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MINETA TRANSPORTATION INSTITUTE

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REPORT 20-40

IMPACT OF REGULAR AND NARROW AV-EXCLUSIVE LANES ON MANUAL DRIVER BEHAVIOR

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16. Abstract

This study attempts to answer the question of how a narrow (9-ft) lane dedicated to Automated Vehicles (AVs) would affect the behavior of drivers in the adjacent lane to the right. To this end, a custom driving simulator environment was designed mimicking the Interstate 15 smart corridor in San Diego. A group of participants was assigned to drive next to the simulated 9-ft narrow lane while a control group was assigned to drive next to a regular 12-ft AV lane. Driver behavior was analyzed by measuring the mean lane position, mean speed, and mental effort (self-reported/subjective measure). In addition to AV lane width, the experimental design took into consideration AV headway, gender, and right lane traffic to investigate possible interaction effects. The results showed no significant differences in the speed and mental effort of drivers while indicating significant differences in lane positioning. Although the overall effect of AV lane width was not significant, there were some significant interaction effects between lane width and other factors (i.e., driver gender and presence of traffic on the next regular lane to the right). Across all the significant interactions, there was no case in which those factors stayed constant while AV lane width changed between the groups, indicating that the significant difference stemmed from the other factors rather than the lane width. However, the trend observed was that drivers driving next to the 12-ft lane had better lane centering compared to the 9ft lane. The analysis also showed that while in general female drivers tended to drive further away from the 9-ft lane and performed worse in terms of lane centering, they performed better than male drivers when right-lane traffic was present. This study contributes to understanding the behavioral impacts of infrastructure adaptation to AVs on non-AV drivers.

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Autonomous vehicles, highway design, traffic safety, driving simulators, human subject testing

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

With the global spread of coverage and popularity of Automated Vehicles (AVs), infrastructure design and standards will need to be adapted toward accommodating and leveraging this emerging technology. However, a full infrastructure adaptation is not going to happen in a day, especially given that the transportation system will be serving both AVs and human-driven vehicles for a while. On freeways and smart corridors, a mix of dedicated AV lanes and regular vehicle lanes seems to be a viable solution. The question remains how these new AV adaptations will affect driver behavior in mixed traffic conditions.

There is a lack of research on the impact of AV-related roadway adaptations (e.g., narrow lane widths) on driver behavior, mobility, and safety in mixed traffic conditions where AVs and human-driven vehicles need to coexist. The goal of this research is to evaluate the mobility and safety impact of an emerging AV-related roadway design solution—a narrow AV-exclusive lane—on human-driven vehicle performance and driver behavior in regular lanes. Through a human subjects-based evaluation and custom-designed driving simulator scenarios mimicking an envisioned lane reconfiguration of the Interstate 15 (I-15) smart corridor in San Diego, this work investigates the driving behavior of human vehicle operators driving on a regular lane adjacent to a narrow AV-exclusive lane as opposed to an AV-exclusive lane of regular size.

This study builds a driving simulator model of the potential reconfiguration for the San Diego I-15 smart corridor. The I-15 Express Lanes (ELs) system is one of the nation's most advanced and innovative highway systems. Between State Route 163 (SR-163) and Via Rancho Parkway, the ELs provide four High Occupancy Vehicle (HOV) and toll-paying FasTrak lanes; using a movable barrier and dependent on the direction of prevailing traffic in morning and afternoon peak hours, the four lanes are configured three to one, one to three, or two to two in the southbound and northbound directions. There is a possibility of adding another lane with a narrow width of 9 ft in the existing area as the leftmost lane. The direction of travel on this additional lane (northbound or southbound) is determined by the movable barrier, similar to the HOV lanes. This lane could be used exclusively by AVs, contributing to more efficient use of the limited space. The behavior of non-AV drivers traveling right next to this AV-exclusive lane is the focus of this study. Therefore, the driving simulator design looks into two lane width configurations of a 9-ft (narrow) and 12-ft (regular) AV-exclusive lane to investigate how the narrow AV lane, compared to the regular AV lane, affects the behavior of non-AV drivers driving adjacent to the AV-exclusive lane. In the simulator setup, the AV-exclusive lane is the leftmost lane, the non-AV driver (simulator participant) drives on the middle lane, and there is another non-AV lane to the right.

In addition to the lane width of the AV-exclusive lane as the main factor (9-ft or 12-ft), the study examines the effect of three other factors: AVs' headway driving on the AV-exclusive lane (1 sec or 3 sec), presence of traffic in the right lane (traffic or no traffic), and gender (female or male). Four scenarios were developed in the simulator with two of them featuring the 9-ft AV-exclusive lane (scenario 1 and 2) and the other two featuring the 12-ft AV-exclusive lane (scenarios 3 and 4). Scenarios 1 and 2—similarly 3 and 4—differed in the presence of traffic in the right lane. In each scenario, two data collection sections were considered, alternating the AVs' headway on the AV-exclusive lane.

The study took place at SDSU Smart Transportation Analytics Research (SDSU-STAR) Lab with a fixed based DriveSafety RS-250 driving simulator. Forty gender-balanced participants were recruited from the age group of 18 to 25 years old. After consent and an adaptation drive, each participant either drove scenarios 1 and 2 or scenarios 3 and 4. For counterbalancing purposes, the scenarios were randomly assigned to participants. Three variables of interest were collected throughout the scenario runs: mean lateral deviation from the center of the lane, mean speed, and mental workload. Statistical modeling was performed to analyze the collected data.

The driving performance was evaluated by measuring the mean speed during the drive, the mean lane position, and the mental effort required to complete the drive. Statistical analysis did not show any statistically significant effects for mean speed and mental effort. However, a wider range of mean speeds for 9-ft AV lane groups was observed visually, suggesting greater speed variation when driving next to the 9-ft lane. Also, some difference in mental effort was observed graphically between male and female drivers driving adjacent to the 12-ft AV lane, while less gender-specific behavior in terms of mental effort was associated with the 9-ft group. Also, generally, females seem to have a wider range of mental effort scores.

For mean lane positioning, statistical analysis showed significant main effects for gender, presence of right lane traffic, and AV headway; female drivers tended to the right, while male drivers to the left of their travel lane. Male drivers showed better lane centering behavior in general. Also, the presence of traffic on the right lane resulted in drivers shifting to the left side. In terms of AV headways, drivers tended to move further away from the AV lane for smaller AV headways. The results also showed some statistically significant interactions among lane width, gender, and right-lane traffic. When comparing the 9-ft group of drivers to the 12-ft group, a general shift to the left was observed when traffic was present in the right lane, and drivers showed better lane centering when driving next to the 12-ft AV lane. When looking at those driving next to the 9-ft lane, again, a general shift to left side was observed in presence of right-lane traffic. Female drivers drove further away from the 9-ft lane. Male drivers showed better lane centering in general and specifically when there was no traffic in the right lane. However, females had better lane centering when there was traffic in the right lane. When looking at the group driving next to the 12-ft lane, again, a general shift to left side was observed in the presence of right-lane traffic. Also, better lane centering behavior was observed in the presence of right-lane traffic.

The results of this study contribute to considerations of a narrow (9-ft) AV-exclusive lane on freeways compared to a regular 12-ft AV-exclusive lane. The findings showed statistically significant difference in lane positioning behavior of drivers in the adjacent lane to the AV lane. Although the overall effect of AV lane width was not significant, there were some significant interaction effects between lane width and other factors (i.e., driver gender and presence of traffic on the next regular lane to the right). In all these significant interactions, there was no case in which those factors stayed constant while AV lane width changed between the groups, indicating again that the significant difference stemmed from the other factors rather than the lane width. However, the trend observed is that drivers driving next to the 12-ft lane have better lane centering compared to those driving next to the 9-ft lane, and this may be noteworthy for safety reasons. Providing highly reflective, clearly visible, and distinct lane markings could be considered to minimize this concern. Driver characteristics—

in this study, gender—had a significant effect on lane positioning behavior, suggesting driver demographics may matter when deciding on AV lane design. The analysis also showed that presence of right-lane traffic is generally accompanied by drivers shifting to the left. Therefore, precautions should be taken when implementing a 9-ft AV lane in the presence of more than one regular lane adjacent to the AV lane. Moreover, though not statistically significant, visualization techniques showed that when driving next to the 9-ft lane, more speed variations were observable, which might be a safety concern. Design considerations such as physical barriers and advanced lane markings separating AV lanes from regular lanes could be considered in order to mitigate the potential negative effect of the regular traffic shifting to the left as well as speed variations.

I. 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, and parking, as well as economic benefits. AVs are predicted to substantially reduce traffic collisions caused by human error factors 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. Platooning is accomplished by longitudinal control (keeping a safe distance to the leading vehicle) of vehicles and making use of vehicle-to-vehicle communication. Economically, automation could result in reduced vehicle insurance costs and improve cars' fuel economy.

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

The purpose of this study is to expand the knowledge base regarding the safety and operational impacts of narrower freeway lanes for AVs in mixed (AVs and human-driven vehicles) traffic conditions. The present work investigates the implications of a narrow AV-exclusive reversible lane on I-15 Express Lanes (ELs) and answers the question of how a 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 with scenarios mimicking San Diego's I-15 smart corridor.

The Interstate 15 (I-15) Express Lanes, running between State Route 163 (SR-163) and Via Rancho Parkway, currently provide four HOV and toll-paying FasTrak lanes (see Figure 1a). Caltrans is seeking more efficient ways to handle increased traffic volumes 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 northbound and southbound directions of the ELs, there would be two 12-ft wide lanes for HOV and FasTrak vehicles (see Figure 1b). With the new configuration, the questions are whether drivers who drive on the regular ELs adjacent to the proposed AV-exclusive lane would change their driving behavior and how this narrow AV-exclusive lane would affect mobility and safety on the regular ELs.

According to AASHTO's Policy on Geometric Design of Highways and Streets, the lane width impacts comfort of driving, operational characteristics (e.g., road capacity), and the likelihood of certain type of crashes. Conventionally, lane widths of 9 to 12 ft are common, with 12-ft lanes 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. According to the 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 studies have investigated the impact of lane width on driving behavior, roadway safety, and mobility in traditional roadways with no AV considerations (for example, 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 the presence of AV-exclusive lanes. This study aims to fill this knowledge gap in the AV literature.

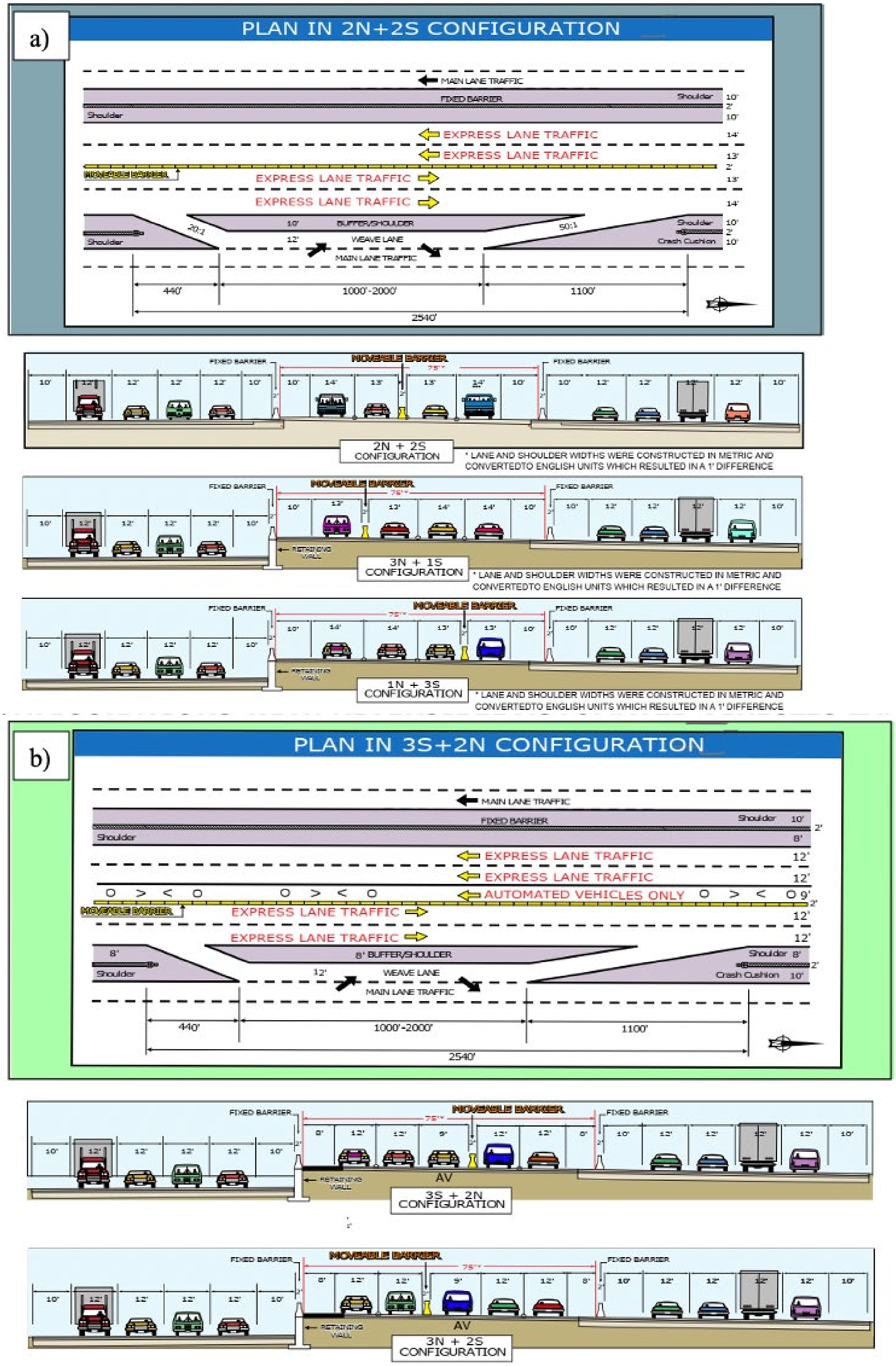


Figure 1. I-15 Express Lanes; a) Existing 4-lane Configurations, b) Configurations with Reversible AV Lane [plans courtesy of Caltrans]

The specific objectives of this study are as follows:

- Identify traffic implications of AV operation in AV-exclusive lanes on driver performance in adjacent lanes; distinguish between the effect of 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 a reconfiguration of the San Diego I-15 smart corridor to accommodate and leverage AV technology.

- Enable transport authorities to make more informed decisions about the development of new lane width standards and roadway reconfiguration for AV technology.

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

II. LITERATURE REVIEW

Despite AVs' potential benefits, multiple concerns arise when considering the introduction of AVs. The first set of concerns contains issues such as over-reliance on automation, possible loss of situation awareness, and loss of the skills needed to perform the automated functions manually when necessary. While these concerns are geared towards automated vehicles, it is also important that drivers of regular vehicles adapt their behavior to accommodate AVs . Along these lines, the purpose of this literature survey is to gain an understanding of the effects of lane width and AV platoon headway on non-AV drivers. Since the literature is limited in its consideration of these specific conditions, the authors considered general studies on lane width and simulator studies related to AVs.

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 studies in the literature in this regard, with a majority showing speed increase in wider lanes. 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. The results showed that lane width had significant effects on driving speed 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). Average driving speed increased from 60.01 kilometers/hour (37.29 miles/hour) in the narrowest lane to 88.05 kilometers/hour (54.71 miles/hour) 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. (2016) gathered both behavioral and crash data and identified an increase of about 2.2 miles/hour (3.54 kilometers/hour) 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. (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, 3.5 m (11.48 ft) and 3 m (9.84 ft), were 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. (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 towards the edge line, whereas this distance remained similar across lane widths during higher-traffic periods.

CRASH STUDIES RELATED TO LANE WIDTHS

A good amount of research has considered the effect of lane width on safety measured using crash data; in most cases, a reduction of lane width has been suggested for congestion control. A study estimated various crash modification factors (CMFs) for different ranges of lane widths using the generalized nonlinear models (GNMs). It was found that the crash rate was highest for 12-ft (3.66-m) lanes and lower for the lane widths 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 interaction effect 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 compared to lane widths greater than 12 ft if the speed limit is higher than or equal to 40 miles/hour (64.37 kilometers/hour). 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 lanes (Lee et al., 2015).

Another study (Wu & Sun, 2015) 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 different lane classifications were collected for the development of CMFs. The lane classifications were as follows: undersized lanes had average width less than or equal to 3.25 m (10.66 ft), standard-sized lanes had average width around 3.45 m (11.32 ft), and oversized lanes had average lane width greater than or equal to 3.75 m (12.30 ft). The scale in this study is different from the scale used in Lee et al. (2015) as the oversized lane width corresponds to medium lane width in Lee et al. (2015). Also, the three different lengths are closer to each other than the Lee et al. (2015) study with a difference of 0.5m (1.6 ft) between the widest and narrowest lane widths. Wu & Sun (Wu & Sun, 2015) established different models of involved vehicle numbers (two-vehicle crash and multi-vehicle crash) and traffic conditions (congested-flow crash and non-congested-flow crash), and CMFs were developed accordingly. The results showed that standard-sized lanes experienced the lowest crash frequency in all kinds of crashes. The total crash frequency of undersized lanes and oversized lanes would increase by 190% and 134%, respectively, compared with standard-sized lanes (Wu & Sun, 2015). However, in a different study, 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.

Using ten years of mid-block crash data on urban arterials and collectors from four cities in Nebraska, Wood et al. (2015) estimated CMFs for various lane widths and crash types. Lane widths 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. Conversely, 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. Similarly, using the same ten-year crash data, Elhenawy et al. (2019)namely: random forest (RF 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 this discrepancy could lead to a potential bias when comparing different studies. For example, Elhenawy et al. (2019)namely: random forest (RF adopted an equation to calculate crash rate, accounting for yearly crash counts, road segment length, AADT, number of lanes, and a tuning parameter for the exposure measure (i.e., number of people over a period of time or across certain distance who are likely to be involved in crashes). Dixon et al. (2016)

found a different result; the safety analysis determined a crash difference between 12-ft and 11-ft lanes on a freeway with 12-ft lanes showing a safety improvement over 11-ft 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 need to be considered.

One study (Bauer et al., 2004) conducted an observational before-and-after evaluation with the empirical Bayes method 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 (Kononov et al., 2012) on the safety of shoulder running (i.e., usage of shoulder as a lane) 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, as well as 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. They also found that the safety benefits of a reduced volume or density per lane outweighed the adverse effects of the lack of a full shoulder (Kononov et al., 2012).

SIMULATOR STUDIES RELATED TO AVS

It is also important to know which simulator studies have been conducted on automated vehicles. This section examines studies on both automated and regular vehicles. A large portion of the literature on automated vehicles is focused on drivers' situational awareness. For example, Young and Stanton (2007) studied the effect of automated longitudinal control on the brake reaction time of drivers and found a striking increase in reaction times for these automated conditions. Similarly, Gold et al. (2015) investigated how the experience of automated driving will change drivers' trust in and attitudes towards automation. A questionnaire administered before and after the driving simulator experience was used to assess trust in automation, safety gain, intention to use AVs, 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 analogously to the self-reported level of trust (Gold et al., 2015). Another study (Mok et al., 2015) on situation awareness investigated the behavior of drivers who are required to take over control of highly automated vehicles from a distracted state. From the study results, the researchers 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).

In a study published in 1999, 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 with 1 sec and at 0.25 sec headways and driving as a platoon leader. The results showed lower levels of activation and mental effort (both physiological and subjectively experienced) 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 a 0.25 sec headway. When driving automatically, most drivers preferred the longer headway of 1 sec.

In contrast to the studies mentioned so far, which have focused on situation awareness in highly automated environments, 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 drivers' 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. However, 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 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 have also been simulator studies on the behavior of regular vehicles in mixed traffic situations. A similar study to the presently proposed research has investigated the behavior of drivers next to AVs with varying headways. This study (Gouy et al., 2014) examined whether a contagion effect would occur among the drivers of regular vehicles from the short time headway held in an AV platoon. The results showed that participants adapted their driving behavior by displaying a significantly shorter average and minimum time headway while driving next to an AV platoon holding short time headways than when time headway was large. They also spent more time keeping a time headway below a safety threshold of one second (Gouy et al., 2014).

In another study, Larburu et al. (2010) studied safe and reliable platooning systems with increased levels of automation. Similar to Gouy et al. (2014), they analyzed subjective opinions of non-platoon users driving near platoons of different sizes, also investigating subjective and objective information obtained from platoon users. The results showed that, in general (around 75%), people felt uncomfortable when intra-platoon gap length was less than 16 meters, and people felt unsafe when it was under 7 meters. A total of 91% of all participants thought that 90 kilometers/hour (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 transmission to the driver was absolutely necessary, and 86% said that an acknowledgment from the driver was required before starting the maneuvers. 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.

III. METHODOLOGY

DRIVING SIMULATOR

The driving simulator used in this study is a DriveSafety RS-250 simulator located at the SDSU Smart Transportation Analytics Research (SDSU-STAR) Lab (see Figure 2). The simulator vehicle 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, plus one main component that controls the other three and communicates with a PC that has the information about the scenarios.

Figure 2. SDSU Smart Transportation Analytics Research (SDSU-STAR) Lab Driving Simulator

SCENARIO DESIGN

The scenarios were built through the HyperDrive software using custom-made tiles (components of the simulator environment development) to mimic a proposed I-15 smart corridor lane reconfiguration in San Diego. The speed limit was set at 65 miles/hour, 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 3). Each begins with a two-lane freeway tile and then is split into a custom-made three-lane tile. After five 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 five miles . The first 5-mile section is referred to as the first section (section 1), and the second 5-mile stretch is the second section (section 2). Within each section, there is an area where the collected data were chosen 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 to move 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 started to move. Also, data collected in the beginning and end of the sections were excluded from the analysis. The beginning portion was taken out to allow the participant to adapt to the new section setup and to minimize the unwanted effect of environmental change on the dependent variables of the study. The final portion of each section was also taken out to eliminate the effect of lane change from section 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 leftmost 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).

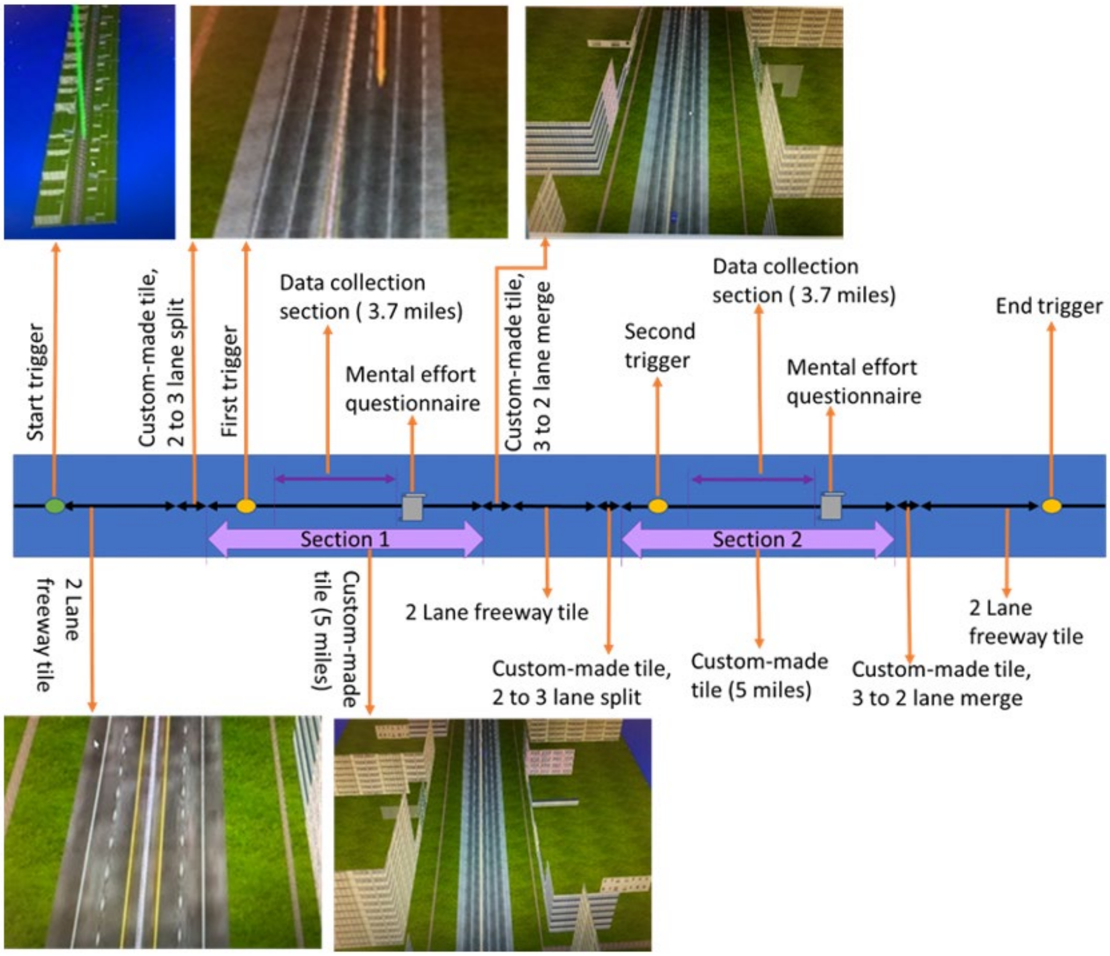


Figure 3. Overview of the Design for the Four Scenarios

Figure 4 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 9-ft and 12-ft AV-exclusive lanes. The test scenarios have a 9-ft lane on the left (AV-exclusive lane) and 12-ft lanes in the center and right. The control scenarios have 12-ft lanes all across, including the AV-exclusive lane. For scenario 1, traffic exists and moves on the AV-excusive lane with a headway of one second in section 1 and a headway of three seconds in section 2. Scenario 2 has the headways reversed for the two sections (i.e., a 3-sec headway in section 1 and a 1-sec headway in section 2) and has traffic in the right lane moving with a one-second headway. Scenarios 3 and 4 are similar to scenarios 1 and 2, respectively, with the caveat that the left lane (AV-exclusive lane) is 12 ft wide in scenario 3 and 4. Towards the end of each section, the specific segment workload of each participant was assessed by assigning Ratings Scale of Mental Effort (RSME) scores. Figure 5, 6, 7, and 8 show some snapshots of the design for scenarios 1 through 4 in the simulator screen. All scenarios were pilot tested prior to data collection.

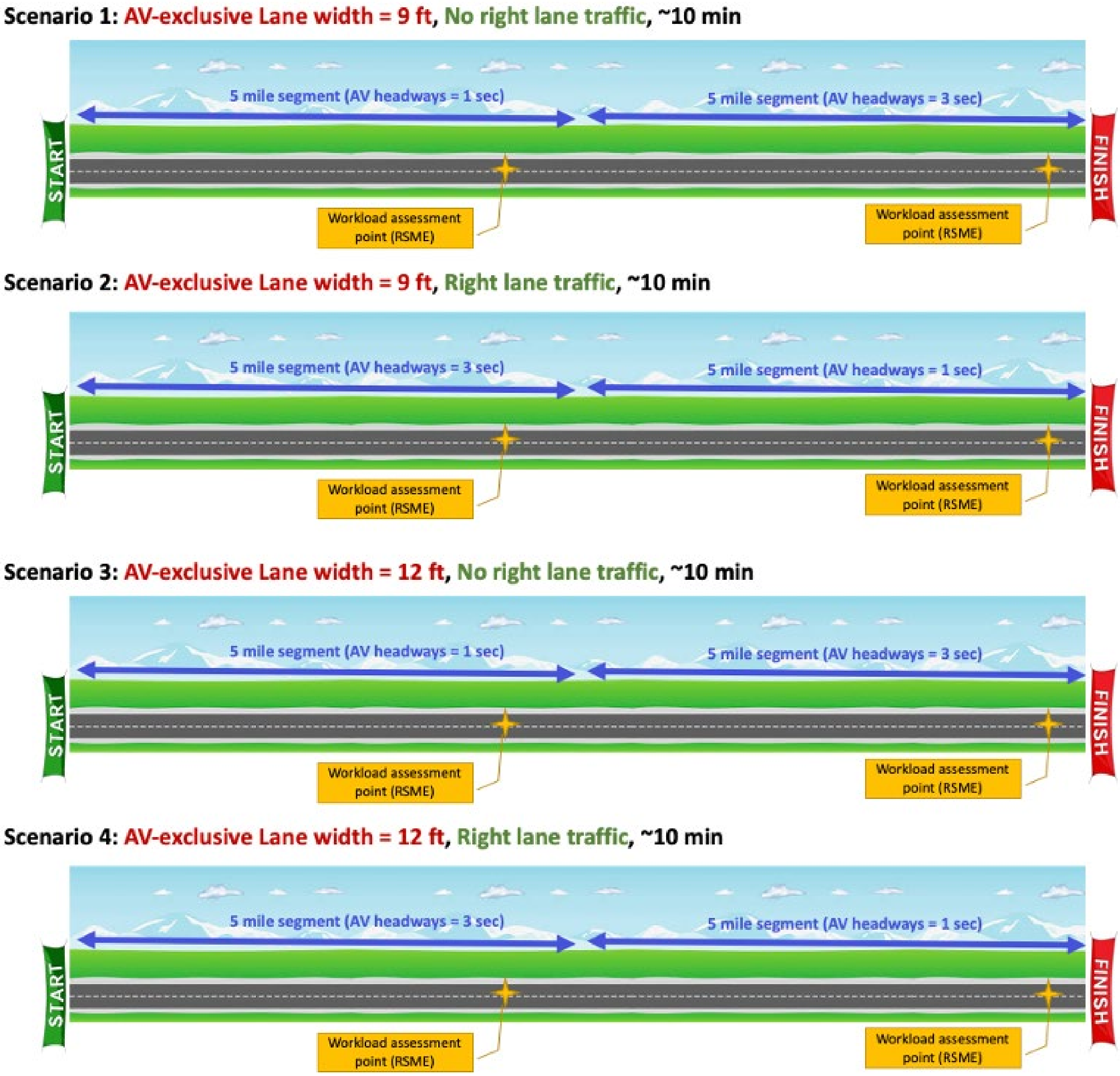


Figure 4. Scenario Designs

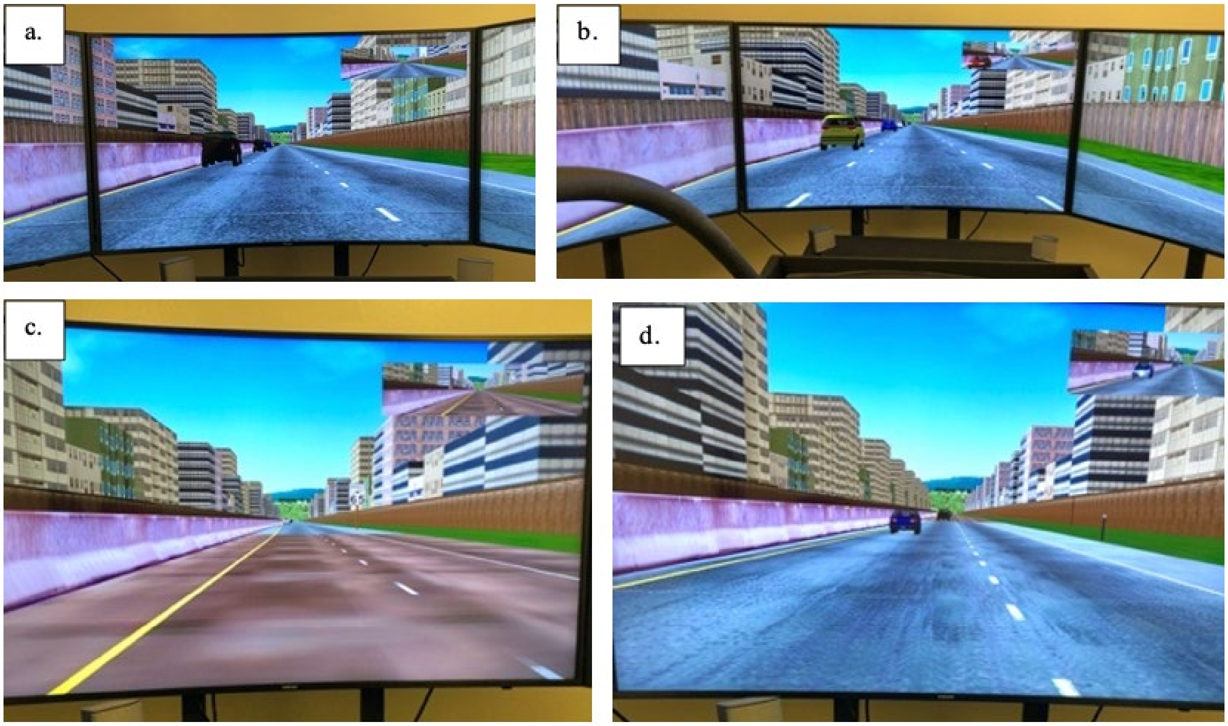


Figure 5. Scenario 1: (a) Entering Section 1, (b) Section 1, (c) Junction between Sections 1 and 2, (d) Transition from Three Lanes to Two after Section 2

Figure 6. Scenario 2: (a) Section 1, (b) Junction between Sections 1 and 2, (c) Beginning of Section 2, (d) Section 2

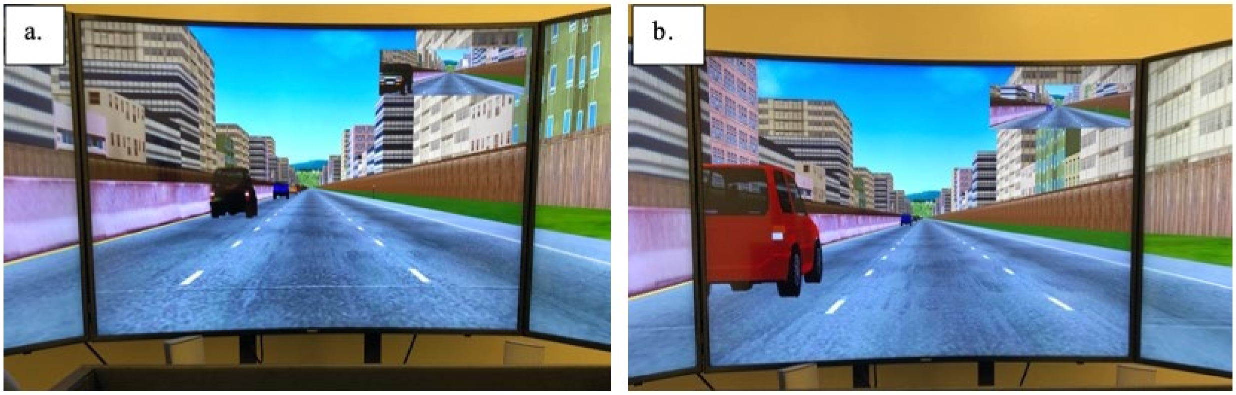


Figure 7. Scenario 3: (a) Section 1, (b) Section 2

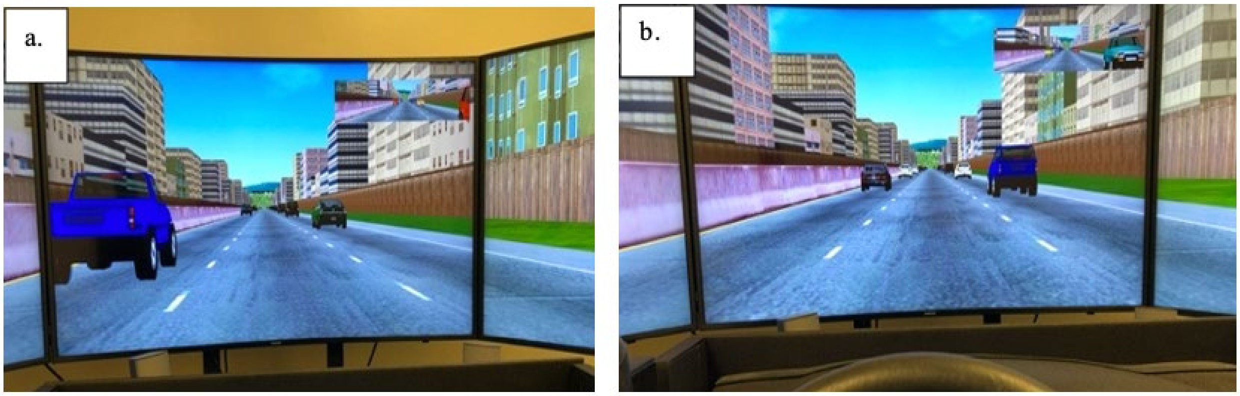


Figure 8. Scenario 4: (a) Section 1, (b) Section 2

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

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 I	Participant group I	Participant group I	Participant group I
12 ft	Participant group II	Participant group II	Participant group II	Participant group II

VARIABLES OF THE STUDY

Independent variables of the study are summarized in Table 2. The second and last columns report 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 that presence of traffic in the right lane and headway of AVs are within-subject variables . 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 fourth column shows the levels of each variable referring to different driving conditions. Headway levels were selected to represent a crowded AV lane vs a light AV traffic condition. Two levels were considered for the AV-exclusive lane width has; the 12 ft is a common practice on freeways and 9 ft was selected to mimic the envisioned I-15 narrow AV-exclusive lane. This study is gender balanced (same number of males and females),

The dependent variables of the study are summarized in Table 3. The simulator tracked speed and lateral distance 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 the Ratings Scale of Mental Effort (RSME, Appendix A) ranging from 0 to 150, with higher values indicating greater 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

SIMULATOR PROCEDURE AND PARTICIPANTS

The procedure of the study was documented, submitted, and approved by the SDSU Institutional Review Board. During their visit, participants began by signing a consent form. Participants were informed about the purpose of the study and its potential risks and benefits, and they were given a brief description of the scenarios. They were then asked to drive an adaptation course in the simulator environment to become familiar with the functionalities of the driving simulator. After that, they were informed about the mental effort scale and proceeded with driving the two assigned scenarios to them. For this study, 40 participants (20 males and 20 females) aged between 18 and 25 were recruited. The recruitment was advertised through flyer distribution on 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.

DATA COLLECTION AND REDUCTION

Data were automatically collected by the simulator after being specified as necessary 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 by all participants, the data were stored on the PC as a datacol file. The frequency of collection for this study was 30Hz. The research team utilized visualization techniques to review all data and identify potentially erroneous findings arising 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 and described in this section

IV. ANALYSIS AND RESULTS

In this section, the data collected from the study are analyzed to determine how different conditions (levels of the independent variables and their interactions) affect the dependent variables. For this reason, appropriate statistical models were used to assess the relationship between them. The models were chosen so that their assumptions would be 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 (e.g., normality) about the data, and these assumptions were checked and verified whenever needed. This procedure was repeated for all of the dependent variables separately.

ANALYSIS OF MEAN LANE POSITION

Figure 9 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 the 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 9-ft lane width, female drivers seem to have more diversion to the right side, whereas male drivers have more negative lane positioning meaning that they drove closer to the 9-ft AV-exclusive lane on their left. As shown in the following section, statistical analysis and hypothesis testing were conducted to confirm or refute the premise of this observation.

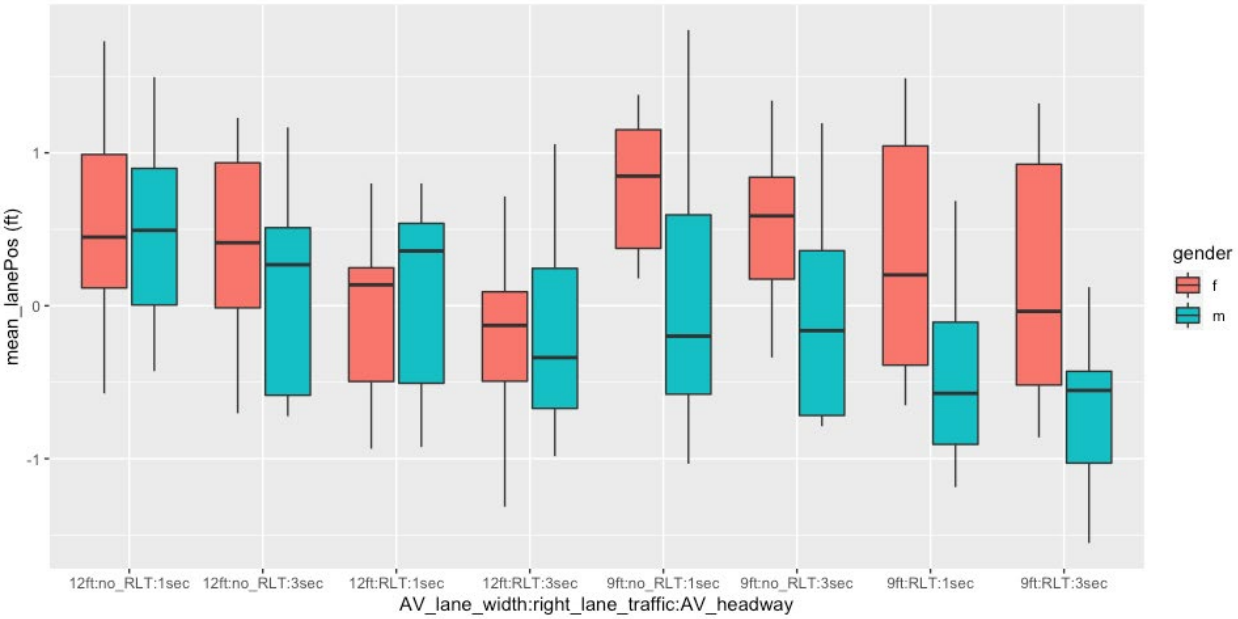


Figure 9. Boxplot of Mean Lane Position for All Treatments

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-subjects 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.

The normality of residuals assumption and the homoscedasticity assumption needed to be verified in order to conduct analysis of variance on the linear models. To check the normality assumption, the Shapiro-Wilk normality test was conducted; this 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) versus sample quantities shown in Figure 10. The graph shows that points lie mostly on the line corresponding to two quantities that came from the same distribution.

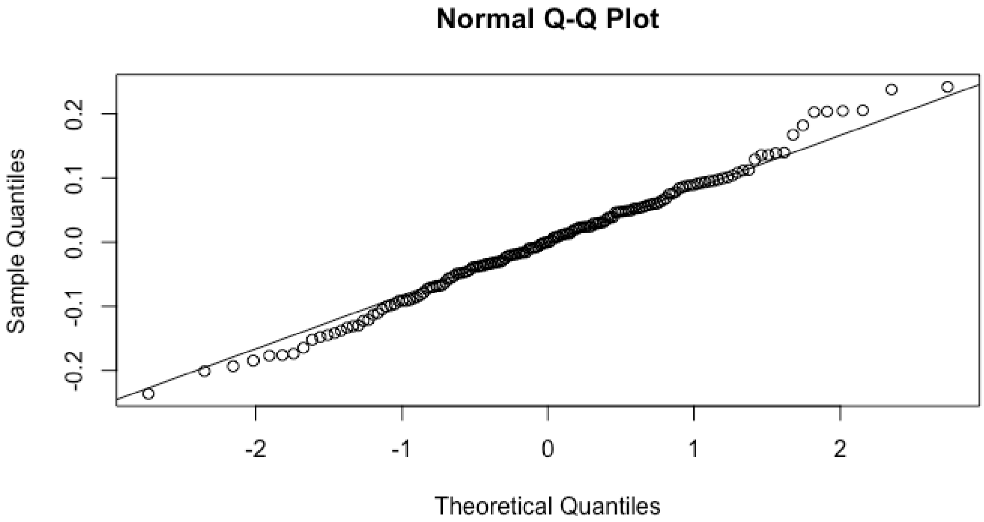


Figure 10. Q-Q Plot of Theoretical (normally distributed) vs. Sample Quantities

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 is shown in Table 4.

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

	DF (degrees of freedom)	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 the 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 four 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 eight 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 11, 12, 13, 14, and 15 contain boxplots comparing different groups. Figure 11 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 12 shows that drivers deviated more to the right in the absence of right-lane traffic. Figure 13 shows that the drivers tended to move 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 14 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, whereas 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 14 shows that females driving next to the 9-ft lane were more successful than males driving next to the 9-ft lane.

Figure 15 shows that the greatest 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, as well as 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 in the right lane and those with traffic in the right lane. According to Figure 15, for all such comparisons, drivers with traffic in the right lane were farther away from the right lane. The only other significant comparison is between females and males driving next to the 9-ft AV exclusive lane with traffic in the right lane, in which case female drivers tended to deviate away from the 9-ft lane while male drivers drove closer to the 9-ft lane, and female drivers had better lane centering performance (smaller absolute value of lane positioning). In terms of lane centering ability, for comparisons between the 12-ft and 9-ft groups, 12-ft groups always had better lane centering. For other comparisons, with the exception of (m,9ft,RLT and m,9ft,no_RLT), all comparisons show that cases with right-lane traffic had better lane centering.

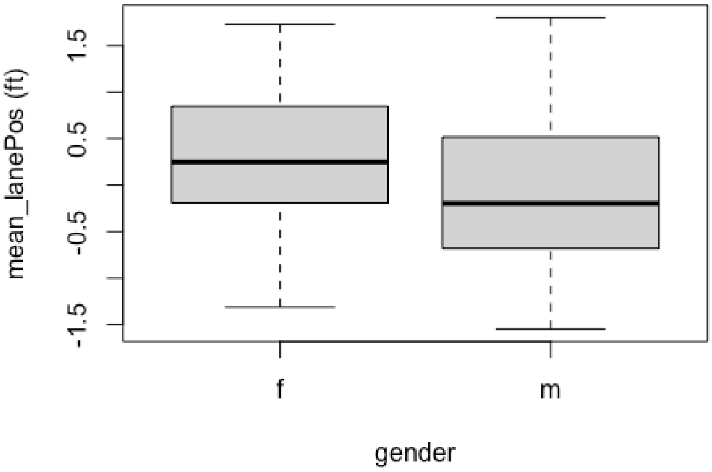


Figure 11. Box Plot of Mean Lane Position for Levels of Gender

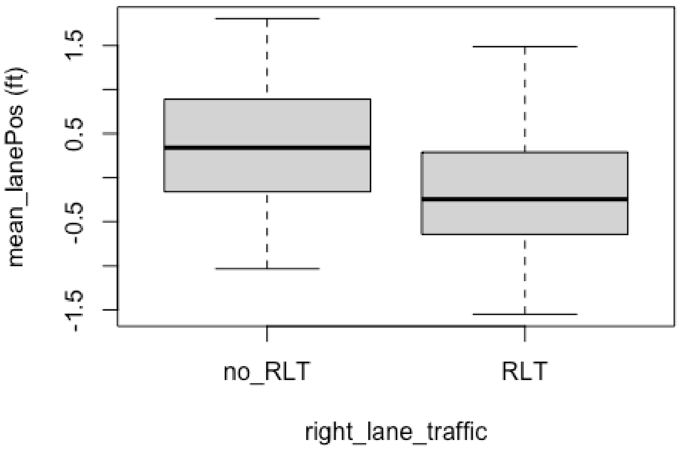


Figure 12. Box Plot of Mean Lane Position for Levels of Right-Lane Traffic

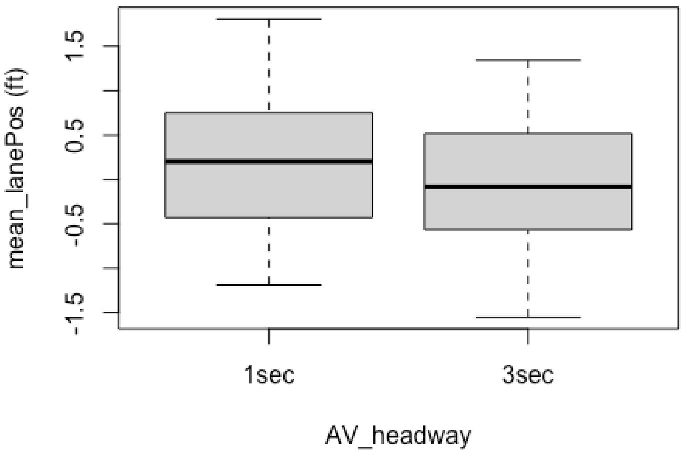


Figure 13. Box Plot of Mean Lane Position for Levels of AV Headway

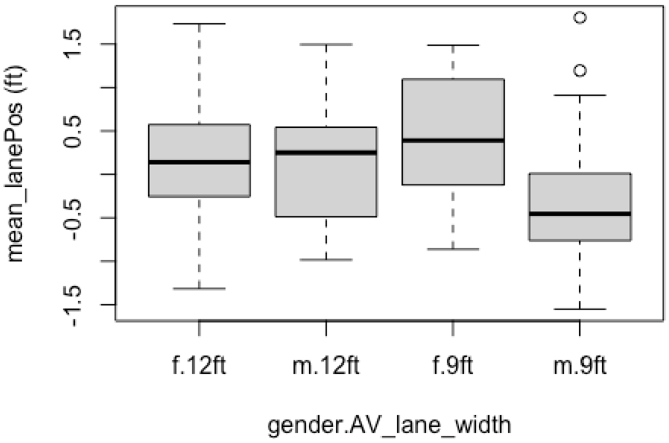


Figure 14. Box Plot of Mean Lane position for Levels of Gender * AV lane width

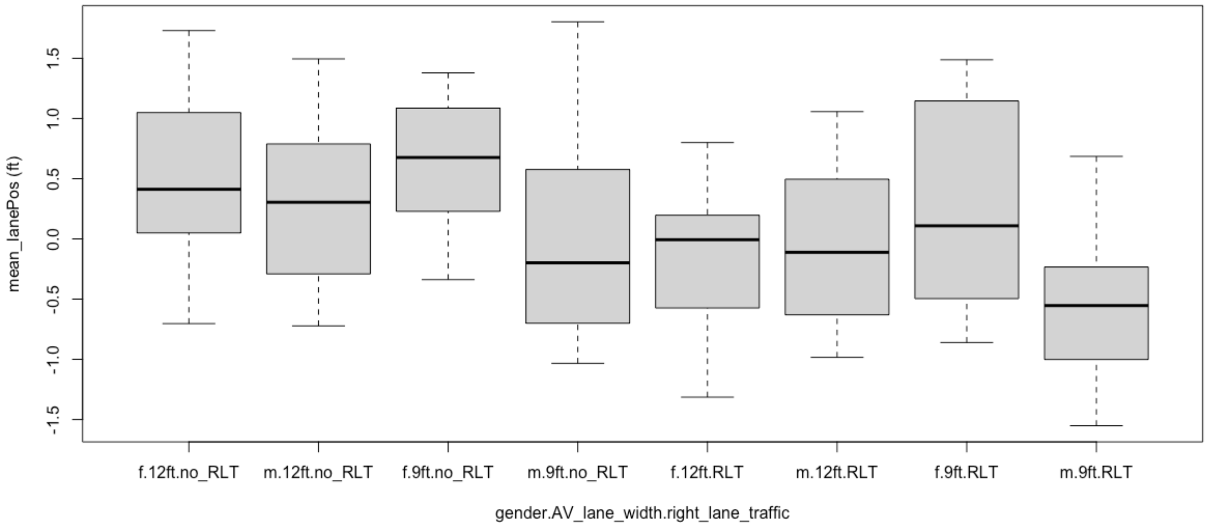


Figure 15. Box Plot of Mean Lane Position for Levels of Gender * AV Lane Width * Right-Lane Traffic

ANALYSIS OF MEAN SPEED

Figure 16 shows a summary of mean speed observed for all the different treatments in the same fashion as Figure 9 summarizes 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. However, it shows a wider range of mean speeds for 9-ft AV-lane groups.

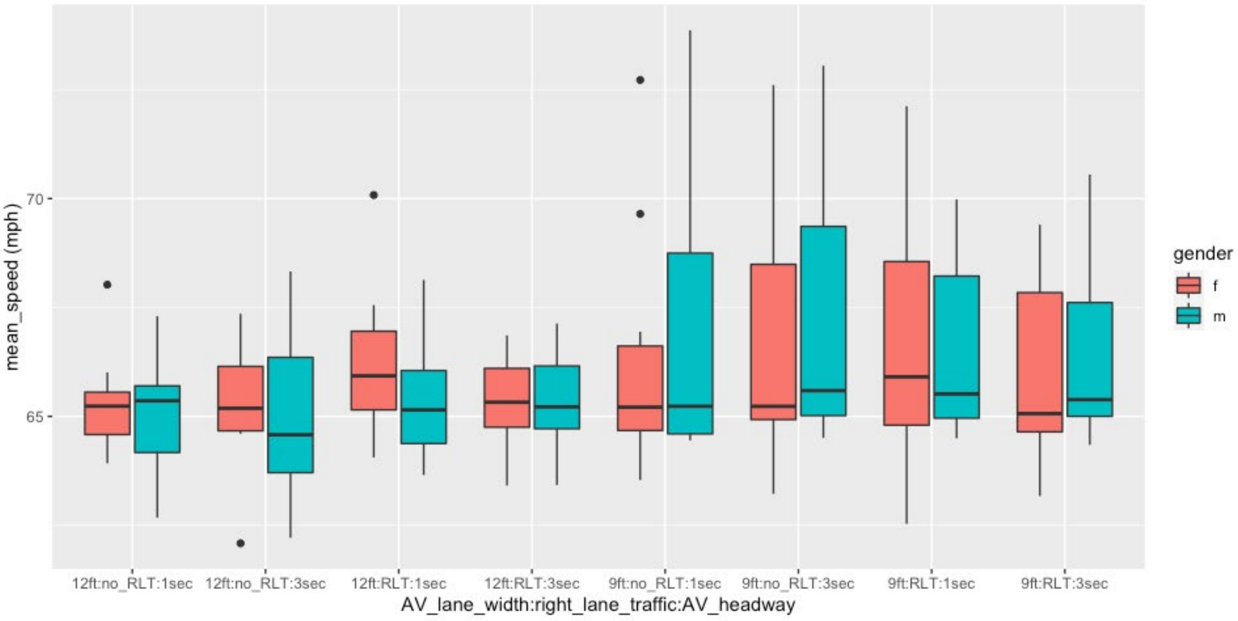


Figure 16. Boxplot of Mean Speed for All Treatments

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 17 also shows that the normality assumption is violated. There are four common options for 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 (Schmidtová, 2016); McDonald, 2009; Zaiontz, 2020) . It is specifically noted that the normality assumption can be violated as long as the sample sizes are equal (called a balanced model) and sufficiently large, and as long as the homogeneity of variance criteria are satisfied (Zaiontz, 2020). According to Zaiontz (2020), a sufficiently large sample size is defined as greater than ten for each group. While in this research the sample sizes are equal and the model satisfies homogeneity of variance (see Table 8), there are exactly ten samples for each of the 16 treatment groups. Hence, the analysis of deviance results of the LMM will not be very reliable. For completeness, the analysis was conducted and the results are shown in Table 9. The pairwise comparisons are shown in Table 10 and Table 11. The difference of mean speed between the significant levels is shown in Figure 18 and Figure 19. 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 the LMM analysis may not be reliable. Thus, more attention was placed on the other analytical options for mean speed.

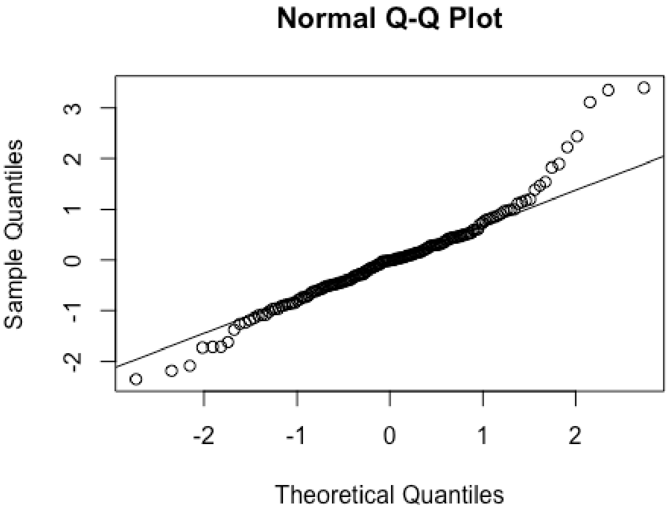


Figure 17. Q-Q plot of Theoretical (normally distributed) vs. Sample Quantities

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_headway	0.268	1	108	0.605
gender:AV_lane_width:right_lane_traffic:AV_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)

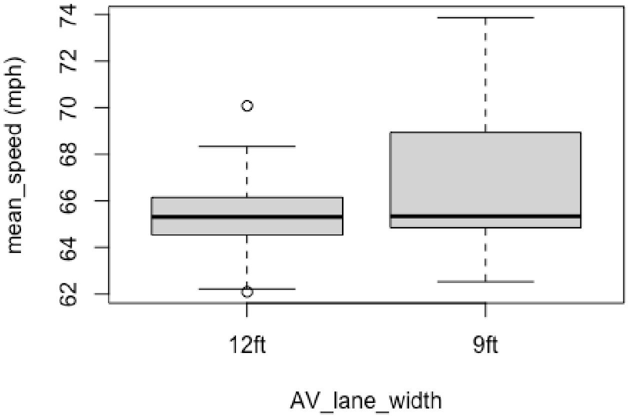


Figure 18. Box Plot of Mean Speed for Levels of AV Lane Width

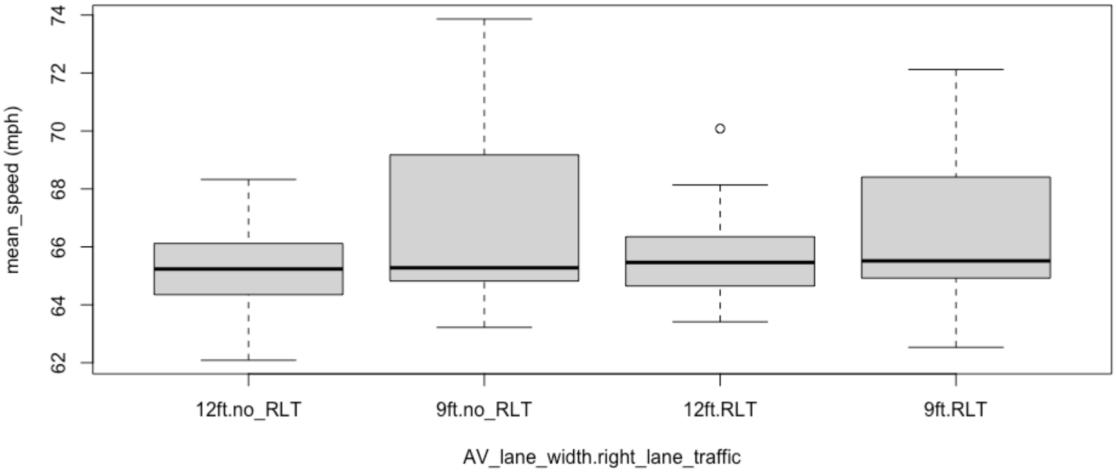


Figure 19. Box Plot of Mean Speed for Levels of AV Lane Width * Right-Lane Traffic

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) and 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 that using the gamma regression is a good choice. The analysis of deviance results of the gamma regression are shown in Table 12. Significant effects are then taken for post-hoc pairwise comparisons of their levels; Table 13 and Table 14 show the post-hoc pairwise comparisons, which do not indicate any significant effects.

Table 12. Analysis of Deviance Table (Type III Wald chi-square 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 Table 15, Table 16, and Table 17. For the pairwise comparisons, the Wilcoxon signed rank and Mann-Whitney U non-parametric pairwise tests were chosen based on whether within- or between-subjects variables were being analyzed. As shown in Table 16 and Table 17, the results comply with the results from the gamma regression model: there are no significant effects.

In summary, out of the four approaches to address the violation of the 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 the mean response. This result confirms the observation made based on Figure 16 at the beginning of the mean speed analysis section: no significant difference in mean speed between the groups is observable. However, it should be noted that a wider range of mean speed for 9-ft AV lane groups can be seen on Figure 16, 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)

Comparison	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

(Adjusted p-values reported: Holm’s method)

Table 17. Post-hoc Analysis for ART Model (AV_lane_width:right_lane_traffic)

Comparison	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

(Adjusted p-values reported: Holm’s method)
Response averaged over levels of right lane

ANALYSIS OF MENTAL EFFORT

Figure 20 shows a summary of mental effort for all the different treatments. 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 variation in mental effort for groups driving alongside the 9-ft AV lane. However, some difference in mental effort can be seen among genders for groups driving alongside the 12-ft AV lane. Also, females seem to have a wider range of mental effort scores.

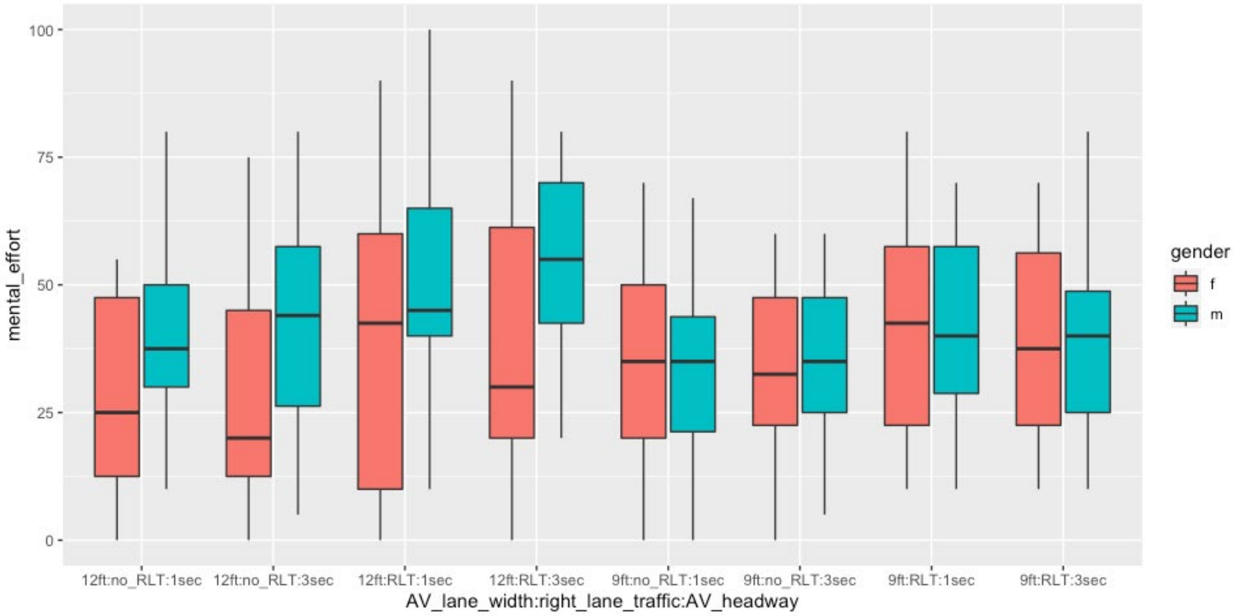


Figure 20. Boxplot of Mental Effort for All Treatments

The data were analyzed by a generalized linear mixed model commonly used for ordinal data called the 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. Table 18 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

V. DISCUSSION AND CONCLUSION

In this study, driving performance was evaluated for subjects driving next to a narrow 9-ft AV-exclusive left lane and was compared to the performance of subjects driving next to a regular 12-ft 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 in 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 9-ft 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 between male and female vehicle operators driving next to the 12-ft AV lane, while less gender-specific behavior was observed in terms of mental effort when driving next to the 9-ft AV lane. Also, generally, females seemed to have a wider range of mental effort scores.

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 they veered less to the left when in the presence of right-lane traffic. Drivers tended to move 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 9-ft 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 9-ft AV lane condition and other groups that had either the 9-ft AV lane condition or the 12-ft AV lane condition. The paragraphs are unique in the sense that—along with the aforementioned comparison condition—they include a unique combination of interaction factors.

When comparing the groups that drove next to the 9-ft AV lane with the groups that drove next to the 12-ft lane, significant difference was seen between some of the groups that drove next to a 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). It should be noted that the parenthetical descriptor of (m,12ft,no_RLT - m,9ft,RLT) refers to the difference between the male participants driving adjacent to the 12-ft AV-exclusive lane with no traffic on the right hand side lane and male participants driving adjacent to the 9-ft AV-exclusive lane with traffic on the right hand side lane. 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 the 12-ft AV lane performed better in terms of lane centering.

When comparing the groups that drove next to the 9-ft AV lane with the groups that drove next to the 12-ft 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 12-ft lane had better lane centering performance.

When comparing groups that drove next to the 9-ft AV lane, significant difference was seen between some of the groups that drove next to a 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 9-ft AV lane, there was also 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 9-ft 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, 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 9-ft 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.

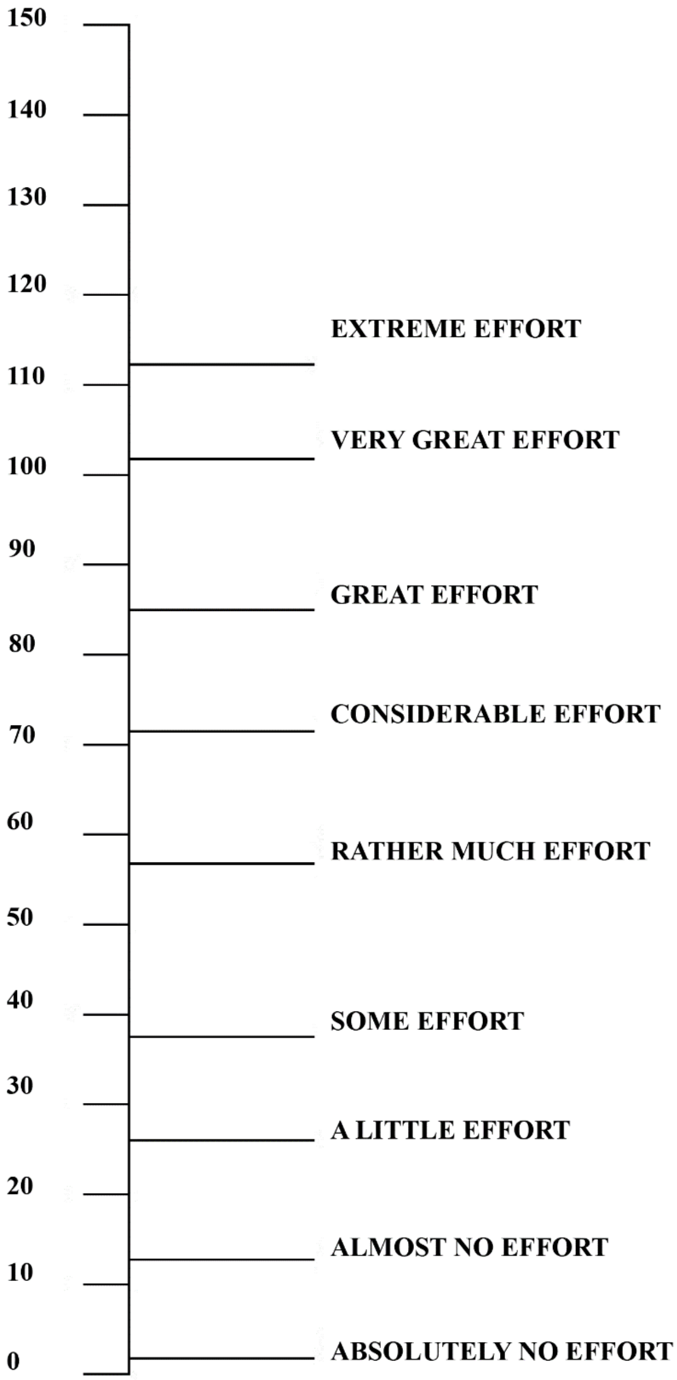
Speed and mental effort were not seen to change significantly when driving next to the 9-ft AV lane. Thus, for new 9-ft AV lanes to be considered safe (in the context of the behavior of drivers in the adjacent lane), the important criterion would be that the addition of the new lane should not cause significant change in the lane position of drivers on the adjacent lane when compared to lane position of those driving next to a 12-ft lane. It should be noted that the significant difference could be caused by other factors. Indeed, based on findings of this study, the overall effect of AV lane width was not significant on 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. However, the trend seen in these comparisons is that drivers traveling next to the 12-ft lane have better lane centering, and this may be noteworthy for safety reasons.

Also, when comparing groups that drove next to the 9-ft lane, it is important for safety to track factors that influence the drivers' lane position to change significantly and determine which levels of those factors cause 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 in the right lane and gender. For the gender comparison, the analysis showed that while in general female drivers tended to drive further away from the 9-ft 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 generally made drivers shift to the left. Hence, precautions should be taken when designing a 9-ft AV lane on the left side of a roadway in the direction of travel in the presence of high-volume 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 prompted changes in lane position, with smaller headways making drivers move further away from the AV lane, but this does not correspond to major changes in lane centering ability.

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

APPENDIX A: RATINGS SCALE OF MENTAL EFFORT

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



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
LMM	Linear Mixed Model
RSME	Ratings Scale of Mental Effort
STAR	Smart Transportation Analytics Research

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