EXTERNAL COMMUNICATION DISPLAYS FOR CONNECTED TRUCK PLATOONS IN MIXED TRAFFIC: A FEDERATED SIMULATOR STUDY

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By

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Approval Page

The undersigned, appointed by the Associate Vice Chancellor of the Office of research and Graduate Studies, have examined the thesis entitled:

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Presented by Michael Schoelz, a candidate for the degree of master of civil and environmental engineering,

And hereby certify that, in their opinion, it is worthy of acceptance.

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Abstract

Truck platooning is anticipated to be the first widespread deployment of connected or automated vehicles (CAV). In addition to familiarizing the public with the function of CAV, a truck platoon has proven benefits to fuel consumption by minimizing drag. These are the primary motivations that have caused companies to develop and deploy these systems, but there are still obstacles opposing their implementation. One obstacle is the issue of communication between CAVs and the surrounding traffic. For example, research has shown that communication between CAV and pedestrians and cyclists is facilitated by using external status displays on the CAVs. In order to investigate the communication between truck platoons and surrounding traffic, a similar model is proposed in this study.

The scenario examined in this study involves trucks forming a truck platoon. Two different external displays in addition to a control display were evaluated for how surrounding traffic behaves while the trucks form their platoon. The three displays are the control (no signal), the word "PLATOON," and a graphic of two trucks with a link. Each of the displays were tested using a federated truck simulator and passenger vehicle simulator. The approaching truck was driven by the same human driver up until the completion of platooning while the passenger vehicle was driven by the research participants. The simulation scenario involved a passenger vehicle following a semi-truck while an approaching truck comes up from behind the passenger vehicle to form the platoon. The actions taken by the passenger vehicle to clear the way for the approaching truck were observed and recorded. After the participants were exposed to the signs once, they were provided with an explanation of truck platoons and were able to ask questions before experiencing three displays scenarios again. Overall, the primary performance result was

that the text display after being provided with information on truck platoons significantly changed the behavior of the passenger vehicle. Furthermore, as in the AV-Pedestrian studies, participants indicated that the external displays were useful. In conclusion, though the behavior was not drastically affected, the results indicate that the displays provide the passenger vehicle drivers with important information that they want to have and that drivers tend to move out of the way when they learn that a truck platoon is forming around them.

I. Introduction

Truck Platooning (TP) is a type of Connected/Automated Vehicle (CAV) technology that is on the verge of being implemented on roadways worldwide. Many are excited by the prospect of TP, its benefits and its overall effect on the public perception of CAV. However, there exist significant hurdles regarding the unintended consequences of TP integration into our transportation infrastructure in addition to the ongoing investigations into the operational feasibility. Therefore, it is prudent to investigate TP to probe its effects on the roadway.

Though TP is not a novel concept, a comprehensive definition that covers all the variations of TP while still being useful is a difficult task. However, all the recent iterations involve at least one truck closely following a lead truck using a virtual tether. The reason the trucks follow each other so closely is to take advantage of the aerodynamics of drafting, i.e.: platoons with a follow distance of <60' decrease the wind resistance for both trucks. In 2018, the Federal Motor Carrier Safety Administration (FMCSA) defined a truck platoon and its expected benefits and this definition is included in Table 1 (Loftus and Tershak 2018). The FMCSA definition is composed of three elements; (1) the trucks are connected through Cooperative Adaptive Cruise Control (CACC), (2) humans control the lateral movement (steering) of the truck while the platoon is engaged, and (3) that the gaps between the trucks dynamically widen if another vehicle intersects a gap. Furthermore, the FMCSA detailed the basic benefits of TP. TP is expected to reduce fuel consumption, take up less room on the roadway (thus increasing capacity) and decrease incidents due to the CACC. Other definitions of TP include Driver-Assisted Truck Platooning (DATP), in which the TP system exerts greater control over the lateral control (Bishop et al. 2017). A third important definition is a Truck String (TS). The difference between a TP and a TS is the follow distance. In particular, a TS uses a headway gap that allows for a comfortable intersection for passenger vehicles (Nowakowski et al. 2015) whereas a TP maintains a shorter distance that is less convenient for passenger vehicles to intersect. These various definitions demonstrate the lack of clarity underlying the TP concept even within the literature. Part of this lack of clarity stems from the fact that there is no widespread implementation yet. Once a model becomes prevalent in the upcoming years, there will be greater clarity on what qualifies as a TP. Though there are many definitions within the umbrella term "Truck Platooning," for the purposes of this study, TP will refer to the broad FMCSA definition.

Table 1: Truck Platoon Definition and Benefits

Truck Platoon Definition and Benefits (Loftus and Tershak 2018)	
Definition	(1) Coordinated operation of two or more trucks via **cooperative cruise control** (lead truck wirelessly connected and in de facto control over the following vehicles throttle, brakes, and brake lights). (2) **Human drivers steer** the lead and following trucks to avoid hazards (lateral control). (3) The gap between trucks will automatically increase if another vehicle intersects the platoon.
Benefits	(1) Fuel reduction and energy savings from aerodynamic drag reduction. (2) Reduced freeway congestion from a reduced follow distance between trucks. (3) Lower reaction times to stimuli could possibly help truck drivers avoid incidents.

Compared to other CAV technologies, TP has been the focus of several different areas of study because of its relative technological ease. The relative ease has also made TPs more likely to be on the road sooner than other forms of CAV. Therefore, the areas of investigation are mature and focused on optimization and impact. One major area of study under investigation is operations and Route Formation which aim to investigate the most optimal way to implement and form TPs (Boysen et al. 2018; Chen and Ahn 2018; Duret et al. 2018; Luo et al. 2018). Another major area of study is in investigating the effect of TPs, particularly the Human-Machine Interface (HMI), on the truck driver. These studies also underscore the importance of familiarity between humans and the TP system's HMIs in the TP's performance (Friedrichs et al. 2016; Heikoop et al. 2017; Hjalmdahl et al. 2017).

However, one area of study that is still yet to be explored in depth is the communication that will take place between a truck platoon and the mixed traffic on the roadway. Though researchers have studied the effects of TPs on Sign Occlusion (Alsghan et al. 2018) and Social Acceptability (Sugimachi et al. 2017), the direct interaction between human passenger vehicle drivers and TPs during formation is still unknown. In particular, more research is needed to understand how these interactions might affect TP formation and what displays are most effective in dealing with interactions between TPs and human passenger vehicles, as well as any possible unintended consequences. Furthermore, taking a cue from the human machine interface studies, the familiarity of human passenger vehicles with TP is also ripe for study.

Therefore, this study will examine the effectiveness of different truck platoon external communication displays on successfully initiating a platoon. During the formation of a platoon, the trucks will be following a rudimentary hybrid method of formation (Saeednia and Menendez 2016) in which the lead truck slows their speed and the following truck is accelerating. A human truck driver initiates the platoon by turning on an external display, alerting traffic to the closing gap between the wo trucks. As seen in CAV-pedestrian studies (Clamann et al. 2017), the use of an external display is an effective method to communicate to pedestrians and cyclists.

Researchers would observe the response of a passenger vehicle between the two platooning trucks as a measure of the utility of these displays in communicating the status of the platoon. By indicating to a passenger vehicle that a TP is imminent, the TP could form more safely and efficiently. The participants in the study will also be provided information regarding truck platoons. By providing an educational introduction to TP, human passenger vehicle drivers could possibly change their behaviors as their familiarity increases. Therefore, there are two main investigations within this study: the effectiveness of external displays on the behavior of a passenger vehicle and the effect of familiarity on the behavior and comfortability on a passenger vehicle.

II. Literature Review

Technical Information

TP is currently being investigated from several different perspectives due to its perception as a test case for the CAV movement. Given this scrutiny, several models of TP have been considered in the literature, but the model that is most likely to be deployed in the near future is detailed in the Federal Freeway Administration's (FHWA) Exploratory Research project. This model, developed by Auburn University in conjunction with Peloton Technology, Peterbilt Trucks, Meritor WABCO and the American Transportation Research Institute (ATRI), is a driver-assisted truck that makes use of CACC (Bishop et al. (2017)). The 2017 report, Evaluation and Testing of Driver Assistive Truck Platooning represents the results from Phase 2 of the FHWA project and explores the potential benefits as well as expected impacts and feasibility. The FHWA Phase 2 DATP system will serve as a base model for this study and provides a good starting point from which to explain the technology that makes TP work. Overall, the FHWA Phase 2 report indicates

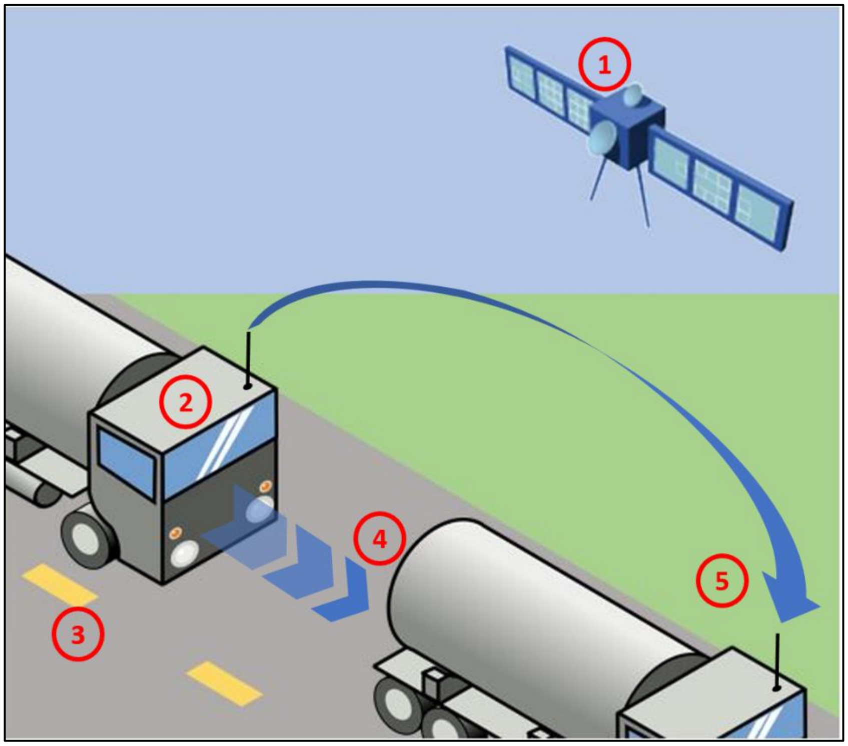
that through the first two phases, the baseline technologies that underpin DATP have been established, tested, and refined and therefore research has turned its attention to the accurate understanding of the benefits and implementation techniques.

zSAE International Levels of Automation (NHTSA 2016)	
Level 0	Human Driver has total control over the driving task.
Level 1	An automated system assists with some part of the driving task.
Level 2	An automated system wholly controls one part of the driving task while a human driver controls the rest of the driving task.
Level 3	An automated system has control of the driving task but requires a human to monitor and take back control depending on the situation.
Level 4	An automated system has total control over the driving task in specific situations.
Level 5	An automated system has total control over the driving task in all situations.

Table 2: CAV Levels of Automation

TP is a relatively simple type of CAV. The FHWA DATP Phase 2 system represents a Level 1 automated vehicle according to the NHTSA standards regarding automated vehicles (Bishop et al. (2017)), meaning that while there is a suite of driver assistive technologies, the driver is still steering and can take control of the braking/throttle at any time. Level 2 systems would begin to exert more control over the steering within the TP suite of technology (NHTSA 2016). The technology developed by the partnership makes use of the trucks' existing Adaptive Cruise Control (ACC) and links two trucks through a Vehicle-to-Vehicle (V2V), dedicated short-range communications (DSRC) network. The ACC system allows the trucks to match speeds through the use of radar mounted on the front of the trucks. Though many ACC systems are already put to use on roadways, by incorporating V2V DSRC to coordinate the throttle, braking and signaling, the ACC system becomes a CACC system (Nowakowski et al. 2015). CACC is a type of level 1 SAE level of automation (Table 2). Since truck platooning makes use of a connected throttle and brake system but still requires a human driver to control the lateral movement, this system would fall under level 1 of the NHTSA/SAE International definitions for automated vehicles (Bishop et al. 2017). DSRC has been developed since 2000 to be the initial primary communication network for CAV; as such it has a low latency (message update time), security and standardization across the CAV industry. Though some in the industry will argue that DSRC is the dial-up internet of the CAV movement, its development has been a critical infrastructure hurdle.

Though the CACC element is the main "truck platooning" technology in use, there are multiple other systems running concurrently to assist the human driver. Figure 1 demonstrates the suite of technologies that work together to create a TP.



1.) Satellite Positioning: coordinating message locations

2.) Human-Machine Interface

3.) Actuation/Lane Assist: Longitudinal control of vehicles.

4.) Radar: Provides longitudinal sensing.

5.) V2V DSRC communications: Low latency exchange of Basic Safety Messages (BSMs) and other performance measures.

Figure 1: DATP technology suite from the FHWA Phase 2 model (Bishop et al. (2017)).

Overall, the goal of all these technologies is to try to minimize the distance between trucks while preventing frontal collision or any crash. The optimal gap for TP is dependent on many variables such as speed, driver comfort, TP system automation level and aerodynamic drag. The range of gap distances is still under investigation but the goal range is between 3-6m (Bishop et al. (2017)) for the ideal TP system in which all driving has been ceded to automated control and the trucks travel in a dedicated lane. For initial systems, where human drivers will still control much of the driving task within mixed traffic, the gap distance stretches to between 10-20m depending on driver comfort. Similarly, two-vehicle platoon models represent the baseline case with the possibility for larger platoons later on.

There are three primary reasons for developing truck platooning: industry interests, safety impacts and public perception. Due to the minimization of drag, truck platooning allows the lead vehicle to save approximately 6% of its fuel while following vehicles can see savings as high as 10% (Lammert et al. (2014)). Due to the small gaps between trucks, the platoon will also take up a smaller area on the roadway, possibly helping relieve congestion (Bhoopalam et al. (2018)). Finally, and perhaps most importantly, truck platooning will be one of the first CV technologies that the public will see on the roadway. The rollout and success of truck platoons and their perception by the public at large will set the stage for more complex automated vehicles (AV) to come after.

There are two expected benefits to TP as well as a third positive externality: fuel savings, congestion relief and a rise in public familiarity for AV. Several studies have examined the effects of TP on fuel economy as these provide the concrete evidence for freight companies to adopt this technology. As mentioned above, the fuels savings from TP are derived from the space reduction between trucks: both lead and following vehicles experience less drag and therefore consume less fuel. The gap distance, speed and vehicle weight all have an impact on the fuel savings (Lammert et al. 2014),(Luo et al. 2018). From these studies, it is clear that while fuel savings are likely, the extent to which these savings are realized depends on the operations and routes taken by trucks. Regardless of the operational concerns, the overall message of ~10% fuel savings is an enticing offer for freight companies (Bishop et al. 2017).

Timeline

Since CAV is still a relatively nascent movement, it is important to establish a timeline of expected events and understand the trajectory of the CAV movement. Currently there are an infinitesimal number of CAV on the roadways and even fewer TPs. Ultimately continued automation and development of TP will result in the need for these vehicles to have their own infrastructure to maximize their efficient use (Mohamed et al. 2018). Obviously though, such an investment in infrastructure for such a specialized need is still many decades away. Between these two points in time however, there will be plenty of people driving their passenger vehicles on the same roadways as TPs. Furthermore, as some studies into the interactions between CAV and pedestrians point out, vulnerable road users will always exist (Stanciu et al. 2018).

A common complaint about CAV in general is that headlines often breathlessly proclaim that these fantastic technologies are just a “few years away.” But such prognostications have been found to be spurious at best. Though it lags behind the most cutting edge, headline-grabbing research by a few years, the most reliable indicator of the arrival of a particular CAV technology is legislative action relating to it. Legislation authorizing TP has been passed in 16 states as of July 2018 (Scribner 2018), indicating that this technology is nearly ready to be implemented.

While the legislation advances signal the advent of TPs, there are some forecasting timelines that focus more on benchmark events rather than the date of their introduction. Litman of the Victoria Transport Policy Institute has continually published a prediction report for a wide variety of AV applications. Litman predicts that following the passage of the requisite legislation, the widespread implementation of platooning on roadways will occur sometime between 2020-2040 (Litman (2013)).

During the next 20 years, several models will be proposed, and changes will be made to facilitate the success of platoons. Litman also predicts that dedicated lanes and mixed vehicle platoons will make their debut in the implementation time period (Litman (2013)). There are several avenues of research that need to be explored before full scale implementation. In their review of research up to 2017, Bhoopalam, et al. summarized the development of truck platooning and made recommendations for future study. The primary area of interest for Bhoopalam was in the planning and optimization of truck platooning from an operational standpoint, given that many of the technological obstacles had acceptable solutions. The operation of truck platooning is often examined from a system-wide perspective; the interoperability, truck eligibility, scheduling, pairing, and route selection all require investigation. Another major area of research involves the "Human-Machine interface." This interface is the module through which the human driver interacts with the DATP system. There are concerns both about the level of alertness as well as the clarity of information being conveyed.

In between these two major research avenues is a third untapped discussion on the interaction between truck platoons and their surrounding traffic. As mentioned in the section on congestion, there are some ideas as to the impact on traffic patterns, but AVs often have an even greater impact than that. The last section of this literature review will explore how AVs handle the interpersonal communications between currently occur naturally between drivers on the road. The best example for this type of communication is between a pedestrian at a crosswalk. A pedestrian often will receive acknowledgement from a driver before crossing and an AV needs to replicate this interaction. Similarly, there is information that needs to be shared to human drivers on the roadway near a truck platoon. Therefore, as with all CAV, truck platoons have to be phased into traffic. However, so far, no research has investigated this aspect of TP.

Table 3 is taken from a Japanese Platoon study in 2013 that was focused on the reducing the environmental impact of TP (Tsugawa 2013). It provides a nice overview of the current context of truck platooning because it shows how the truck platoon phase-in has been developed. When the study was published, Adaptive cruise control to reduce fuel consumption was the goal. Since then, the CACC systems have been developed. Over the next few years as these systems become more commonplace, it is like that greater and greater control of the driving task will be ceded to the platooning system. Of course, that can only occur with a sterling track record for safety and responsible integration into our transportation eco-system, which involves much more than just what's traveling on our pavements.

Table 3: A Timeline for the implementation of Truck Platoons

Truck Platoon Timeline (Tsugawa 2013).			
	Previously Developed	Near Future	Far Future
Concept	Eco driving by ACC	Platooning by CACC (ACC+V2V)	Platooning by CACC and lateral control
Objectives	Energy Savings	Energy Savings with minimal traffic impact	Energy Savings and efficient logistics
Mixed or Dedicated Lane	Mixed	Mixed	Dedicated Lane
Energy Savings Goal	Eco, Safety and Workload reduction	Drag reduction (8-15%)	Drag Reduction (18%)
Drivers	In each truck	In each truck	Only in lead

Truck Platoon Operations

Perhaps the last major obstacle to TP on the roadways is operational: how can we maximize the TP effects? As it applies to this report, operations underpin the conditions for how the platoon is formed.

Bhoopalam et al. separates the different platoon planning systems into three modes: scheduled/static planning, real-time/dynamic planning, and opportunistic/ad-hoc planning. The difference between these three modes is essentially when the trucks announce their trip intentions: static platooning is coordinated using known trips and scheduling departures together, whereas dynamic platooning comes from matching trucks with similar routes and opportunistic platooning occurs on the road when driver notice similar travel paths. There are two main variables that effect how these plans are put into practice: minimizing fuel costs system/fleet-wide and maximizing the number of trucks in a platoon. These two factors may be correlated but ultimately are not equivalent. Bhoopalam et al. also includes a helpful discussion on the factors/constraints that will affect platoon formation. Overall, they conclude that dynamic planning operations are ripe for study as well as dealing with uncertainty, system sustainability and network design.

Though somewhat trivial from wide perspective of these operational studies, how a potential follower truck communicates with the lead truck to form a platoon is another critical piece of TPs. Saeednia and Menendez propose a strategy for the most efficient method for forming a platoon on the roadway. In previous studies, only two formation strategies were used: the “catch-up” or the “slow down.” Saeednia and Menendez propose a hybrid strategy in which both the follow vehicle speeds up and the lead vehicle slows down and found it to be the fastest way to platoon using the maximum possible speed for the trucks until formation (Saeednia and Menendez 2016).

Traffic Impact

TP is likely to have an important influence on freeway traffic flow. Interestingly, simply the presence of TP on the roadway may be enough to cause some benefits to traffic flow on freeways.

Though the microscopic simulations indicate a benefit for freeway traffic, there are still some direct actions that TPs can take to influence the surrounding traffic. Chen and Ahn investigated the intriguing potential for CAV and TP to influence the lane-changing behavior of human passenger vehicles (Chen and Ahn 2018). The study proposes three methods by which a

TP can control the surrounding traffic's lane changing behavior to help alleviate merge bottlenecks and minimize voids and disturbances. In particular, the "Gap Redistribution" strategy attempts to strategically open up gaps in merge areas to allow for a lane change (Chen and Ahn 2018). Though the study simply offered these strategies as theoretically feasible, an important implementation technique could involve communication displays for human drivers.

However, though these microsimulation studies and strategies for influencing traffic seem promising, there are negative effects from the introduction of TP as well. Sign Occlusion is an excellent example of these negative effects. If the visibility of a post-mounted sign is significantly affected, traffic safety issues will likely follow. Alsghan et al. produced a microsimulation study in which the effect of TPs on sign occlusion and found that as traffic volume, truck percentage and truck platooning percentage all increased the percentage of vehicles blocked (Alsghan et al. 2018). Alsghan et al. conclude that more research is warranted to determine how to mitigate this impact. This study represents progress on one possible solution with its application of TP communication displays.

CAV-Human Communication and Social Acceptability

As noted in the FHWA Phase 2 report, public acceptance is an important consideration for the proliferation of TP. There are two major influences on the public acceptance of TP: personal interactions and media reports/word of mouth. While media reports effect on the perception of CAV is outside the scope of this study, they still provide some excellent examples of how people interact with CAV. For example, a 2016 *The Verge* article on a Google/Waymo vehicle that caused a crash demonstrated that the lack of interpersonal communication between the CAV and a human driven bus (Ziegler 2016). Though the circumstances of this crash are not directly applicable to TPs, it does illustrate the larger point that while CAV are learning how to navigate roads with human drivers, human drivers will need to learn how to navigate roads with CAV. Given the fact that CAV often make use of new technologies such as CACC, learning how human drivers respond to these new behaviors is the primary research motive of this report. As mentioned above, there have been studies that examined the impact of TP on traffic at the microscopic levels but examining driver behavior in response to TP events is yet to be investigated fully.

A basic investigation of Human-TP interaction occurred in a study looking at the physiological response to encountering a TP. The results and methods are similar to that of the HMI studies. Sugimachi, et al. used a questionnaire to investigate the psychological burden experienced by passenger vehicle drives as they overtake a TP (Sugimachi et al. 2017). The researchers found that there was an increased level of tension the closer the subjects came to the TP.

However, there have been several studies in the area of AV and pedestrian interpersonal communications that would help inform this study. Stanciu, et al. provide the groundwork study by identifying issues that CAV will likely have on the roadway. From their survey of the communication methods used in Human-CAV interactions particularly between CAV and pedestrians and cyclists, the authors were able to conclude that standardizing and expanding the roadways signals used to communicate actions and intent will help comprehension from both the CAV and the human actor (Stanciu et al. 2018). Furthermore and perhaps more importantly, that although CAV movements and intentions may be come easily predictable over time, Stanciu et al. recommend that CAV "should still have a means of communicating intent, or at least inform road users of when they are in automated mode. Communication of intent may also help road users become more comfortable around [CAV].”

Similarly, Clammann et al. used a field experiment to evaluate the effectiveness of CAV-external display for communicating to pedestrians. The study showed that pedestrians made decisions based on existing crossing strategies rather than the displays outside the AV (Clamann et al. 2017). However, the majority of participants agreed that an external vehicle display was necessary for AV-pedestrian interactions.

III. Methodology

The methodology of this study consists of two phases: the simulation scenario and the post-simulator survey. The development of these two phases will be explained in detail in this section. The participant survey is included in Appendix A while the hosting manual for processing the individual participants through the trial is included in Appendix B. This section will provide an account of the hardware and software builds for the truck simulators, the calibration efforts, the experimental details of the virtual scenario including the display designs that were tested, the procedure followed and the general characteristics of the participants and an explanation of the measures of effectiveness and post-simulator survey.

ZouSim Simulators

The ZouSim simulator suite has been an ongoing project for the ZouTrans lab at the University of Missouri for the past five years. As a result of this report have added a new mode

Figure 2: The ZouSim Simulator Suite. Clockwise from top left: Car Simulator, Bike Simulator, Wheel Chair Simulator and Pedestrian Simulator

of transportation to the current suite. However, before addressing the specifics of the ZouSim simulator suite and specifically the truck simulator, there are a few simulator principals to be addressed.

The purpose of an individual transportation simulator is twofold; simulators are a safe and inexpensive method to investigate transportation problems. While a test-track and a physical vehicle have high start-up, maintenance and construction costs, a virtual simulator only requires a small fraction of these costs. Furthermore, while there is some associated "simulator sickness," the overall risk of harm to participants is negligible compared to testing in the real world. The cost and safety benefits of simulators do come at a sacrifice—a virtual simulator will always lack true fidelity with the real world, although this loss can be minimized. Therefore, it is the goal of the ZouSim simulator suite to provide adaptable, mid-level simulators that can be entirely managed in-house. "Adaptable" to meet the widely varying needs of transportation applications and "mid-level" to meet an acceptable level of fidelity, built modularly with consumer products, as opposed to a "high-level" simulator developed by a vendor and purchased as a package.

The ZouSim suite contains five modes of transportation that are all adaptable and mid-level. The first developed was a bike simulator, followed by a passenger vehicle, wheelchair, pedestrian and finally the truck simulator developed in this study. The first four of these simulators are depicted in Figure 2 on the previous page. The figure shows the passenger vehicle, wheelchair and pedestrian simulators using projected images while the bicycle simulator uses a television monitor. These simulators have been used to study a wide variety of applications from evaluating bike routing and signage information to combining the car and pedestrian simulators into a network and studying the interaction between a CAV and a pedestrian. Each of the simulators have been developed by students and make use of a several modular hardware units. The primary program used in scenario development is Unity, a cross-platform simulation engine. The assets that populate the virtual environment are either purchased from the Unity Asset store or designed in-house using SketchUp, a 3-D modeling program. The scripts for the scenario are written in C#.

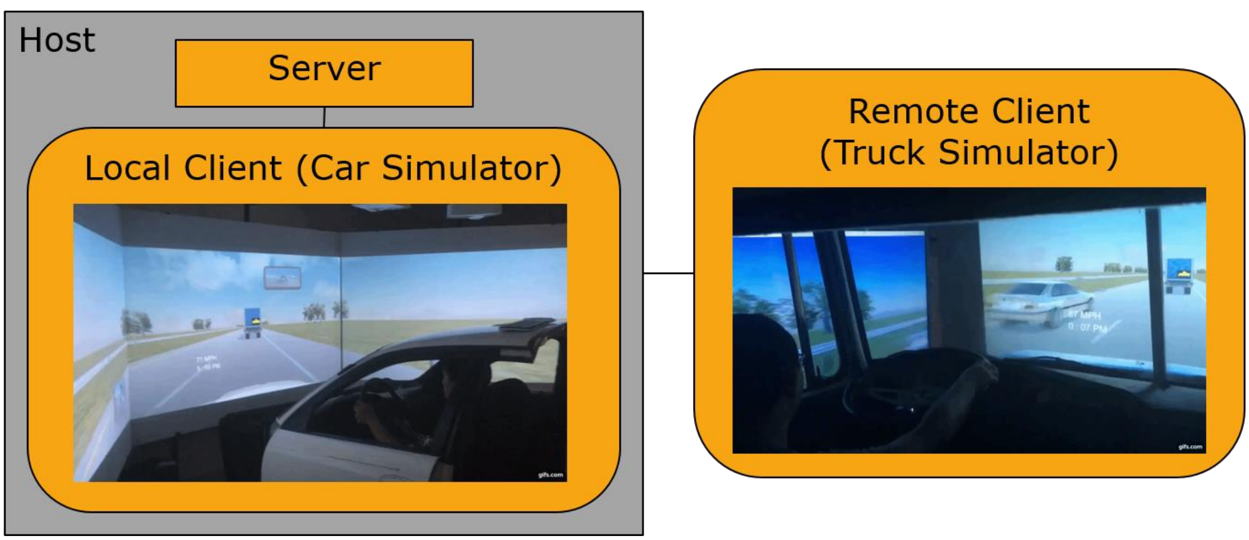


Figure 3: A conceptual model of the use of federated simulators: The host device consists of the server and the local subject, in this case the car simulator. The second device is the remote client (the truck simulator) and it connects to the server allowing both subjects to interact in the virtual scenario.

This study also makes use of the ZouTrans lab’s capacity for federated simulators. Federated simulators allow two subjects to enter a virtual scenario at the same time so that their interactions can be observed. An elemental framework of how federated simulators were used in this study is displayed in Figure 3 on the previous page. The host computer controls the server and the local client, meaning that it operates as the base for both the network and one subject. In this study, the local client is the car simulator while the truck simulator is controlled by the remote client. The remote client networks with the host and sends and receives data so that the actions of both the local and the remote clients can be displayed on both machines simultaneously.

Truck Hardware

The truck simulator in particular is based on the ZouSim passenger vehicle simulator. It makes use of a Volvo truck cab as shown in Figure 4. The truck simulator hardware uses a Logitech

Figure 4: The Zou Sim Truck Simulator (Clockwise from top right): View of simulator during testing. The ZouSim truck simulator with the Unity Editor projected on screen. The Logitech G920 steering and pedal inputs. View of simulator "under the hood."

G920, which provides the steering interface to the Volvo wheel and pedal inputs. For tactile feedback, a Buttkicker is attached beneath the driver's seat. The Buttkicker uses audio input to produce vibrations using a "low frequency transducer" to replicate vibrations experienced inside a vehicle due to the vehicle-road interactions and the powertrain (ButtKicker.com 2018). Finally, the virtual scenario is displayed using a Alienware computer running Windows 10 and outfitted with NVIDIA GeForce GTX 1080 graphics card and Intel® Core™ i7-8700 processor. The scenario is projected using a Optoma 1080P projector onto a 60"x102" screen that was built in-house.

The truck cab was built in place in the ZouSim Lab due to the large size and weight of the cab. The truck was deep cleaned, and any exposed components and wires removed. The most difficult aspect in building the vehicle simulator proved to be the same for the truck: the steering wheel mount. The original steering wheel and column were removed, and the steering wheel salvaged. To salvage the steering wheel the rivets that connected the steering wheel from the steering column had to be drilled out. The steering wheel mount is based off the custom wheel mount in the car simulator. In the car simulator, the Logitech G27 steering wheel has two internal clamps that affix the steering wheel to a custom-built base mounted to the vehicle cab. However when using the car simulator, there is still considerable amount of unintended movement within this design and the clamps can also become loose as well. To avoid this issue in the truck simulator, the internal clamps of the Logitech G920 controller were removed. A custom-built wood base was more stably affixed to the truck cab console and the holes were drilled into the G920 shell to securely mount the steering wheel. This solution has proved to be an improvement over the vehicle simulator and it is suggested that a similar process adapt the Logtitech G27 to solve these persistent instability issues. The custom base was built into place where the original steering wheel used to be.

The Logitech G920 steering wheel was also removed and replaced by the salvaged steering wheel. There were two obstacles to replacing the G920 stock wheel with salvaged steering wheel. First, the G920 has several button inputs that are interlaced with the stock steering wheel. Once these stock wheel was removed, these button inputs were placed back in their original position. However, without the stock steering wheel, they protruded ~1/2" above the G920 steering wheel base. The salvaged steering wheel was installed above these protruding buttons by using spacers and a custom-machined steel adapter. The adapter was machined with the help of Matthew Marciniak in the college's Engineering Technical Services. A conceptual view of the salvaged steering wheel and the G920 device is shown in figure 5 at right. Ultimately, for the purposes of this project, this was a useful solution to the issue of mounting of the steering wheel. For future projects, the spacers and screws used to affix the steering wheel could be stabilized by an epoxy or glue.

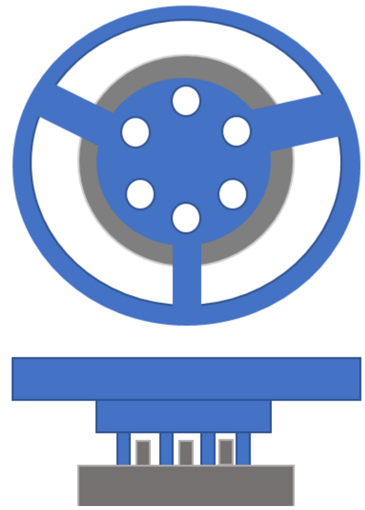


Figure 5:Salvaged steering wheel (in blue) and adapter attached to the Logitech G920 (in grey).

Truck Calibration

The truck required quite a bit of calibration to achieve the level of validity necessary for this scenario. This calibration occurred in three phases: first, the physical aspects of the truck and the hardware were installed to replicate the look and feel of a semi-truck. Second, the research team carried out a truck comparison validation in which the truck was calibrated in the virtual world to match the performance and visual fidelity. Finally, the scenario and experiment were calibrated to achieve the desired experimental conditions. The third phase will be addressed in the experimental design section. The physical and truck comparison calibration was assisted by Matt Marciniak, a University of Missouri Engineering Technical Services professional who has a CDL license and 21 years of experience with freight trucks. Additionally, Mr. Marciniak has owned and operated a dump truck business and relied on his expertise as a mechanic to keep his truck in good working order.

The first changes that Mr. Marciniak suggested were physical in nature. The pedals were initially mounted on a board that placed them 18” from the seat base. Upon calibration from Mr. Marciniak, they were adjusted to 21”. Similarly, the driver’s seat was initially installed at a chair height of ~13” and then adjusted to a more natural 18”. One important note: when clearing the truck of debris, the researcher destructively removed the driver’s seat. The driver’s seat initially came with an air-ride suspension that could be raised or lowered to meet the needs of the driver. The suspension system was mistakenly removed due to perceived malfunction. However, Mr. Marciniak indicated that this was not necessary and that it may be worthwhile for future studies to pursue a replacement for this component.

A major concern in past simulator studies has been in the steering wheel input calibration. In this study, a solution to this issue has been found. This issue is that while driving in either the passenger vehicle simulator or the truck simulator, the virtual vehicle tends to drift within a lane. This drift results in the driver having to weave back in forth within the lane as one overcorrection leads to further overcorrection.

Ultimately, investigating this issue has revealed a hardware feature within the Logitech controller. The passenger vehicle simulator uses a G27 Logitech steering wheel and within the steering wheel software, there is a “deadzone” setting as shown in Figure 6. This deadzone is an envelope of approximately 5° on either side of center in which the steering wheel will not register any input. The reason the deadzone exists is that in gaming applications, when a controller may lose its ability to reliably return to center; the deadzone is a margin for the controller to achieve center. For the purposes of the simulator studies this is a serious issue in validity that needed to be corrected. The solution is to simply set the deadzone to 0°.

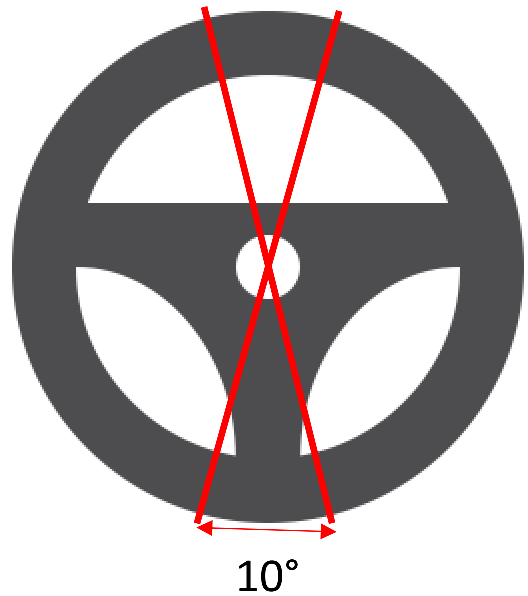


Figure 6: Illustration of a steering wheel deadzone

Unfortunately, this solution was available for the passenger vehicle simulator but not for the truck simulator. The G27 controller and related software, despite its age, has more control over the settings that govern the input whereas the newer G920 and updated software does not seem to allow for deadzone manipulation. However, considering that for this study, a member of the research will be driving the truck simulator, this issue is not critical to the fidelity of the study. For a future study in which participants drive the truck, the deadzone will need to be eliminated within the G920 controller.

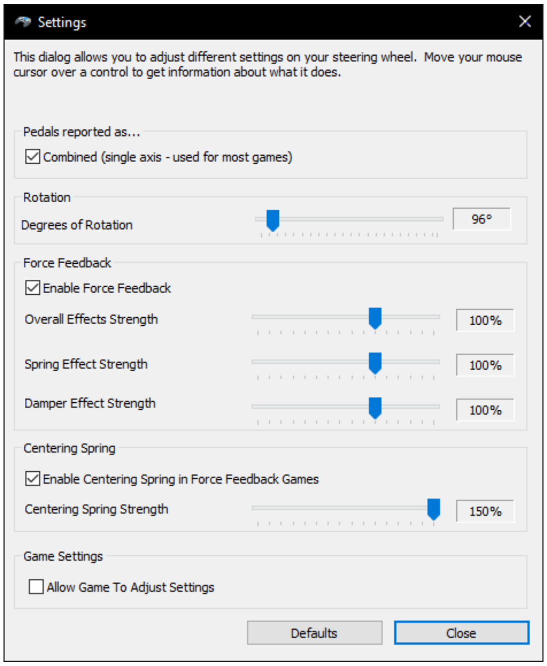


Figure 7: (left) G27 Logitech Profiler settings, (below) the G920 settings. In addition to the degree of rotation/wheel operating range, another important setting is the centering spring strength. By increasing this value, the vehicle tends to feel like it has more weigh. This is an excellent example of an aesthetic variable that is difficult to measure but greatly adds to the experience of the participant.

Another issue with regard to steering involves the settings of the Logitech profiler. The physical input from the steering wheel is controlled by a few variables within the logitech controller itself and are very important to the performance of the truck. The final settings are shown in figure 7 above. There is not much that is controlled primarily within the Logitech profiler, but these items can be critical to the fidelity of the simulator. Of particular importance is the "Degrees of Rotation" or Wheel Operating range. These are the values that control the how the steering wheel inputs the turning information and is critical to the under/oversteering that participants experience.

Whereas the Logitech controller profile only handles a few of the raw inputs, the information in Unity can be drastically changed. The Logitech raw input is fed into a virtual truck system that is modeled on the mechanics of a generic truck. The initial truck specifications are shown in Figure 8 with the problem areas highlighted. The changes made were all carried out to achieve a level of realism as described by Mr. Marciniak. The gears initially shifted too quickly. Therefore, the gear shifting threshold a was increased from 80% to 95%, meaning the truck would remain in the lower gear longer before shifting to the higher gear. An extra gear was also added. However, the most important changes occurred in the virtual truck's power and torque. According to Mr. Marciniak, the acceleration and progression through each of the gears occurred too quickly. The maximum engine torque, brake torque and highest engine rpm were all adjusted iteratively until a feasible acceleration occurred. "Feasible" because this truck is intended to be a representation of a truck and therefore matching this experience exactly to a specific truck would be unnecessary. The top speed was also capped at 120 from 220 km/hr or approximately 75 mph though this was primarily for experimental design purposes. Once these modifications to the truck specifications were made, Mr. Marciniak deemed that the truck had achieved verisimilitude.

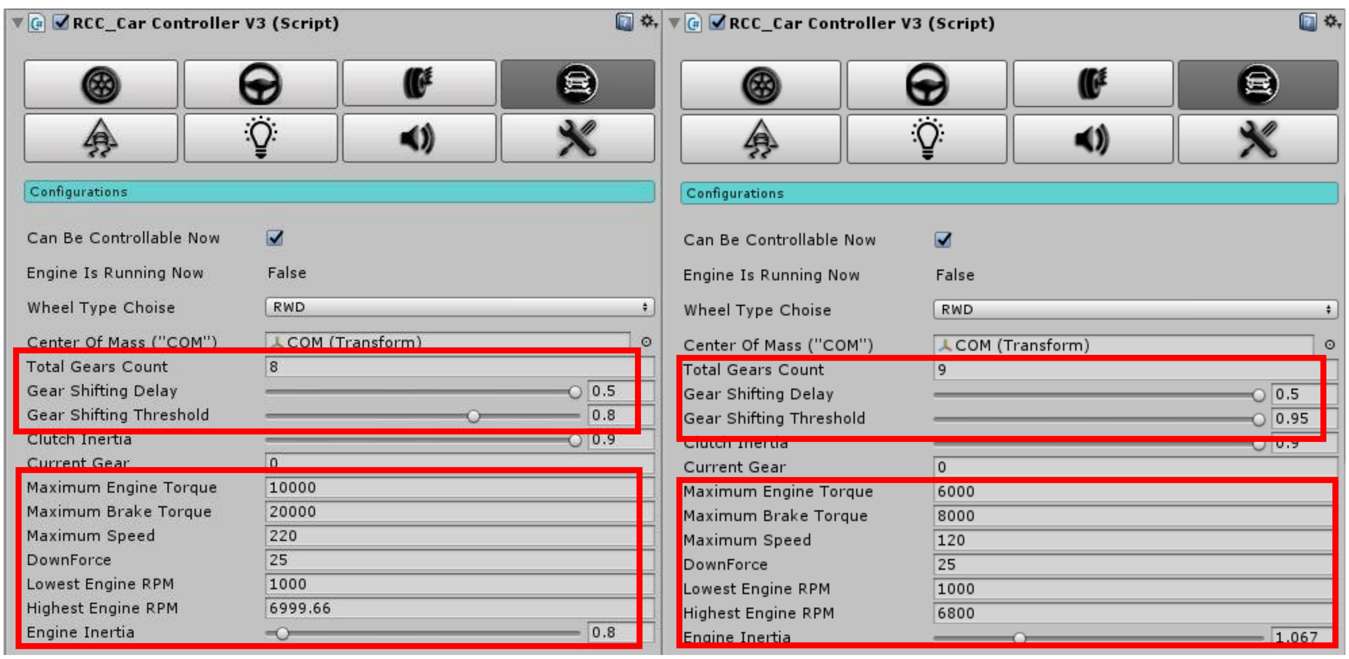


Figure 8: Initial (left) and Final (right) truck specifications. Changes Highlighted.

Scenario Design

With the hardware and software specifications for the truck and vehicle simulators set, the final stage of calibration occurred within the scenario itself. However, before the modifications can be addressed, the conceptual framework for the scenario must be explained. The scene involves two trucks, referred to as lead truck and follow truck, and one passenger vehicle, referred to as the simulator car. Both the follow truck and the simulator car are driven by humans, while the lead truck behavior is coded and takes cues from each of the two human drivers. The scenario is set up to have three phases depicted in Figure 9 on the following page. First each of the human driven vehicles must naturally reach a scenario initiation point. Then, with each of the vehicles in the correct position, a platoon is initiated. The simulator car's reaction to the displays and subsequent behavior is recorded. Finally, the scene ends, and the next scenario begins. The displays themselves will be discussed in more detail in the following section, Display Designs.

The scenario has three phases each participant experiences within a simulation run. Figure 9 provides an overview of the scheme of each scenario. In phase A, the simulator car reaches highway speeds and achieves a headway gap of 328 ft (100 m) to the lead truck. Phase A begins with all vehicles in their start positions; simulator car in the rest area and the trucks in position on the highway. Once the simulator is given the go-ahead, the simulator car progresses down the freeway entrance and the lead truck moves forward at 60% of the simulator car speed. Once the simulator car reaches the specified lead gap of 328 ft (100m), the lead truck increases its speed to match the simulator car to preserve the lead gap. The lead truck must maintain a constant initial lead gap across all the trials to ensure that each participant views the display at the same distance to start the interaction. The change in the lead truck speed signifies that the simulator car is in position to begin the TP initiation and the scenario enters phase B.

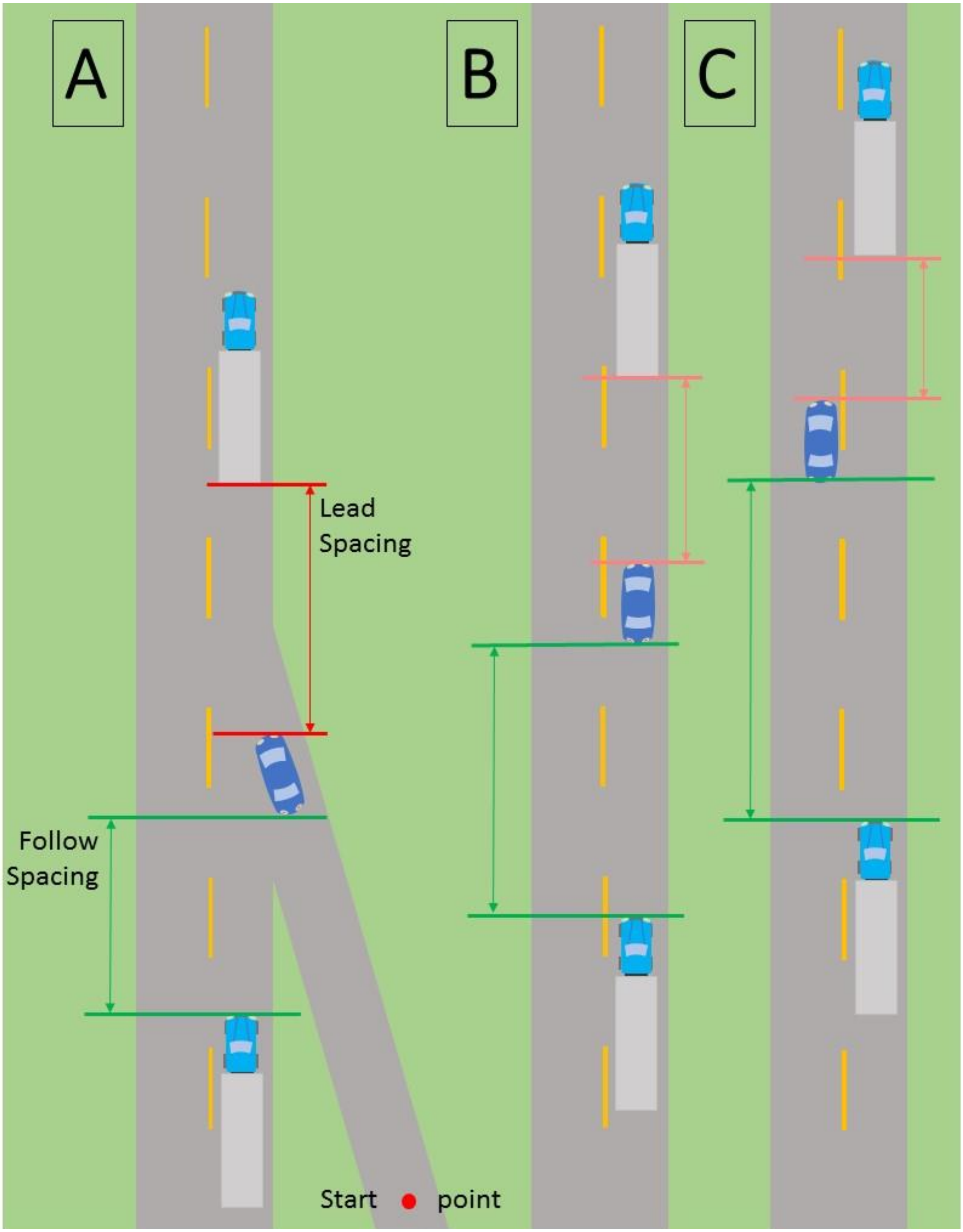


Figure 9: Phases of the experimental scenario. Phase A: scenario setup, lead truck proceeds down the roadway at 60% speed of the simulator vehicle until simulator car is in position. Then, lead spacing held constant until follow truck is in position. Phase B: Truck platoon initiates, lead and follow spacing are recorded but no longer influence the lead truck. Phase C: scene end, simulator car either merges left or the scenario times out after two minutes.

Phase B requires that the follow truck move into position to initiate the TP process. While the lead truck and simulator car hold steady at the simulator car's desired speed (e.g.: speed limit is 60 mph), the follow truck approaches from behind. Once the follow truck reaches a follow distance of 328 ft (100 m), the displays on the trucks all turn on and the data begins to record. 328 ft feet was selected because it allows the displays to turn on at a viewable distance. Since TPs are initiated at the behest of the drivers in the lead and follow trucks and the range of DSRC is approximately 1000 ft (300 m), any distance within this range could have been used. The lead gap separating the lead truck and the simulator car is broken; the speed of the lead truck progressively drops down to 55 mph. A speed of 55 mph is a common TP platooning speed as discussed in the Literature Review section. Furthermore at this speed, the follow truck is able to move into its final TP position without exceeding the speed limit (60mph). With the lead truck travelling a constant 55 mph and the follow truck maintaining the 328 ft gap behind the simulator car, the simulator car is free to react to the displays.

The ending of the scenario is phase C shown in Figure 9. The possible interactions that could occur are (1) the simulator car closes the gap with the lead truck and merges left to pass or (2) the simulator car adjusts their speed to match the lead truck and remain behind the lead truck. If the exhibited behavior of the simulator car is to remain behind the lead truck, then the scenario times out after 120 seconds and the scenario is reset. If the simulator car chooses to pass the lead truck, then the scenario ends when it has successfully passed. The gap between the following truck and the simulator car was preserved so as to not cause the driver to initate a lane change because of a closing truck but due to the external displays.

Figure 10:Calibrating the sight distance in Unity. Top: the AFAD device at a known distance of 250 ft. Bottom: The Virtual AFAD at the same distance.

In setting up this scenario, there were a few adjustments that were needed to ensure that participants provided some valid results. The lead gap that represents the end of phase A and changes the lead truck speed to match the simulator car was perhaps the most critical. Initially, this gap was set 196 ft (60 M). However, when vehicles reached this lead gap, the truck seemed to be going far slower than the vehicle and in-house alpha testers wanted to pass to avoid a collision. The lead gap was increased to 328 ft (100M) and at this distance, the testers reported that they did not feel the need to pass due to the lead gap. The lead gap could have been set to a much larger gap but that would require the simulator scenario to last much longer as the simulator car traverses that distance. Furthermore, researchers were interested in observing the immediate reaction to the displays turning on and therefore it was important that the simulator cars were within sight distance of the displays.

The within sight distance calibration followed the work of a previous ZouSim study of Automated Flaggers (AFADs). As seen in the figure 10 above, the real AFAD was recorded at a known distance. In Unity, the camera field of view was adjusted so that the virtual AFAD matched the height of the physical AFAD. This study used the same base settings as the AFAD study and was visually checked to see that trucks were viewed in the simulator as they would be in real life.

Display Designs

Three display designs were tested as a part of this study. The displays as shown in figure 11 and include a control, a text design and a graphical design. There is no current signage available yet developed within the Manual of Uniform Traffic Control Devices (MUTCD) and so these designs were created based on other similar signs. A fourth option that included a combination of text and graphic was initially considered but it was determined that for simplicity of message, only text and graphic options would be tested. Graphic and text are the two common methods for communication on road signs which was why these two options were considered.

The designs tested were created specifically for this study and therefore many factors had to be considered. Design decisions on the color, size, visibility placement, and content were all based on current MUTCD regulations, though some standards such as size were exceeded. The first factor investigated was color. Since these displays are in effect specialized indicators, it was not a trivial decision to determine what category of color the sign. Sign Color is regulated by Section 2A.11 (FHWA 2009). The colors coral, purple and light blue are currently unassigned and are intended to be used for future purposes, so they could have been used. However, using these unassigned colors would possibly confound the results due to the novelty of using an unaccustomed color and were therefore eliminated from consideration. Since many of the reference signs used as a model come from the MUTCD section on temporary traffic control (TTC) in work zones, orange was another option considered. However, these displays are not TTC and orange was subsequently eliminated. Red, green and brown were considered to be inappropriate for this application, leaving white and yellow as possible options. Yellow was chosen over white because its common use as a warning. MUTCD yellow is displayed by Pantone 116c.

Figure 11: Examples of the Display Designs (from left): the control display, the text display, the graphic display.

The size, visibility and placement of the displays required several iterations of adjustments after making some initial assumptions based on the MUTCD regulations. The issue was to ensure that the sign was easily visible at an early enough distance to allow for natural

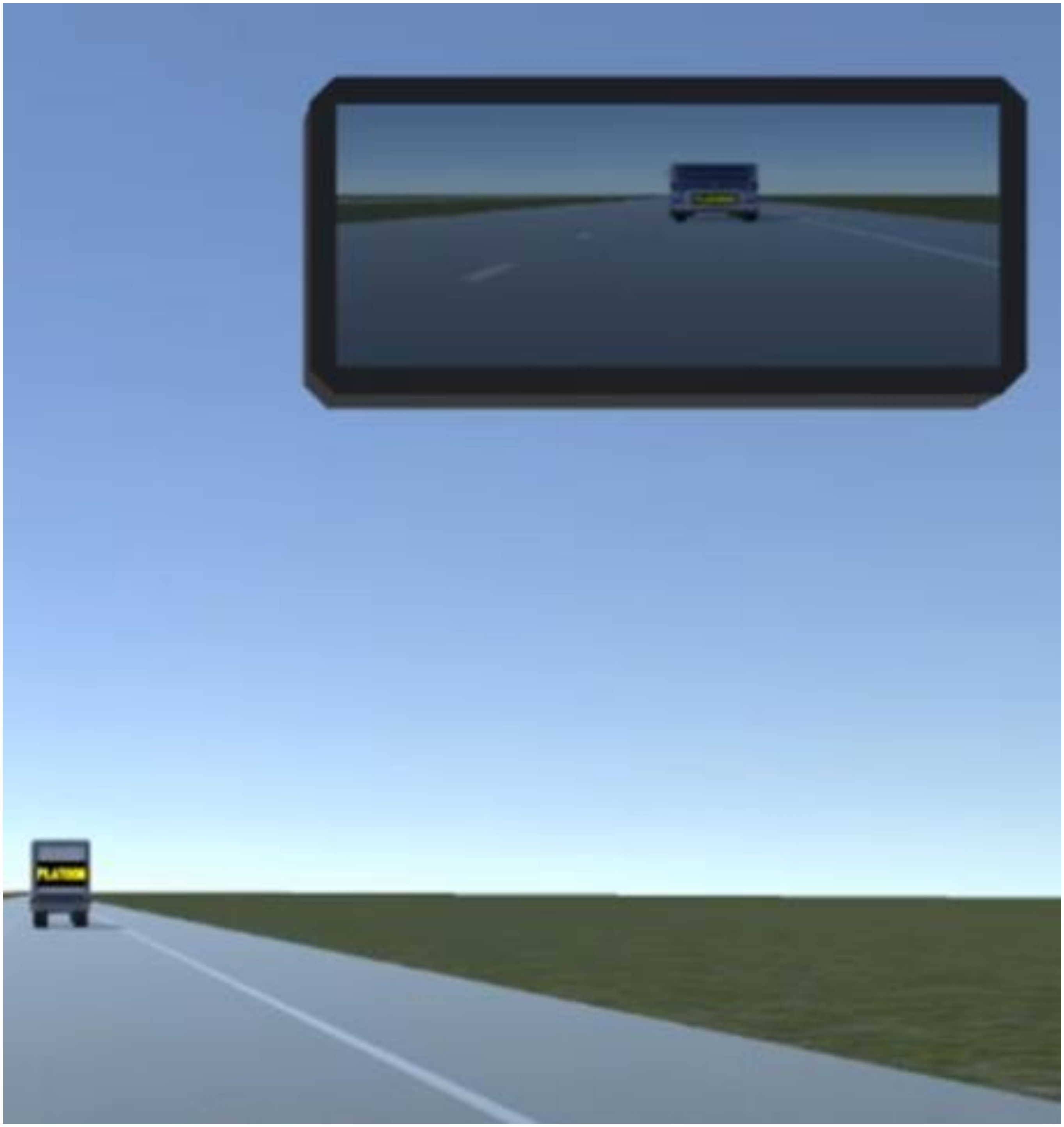


Figure 12: View from the Simulator scenario of the lead and follow truck. (Taken from participant trial.)

lane-change behavior. The placement of the sign was the relatively simplest aspect to select. The displays would be placed on the rear and front of the truck in order identify both the lead and follow vehicle on the roadway. Figure 12 provides an example of how this would look in the scenario.

Furthermore, the actual placement of the sign followed Section 6F.54: Pilot Car Follow Me Sign. This regulation provided an example of a message communicated to a follow vehicle that was mounted on a lead vehicle and states that the sign "shall be mounted in a conspicuous position on the rear of the vehicle" (FHWA 2009).

However, the most challenging aspect of the display creation was in designing for the visibility and size. These two aspects are linked in that visibility determines the size of the sign. MUTCD is filled with size and visibility specifications based on the sight distance and time needed to perceive and understand a sign. Initial regulations (Section 2C.04, 2C.40, 2H-05, Table 6F-1) led the researchers to believe that 36"x18" sign would suffice for the purposes of this study. However, upon alpha testing, it was clear that the sign was too small and for clarity, the sign was enlarged to 40"x20" for the front sign and 72"x36" for the rear sign. These signs are much larger than perhaps is needed but determining a good size based on sight distance, perception and cost is outside the scope of this study. The influence of a clear message is the purpose of these signs and therefore if a sign is too small, this would negatively influence the results. A subsequent study could be investigated into determining a fair size for these displays.

The control design of no sign was also tested both as a baseline and also on its own merits. MUTCD regulation 2A.04 on the excessive use of signs provides an important reminder that too many signs on the roadway lose their effectiveness. Therefore, if a sign doesn't promote "reasonably safe and efficient operations" then the overall message of traffic signs is diluted.

Figure 14: The graphical design

Figure 13: The text design

The graphical design (figure 14) was based on two principles. First that the image should show two trucks in sequence and second that the two trucks are somehow "linked." The message was meant to be almost sentential in that simply saying "truck link truck," is nearly a complete sentence in itself. The image was created by using the truck symbol RG-190 of Chapter 2H Recreational and Cultural Interest Area Signs (FHWA 2009) and a new symbol created specifically for this study. The primary difficulty in creating this design was that the width and height of the graphic did not match the width and height of the display and therefore could not be scaled to completely fill the display space.

The text design (figure 15) was more complicated than the graphical design in that the word “Platoon” in regard to TP is still a relatively unfamiliar term (hence the inclusion of education into the experimental design). However, alternative words or phrases were either deemed too long or inexact with regard to the concept of TP.

Procedure

The procedure for each participant is laid out in the Hosting Manual (Appendix B). Once a participant arrives, they are introduced to the research team and asked to sign an informed consent form concerning the risks of simulator sickness. The informed consent form is approved by the MU Institutional Review Board (IRB) and required due to the use of human research subjects. The participant then completes a brief warm-up to become familiar with the simulator and its controls, similar to how someone must adjust to the differences in a rental car. During the warm-up section, the participant is asked to accelerate, decelerate and perform a lane change until they feel comfortable navigating the virtual vehicle.

With the subject familiar with the simulator vehicle, the scenario testing can begin. The testing scenarios begin with exposing the participant to each of the three display options with no introduction. The testing is then paused, and the participant is provided with information regarding truck platoons. After the explanation, the participant is again exposed to the three displays. The combinations for each of the simulation runs are shown in Table 4. The displays for the scenario were randomly designated and initiated before any vehicle begins.

Table 4: Combination of Experimental Treatments

TP Display Design and Education Experimental Runs		
Run	**Display**	**Education**
1	Control	Pre-Education
2	Graphic	Pre-Education
3	Text	Pre-Education
4	Control	Post-Education
5	Graphic	Post-Education
6	Text	Post-Education

The sequence of the runs was randomized in order to prevent sequence or order bias from effecting the results (Perrault 1975). The Pre- and Post-Education sequences were randomized separately, resulting in 12 possible sequences.

While the participants are driving in the simulator car, the trials are fully recorded, including driver views and vehicular data. The data from each participant is shown in the upper left-hand corner of their screen, out of peripheral vision of the participant when the participant is looking down the road, in order to correlate vehicular data with the video driver views. The vehicular data is gathered and processed to evaluate each of the measures of effectiveness (MoEs) and is explained in more detail in the Measures of Effectiveness section. Each participant's recording is reviewed to collect the relevant data at each of the important events for the scenario. The data was then reduced and analyzed using a student's T-test statistical analysis. At the conclusion of the testing scenarios, the post-simulator survey is administered and more information on the collection and processing of the survey data can be found in the Post-Simulator Survey section.

Within the scenario there were two additions to the sequence of events from the experimental design. The first was that when vehicles merge onto the freeway, some participants immediately merged left to pass the lead truck. Of course, they had no way of knowing that the lead truck would match their speed exactly and that therefore the lead truck was impossible to pass. In order to have the participants in the correct position to start the TP initiation, the participant was simply reminded to stay in the right lane. While these actions were carried out, the follow truck driver remained at a distance to avoid accidentally initiating the platoon. Furthermore, once the simulator vehicle merged left, the follow truck increased its speed to finish the TP initiation. The follow truck never passed the simulator car even though it was in the left lane.

Finally, each scenario was treated as its own separate instance, meaning that the scenario was reset to the starting location after each trial. The separating of each trial is opposed to having the simulator car drive continuously while TP form around them throughout a run. The reason for progressing through each scenario this way was to create the exact same conditions for each starting location and for its simplicity in experimental design. While it may have provided an additional modicum of fidelity to have each simulator vehicle progress through each scenario continuously, doing so would require that both trucks abruptly appear on the roadway and is needlessly complicated. The tradeoff in fidelity was deemed not great enough to continuously present each scenario.

Participants

This study uses human trials to gather data on the behavior exhibited in the simulator. In order to conduct human subject research, the research plan is submitted and approved by the

IRB. Though simulator research is inherently less hazardous than field trials on the same subject matter, there is still the possibility that some participants may experience simulator sickness. Therefore, this risk must be disclosed before the trial and informed consent of these risks must be obtained in writing. The risks of simulator sickness can be mitigated by fine tuning the scenario and its feedback to subjects to minimize the disconnect between the perception of movement and the absence of some physical cues. In addition to the informed consent, regular check-ins with the participant throughout testing also help minimize the effects of simulator sickness.

Thirty individuals were selected to take drive the passenger vehicle in the simulator study. Since TPs will platoon on interstates traversed by a wide variety of individuals, the participants were intended to be representative of the population that travels on freeways in age and gender. Table 5 below provides information on the demographics of the sample population.

Table 5: Participant Demographics

Demographic information							
Gender		**Age**				**Urban vs. rural**	
Male	Female	16-25	26-40	41-55	56-70	Urban	Rural
50%	50%	33%	47%	0%	20%	70%	30%

All 30 participants signed the informed consent form, and none were unable to finish the scenarios due to simulator sickness. These 30 individuals were recruited via flyers to the public and informally through personal invitations. As stated in the Procedure, the protocol for each trial consisted of introductions, informed consent, a warm-up, the testing scenarios and the post-simulator survey. At the conclusion of each trial, each participant received compensation for assisting in carrying out the research.

Measures of Effectiveness

The study examined four MoEs for the six experimental treatments in addition to collecting data on the behavior taken by the participants. Three of the MoEs were taken directly from the vehicle data while the fourth is a derived from vehicle data. Only two options can be taken by the subjects, lane change or no lane change. Since no lane change results in a timeout after 2 minutes, the simple collection of this behavior choice was undertaken and only the first MoE were examined. All four MoEs were investigated for the lane change event. All the MoEs are captured during phase B of the scenario design, after the TP has begun to initiate and the displays turn on. The data for each event described was captured in the recording of each participant's trial.

- MoE 1: Time to First reaction

The time to first reaction is simply the first observable reaction time in seconds after displays turn on. There were three behaviors that were observable: the use of the blinker, a lane change or a slow-down of greater than 5 mph. This event helps explain when drivers felt they needed to take action in response to the displays turning on. This measure is primarily an efficiency measure on the effectiveness of the display in indicating an action.

- MoE2: Lead Gap at Lane Change

The Lead gap at lane change was collected by determining the point at which a lane change occurs and then recording the distance in feet between the lead truck and simulator car. This measure captures the gap distance at which the subject made the lane change and is also used to determine the time to collision (TTC) MoE. This measure is both an efficiency measure in that it shows the effectiveness of the display in clearing the lane behind the lead truck thereby allowing the TP initiation.

- MoE3: Time to Lane Change

The time to lane change is the time in seconds it takes for a vehicle to clear the lane behind the lead truck thereby allowing the TP initiation to complete. It is primarily an efficiency measure for this reason.

- MoE4: Time to Collision at lane change

The TTC is a derived measure that shows the time it would take for two vehicles to collide if they're current trajectories remain unchanged. The TTC is computed by equation 1.

$$TTC = \frac{Lead\ Gap}{Vsim - Vlead}$$

This equation takes the lead gap at lane change and divides it by the difference in speeds between the simulator car and the lead truck. The lead truck is always traveling at 55 mph, so the only new variable needed is the speed at lane change for the simulator car. This is primarily a safety/comfort measure in that it shows the how the simulator car interacts with the slower moving lead truck.

Post-Simulator Survey

The post-simulator survey collects preferential and complementary data to the simulator study. It is used to capture participants attitudes and insights regarding their behaviors, preferences, their simulator experience and demographic information.

The simulator survey was formulated similarly to Zhu Qing's "Evaluation of Autonomous Vehicle-Pedestrian Interactions" study. Qing's study looked at a variety of different signs to examine the interaction between AV and pedestrians at crosswalks. The primary questions used in the survey (Appendix A: Simulator Survey) were based on similar questions in Qing's survey. These questions attempted to gather information on the stated preference, clarity, visibility, safety and comprehension of the displays. These five categories are the primary criteria for evaluating the efficacy of a sign. Also provided is a space for comments on each of the displays to provide researchers with background on their reasons for their preferences. It also investigated the comfort, familiarity and ideas on the type of information they would want in TP initiation event. Furthermore, the survey also included a section on demographic information, simulator evaluation and simulator sickness (SSQ) that is included in every ZouSim simulator study. The SSQ was formulated to diagnose simulator sickness (Kennedy et al. 1993) in participants and is used in all ZouSim studies These questions are primarily for the betterment of the simulators and are not related to the study at-hand.

IV. Results

Performance Analysis

Overall, the results show a clear behavior preference for changing lanes in the presence of a TP initiation. Of all 180 simulation runs, only 13 ended in a timeout end-state. Of the 167 other scenarios, 164 provided useable results for the lane change MoEs. The other 3 simulation runs resulted in either a mistrial (1 run) or an unfortunate glitch in the recording program (2 runs) rendering the results unusable. Table 6 provides a table of this breakdown. From this data, it is clear that while lane change was the preferred end state, no lane change end state did occur.

Table 6: End State behaviors

End State		
Lane Change	164 runs	91%
No Lane Change	13 runs	7.2%
Unusable Data	3 runs	1.7%
Total	180 runs	100%

In evaluating each of the MoEs, a student's T-test was used to compare the means of each of the categories. The desired level of confidence was 95% which is highlighted in green in each of the following tables. The confidence level of 90% is highlighted in yellow because these results are close to the desired level of confidence.

- MoE 1: Time to First reaction:

The results for MoE1 are contained in the data tables under Table 7. Starting from the left, the table of means and differentials shows that in general, the displays had lower means compared to the control display, i.e. several differentials are negative. However, the tables to

Table 7: MoE1: Time to first Reaction in seconds

the right all provide perspective on how significant those differentials are. Only the comparison between the control and the text display after TP information is provided is significant on a scenario comparison basis. In that scenario, participants first reaction was 2.37 seconds earlier. The significance is highlighted in green (0.0351). Furthermore, while no single display had a

MoE1: Time to First Reaction (seconds), mean, difference, and student's T-test p-values

Treatment	Mean	diff
Pre-Ed	22.70	base
Post-Ed	19.18	-3.52
Control	22.83	base
Text	19.49	-3.34
Graphic	20.17	-2.66
Pre-Con	26.07	base
Pre-txt	21.79	-4.28
Pre-grph	20.21	-5.86
Post-con	19.81	base
post txt	17.43	-2.37
post grph	20.13	0.32

Pre-Education p-Values

	PRE TXT	PRE Grph
PRE Contr	0.414074	0.266908
PRE TXT	na	0.735534
PRE Grph		na

Post Education p-Values

	ED txt	Ed grph
ED Cont	0.035122	0.89817
ED txt	na	0.357005
Ed grph		na

Treament p-Values

	Txt	Graphic
Cont	0.197601	0.346829
Text	na	0.762626
Graphic		na

Education p-Values

	Pre v. Ed
Con	0.064804
Tex	0.185023
Graph	0.305506
All	0.011795

	Pre	Post
disp vs. Cont	0.288129	0.751455

significant different in means before and after receiving information on TPs, taken as a whole, the information resulted in a 3.52 second decrease in reaction time. The significance of this reduction in time is also highlighted in green (0.0118).

- MoE2: Lead Gap at Lane Change

The results of the Lead Gap at lane change produced the most significant changes in behavior. Table 8 shows the collected results from MoE2. The text display and graphic display after receiving information on TP increased their lead gap by 27.93 ft and 26.70 ft respectively vs. the control with information. In this MoE, the combination of either display and information regarding TP resulted in an increase in the lead gap.

Table 8: Lead Gap at Lane Change

- MoE3: Time to Lane Change

The results for the MoE3 mirror that of MoE1 and can be seen in table 9. This MoE is the most important for allowing the TP to form in that when the simulator car actually changes lanes,

MoE2: Lead Gap at Lane Change (feet), mean, difference, and student's T-test p-values

Treatmen	Mean	difference
Pre-Ed	117.42	base
Post-Ed	129.14	11.72
Control	108.83	base
Text	128.35	19.53
Graphic	128.75	19.93
Pre-Con	109.58	base
Pre-txt	115.89	6.32
Pre-grph	118.08	8.50

Pre-Education p-Values

	PRE TXT	PRE Grph
PRE Contr	0.291243	0.136284
PRE TXT	na	0.70682
PRE Grph		na

Post Education p-Values

	ED txt	Ed grph
ED Cont	0.016103	0.006887
ED txt	na	0.806074
Ed grph		na

Treament p-Values

	Txt	Graphic
Cont	0.010892	0.002537

Education p-Values

	Pre v. Ed
Con	0.953148

MoE3: Time to Lane Change (seconds), mean, difference, and student's T-test p-values

Treatmen	Mean	difference
Pre-Ed	30.00	base
Post-Ed	22.65	-7.35
Control	27.29	base
Text	[illegible]	[illegible]
Graphic	27.60	0.31
Pre-Con	30.77	base
Pre-txt	27.72	-3.05
Pre-grph	31.44	0.67
Post-con	24.06	base
post txt	19.73	-4.33
post grph	23.90	-0.16

Pre-Education p-Values

	PRE TXT	PRE Grph
PRE Contr	0.474518	0.895151
PRE TXT	na	0.159508
PRE Grph		na

Post Education p-Values

	ED txt	Ed grph
ED Cont	0.015162	0.655264
ED txt	na	0.282623
Ed grph		na

Treament p-Values

	Txt	Graphic
Cont	0.169757	0.745678
Text	na	0.072955
Graphic		na

Education p-Values

	Pre v. Ed
Con	0.05243
Tex	0.091413
Graph	0.019559
All	5.61E-05

	Pre	Post
disp vs. Cont	0.816521	0.477341

Table 9: Time to Lane Change

then the TP can form. The range of means was approximately 20-30 seconds. Like MoE1, the time to lane change decreased 4.33 seconds for the text display with information vs. the control with information. However, for all displays once information about TP was received, participants merged and average of 7.33 seconds sooner. Also of note: this MoE contained the only instance of a performance difference between test and graphic displays at a 90% confidence level. This is perhaps because the mean graphic display time to lane change was in fact slightly larger than the control (the difference in mean between graphic and control was 0.67 and -0.16 for pre and post information respectively), resulting in a difference of means of 3.95 seconds.

- MoE4: Time to Collision

Lastly, the TTC means show that only after the information was received was there a difference in means between the text display and the control. The presence of the text display and information resulted in an increase of 1.78 seconds vs. the control display. In general, the results from this MoE are insignificant as can be seen in table 10.

Table 10: Time to Collision at Lane Change

MoE4: Time to Collision (feet), mean, difference, and student's T-test p-values

Treatmen	Mean	difference
Pre-Ed	12.13	base
Post-Ed	12.97	0.84
Control	11.34	base
Text	11.30	-0.04
Graphic	13.92	2.58
Pre-Con	13.11	base
Pre-txt	11.26	-1.86
Pre-grph	12.02	-1.09
Post-con	9.57	base
post txt	11.34	1.78
post grph	15.83	6.26

Pre-Education p-Values

	PRE TXT	PRE Grph
PRE Contr	0.511741	0.680689
PRE TXT	na	0.596908
PRE Grph		na

Post Education p-Values

	ED txt	Ed grph
ED Cont	0.035578	0.090389
ED txt	na	0.221932
Ed grph		na

Treament p-Values

	Txt	Graphic
Cont	0.978481	0.256119
Text	na	0.179562
Graphic		na

Education p-Values

	Pre v. Ed
Con	0.256055
Tex	0.958712
Graph	0.275421
All	0.944448

	Pre	Post
disp vs. Cont	0.571514	0.15005

Survey Results

The attitudes and stated preferences of the participants were collected in the post simulator survey. The 12-question survey asked participants to rate their level of familiarity, evaluate the display designs, assess their comfort and the utility of the displays and provide feedback on their chosen behaviors. Complete tables of responses are found in Appendix C.

Table 11: Participant attitudes to TP

Familiarity, Comfort and Utility		
Familiarity	**Comfort**	**Utility**

2.03	3.97	3.90

Table 11 shows how participants rated their attitudes towards TP in this study. The scale for each question was from 1-5 where 1 was least familiar, comfortable or found the displays the least useful while 5 was the most familiar, comfortable or found the displays the most useful. From this table it would seem that participants were not generally very familiar with TP but ultimately felt comfortable and found the display to be useful.

In evaluating the displays, participants were asked to provide a ranking from 1-3 in terms of their preference. Based on this feedback, a Friedman rank test was used to evaluate the responses. As shown in Table 12, for both the front and rear displays, the text results were preferred over graphic with the control display consistently behind both. The non-parametric test demonstrates that these results were statistically significant at a high level of confidence.

Table 12: Display Design Ranks

Front of Truck, Chi-Square=34.85, DF=2, P=0.000			
	N	Est. Median	Sum of Ranks
Control	26	3	75.0
Text	26	1	33.0
Graphic	26	2	48.0

Rear of Truck, Chi-Square=35.15, DF=2, P=0.000			
	N	Est. Median	Sum of Ranks
Control	26	3	76
Text	26	1	35
Graphic	26	2	45

After ranking the display based on their preferences, the participants were asked to evaluate the displays on a variety of criteria to help understand the tradeoffs between each option. The scale used was from 1-10, with 1 meaning the least clear, visible, safe or

Table 13: Evaluation of the display designs for clarity, visibility, safety and comprehension

Clarity						
	Mean	Median	Diff	*p*-Value	Diff	*p*-Value
Control	2.82	1	Baseline		N/A	

Text	8.25	8	5.43	0.000	Baseline	
Graphic	7.29	8	4.46	0.000	-0.96	0.105
Visibility						
	Mean	Median	Diff	*p*-Value	Diff	*p*-Value
Control	3.14	1	Baseline		N/A	
Text	8.00	8	4.86	0.000	Baseline	
Graphic	7.36	8	4.21	0.000	-0.64	0.345
Safety						
	Mean	Median	Diff	*p*-Value	Diff	*p*-Value
Control	3.04	1	Baseline		N/A	
Text	7.86	8	4.82	0.000	baseline	
Graphic	7.43	7.5	4.39	0.000	-0.43	0.378
Comprehension						
	Mean	Median	Diff	*p*-Value	Diff	*p*-Value
Control	2.21	1	Baseline		N/A	
Text	7.61	8	5.39	0.000	Baseline	
Graphic	7.14	7	4.93	0.000	-0.46	0.446

comprehensible and 10 the most clear, visible, safe or comprehensible. Table 13 shows the results of this evaluation using a Mann-Whitney test with a 95% confidence level. Using the control display as a baseline, both the test and graphic display demonstrated a clear improvement over no display at all. In each case, the control display mean was under 4 with a median of 1 point. This data is somewhat expected in that a platooning truck without any display at all is indistinguishable from a conventional truck. The comments also indicate that the control truck simply offered no information and therefore wasn't helpful in communicating any information. It is interesting to note however, that safety was rated so low, considering there is no difference between the control truck and a conventional one.

Between the text and the graphic displays, there were no significant differences observed in their scores. Though the text display did have a higher mean in each of the categories, this was not a significant difference compared to the graphic.

V. Conclusion

Overall, the results of this study demonstrate some significant results, but the magnitude of the changes is relatively small. The most consistent result was that the text display resulted in modest changes in behavior vs a control display and that information about TP led to similarly modest changes as well. In terms of clearing the lane of the obstacle of a passenger vehicle for a truck platoon, the text display is effective, but not enough to dramatically change the initiation of a TP. In other words, displays do not appear to have a strong performance benefit for dealing with the obstacle of passenger vehicles. A result that would have been strong would have been immediate reactions to the displays and vacating the lane to allow the TP to form. However, in both MoE1 and 3, the time to reaction and lane change was never less than 17 and 19 seconds respectively (for text display with information). Considering that TPs will be linked for a timescale on the order of hours, a few seconds difference in the time to initiation is not major concern.

Another significant result would have been observing a large proportion of participants staying behind the lead truck as this would mean that passenger vehicles may pose a greater obstacle to platoon formation. However, only four participants exhibited this behavior and only 1 persisted after being informed about TP and how they operate. At the outset of this study, there was an interest in observing whether vehicles remain in the lane to take advantage of the drafting that a TP provides, but this concept was unfounded by the results.

However, from the survey and the performance results, the clear influence of information about TP is interesting. The level of comfort and utility of the displays despite participants relative unfamiliarity in encouraging for the implementation of TPs. Providing information to the participants did influence their behavior and the feedback from the survey demonstrates that this information was well received. Most of the comments back up this conclusion.

Lessons Learned

As the ZouSim lab continues to expand and take on new projects, there are several important lessons that should be incorporated into subsequent studies. First, it was clear from the data that in a few cases, though participants indicated that they were ready to begin the testing phase, a longer warm-up would have been useful. In four different participant trials, the subject did not achieve a speed of 55 mph before the TP initiation phase when they began the trial and merged onto the freeway section of the scenario. This is in part an oversight by the researchers in that the follow truck vehicle operator should have slowed to allow the subject to reach 55 mph. However, considering it primarily happened in the either the first or second scenarios but not later sections, it would seem that the subject simply needed more time to get used to merging in the warm-up session.

The survey comments also reveal a few improvements that can be made to the steering wheel. Whereas in past studies, the simulator experience comments detailed oversteering, the steering wheel now seems to understeer. Improving the simulator settings will help address this issue but it will take more calibration than was achievable for this project.

VI. Appendix A: Simulator Survey

Participant #: ___ Date ________________________

Communication Signals for Truck Platoons in Mixed Traffic: A Simulator Study

A platoon of vehicles refers to when vehicles follow each other in a caravan. Proper communication between **connected vehicle truck platoons** and **passenger vehicles** has an undetermined effect on safety and beneficial platooning.

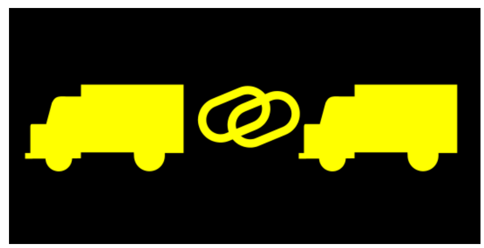
Please tell us your perspectives on interpreting these signals.

1. **What is your familiarity with closely-spaced connected truck platoons?**

Not familiar at all 1 2 3 4 5 Very Familiar

2. Briefly describe what each of these displays mean to you:

A



B

Option A:

Option B:

1a

1b

1c

3. When an approaching Truck attempting to platoon comes up behind you, please rank your preference from [1] being most preferred to [4] being least preferred.

[ ] Figure 1a [ ] Figure 1b [ ] Figure 1c

4. Please rate all designs from a scale of 1 (worst) to 10 (best) with respect to following:

			
Clarity			
Visibility			
Safety			
Comprehension			
Comments			

2A 2B 2C

5. **When the truck you are following is indicating that an approaching truck is attempting to platoon, please rank your preference from [1] being most preferred to [4] being least preferred.**

   [ ] Figure 2a [ ] Figure 2b [ ] Figure 2c

6. **Please rate all designs from a scale of 1 (worst) to 10 (best) with respect to following:**

			
Clarity			
Visibility			
Safety			
Comprehension			
Comments			

7. **When you were placed between a leading platoon truck and prospective platooning truck, was it clear what action you were supposed to take?**

   [ ] yes   [ ] no

   If you answered no, please explain why not.

8. What action do you think you were supposed to take?

   (a) change to passing lane to let trucks platoon

   (b) slow down let truck pass

   (c) just drive normally without reacting to the truck platoon

   (d) other, explain:

9. **Overall, how comfortable do feel in the presence of truck platoons?**

   Not comfortable at all   1   2   3   4   5   Totally comfortable

10. **Overall, how useful was the information was included in the displays [text or graphic]?**

    Not Useful   1   2   3   4   5   Very Useful

11. **How did your perception of closely spaced connected truck platoons change as a result of this study, if at all?**

12. **What information would you like to these communicated from the Truck Platoon during an interaction?**
    a.) **Status of Platoon (About to couple/decouple)**
    b.) **Number of trucks in the platoon**
    c.) **Whether it is okay to merge in between trucks in a closely-spaced connected platoon**
    d.) **Other (Explain):**

Please answer the following questions about your simulator experience.

13. I felt like I was actually there on the roadway.

[ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree

14. I felt like I could travel the scenario freely.

[ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree

15. Did any issues arise during the use of the vehicle simulator?

[ ] Yes [ ] No

If yes, please explain the issue(s) that you experienced: ____
____
____

Please answer the demographic questions below.

16. Age range

[ ] 16-25 [ ] 26-40 [ ] 41-55 [ ] 56-70 [ ] 71-95

17. Gender

[ ] Male [ ] Female

18. My Residency

[ ] Urban [ ] Rural

19. Please enter any additional comments you may have regarding this study.

____
____
____

Simulator Sickness Questionnaire

Instructions: Circle how much each symptom below is affecting you right now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficult focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. Fullness of the Head	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eye closed	None	Slight	Moderate	Severe
14. *Vertigo	None	Slight	Moderate	Severe
15. **Stomach awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

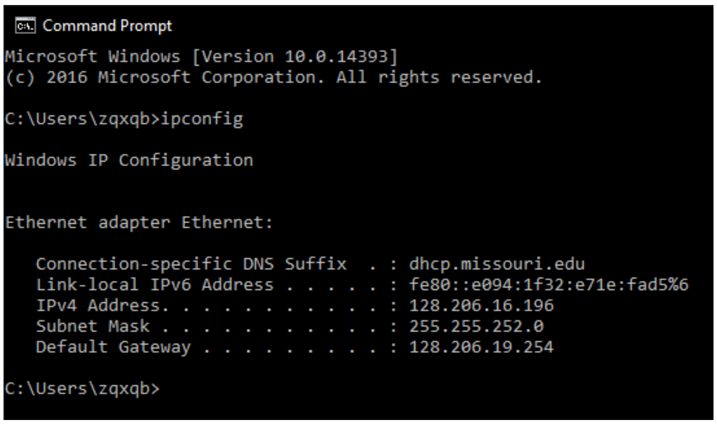
* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea. Please contact Dr. Carlos Sun (csun@missouri.edu) for additional comments, concerns or information on this survey. Thank you for completing this survey! We greatly appreciate your time!

VII. Appendix B: Hosting Manual

A. Preparation Stage

1.) Provide a bottle of water as needed.
2.) Turn on the Fan
3.) Start the BandiCam recorder on the vehicle simulator
4.) Check the IP address from the Host (vehicle Simulator). Open the command prompt. Type "ipconfig." Record the IPv4 address as seen below:



```
Command Prompt
Microsoft Windows [Version 10.0.14393]
(c) 2016 Microsoft Corporation. All rights reserved.

C:\Users\zqxqb>ipconfig

Windows IP Configuration


Ethernet adapter Ethernet:

   Connection-specific DNS Suffix  . : dhcp.missouri.edu
   Link-local IPv6 Address . . . . . : fe80::e094:1f32:e71e:fad5%6
   IPv4 Address. . . . . . . . . . . : 128.206.16.196
   Subnet Mask . . . . . . . . . . . : 255.255.252.0
   Default Gateway . . . . . . . . . : 128.206.19.254

C:\Users\zqxqb>
```

B. Pre-vehicle Stage

1.) Introduce Yourself. Say: **"Welcome to the Zousim Lab, thank you for participating in today's trial. My name is Michael Schoelz and this is my research partner, XXX. I will be driving the truck while you'll be in the vehicle and XXX will be providing technical support."**
2.) Indicate where the restrooms are and ask if the participant needs to use the restroom before we begin.
3.) Have the participant sign the consent forms (2 copies as necessary)
4.) Have the participant enter the vehicle simulator and fasten seatbelt.
5.) Dim the lights as needed.

HotKeys:

Q=initial link

1,2,3= scene number

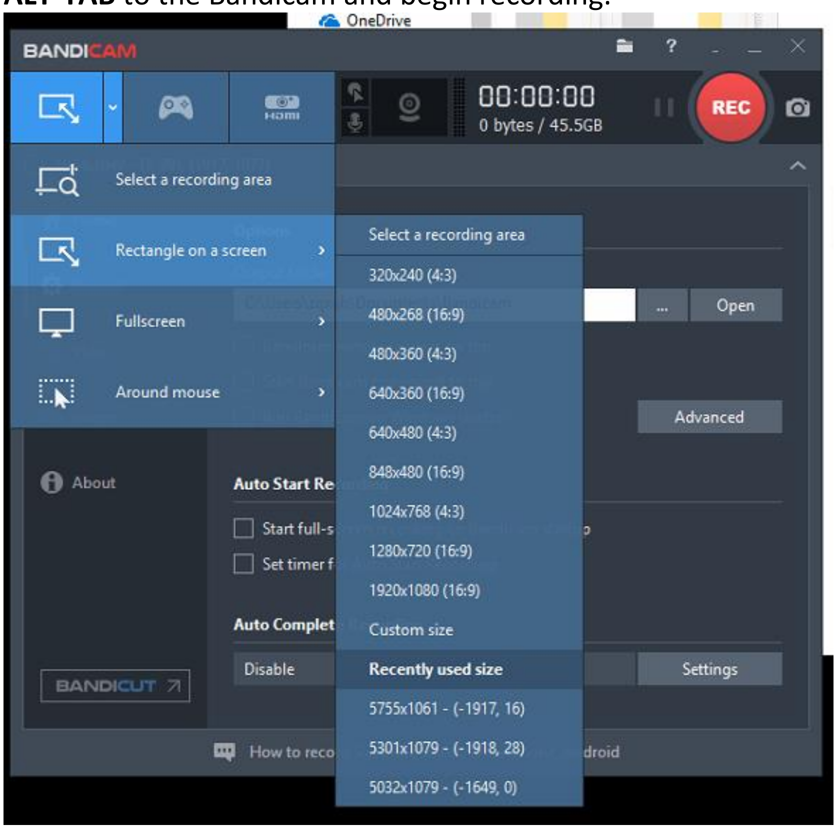
B= scene break/rest

C. Warm-Up Stage.

1.) Open the WarmUp program and expand it.
2.) Give the Instruction: **“To start, we’ll have you warm up to get used to driving the simulator. The speed limit is 60 mph. Please drive until you feel comfortable accelerating, braking, and merging. It may take a few minutes to get used to the controls. We recommend that you try to stay in a lane as closely as possible and then once you feel comfortable with that making a few merges and test the brakes. Once you are ready please let us know and bring the vehicle to a full stop.”**
3.) After the participant is ready, ask them to bring the car to a stop and **ALT-F4** to close the warmUp.

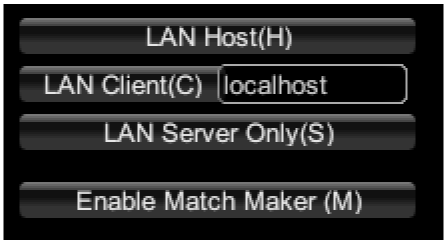
D. Simulator Procedure

1.) Load the first scene: CarTestNetwork.
2.) **ALT-TAB** to the Bandicam and begin recording.



Select 5032x1079 and then expand the window to fill the space. Click record and then **ALT-TAB** back to Cartestnetwork.

4.) Click HOST as shown below but tell the participant to wait patiently in the vehicle as we set up the test.



5.) Have the Truck dial-in using the IP address.

6.) **Press "Q" then the scene # in both the truck and the passenger vehicle.** Note, the randomization is on the googlesheets page of participants.

7.) Give the Instruction, **"We have now reset the program and ready to begin the test. You will drive on the freeway normally. The right lane is the driving lane and the left lane is the passing lane. Once you finish the scene, the scenario will automatically stop. Remember that we are not testing your performance so please try to relax and drive as normally as possible. Please use the right lane as much as possible."**

8.) The participant will then begin the test. When the scene is complete, RESET by pressing the **"B" key** followed by stop in the upper left hand corner.

Note: the scene can be completed by either the simulator vehicle passing the lead truck or not passing the lead truck. If the simulator vehicles does not pass the lead truck, timeout the scene at 2 minutes.

9.) To load the next scene press "HOST" then "Q" and finally the correct randomized scene #.

10.) After the third scene, Say, **"We will now provide you with a little information about how truck platoons work. A truck platoon is two or more trucks that have a coordinated, digital, wireless system for braking, acceleration, indicators and in later generations even steering. They work by maintaining a gap between each of the two trucks of about 30-60 ft. (10-20m). By driving so closely together, the trucks take advantage of aerodynamic forces and both vehicles have a reduction in wind resistance. In other words, truck platoons allow truck to use less fuel to do the same work. Do you have any questions?**

Answer any question except how to respond to truck platoons on the road.

"We will now reset the scenario and repeat the scenes."

11.) Press Host, "Q" and the next randomized scene #.

12.) When all trials are complete, press **ALT-TAB** to the bandicam and stop the recording.

E. Post-simulator

1.) Administer the paper surveys
2.) Hand out the gift card and fill out the receipt.
3.) Staple the receipt consent and survey together and place in the designated area for data processing.

VIII. Appendix C: Raw Data Tables

Performance Results

Table C.1.1: MoE1: Time to Reaction (seconds)

Part#	PRE Control	PRE TXT	PRE Grph	ED Cont	ED txt	Ed grph
1	11.85	13.28	66.45	8.07	14.9	6.17
2	21.42	10.53	22.4	18.98	4.4	5.33
3	13.37	13.73	13.05	11.45	6.32	1.72
4	11.87	21.63	8.4	10.72	13.8	13.88
5	86.95	29.67	42.25	23.38	23.7	25.6
6	38.47	26.95	22.3	31.68	27.83	30.85
7	16.55	15.83	14.37	14.85	17.02	19.57
8	21.8		15.97	16.68	14.05	18.97
9				21.26	13.68	73.57
10	20.2	13.83	24.25	15	21.43	12.55
11				50.52	42.8	84.08
12	14.37	14.37	6.47	18.42	9.27	25.75
13	13.6	17.37	9.82	18.65	15.47	17.4
14	7.43	17.83	14.92	8.05	1.42	1.5
15	93.82	1.53	2.47	15.02	15.8	15.43
16	48.6	38.12	34.78	32.7	28.23	31.4
17	17.43	22.87	35.47	21.68	13.68	20.97
18	15.11	14.18	17.3	13.88	9.95	11.87
19	16.25	10.05	16.2	14.05	10.48	11.23
20	29.65	79.8	0.88	55.62	62.38	38.2
21	33.42	28.57	2.5	15.43	14.68	13.37
22	21.35	23.13	27.08	18.83	16.67	18.07
23	33.4	91.9	84.75	20.7	4.97	10.53
24	14.42	10.7	14.03	12.1	10.48	11.45
25	20.55	5.17	13.27	19.3	25.05	5.18
26	18.83	4.02	7.53	10.7	7.62	7.42
27						
28	25.77	19.77	0.63	19.9	23.63	16.63
29	19.1	17.23	19.83	22.53	20.13	19.07
30	18.37	4.44	8.27	14.24	15.73	15.88
avg	26.07	21.79	20.21	19.81	17.43	20.13

Table C.1.2: MoE2: Lead Gap at Lane Change (feet)

Part#	PRE Control	PRE TXT	PRE Grph	ED Cont	ED txt	Ed grph
1	160.72	170.56	160.72	180.4	131.2	200.08
2	104.96	150.88	114.8	127.92	223.04	226.32
3	104.96	95.12	88.56	150.88	206.64	275.52
4	150.88	144.32	206.64	186.96	141.04	180.4
5	88.56	91.84	121.36	98.4	88.56	111.52
6	45.92	68.88	78.72	39.36	55.76	49.2
7	55.76	65.6	95.12	95.12	62.32	59.04
8	72.16		82	68.88	98.4	88.56
9				98.4		39.36
10	141.04	160.72	118.08	104.96	95.12	170.56
11		0	0	68.88	78.72	75.44
12	160.72	108.24	268.96	82	232.88	88.56
13	101.68	82	121.36	95.12	127.92	59.04
14	173.84	118.08	173.84	180.4	268.96	242.72
15	118.08	88.56	131.2	101.68	91.84	78.72
16	55.76	62.32	59.04	72.16	65.6	68.88
17	98.4	104.96	127.92	101.68	127.92	104.96
18	85.28	104.96	65.6	98.4	150.88	124.64
19	98.4	157.44	98.4	104.96	150.88	134.48
20	124.64	88.56	62.32	32.8		
21	150.88	88.56	88.56	147.6	160.72	177.12
22	62.32	65.6	52.48	59.04	75.44	59.04
23	104.96	55.76	55.76	131.2	252.56	236.16
24	111.52	147.6	104.96	127.92	154.16	157.44
25	131.2	246	190.24	141.04	104.96	219.76
26	196.8	255.84	209.92	157.44	242.72	216.48
27						
28	49.2	91.84	160.72	72.16	82	88.56
29	82	91.84	65.6	65.6	78.72	104.96
30	127.92	223.04	203.36	144.32	124.64	137.76
avg	109.58	115.89	118.08	108.13	136.06	134.83

Table C.1.3: MoE3: Time to Lane Change (seconds)

Part#	PRE Control	PRE TXT	PRE Grph	ED Cont	ED txt	Ed grph
1	16.05	15.88	73.35	13.07	20.2	12.65
2	24.92	16.13	27.2	21.68	10.1	10.93
3	18.7	19.3	19.73	15.32	11.22	6.1
4	14.67	24.53	11.2	13.92	16.2	16.08
5	92.85	33.87	48.25	30.58	29.7	33.1
6	43.87	31.45	25.9	35.68	34.13	36.77
7	25.35	21.53	19.45	19.45	21.72	22.97
8	26.1		20.37	21.38	19.15	22.57
9				24.25		77.27
10	24.6	18.53	27.95	19.6	27.13	17.05
11				54.92	46.62	88.98
12	19.37	18.97	8.07	22.62	9.27	27.95
13	18.72	20.37	17.42	21.73	19.27	22
14	13.83	21.93	19.12	13.15	6.52	8.5
15	101.22	47.53	24.47	18.92	21.4	20.53
16	48.6	40.32	37.68	37.2	28.23	31.4
17	21.53	28.37	41.27	25.18	17.38	25.57
18	20.32	18.78	21.6	19.18	15.25	17.07
19	20.83	14.95	20.02	19.05	15.28	16.43
20	37.23	85.47	86.12	59.68		
21	33.42	28.57	50.7	15.43	14.68	13.37
22	24.95	27.53	31.28	22.93	21.27	22.07
23	39.5	95.5	88.65	25.1	7.57	14.23
24	18.32	15.5	19.23	16.98	15.48	15.65
25	25.25	10.77	17.97	24.5	29.75	11.88
26	23.63	7.42	12.23	15.6	11.12	12.22
27						
28	31.27	25.27	42.53	25.3	28.43	22.43
29	23.3	22.02	24.53	27.03	24.63	23.67
30	22.37	10.24	12.57	18.24	10.93	19.68
avg	30.77	27.72	31.44	24.06	19.73	23.90

Table C.1.4: MoE4: Time to Collision at Lane Change (seconds)

Part#	PRE Control	PRE TXT	PRE Grph	ED Cont	ED txt	Ed grph
1	15.65	19.38	21.92	13.67	12.78	17.05
2	10.22	12.86	9.78	10.90	19.01	22.04
3	7.95	7.21	6.71	11.43	15.65	20.87
4	11.43	14.06	15.65	15.93	10.68	15.38
5	30.19	10.44	16.55	11.18	20.13	12.67
6	5.22	9.39	6.71	6.71	7.60	4.79
7	5.43	4.97	7.21	7.21	4.72	6.71
8	6.15	3.28	6.21	5.22	7.45	12.08
9	2.24	2.24	2.24	9.58	2.24	13.42
10	96.17	21.92	26.84	8.95	10.81	116.29
11	2.24	2.24	2.24	11.74	13.42	25.72
12	12.18	8.20	36.68	6.21	17.64	6.71
13	7.70	6.21	9.19	7.21	9.69	4.47
14	13.17	10.06	14.82	13.67	20.38	18.39
15	20.13	7.55	11.18	7.70	7.83	5.96
16	7.60	6.07	5.75	7.03	5.59	5.87
17	8.39	10.22	17.44	11.55	10.90	10.22
18	6.46	7.95	4.97	7.45	11.43	9.44
19	8.39	11.93	7.45	7.95	11.43	10.19
20	12.14	30.19	7.08	3.73	3.28	3.28
21	17.15	10.06	15.10	11.18	12.18	13.42
22	5.31	11.18	5.96	4.47	5.72	4.47
23	8.95	7.60	9.50	14.91	21.53	26.84
24	8.45	11.18	7.95	9.69	11.68	13.42
25	17.89	33.55	25.94	19.23	14.31	21.41
26	19.17	21.80	17.89	13.42	23.64	21.09
27	2.24	2.24	2.24	2.24	2.24	2.24
28	4.79	7.83	15.65	7.03	7.99	6.71
29	7.99	6.96	6.39	7.45	7.67	10.22
30	12.46	19.01	17.33	12.30	10.62	13.42
avg	13.11	11.26	12.02	9.57	11.34	15.83

Survey Results

Table C.2.1: Front Display Rankings/Preferences

				Front Control				Front Text				Front Graphic			
Pa#	CO	TXT	GR	Cla	Vis	Saf	Cm	Cla	Vis	Saf	Cm	Cla	Vis	Saf	Cm
1	3	2	1	1	1	1	1	8	8	8	8	10	10	10	10
2		1													
3	3	2	1	1	1	1	1	8	8	7	9	8	10	7	10
4	3	1	2	1	1	1	1	10	10	7	7	6	10	10	10
5	3	1	2	1	1	1	1	6	6	6	6	4	4	4	4
6	3	2	1	1	1	4	1	4	4	6	4	9	9	7	8
7	3	1	2	10	10	1	1	10	10	10	10	8	5	8	5
8		1		10	10	10	10	7	4	8	10	7	4	8	10
9		1		5	10	5	5	8	8	8	8	10	9	8	10
10	2	1	3	5	5	5	5	10	8	8	1	1	8	6	1
11	3	1	2	5	5	5	5	10	10	10	10	7	5	7	5
12	3	1	2	1	1	1	1	10	10	9	10	10	10	9	10
13	3	1	2	1	1	5	1	8	8	7	8	4	4	6	5
14		1													
15	3	1	2	1	1	1	1	10	10	10	10	10	10	10	10
16	3	1	2	1	3	1	1	7	7	7	6	6	6	6	6
17	3	1	2	1	1	1	1	8	10	8	9	8	7	8	5
18	3	1	2	1	1	5	1	9	7	8	7	8	4	7	5
19	3	1	2	6	8	8	6	8	8	8	10	8	8	8	8
20	3	1	2	1	1	1	1	8	8	8	8	7	7	7	7
21	3	1	2	5	5	5	5	10	10	10	10	7	7	7	7
22	3	1	2	1	1	1	1	9	10	10	9	10	8	9	8
23	3	1	2	6	6	6	1	10	7	7	10	5	3	6	7
24	1	3	2	5	5	5	5	6	5	7	3	8	10	8	7
25	3	1	2	1	1	1	1	10	10	10	8	9	10	10	10
26	3	1	2	4	4	2	1	9	9	6	7	8	8	6	6
27	3	2	1	1	1	1	1	8	8	8	8	10	10	10	10
28	3	2	1	1	1	1	1	3	3	3	3	8	8	8	8
29	3	1	2	1	1	5	1	7	8	6	4	4	8	6	6
30	3	1	2	1	1	1	1	10	10	10	10	4	4	2	2
avg	2.88	1.23	1.85	2.82	3.14	3.04	2.21	8.25	8.00	7.86	7.61	7.29	7.36	7.43	7.14

Table C.2.2: Rear Display Rankings/Preferences

				Front Control				Front Text				Front Graphic			

Pa#	CO	TXT	GR	Cla	Vis	Saf	Cm	Cla	Vis	Saf	Cm	Cla	Vis	Saf	Cm
1	3	2	1	1	1	1	1	8	8	8	8	10	10	10	10
2		1													
3	3	1	2	1	1	1	1	10	9	10	10	9	10	9	9
4	3	2	1	1	1	1	1	10	10	7	7	6	10	10	10
5	3	1	2	1	1	1	1	8	8	8	8	7	7	7	7
6	3	2	1	1	1	4	1	5	9	9	4	10	10	9	9
7	3	2	1	10	10	1	1	10	10	10	8	8	8	10	8
8		1		10	10	10	10	7	4	8	10	7	4	8	10
9		1		5	10	5	5	8	10	9	9	10	10	10	10
10	2	1	3	5	5	5	5	10	8	8	1	1	8	6	1
11	3	1	2	5	5	5	5	10	10	10	10	7	5	7	5
12	3	1	2	1	1	1	1	10	10	9	10	10	10	9	10
13	3	1	2	1	1	5	1	9	9	7	9	5	5	6	5
14		1													
15	3	1	2	1	1	1	1	10	10	10	10	5	5	5	5
16	3	1	2	1	1	1	1	7	8	7	7	7	8	6	6
17	3	1	2	1	1	1	1	8	10	8	5	8	7	8	5
18	3	1	2	1	1	5	1	9	7	8	7	8	5	7	7
19	3	1	2	6	8	8	6	10	8	10	10	8	8	10	10
20	3	1	2	1	1	1	1	9	9	9	9	7	7	7	7
21	3	1	2	5	5	5	5	10	10	10	10	7	7	7	7
22	3	1	2	1	1	1	1	10	10	10	9	8	9	8	9
23	3	1	2	4	4	4	4	10	5	7	8	5	5	5	5
24	2	3	1	5	4	5	5	6	5	7	3	8	10	8	7
25	3	2	1	1	1	1	1	10	10	10	10	10	10	10	10
26	3	1	2	4	4	3	4	8	8	7	7	7	7	6	6
27	3	2	1	1	1	1	1	9	9	9	9	10	10	10	10
28	3	2	1	1	1	1	1	5	5	5	5	8	8	8	8
29	3	1	2	1	1	5	1	8	8	6	4	5	8	6	6
30	3	1	2	1	1	1	1	10	10	10	10	4	4	2	2
avg	2.92	1.30	1.73	2.75	2.96	3.00	2.43	8.71	8.46	8.43	7.75	7.32	7.68	7.64	7.29

Table C.2.3: Behavior and Comfort

Part#	Familiarity	Understood		Behavior		Comfort	Utility	Status of Plat	# of Truck	Merging Info
1	1	yes		a		5	5	1	1	1
2	3	yes		a		5	5	1	0	1
3	1	yes		a		4	5	0	0	1
4	1	yes		a		4	5	1	0	1
5	1	no		a		5	3	1	0	0
6	3	no		a		5	4	0	0	1
7	3	no		c		5	4	1	1	1
8	1	no		c		5	2	1	0	0
9	4	no		a		3	5	1	1	0
10	1	no		a		4	2	1	1	0
11	4	no		a		2	4	1	1	0
12	1	yes		a		3	5	1	0	0
13	4	no		c		4	3	0	1	1
14	1	yes		a		3	4	1	1	1
15	1	no		c		1	1	0	0	1
16	3	yes		a		4	5	1	1	1
17	1	no		c		4	4	1	0	1
18	1	yes		a		5	4	1	0	1
19	1	no		c		4	2	1	0	1
20	5	yes		c		1	4	1	1	1
21	1	yes		a		5	5	1	0	0
22	1	no		a		3	3	1	1	1
23	1	yes		c		5	5	1	0	0
24	1	no		c		5	4	0	1	1
25	1	no		c		5	3	1	0	1
26	5	yes		a		2	5	1	0	0
27	5	yes		a		5	3	0	1	0
28	1	no		a		4	5	0	0	1
29	2	yes		a		4	4	1	1	0
30	2	no		a		5	4	1	0	0
Avg	2.03	%yes	46.67%	%a	66.67%	3.97	3.90	Count	Count	Count
		%no	53.33%	%b	0.00%			23	13	18
				%c	33.33%					

Simulator Experience and Participant Demographics

Table C.3: Simulator Experience and Participant Demographics

Part #	Fidelity	Free movement	Sim Issues	Age	Gender	Urban v. Rural
1	neutral	Agree	No	56-70	Female	Urban
2	Agree	Strongly Agree	No	56-70	Male	Urban
3	Strongly Disagree	Agree	No	26-40	Male	Urban
4	Agree	Agree	No	16-25	Female	Urban
5	Agree	Agree	No	26-40	Male	Urban
6	Agree	Agree	No	16-25	Male	Rural
7	Agree	Agree	No	26-40	Male	Rural
8	Agree	Agree	No	56-70	Female	Urban
9	Neutral	Agree	No	26-40	Male	Urban
10	Disagree	Agree	Yes	26-40	Female	Urban
11	Disagree	Neutral	No	26-40	Female	Urban
12	Agree	Neutral	Yes	26-40	female	rural
13	neutral	disagree	Yes	56-70	Male	Urban
14	Agree	Neutral	No	26-40	Female	Urban
15	Disagree	Neutral	Yes	56-70	Male	Urban
16	Agree	Strongly Agree	No	26-40	Female	Urban
17	Agree	Agree	Yes	16-25	Male	Urban
18	Agree	Agree	No	16-25	Male	Urban
19	Agree	Agree	No	26-40	Male	Rural
20	Agree	Agree	No	26-40	Female	Rural
21	Neutral	Agree	Yes	16-25	Female	Urban
22	Agree	Agree	No	16-25	Female	Rural
23	Agree	Agree	No	26-40	Male	Urban
24	agree	Agree	no	16-25	Male	Urban
25	Agree	Agree	No	26-40	Male	Rural
26	Agree	Agree	No	26-40	Male	Rural
27	Agree	Agree	No	16-25	female	Urban
28	Agree	Strongly Agree	No	56-70	Male	Rural
29	Strongly Agree	Strongly Agree	No	16-25	Male	Urban
30	Agree	Agree	No	16-25	female	urban

Simulator Sickness

Table C.4: Simulator Sickness

	None	Slight	moderate	severe

General Discomfort	76.67%	20.00%	3.33%	0.00%
Fatigue	96.67%	3.33%	0.00%	0.00%
Headache	90.00%	3.33%	6.67%	0.00%
Eye Strain	80.00%	16.67%	3.33%	0.00%
Difficulty Focusing	83.33%	16.67%	0.00%	0.00%
Salivation Increase	86.67%	10.00%	3.33%	0.00%
Sweating	100.00%	0.00%	0.00%	0.00%
Nausea	80.00%	16.67%	3.33%	0.00%
Difficulty Concentrating	90.00%	10.00%	0.00%	0.00%
Fullness of the Head	93.33%	3.33%	3.33%	0.00%
Blurred Vision	96.67%	3.33%	0.00%	0.00%
Dizziness with Eyes open	83.33%	13.33%	0.00%	3.33%
Dizziness with Eyes closed	93.33%	3.33%	0.00%	3.33%
Vertigo	90.00%	6.67%	3.33%	0.00%
Stomach Awareness	86.67%	6.67%	6.67%	0.00%
Burping	100.00%	0.00%	0.00%	0.00%

References

Alsghan, I., Chitturi, M., and Noyce, D. (2018). "Sign Occlusion Impacts of Truck Platooning on Highways." *Transportation Research Board 97th Annual Meeting*Washington, D.C., 7.

Bhoopalam, A. K., Agatz, N., and Zuidwijk, R. (2018). "Planning of truck platoons: A literature review and directions for future research." *Transportation Research Part B: Methodological*, 107, 212-228.

Bishop, R., Bevly, D., Humphreys, L., Boyd, S., and Murray, D. (2017). "Evaluation and testing of driver-assistive truck platooning: Phase 2 final results." *Transportation Research Record*, 11-18.

Boysen, N., Briskorn, D., and Schwerdfeger, S. (2018). "The identical-path truck platooning problem." *Transportation Research Part B: Methodological*, 109, 26-39.

ButtKicker.com (2018). "Buttkicker FAQ." <https://thebuttkicker.com/faq/>. (November 16, 2018).

Chen, D., and Ahn, S. (2018). "Harnessing Connected and Automated Vehicle Technologies to Control Lane Changes at Freeway Merge Bottlenecks." *Transportation Research Board 97th Annual Meeting*Washington D.C., 5.

Clamann, M., Aubert, M., and Cummings, M. (2017). "Evaluation of Vehicle-to-Pedestrian Communication Displays for Autonomous Vehicles." 13.

Duret, A., Wang, M., and Leclercq, L. (2018). "Truck Platooning Strategy Near Merge: Heuristic-Based Solution and Optimality Conditions." *Transportation Research Board 97th Annual Meeting*Washington, D.C., 19.

FHWA (2009). "Manual on Uniform Traffic Control Devices for Streets and Highways."

Friedrichs, T., Ostendorp, M.-C., and Ludtke, A. "Supporting drivers in truck platooning: Development and evaluation of two novel human-machine interfaces." *Proc., 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, AutomotiveUI 2016, October 24, 2016 - October 26, 2016*, Association for Computing Machinery, Inc, 277-284.

Heikoop, D. D., de Winter, J. C. F., van Arem, B., and Stanton, N. A. (2017). "Effects of platooning on signal-detection performance, workload, and stress: A driving simulator study." *Applied Ergonomics*, 60, 116-127.

Hjalmdahl, M., Krupenia, S., and Thorslund, B. (2017). "Driver behaviour and driver experience of partial and fully automated truck platooning a simulator study." *European Transport Research Review*, 9(1), 12.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., and Lilienthal, M. G. (1993). "Simulator Sickness Questionnaire: An enhanced method for Rehabilitation Training of Postural Balance." *The International Jounal of Aviation Pyschology*, 3, 203-220.

Lammert, M. P., Duran, A., Diez, J., Burton, K., and Nicholson, A. (2014). "Effect of Platooning on Fuel Consumption of Class 8 Vehicles Over a Range of Speeds, Following Distances, and Mass." *SAE International Journal of Commercial Vehicles*, 7(2), 15.

Litman, T. (2013). *Autonomous Vehicle Implementation Predictions: Implications for Transport Planning*, Victoria Transport Policy Institute.

Loftus, J., and Tershak, R. "Truck Platooning: The State of the Industry and Future Research Topics." *Proc., 2018 Transportation Research Board 97th Annual Meeting*, 12.

Luo, F., Larson, J., and Munson, T. (2018). "Coordinated platooning with multiple speeds." *Transportation Research Part C: Emerging Technologies*, 90, 213-225.

Mohamed, A., Laman, H., Oloufa, A., and Abou-Senna, H. (2018). "A Framework for Assessing the Impacts of State Level Platooning Truck Only Lane Strategies in Florida." *Transportation Research Board 97th Annual Meeting*Washington DC, 22.

NHTSA (2016). "Federal Automated Vehicles Policy: Accelerating the Next Revolution in Roadway Safety." U. S. D. o. Transportation, ed.District of Columbia, 116.

Nowakowski, C., Shladover, S. E., Lu, X., Thompson, D., and Kailas, A. (2015). "Cooperative Adaptive Cruise Control (CACC) for Truck Platooning: Operational Concept Alternatives." *UC Berkeley: California Partners for Advanced Transportation Technology*, 50.

Perrault, W. D. (1975). "Controlling order-effect bias." *The Public Opinion Quarterly*, 39 (4), 544-551.

Saeednia, M., and Menendez, M. (2016). "Analysis of strategies for truck platooning: Hybrid strategy." *Transportation Research Record*, 2547, 41-48.

Scribner, M. (2018). "Authorizing Automated Vehicle Platooning." <https://cei.org/content/authorizing-automated-vehicle-platooning>. (2018).

Stanciu, S. C., Eby, D. W., Molnar, L. J., St. Louis, R. M., Zanier, N., and Kostyniuk, L. P. (2018). "Pedestrians/Bicyclists and Autonomous Vehicles: How Will They Communicate?" *Transportation Research Record*, 9.

Sugimachi, T., Ryo, H., and Yoshihiro, S. (2017). "Evaluation of General Drivers' Acceptability of Truck Platoon Using Driving Simulator." *Transactions of Society of Automotive Engineers of Japan*, 48(5), 1121-1126.

Tsugawa, S. "An overview on an automated truck platoon within the energy ITS project." *Proc., 7th IFAC Symposium on Advances in Automotive Control, AAC 2013, September 4, 2013 - September 7, 2013*, IFAC Secretariat, 41-46.

Ziegler, C. (2016). "A Google Self-Driving Car caused a crash for the first time." *The Verge*, Vox Media, online.