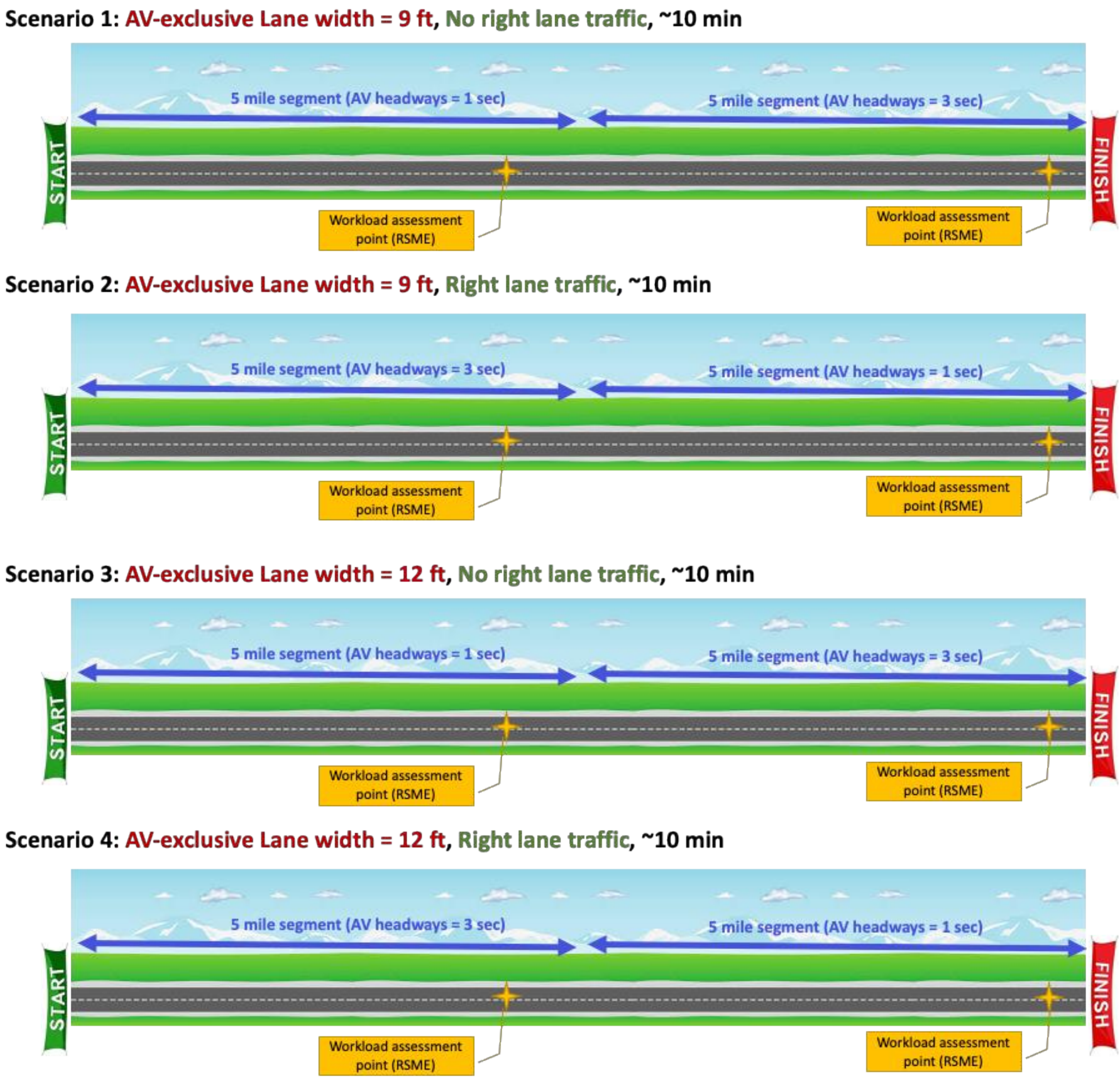

Figure 3. Scenario designs

Table 1: Experimental design matrix

	Presence of traffic in the right lane			
	Present		Not Present	
	AVs headway		**AVs headway**	
AV-exclusive lane width	1 sec	3 sec	1 sec	3 sec
9 ft	Participant group 1	Participant group 1	Participant group 1	Participant group 1

12 ft	Participant group 2	Participant group 2	Participant group 2	Participant group 2

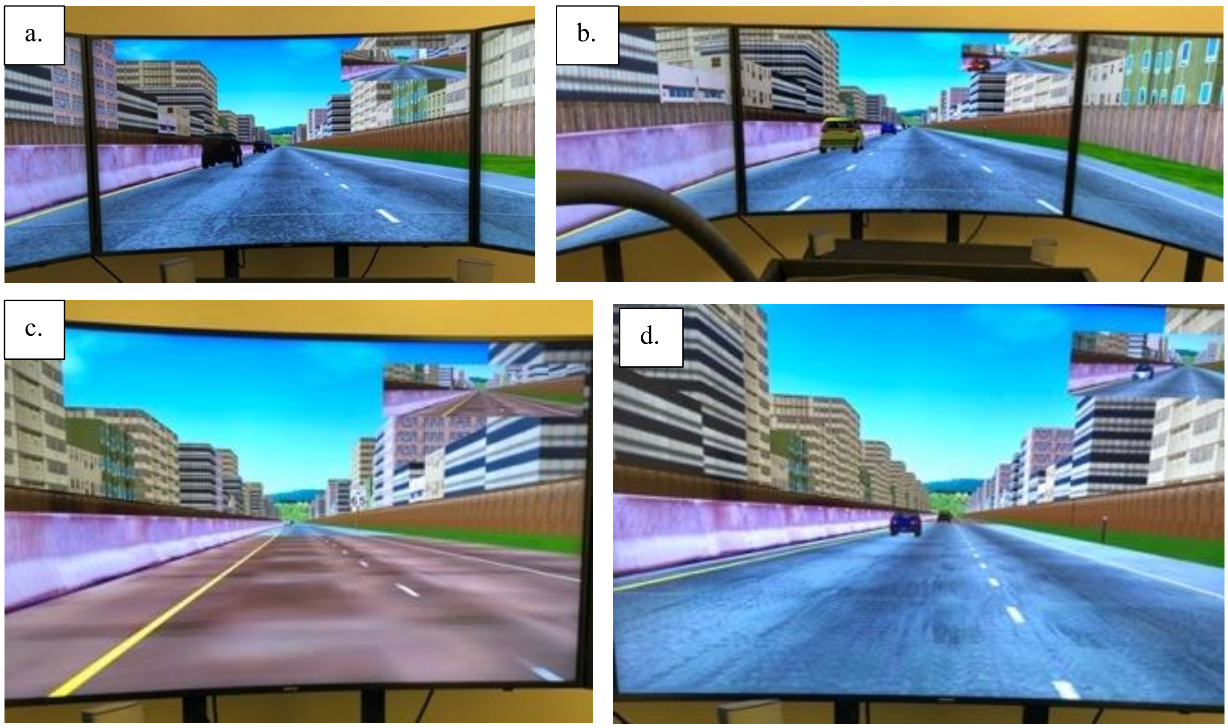

Figure 4. scenario 1: a) entering section 1, b) section 1, c) junction between section1 and 2, d) transition from 3 lanes to 2 after section 2

Figure 5. Scenario 2: a) section1, b) junction between section1 and 2, c) beginning of section2, d) section2

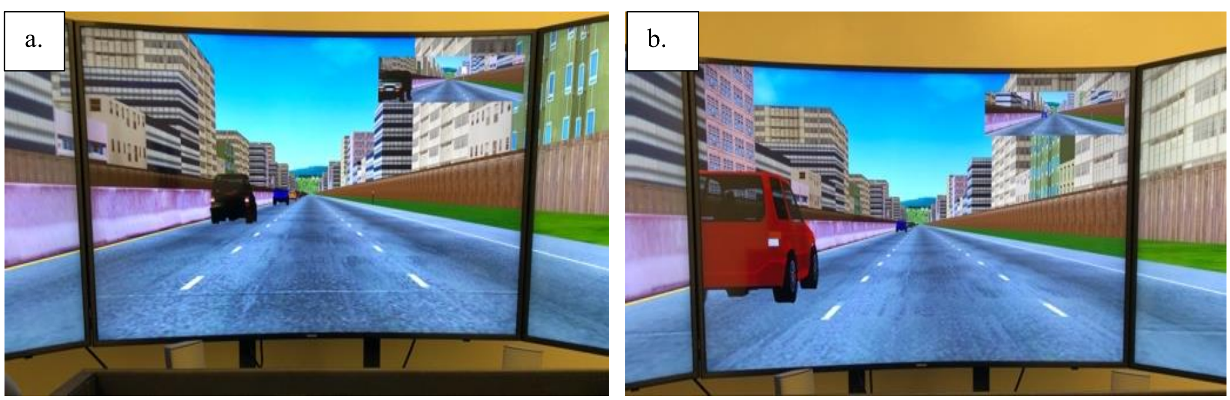

Figure 6. Scenario 3: a) section 1, b) section 2

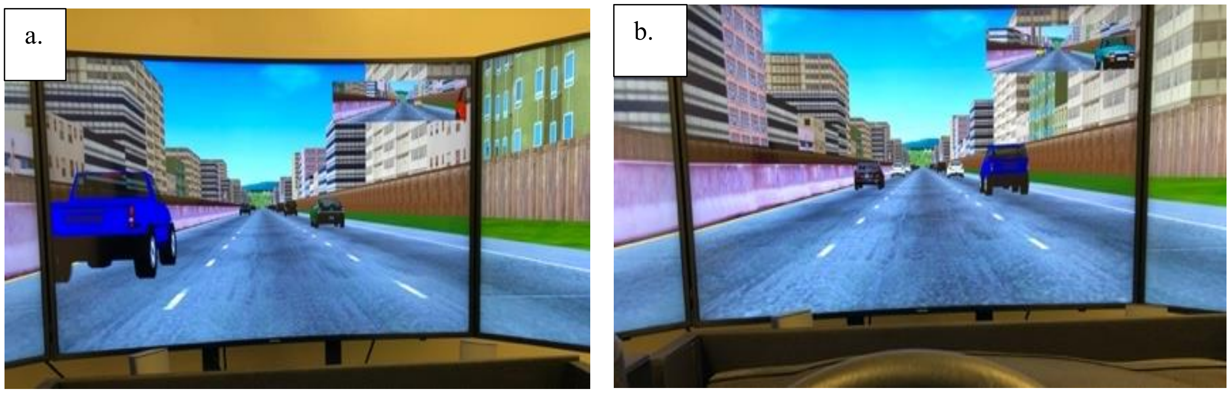

Figure 7. Scenario 4: a) section 1, b) section 2

6.3. Variables of the study

As shown in Table 2, the 4 independent variables of the study were gender of the participants, presence of traffic in the right lane, AV-exclusive lane (left lane) width, and headway of AVs on the AV-exclusive lane. The second and last columns indicates shortened versions of the variable and level names used for convenience in the analysis section's plots and tables. The third column in the table shows if the variable is between or within subject. Within subject variables are variables for which the subjects try all of their levels and between subject variables are variables for which each subject tries one of their levels. The forth column shows the levels of each variable; gender has two levels and the study is gender balanced (same number of males and females), headway has 2 levels of 1 second and 3 seconds, right lane traffic has two levels (present and not present), and left lane width has 2 levels of 9ft and 12 ft.

The dependent variables of the study are mean speed, mean lateral distance, and participant workload as shown in Table 3. Variables' short name, unit, type/range, and descriptions are provided in the columns of the table, respectively. Speed and lateral distance were tracked for 30 frames per second by the simulator. Mean of speed and lateral distance were calculated for section 1 and 2 of the scenarios to summarize the information. Workload was measured at the end of each section by asking participants to score the rating of mental effort according to a Ratings Scale of Mental Effort (RSME) scores (Appendix A) ranging from 0 to 150 with latter indicating maximum mental effort.

Table 2 Independent variables

Variable	Variable short name	Type (Between/Within subject)	Levels	Level short names
Gender	gender	Between	Male or Female	M or F
Presence of traffic in the right lane	right_lane_traffic	Within	right lane traffic or no right lane traffic	RLT or no_RLT
AV-exclusive lane (left lane) width	AV_lane_width	Between	9 feet or 12 feet	9ft or 12ft
Headway of the AVs	AV_headway	Within	1 second or 3 seconds	1sec or 3sec

Table 3 Dependent variables

Variable	Variable short name	Unit	Type/Range	Description
Mean Speed	mean_speed	Miles per hour	Continuous/positive	Mean of distance over time
Mean Lateral position	mean_lane_pos	feet	Continuous/positive is to the right, negative is to the left	Mean lane offset. Measurement is based on the center point of the car to the center of the lane
Mental effort	mental_effort	None	Ordinal/between 0 and 150	Amount of workload/mental effort taken to complete a task

6.4. Simulator procedure and participants

The procedure of the study was documented, submitted, and approved by the SDSU Institutional Review Board (IRB). During their visit, participants began by signing a consent form. They were informed about the purpose of the study, its potential risks and benefits, and were given a brief description of the scenarios. They were then asked to perform an adaptation drive to become familiar with the functionalities of the driving simulator. After the adaptation drive, they were informed about the mental effort scale and proceeded with driving the two assigned scenarios to them. 40 participants (20 males and 20 females) aged between 18 and 25 were recruited for this study. The recruitment was advertised through distribution of flyers in the university campus and by email. Each participant received $25 compensation upon completion of the study. The study took around 40 minutes for each participant.

6.5. Data collection and reduction

Data were automatically collected by the simulator after being specified as needed in the source code. The variables of interest and the frequency of data collection were defined through the scenario's source code as well. Upon completion of the scenarios, the data were stored on the PC as a datacol file. The frequency of collection for this study was 30Hz. The simulator tracks values for a set of default variables which were not needed for this study and so they were taken out for the analysis. The research team utilized visualization techniques to review all data to identify potentially erroneous findings due to data collection errors, simulator failure, participant entry errors, or other data issues that may impact data veracity. Also, automatic data collection took place for the entire duration of the scenario. However, the size of the data was reduced to contain only the useful information for the data collection sections as shown earlier in Figure 2.

7. ANALYSIS AND RESULTS

In this section, the data collected from the study are analyzed to see how different conditions (levels of the independent variables and their interactions) affect the dependent variables. For this reason, appropriate statistical models were used to hypothesize the relationship between them. The models were chosen so that their assumptions were relevant to the data and they were fitted using well-known methods implemented in popular R libraries. The models were then evaluated using analysis of variance techniques. These tests usually have their own assumptions about the data, and they were checked whenever needed. This procedure was repeated for all of the dependent variables separately.

7.1. Analysis of mean lane position:

Figure 8 shows a summary of mean lane position for all the different treatments. The y-axis is the mean lane position and the x-axis is all the possible levels of the interaction between lane width, right lane traffic, and headway. With gender variable included using different color box plots, it is possible to see the interaction of all of the independent variables. This plot was used to provide a visual and intuitive interpretation of the data.

Looking at the figure, for 9ft lane width, female drivers seem to have more diversion to the right side where male drivers have more negative lane positioning meaning that they drove closer to the 9ft AV-exclusive lane on their left. Statistical analysis and hypothesis testing were conducted to confirm or refute the premise of this observation.

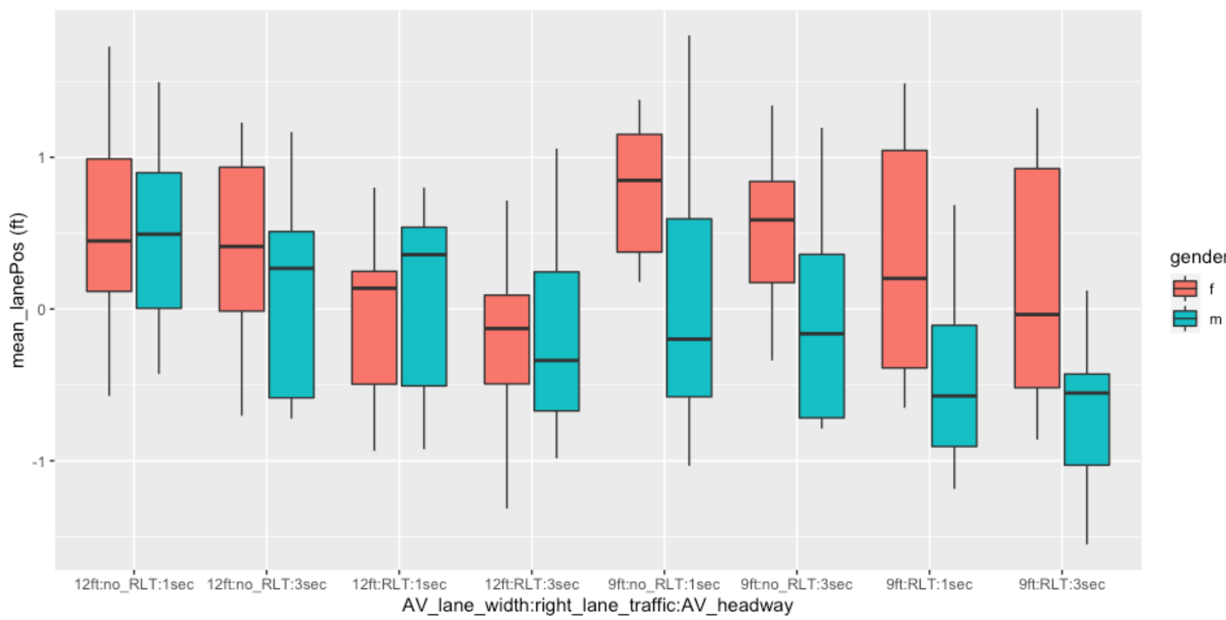

Figure 8. Boxplot of mean lane position for all the different treatments

The data was modeled by a Linear Mixed Model (LMM). The linearity means that the dependent variables are modeled as a linear function of the independent variables. The model is also a mixed model meaning it has both fixed and random effects. The random effects are used to describe the within subject nature of the data. The model's formula in R syntax was mean_lanePos ~ gender * lane_width * right_lane * headway + (1|subject), indicating that the mean_lanePos is modeled as a function of independent variables and the interactions between them.

There are normality of residuals assumption and the homoscedasticity assumption that needed to be verified in order to conduct analysis of variance on linear models. To check the normality assumption, the Shapiro-Wilk normality test was conducted; which gave a non-significant p-value of 0.684 indicating no significant departure from normality. The normality criterion can also be checked visually using a Q-Q plot of theoretical (normally distributed) vs sample quantities shown in Figure 9. The graph shows that points lie mostly on the linear line corresponding to two quantities that came from the same distribution.

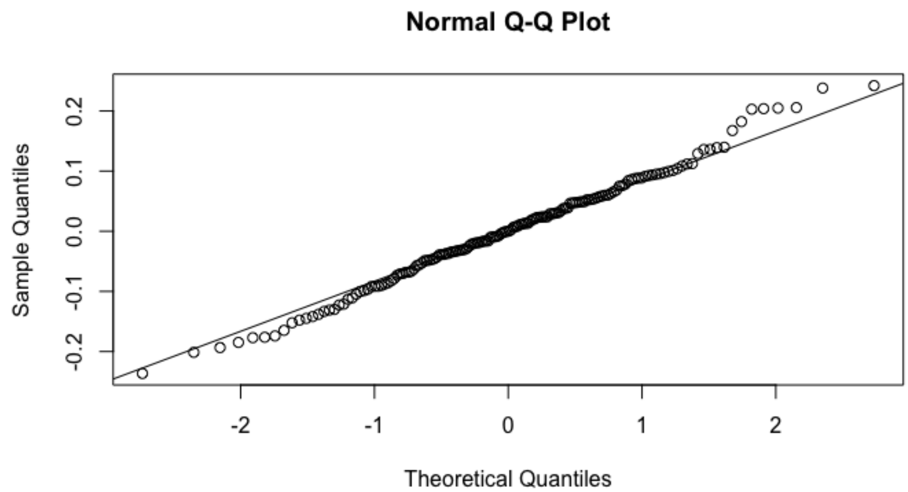

Figure 9. Q-Q plot of theoretical (normally distributed) vs sample quantities

The homoscedasticity assumption was checked using Leven's test for homogeneity of variance with median as center also known as the Brown-Forsythe test. The result of which is shown in Table 4.

Table 4. Levene's Test for Homogeneity of Variance (center = median)

	Df	F value	Pr(>F)
group	15	0.564	0.897
	144	NA	NA

According to Table 4, the homoscedasticity assumption is also valid as the p-value is not significant, so there is more confidence in the results from analysis of deviance (Table 5) of the established linear model. The deviance is used to compare two models, in particular in the case of Generalized Linear Models (GLM), where it has a similar role to residual variance from analysis of variance (ANOVA) in linear models. In the case of a GLM with normal distribution and identity link (i.e. regular regression), analysis of deviance is equivalent to ANOVA.

Table 5. Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger df)

	F	Df	Df.res	Pr(>F)
(Intercept)	1.221	1	36	0.276
gender	4.540	1	36	0.040 *

AV_lane_width	0.136	1	36	0.713
right_lane_traffic	77.670	1	108	0.000 ***
AV_headway	14.460	1	108	0.000 ***
gender:AV_lane_width	3.388	1	36	0.073 .
gender:right_lane_traffic	0.200	1	108	0.655
AV_lane_width:right_lane_traffic	0.012	1	108	0.913
gender:AV_headway	0.382	1	108	0.537
AV_lane_width:AV_headway	0.033	1	108	0.855
right_lane_traffic:AV_headway	0.154	1	108	0.695
gender:AV_lane_width:right_lane_traffic	3.721	1	108	0.056 .
gender:AV_lane_width:AV_headway	0.686	1	108	0.409
gender:right_lane_traffic:AV_headway	0.006	1	108	0.937
AV_lane_width:right_lane_traffic:AV_headway	0.070	1	108	0.791
gender:AV_lane_width:right_lane_traffic:AV_headway	1.141	1	108	0.287

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 5 shows that gender, right_lane_traffic, AV_headway, the interaction between gender and AV_lane_width, and the interaction between gender, AV_lane_width, and right_lane_traffic had significant effects on the value of mean lane position. The significance level is determined by the p-value which is the lowest for right_lane_traffic and AV_headway, second lowest for AV_lane_width, and third lowest for the interaction between gender and AV_lane_width and the interaction between gender, AV_lane_width, and right_lane_traffic.

Table 6 and Table 7 show the post-hoc pairwise comparison of the significant interaction effects.

Table 6. Post-hoc analysis of the interaction between gender and AV lane width

contrast	estimate	SE	df	t.ratio	p.value
f,12ft - m,12ft	0.016	0.079	36	0.205	0.996
f,12ft - f,9ft	-0.082	0.079	36	-1.040	0.727
f,12ft - m,9ft	0.140	0.079	36	1.768	0.305

m,12ft - f,9ft	-0.099	0.079	36	-1.245	0.602
m,12ft - m,9ft	0.124	0.079	36	1.563	0.412
f,9ft - m,9ft	0.223	0.079	36	2.808	0.038 *

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Results are averaged over the levels of: right_lane_traffic, AV_headway
Degrees-of-freedom method: kenward-roger
P value adjustment: tukey method for comparing a family of 4 estimates

Table 7. Post-hoc analysis of the interaction between gender, AV lane width, and right lane traffic

contrast	estimate	SE	df	t.ratio	p.value
f,12ft,no_RLT - m,12ft,no_RLT	0.057	0.083	43.150	0.694	0.996
f,12ft,no_RLT - f,9ft,no_RLT	-0.050	0.083	43.150	-0.611	0.998
f,12ft,no_RLT - m,9ft,no_RLT	0.146	0.083	43.150	1.759	0.649
f,12ft,no_RLT - f,12ft,RLT	0.193	0.034	108.000	5.540	0.000 ***
f,12ft,no_RLT - m,12ft,RLT	0.168	0.083	43.150	2.021	0.480
f,12ft,no_RLT - f,9ft,RLT	0.079	0.083	43.150	0.948	0.979
f,12ft,no_RLT - m,9ft,RLT	0.328	0.083	43.150	3.941	0.006 **
m,12ft,no_RLT - f,9ft,no_RLT	-0.108	0.083	43.150	-1.306	0.891
m,12ft,no_RLT - m,9ft,no_RLT	0.088	0.083	43.150	1.065	0.960
m,12ft,no_RLT - f,12ft,RLT	0.135	0.083	43.150	1.629	0.730
m,12ft,no_RLT - m,12ft,RLT	0.110	0.034	108.000	3.164	0.040 *
m,12ft,no_RLT - f,9ft,RLT	0.021	0.083	43.150	0.254	1.000

m,12ft,no_RLT - m,9ft,RLT	0.270	0.083	43.150	3.247	0.042 *
f,9ft,no_RLT - m,9ft,no_RLT	0.197	0.083	43.150	2.371	0.281
f,9ft,no_RLT - f,12ft,RLT	0.244	0.083	43.150	2.935	0.090 .
f,9ft,no_RLT - m,12ft,RLT	0.219	0.083	43.150	2.633	0.172
f,9ft,no_RLT - f,9ft,RLT	0.130	0.034	108.000	3.721	0.007 **
f,9ft,no_RLT - m,9ft,RLT	0.379	0.083	43.150	4.553	0.001 **
m,9ft,no_RLT - f,12ft,RLT	0.047	0.083	43.150	0.564	0.999
m,9ft,no_RLT - m,12ft,RLT	0.021	0.083	43.150	0.261	1.000
m,9ft,no_RLT - f,9ft,RLT	-0.067	0.083	43.150	-0.810	0.991
m,9ft,no_RLT - m,9ft,RLT	0.181	0.034	108.000	5.202	0.000 ***
f,12ft,RLT - m,12ft,RLT	-0.025	0.083	43.150	-0.302	1.000
f,12ft,RLT - f,9ft,RLT	-0.114	0.083	43.150	-1.375	0.863
f,12ft,RLT - m,9ft,RLT	0.134	0.083	43.150	1.618	0.737
m,12ft,RLT - f,9ft,RLT	-0.089	0.083	43.150	-1.072	0.959
m,12ft,RLT - m,9ft,RLT	0.160	0.083	43.150	1.920	0.545
f,9ft,RLT - m,9ft,RLT	0.249	0.083	43.150	2.993	0.079 .

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Results are averaged over the levels of: AV_headway

Degrees-of-freedom method: kenward-roger

P value adjustment: tukey method for comparing a family of 8 estimates

Table 6 and Table 7 show that the significant difference in mean lane position exists between (f,9ft and m,9ft), (f,12ft,no_RLT and f,12ft,RLT), (f,12ft,no_RLT and m,9ft,RLT) , (m,12ft,no_RLT and m,12ft,RLT), (m,12ft,no_RLT and m,9ft,RLT), (f,9ft,no_RLT and f,12ft,RLT), (f,9ft,no_RLT and f,9ft,RLT), (f,9ft,no_RLT and m,9ft,RLT), (m,9ft,no_RLT and m,9ft,RLT), and (f,9ft,RLT and m,9ft,RLT).

Figure 10, Figure 11, Figure 12, Figure 13, and Figure 14 contain boxplots for comparing different groups. Figure 10 shows that female drivers tended to the right while the male drivers tended to the left of the center line. Also, female drivers deviated more from the center line. Figure 11 shows that drivers deviated more to the right in the absence of right lane traffic. Figure 12 shows that the drivers tended to get farther from the AV lane when the AVs had smaller headways. In terms of lane centering, the comparison of deviation from the center position for the levels of AV headway and right lane traffic shows almost no difference.

As Figure 13 shows, the difference in mean lane position between genders is statistically significant for 9 ft lane width. More specifically female drivers tended to deviate away from the 9 ft lane where male drivers drove closer to the narrow lane. This is the only significant comparison of this figure according to Table 6. In terms of lane centering ability, Figure 13 shows that females driving next to the 9ft lane were more successful than males driving next to the 9ft lane.

Figure 14 shows that the most difference in the mean lane position is observed between females driving next to the 9 ft AV exclusive lane on their left without traffic on the right, and males driving next to the 9 ft lane on their left with right lane traffic which is also shown statistically significant in Table 7. Most of the significant comparisons in Table 7 are between groups with no traffic on the right lane and those with traffic on the right lane. According to Figure 14, for all such comparisons, drivers with traffic on the right lane were farther away from the right lane. The only other significant comparison is between females and males driving next to the 9ft AV exclusive lane with traffic on the right lane in which case female drivers tended to deviate away from the 9 ft lane while male drivers drove closer to the 9ft lane and female drivers had better lane centering performance (smaller absolute value of lane positioning). In terms of lane centering ability, for comparisons between 12ft and 9ft groups, 12ft groups always had better lane centering. For other comparisons, with the exception of m,9ft, RLT vs m,9ft,no_RLT, all comparisons show that cases with right lane traffic had better lane centering.

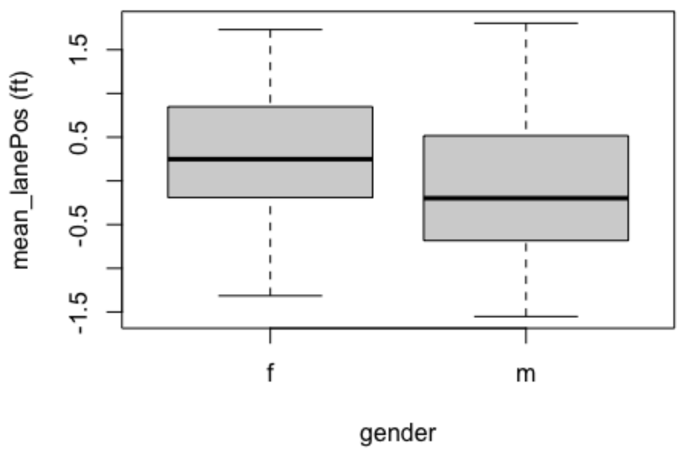

Figure 10. Box plot of mean lane position for levels of gender

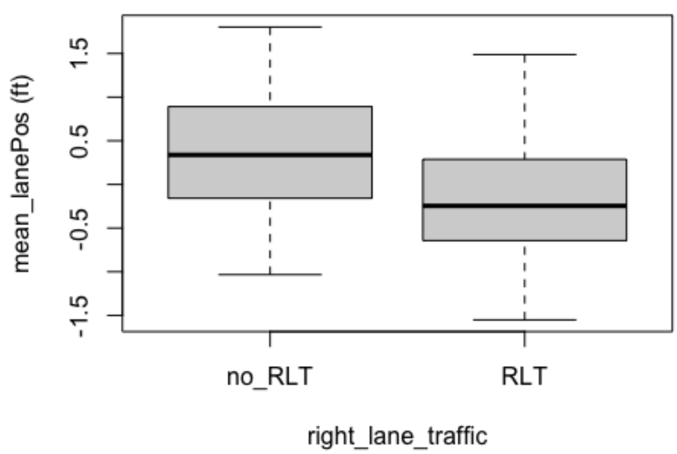

Figure 11. Box plot of mean lane position for levels of right lane traffic

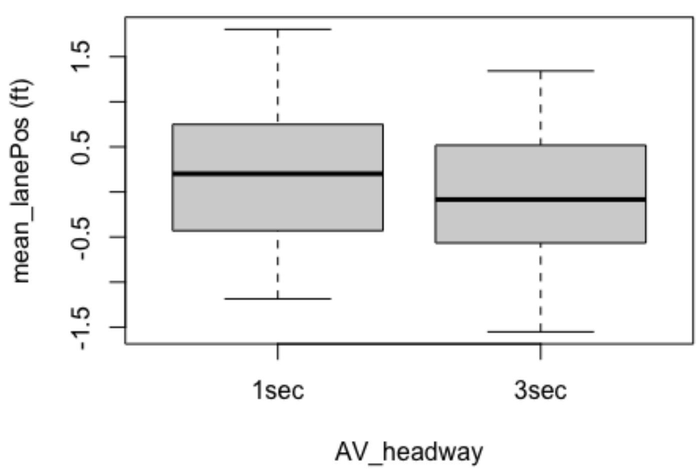

Figure 12. Box plot of mean lane position for levels of AV headway

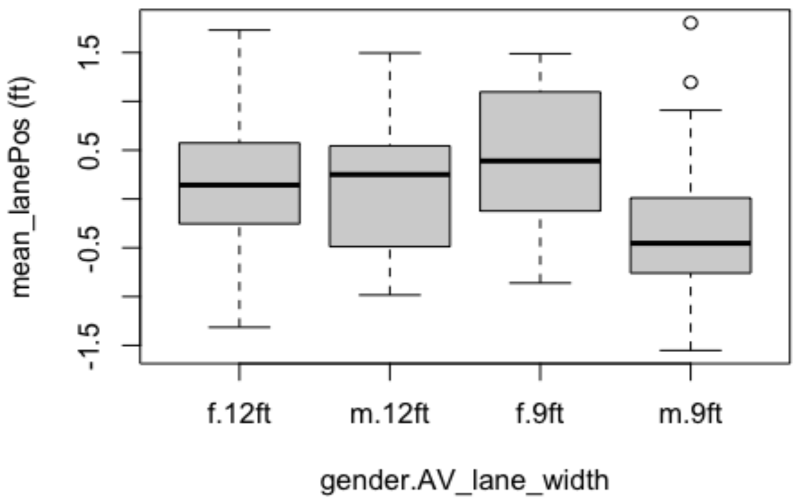

Figure 13. Box plot of mean lane position for levels of gender * AV lane width

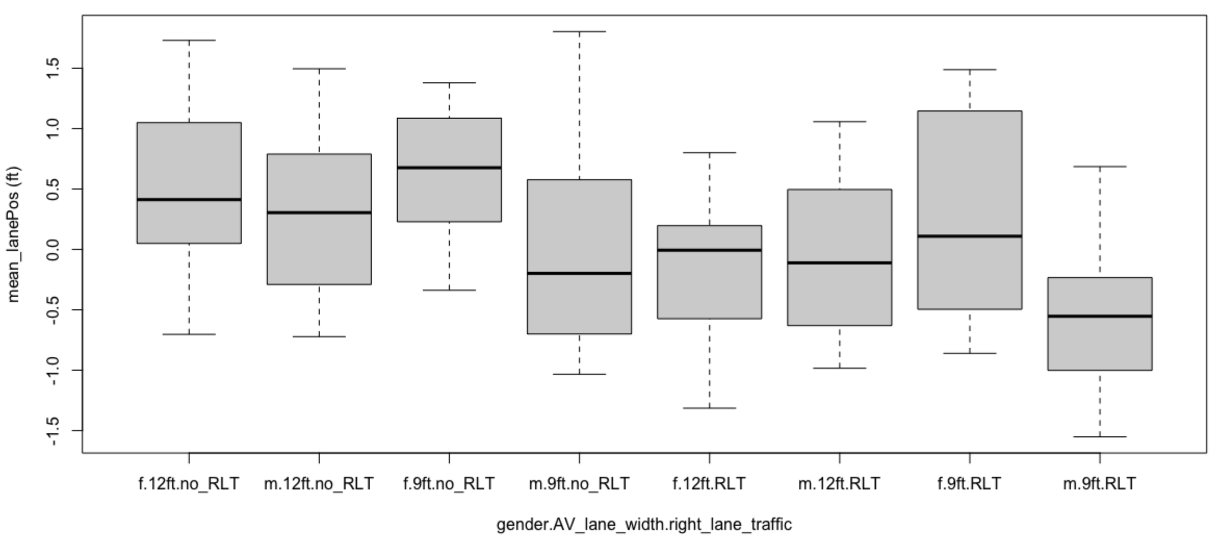

Figure 14. Box plot of mean lane position for levels of gender * AV lane width * right lane traffic

7.2. Analysis of mean speed:

Figure 15 shows a summary of mean speed observed for all the different treatments in the same fashion that Figure 8 does for mean lane position. The y-axis is the mean speed and the x-axis is all the possible interaction levels between lane width, right lane traffic, and headway. This plot is used to provide a visual and intuitive interpretation of the data. The plot does not suggest a significant difference in mean speed between the groups. Though, it shows a wider range of mean speed for 9ft AV lane groups.

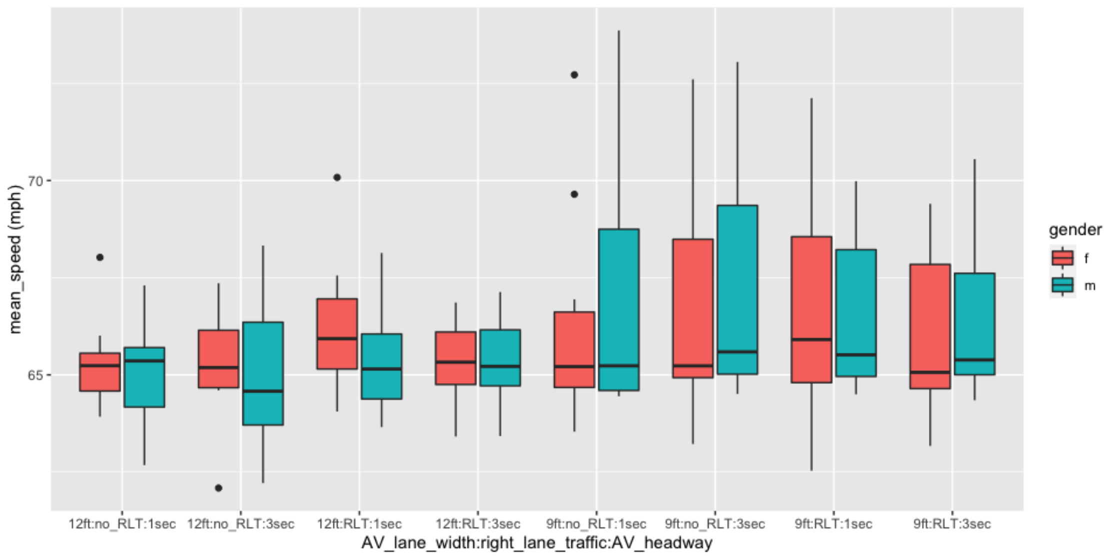

Figure 15. Boxplot of mean speed for all the different treatments

Similar to mean lane position, the data can be analyzed with a Linear Mixed Model (LMM). However, the Shapiro-Wilk test gives a significant p-value (0.000) and the Q-Q plot in Figure 16 also shows that the normality assumption is violated. There are four common options of dealing with this complication and all are detailed here.

The first option is to ignore the normality violation. As noted in several resources, parametric tests are not extremely sensitive to deviations from their assumptions (*What to Do If the Residuals in NR Are Not Normally Distributed?*, n.d.)(McDonald, 2009)(Zaiontz, 2020). It is specifically noted that normality assumption can be violated as long as the sample sizes are equal (called a balanced model), sufficiently large, and as long as the homogeneity of variance criteria is satisfied (Zaiontz, 2020). According to (Zaiontz, 2020), sufficiently large sample size is defined as greater than 10 for each group. While the sample sizes are equal and the model satisfies homogeneity of variance (see **Error! Reference source not found.**), there are exactly 10 samples for each of the 16 treatment groups. So, the analysis of deviance results of the linear mixed model will not be very reliable. For completeness, the analysis was conducted and the results are shown in **Error! Reference source not found.**. The pairwise comparisons are shown in **Error! Reference source not found.** and **Error! Reference source not found.**. The difference of mean speed between the significant levels is shown in Figure 17 and Figure 18. Both figures show very similar speeds between the groups contradicting the existence of any significant difference in mean speed between the levels. This further suggests that this analysis may not be reliable. Thus, more attention was placed on the other analysis options for mean speed.

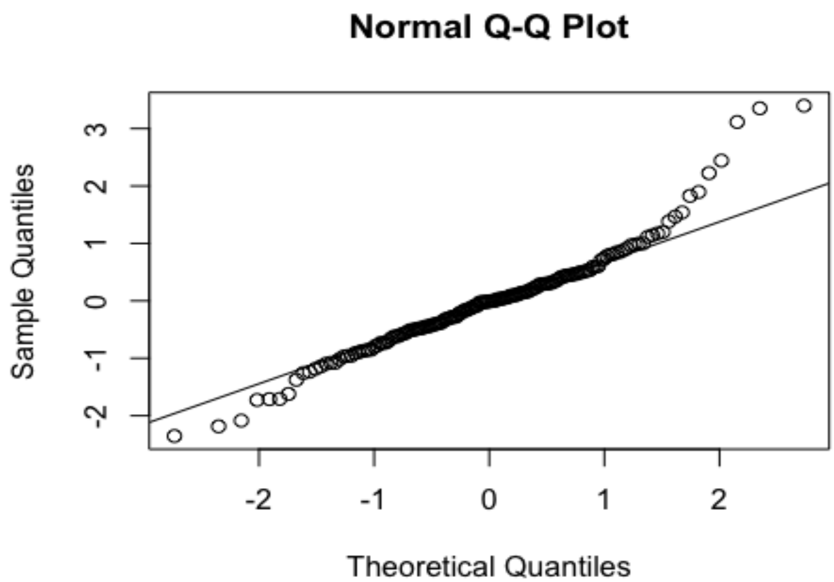

Figure 16. Q-Q plot of theoretical (normally distributed) vs sample quantities

Table 8. Levene's Test for Homogeneity of Variance (center = median)

	Df	F value	Pr(>F)
group	15	0.980	0.478
	144	NA	NA

Table 9. Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger df)

	F	Df	Df.res	Pr(>F)
(Intercept)	44668	1	36	0.000
gender	0.011	1	36	0.914
AV_lane_width	3.663	1	36	0.063 .
right_lane_traffic	0.037	1	108	0.846
AV_headway	0.480	1	108	0.489
gender:AV_lane_width	0.488	1	36	0.488
gender:right_lane_traffic	1.003	1	108	0.318
AV_lane_width:right_lane_traffic	5.697	1	108	0.018 *
gender:AV_headway	1.755	1	108	0.188
AV_lane_width:AV_headway	0.421	1	108	0.517
right_lane_traffic:AV_headway	2.841	1	108	0.094 .

gender:AV_lane_width:right_lane_traffic	0.407	1	108	0.524
gender:AV_lane_width:AV_headway	0.042	1	108	0.837
gender:right_lane_traffic:AV_headway	1.179	1	108	0.280
AV_lane_width:right_lane_traffic:AV_head way	0.268	1	108	0.605
gender:AV_lane_width:right_lane_traffic:A V_headway	0.010	1	108	0.920

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 10. Simultaneous Tests for General Linear Hypotheses (AV_lane_width:right_lane_traffic)

	Estimate Std.	Std. Error	t value	Pr(>|t|)
12ft,no_RLT - 9ft,no_RLT	-1.609	0.648	-2.484	0.093 .
12ft,no_RLT - 12ft,RLT	-0.448	0.245	-1.825	0.312
12ft,no_RLT - 9ft,RLT	-1.228	0.648	-1.896	0.312
9ft,no_RLT - 12ft,RLT	1.161	0.648	1.792	0.312
9ft,no_RLT - 9ft,RLT	0.380	0.245	1.550	0.312
12ft,RLT - 9ft,RLT	-0.780	0.648	-1.204	0.312

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- holm method)

Table 11. Simultaneous Tests for General Linear Hypotheses (right_lane_traffic:AV_headway)

	Estimate Std.	Std. Error	t value	Pr(>|t|)
no_RLT,1sec - RLT,1sec	-0.326	0.245	-1.329	0.933
no_RLT,1sec - no_RLT,3sec	-0.172	0.245	-0.702	1.000
no_RLT,1sec - RLT,3sec	0.086	0.245	0.353	1.000
RLT,1sec - no_RLT,3sec	0.154	0.245	0.627	1.000
RLT,1sec - RLT,3sec	0.413	0.245	1.682	0.573
no_RLT,3sec - RLT,3sec	0.258	0.245	1.054	1.000

(Adjusted p values reported -- holm method)

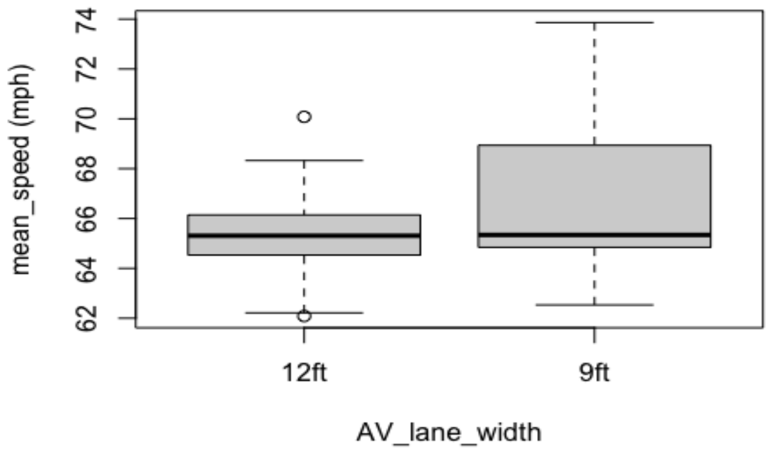

Figure 17. Box plot of mean speed for levels of AV lane width

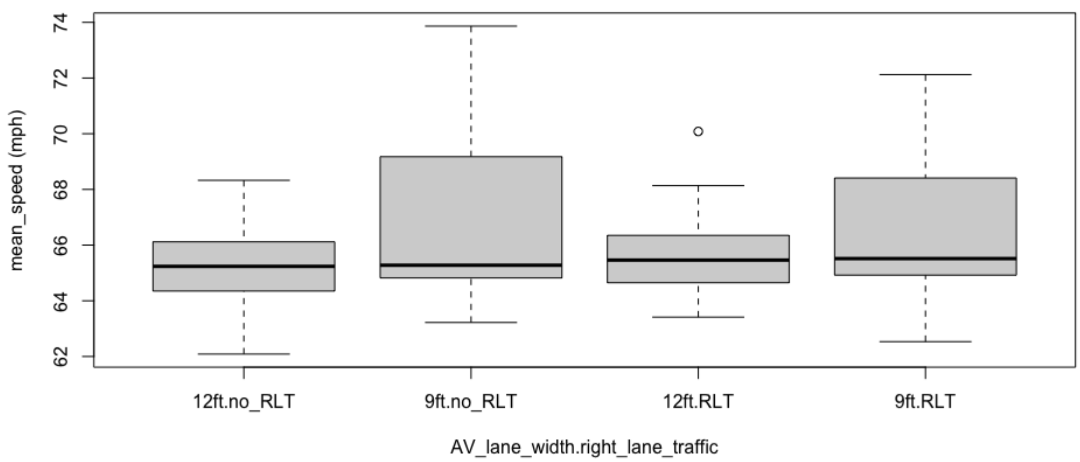

Figure 18. Box plot of mean speed for levels of AV lane width * right lane traffic

The second option is to apply a transformation to the response variable that would make the model respect the normality assumption. The most common transformations are log, square root and arcsine transformations (McDonald, 2009). Log transformation is normally used for continuous positive data and therefore it is the most suitable in this case (McDonald, 2009). Using R syntax, with the log transformation the model will be log(mean_speed) ~ gender * lane_width * right_lane * headway + (1|subject).

However, the shapiro-wilk test for the linear mixed model involving the transformed response gives a significant p-value (0.000) indicating that the transformation was not successful at making the model satisfy the normality assumption.

The third option is to use a Generalized Linear Mixed Model. Generalized linear models extend linear models by allowing non-normal response distributions. To select a

Generalized linear model, a family and a link function must be specified. The family specifies the distribution of the response and the link function specifies the relation between the response and the linear model. Each family has a default link function called the canonical link function. Among the different options for the family parameter, the Gamma distribution is recommended for continuous response variables that are positively skewed (Phillips, 2017) (Portugués, 2019) which is used in this study. Looking at the conditional distribution of the response, some positive skew can be seen for several groups, and this gives some assurance for using the gamma regression. The analysis of deviance results of the gamma regression is shown in **Error! Reference source not found.**. Significant effects are then taken for post-hoc pairwise comparisons of their levels; **Error! Reference source not found.** and **Error! Reference source not found.** show the post-hoc pairwise comparisons which do not indicate any significant effects.

Table 12. Analysis of Deviance Table (Type III Wald chisquare tests)

	Chisq	Df	Pr(>Chisq)
(Intercept)	26800	1	0.000
gender	0.006	1	0.937
AV_lane_width	1.748	1	0.186
right_lane_traffic	0.070	1	0.790
AV_headway	0.621	1	0.430
gender:AV_lane_width	0.319	1	0.572
gender:right_lane_traffic	1.161	1	0.281
AV_lane_width:right_lane_traffic	7.060	1	0.007 **
gender:AV_headway	2.133	1	0.144
AV_lane_width:AV_headway	0.519	1	0.471
right_lane_traffic:AV_headway	3.464	1	0.062 *
gender:AV_lane_width:right_lane_traffic	0.478	1	0.489
gender:AV_lane_width:AV_headway	0.044	1	0.833
gender:right_lane_traffic:AV_headway	1.481	1	0.223
AV_lane_width:right_lane_traffic:AV_headway	0.304	1	0.580
gender:AV_lane_width:right_lane_traffic:AV_headway	0.012	1	0.910

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 13. Simultaneous Tests for General Linear Hypotheses (AV_lane_width:right_lane_traffic)

	Estimate Std.	Std. Error	t value	Pr(>|t|)
12ft,no_RLT - 9ft,no_RLT	0.000	0.000	1.801	0.358
12ft,no_RLT - 12ft,RLT	0.000	0.000	2.052	0.241
12ft,no_RLT - 9ft,RLT	0.000	0.000	1.348	0.533
9ft,no_RLT - 12ft,RLT	0.000	0.000	-1.248	0.533
9ft,no_RLT - 9ft,RLT	0.000	0.000	-1.703	0.358
12ft,RLT - 9ft,RLT	0.000	0.000	0.796	0.533

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- holm method)

Table 14. Simultaneous Tests for General Linear Hypotheses (right_lane_traffic:AV_headway)

	Estimate Std.	Std. Error	t value	Pr(>|t|)
no_RLT,1sec - RLT,1sec	0.000	0.000	1.505	0.662
no_RLT,1sec - no_RLT,3sec	0.000	0.000	0.758	1.000
no_RLT,1sec - RLT,3sec	0.000	0.000	-0.369	1.000
RLT,1sec - no_RLT,3sec	0.000	0.000	-0.747	1.000
RLT,1sec - RLT,3sec	0.000	0.000	-1.874	0.365
no_RLT,3sec - RLT,3sec	0.000	0.000	-1.128	1.000

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
(Adjusted p values reported -- holm method)

The fourth option is to use a non-parametric model such as the aligned rank transform (ART) that does not make any assumptions about the response distribution. The analysis of deviance results and the pairwise comparisons are shown in **Error! Reference source not found.**, **Error! Reference source not found.**, and **Error! Reference source not found.**. For the pairwise comparisons the Wilcoxon signed rank and Mann-Whitney U non-parametric pairwise tests were chosen based on whether within or between subject variables were being analyzed. As shown in **Error! Reference source not found.** and **Error! Reference source not found.** the results comply with the results from the Gamma regression model in that there are no significant effects.

In summary, out of the four approaches to address the violation of normality assumption, the result of the linear model proved to be unreliable. The log transform was not able to force the data to conform to the normality assumption either. For these reasons the data were analyzed using a generalized linear model called the gamma regression and also analyzed using a non-parametric method called the aligned rank transform. Both methods found no model significantly better than mean response. This result confirms the observation made based on Figure 15 at the beginning of the mean speed analysis section that no significant difference in mean speed between the groups is observable. However, it should be noted that a wider range of mean speed for 9ft AV lane groups can be seen on Figure 15 suggesting more speed variations when driving next to the 9-ft lane.

Table 15. Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger df)

	F	Df	Df.res	Pr(>F)
gender	0.000	1	36	0.987
AV_lane_width	1.268	1	36	0.267
right_lane_traffic	1.866	1	108	0.174
AV_headway	0.194	1	108	0.660
gender:AV_lane_width	0.546	1	36	0.464
gender:right_lane_traffic	0.367	1	108	0.545
AV_lane_width:right_lane_traffic	4.048	1	108	0.046 *
gender:AV_headway	1.909	1	108	0.169
AV_lane_width:AV_headway	0.296	1	108	0.587
right_lane_traffic:AV_headway	2.895	1	108	0.091 .
gender:AV_lane_width:right_lane_traffic	1.165	1	108	0.282
gender:AV_lane_width:AV_headway	0.112	1	108	0.737
gender:right_lane_traffic:AV_headway	1.728	1	108	0.191
AV_lane_width:right_lane_traffic:AV_headway	0.971	1	108	0.326
gender:AV_lane_width:right_lane_traffic:AV_headway	0.123	1	108	0.725

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 16. Post-Hoc analysis for ART model (right_lane_traffic:AV_headway)

Camparison	P-values	Model/Test

1sec_no_RLT - 1sec_RLT	0.265	Wilcoxon signed rank test
1sec_no_RLT - 3sec_no_RLT	1.000	Wilcoxon signed rank test
1sec_no_RLT - 3sec_RLT	1.000	Wilcoxon signed rank test
1sec_RLT - 3sec_no_RLT	1.000	Wilcoxon signed rank test
1sec_RLT - 3sec_RLT	0.095	Wilcoxon signed rank test
3sec_no_RLT - 3sec_RLT	1.000	Wilcoxon signed rank test

p-values adjusted with holm's method

Table 17. Post-Hoc analysis for ART model (AV_lane_width:right_lane_traffic)

Camparison	P values	Model/Test
9ft_no_RLT - 12ft_no_RLT	0.969	Mann-Whitney U test
9ft_no_RLT - 12ft_RLT	1.000	Mann-Whitney U test
9ft_ RLT - 12ft_no_RLT	0.869	Mann-Whitney U test
9ft_ RLT - 12ft_RLT	1.000	Mann-Whitney U test

9ft_RLT – 9ft_no_RLT	1.000	Wilcoxon signed rank test
12ft_RLT – 12ft_no_RLT	0.796	Wilcoxon signed rank test

p-values adjusted with holm's method
response averaged over levels of right_lane

7.3. Analysis of mental effort

Figure 19 shows a summary of mental effort for all the different treatments in a similar fashion as presented earlier for other variables. The y-axis is the mental effort and the x-axis is all the possible interaction levels between lane width, right lane traffic, and headway. This plot provides a visual and intuitive interpretation of the data. The plot suggests that there is not much difference in mental effort for groups with 9ft AV lane. However, some difference in mental effort can be seen among genders for groups with 12ft AV lane. Also, females seem to have a wider range of mental effort score.

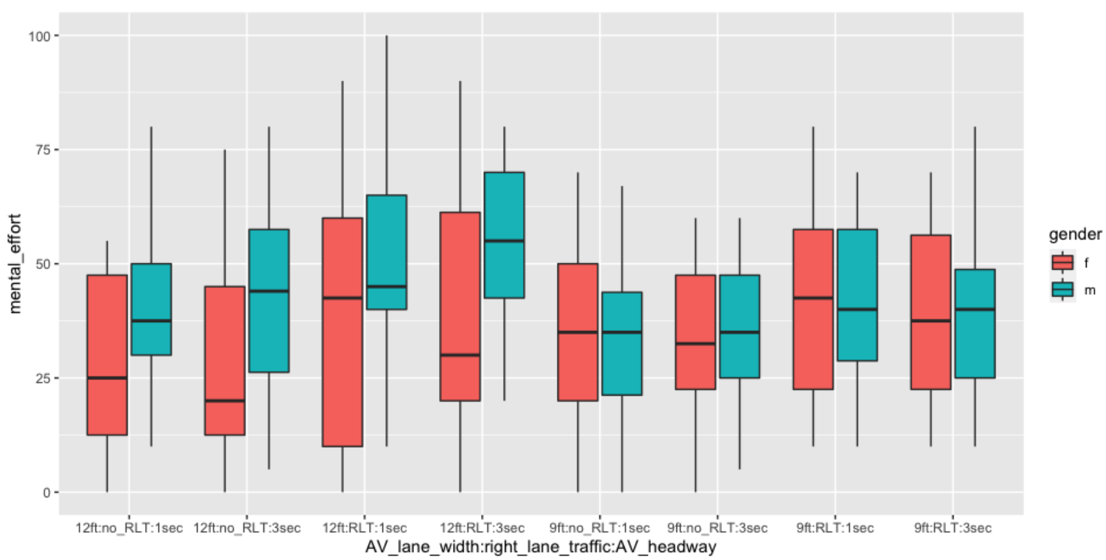

Figure 19. Boxplot of mental effort for all the different treatments

The data were analyzed by a Generalized Linear Mixed Model (GLMM) commonly used for ordinal data called Cumulative Link Mixed Model (CLMM). These models might be considered the best approach for data with ordinal dependent variables in many cases (Mangiafico, 2016) and since Likert scale ratings such as the mental effort ratings are treated as ordinal data, they were modeled by a CLMM. **Error! Reference source not found.** shows the analysis of deviance results. As indicated in the table no statistically significant results were observed.

Table 18. Analysis of Deviance Table (Type II tests)

	LR Chisq	Df	Pr(>Chisq)
gender	0.000	1	1.000
AV_lane_width	0.000	1	0.999
right_lane_traffic	0.000	1	0.999
AV_headway	0.000	1	1.000
gender:AV_lane_width	0.000	1	1.000
gender:right_lane_traffic	0.000	1	1.000
AV_lane_width:right_lane_traffic	0.000	1	0.999
gender:AV_headway	0.000	1	1.000
AV_lane_width:AV_headway	0.000	1	1.000
right_lane_traffic:AV_headway	0.000	1	1.000
gender:AV_lane_width:right_lane_traffic	0.000	1	0.999
gender:AV_lane_width:AV_headway	0.000	1	0.999
gender:right_lane_traffic:AV_headway	0.000	1	0.999
AV_lane_width:right_lane_traffic:AV_headway	0.000	1	1.000
gender:AV_lane_width:right_lane_traffic:AV_headway	0.309	1	0.5784

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

8. DISCUSSION AND CONCLUSION

In this study, driving performance was evaluated for subjects driving next to a narrow 9ft AV exclusive left lane and was also compared to the performance of subjects driving next to a regular 12ft AV exclusive left lane. Factors including presence of right lane traffic, AV headway, and gender were monitored and analyzed along with AV lane width to investigate the individual and interaction effects of these variables on driving behavior. AV headways were set to be 1 or 3 seconds, and on the right lane there was either traffic present or no traffic at all. The driving performance was evaluated by measuring the mean lane position, the mean speed during the drive, and the mental effort required to complete the drive.

For mean speed and mental effort, the analysis results did not show any statistically significant differences between the groups. However, visually a wider range of mean speed for 9ft AV lane groups was observed suggesting more speed variation when driving next to the 9-ft lane. Also, for mental effort, some difference in mental effort was observed graphically among male and female drivers driving next to the 12ft AV lane suggesting less gender-specific behavior was observed in terms of mental effort when driving next to the 9ft AV lane. Also, generally, females seemed to have a wider range of mental effort score.

Mean lane position analysis led to several statistically significant main effects and interactions. For the main effects, gender, right lane traffic, and AV headway turned out to be significant. Female drivers tended to the right while the male drivers tended to the left of the center line and male drivers had better performance in terms of lane centering. Drivers deviated more (larger absolute value of lane positioning) to the right in the absence of right lane traffic while less to the left when there is right lane traffic. Drivers tended to get farther from the AV lane when the AVs had smaller headways.

Looking at the interaction effects and for comparisons between groups whose difference of mean lane position was significant, the emphasis was put on comparisons where at least one of the groups drove next to the 9ft AV lane as lane width is the most important variable of the study. For this reason, each of the next five paragraphs discusses significant comparisons between groups that had the 9ft AV lane condition and other groups that had either 9ft AV lane condition or 12 ft AV lane condition. The paragraphs are unique in the sense that along with the mentioned comparison condition, they include a unique combination of interaction factors.

When comparing the groups that drove next to the 9ft AV lane with the groups that drove next to the 12ft lane, significant difference was seen between some of the groups that drove next to the right lane with traffic and those that drove next to a right lane without traffic. The significant difference in mean lane position was between (m,12ft,no_RLT - m,9ft,RLT), and also between (f,9ft,no_RLT - f,12ft,RLT). For both cases drivers shifted to the left when there was traffic present in the right lane and for both cases drivers in the group with 12ft AV lane performed better in terms of lane centering.

When comparing the groups that drove next to the 9ft AV lane with the groups that drove next to the 12ft lane, there was also a significant difference seen between two groups with different genders and different right lane traffic conditions. This difference was between (f,12ft,no_RLT - m,9ft,RLT). In this case female drivers who were driving next to the 12ft lane, had better lane centering performance.

When comparing groups that drove next to the 9ft AV lane, significant difference was seen between some of the groups that drove next to the right lane with traffic and some that drove next to a right lane without traffic. The difference in mean lane position was between (f,9ft,no_RLT - f,9ft,RLT), and also between (m,9ft,no_RLT - m,9ft,RLT). For both cases drivers shifted to the left when there was traffic present in the right lane. For the first case, drivers with right lane traffic had better lane centering while for the second case it was the opposite.

When comparing the groups that drove next to the 9ft AV lane, there was also a significant difference observed between two groups with different genders and different right lane traffic conditions. This difference was between (f,9ft,no_RLT - m,9ft,RLT). In this case male drivers, who drove next to the right lane with traffic, had better lane centering performance.

When comparing groups that drove next to the 9ft AV lane, significant difference was also seen between some of the groups with different genders. The difference in mean lane position was between (f,9ft,RLT - m,9ft,RLT) and (f,9ft - m,9ft). For both cases, female drivers drove further away from the 9 ft lane. For the first case the female drivers had better lane centering performance and for the second case, male drivers had better lane centering performance.

The only remaining significant comparison that does not include the 9ft AV lane width as a factor, is the significant difference between (m,12ft,no_RLT - m,12ft,RLT), and also between (f,12ft,no_RLT - f,12ft,RLT). In both cases, groups with right lane traffic shifted to the left and had better lane centering performance.

Speed and mental effort were not seen to change significantly when driving next to the 9ft AV lane. Thus, for new 9ft AV lanes to be considered safe (in the context of the behavior of drivers in the adjacent lane), the important criterion would be that the addition of the new lane should not cause significant change in the lane position of drivers on the adjacent lane when compared to lane position of those driving next to a 12ft lane. It should be noted that the significant difference could be caused with other factors. Indeed, based on findings of this study, the overall effect of AV lane width was not significant on the lane positioning but there were some significant interaction effects between lane width and other factors. In those cases, the change in AV lane width is accompanied by the change in gender, right lane traffic condition, or both, and there is no case in which those factors stay constant while AV lane width changes between the groups. This gives some confidence that the changes are caused by the other factors and not by changing lane width. But the trend being seen in these comparisons is that drivers driving next to the 12ft lane have better lane centering and this may be of safety concerns.

Also, when comparing groups that drove next to the 9ft lane, it is important for safety to track factors that make the drivers' lane position change significantly and see which level of those factors causes drivers to deviate further from the center of the lane. Looking at the results, the factors that had such an effect were presence of traffic on the right lane and gender. For gender comparison, the analysis showed that while in general female drivers tended to drive further away from the 9ft lane and performed worse in terms of lane centering, they performed better than male drivers when right lane traffic was present. For the comparison of right lane traffic conditions, the analysis showed that presence of right lane traffic was generally made the drivers to shift to the left. Hence, cautious should be taken when designing a 9ft AV lane to the left in the presence of high regular lane traffic on the right side; there are design considerations such as clearly visible pavement markings or raised medians that could be used to mitigate the potential negative effect of this shift to the left. It should also be noted that the overall effect of AV headway also showed changes in lane position with smaller headways making drivers to drive further away from the AV lane, but it does not correspond to major change in lane centering ability.

The findings of this study contribute to the introduction of AVs to the roads and the behavioral impacts on human driven vehicles driving adjacent to AV lanes. Most observations suggest that driving adjacent to 9ft AV lanes would be as safe as driving next to 12ft AV lanes with the exceptions in which performance drop was observed in lane centering. Also, driver characteristics such as gender seem to have significant impact on the performance of driving adjacent to narrower lanes. Further studies could shed more light on this emerging topic of infrastructure adaptation to AV technology. Future research experiments are recommended with different factors (e.g., drivers in different age group, weather condition, driving on curvature, presence of access points), more data, different statistical techniques, and conducting a field experiment.

ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
AV	Automated Vehicle
ART	Aligned Rank Transform
CLMM	Cumulative Link Mixed Model
CMF	Crash Modification Factors
EL	Express Lane
GLM	Generalized Linear Model
GLMM	Generalized Linear Mixed Model
GNM	Generalized Nonlinear Model
HSM	Highway Safety Manual
IRB	Institutional Review Board
LMM	Linear Mixed Model
RSME	Ratings Scale of Mental Effort
STAR	Smart Transportation Analytics Research
THW	Time Headway

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APPENDIX:

Please indicate, by making the vertical axis below, how much effort it took for you to complete the task you have just finished.