Training Drivers to Automated Vehicles

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Contents

1. Acceptance of Automated Vehicles

The concept of autonomous vehicles (AVs) has received mixed responses from the general public. There is little doubt that the technology is incredibly advanced and a great innovation for society, but many individuals are wary of using it and have deep concerns about their design, capabilities, usability, and ethics. Like any disruptive innovation, there are significant hurdles to leap over before AVs are fully accepted and used. Simply put, many people do not want to relinquish control on the roads to a machine – no matter how advanced it is. They are concerned about the AVs' ethical decision-making process – for example, whether to prioritize the safety of the passenger or pedestrian in an unavoidable accident. They are concerned about whether AVs are actually safer than the average driver. They are concerned as to whether AVs will actually avoid all avoidable accidents. These technical issues will be solved with time, but one issue remains: people do not presently trust AVs, according to studies done by Pew Research, AAA, and PAVE Campaign [2], [3], [5], no matter how safe they are. A valid assumption is therefore to hypothesize that one way to increase driver safety through the use of AVs is to train drivers to be comfortable with them.

Surprisingly, autonomous vehicle systems have been around for a very long time [6]. An early autopilot system was developed by Sperry Gyroscope Co in 1933 to manage an airplane's heading during an around-the-world flight. An early cruise control was developed in 1945 and commercialized in 1958. The first fully self-driving wheeled vehicle was built in 1961 by James Adams, a Stanford engineering graduate student, to drive on the moon. The Cart had cameras and was programmed to autonomously follow a white line on the ground. In 1977, Tsuluba Mechanical in Japan developed a passenger vehicle that could recognize street markings and drive at almost 20mph. In 1987, German engineer Ernst Dickmanns outfitted a vehicle with cameras and 60 processing modules to detect objects on the road. This innovation was called VaMoRs. It was able to navigate the Autobahn at up to 60 mph.

As with many inventions, innovation was accelerated by the US Military [6]. General Atomics developed the MQ-1 Predator in 1995, a remotely piloted drone outfitted with cameras, sensors, and munitions. From 2004-2013, DARPA, the US DOD research arm, sponsored a series of autonomous vehicle competitions. In the 2004 DARPA Grand Challenge, competitors were challenged to create a vehicle that could self-navigate 150 miles of roadway in the desert. In the 2007 DARPA Urban Challenge, four vehicles successfully completed a 60-mile urban route in the allotted six hours.

Autonomous driving technology became mainstream in 2015 with the advent of the Tesla Autopilot [1], a hands-free highway driving technology. Currently, Tesla offers Enhanced Autopilot, which navigates, changes lanes, parks, and summons (moves cars in and out of tight spaces), as well as Full Self-Driving, which identifies and follows stop signs and traffic signals. Tesla is currently developing a full autosteer on city streets. Still, Tesla's autonomous driving technology currently requires driver supervision.

According to the SAE, there are six levels of autonomous driving technology [21]. Level 0: No Automation is when the driver performs all tasks related to driving, all the time. Level 1: Driver Assistance is when a system assists *either* acceleration/braking or steering. Levels 0 and 1 require human drivers to fully monitor the driving environment. In Level 2: Partial Automation, driver assist systems control both steering and acceleration/deceleration. In Level 3: Condition Automation, automated systems perform all aspects of driving, assuming that the human driver will respond and intervene as needed. Levels 2 and 3 require the driver to still be in control of the car but let the autonomous technology control certain things at certain times. In Level 4: High Automation, an automated system performs all aspects of driving without any human response in a defined area with weather constraints. In Level 5: Full Automation, driving is fully performed by an automated driving system in all conditions and locations with no need for human intervention. In levels 4 and 5, the automated system monitors the driving environment instead of the human. Currently, Tesla's Full Self Driving is a level 2 system [1].

Yet, despite the high level of autonomy of these systems, a significant of training is required for optimal use of the automation. AV systems face great challenges if humans do not understand their Operational Design Domain. Human drivers need to learn how to effectively operate (and not operate) AVs. AVs need to be safe enough for people to trust them. Training is necessary to help people understand the limits of the AVs. In the same way that people understand their own driving style (how they accelerate, brake, turn, avoid accidents, overtake, etc.), people need to understand and become comfortable with the driving style of their AVs. Additionally, people need to be trained on when to take over the car's controls if the car is making a mistake or is about to crash.

According to studies done by Pew Research, PAVE, and AAA [2], [5], [3], people are quite apprehensive about being passengers in self-driving vehicles. They are concerned about the ethical choices that AV systems might make and how AV manufacturers prioritize pedestrians, passengers, or other drivers in an unavoidable accident. Drivers worry whether the decision made by the car will be the right one and whether it will compromise their own safety. Dr. JF Bonnefon from the Toulouse School of Economics and the Massachusetts Institute of Technology asserts that, even if AVs are proven safer than the average driver, people will refuse to accept that they are safer than their own driving (whether they are above or below the average). According to AAA, only 9% of US drivers in 2023 trust self-driving vehicles and would ride in them [3]. As AVs become safer and reach our dealerships, it is imperative that drivers be trained on how to use them, and how to trust and be comfortable in them. AV driver training will indeed accelerate AV acceptance.

The goal of the simulation study presented in this research report is to test the efficacy of AV training simulators. In this project, study participants completed surveys before and after completing an AV simulation.

2. Acceptance of Automated Vehicles

2.1. Consumer Apprehension of Autonomous Vehicles

There has been significant public apprehension about adopting autonomous vehicles (AVs) due to a variety of concerns. According to several European studies (Cunningham et al., 2019; Wicki and Bernauer, 2018), which collected data from 109 countries, software hacking, and misuse are the largest concerns in fully automated driving technologies [7], [8], [9]. There are great concerns around moral and ethical dilemmas. The classic “trolley problem” [4], e.g., whether an AV needs to decide whether to prioritize pedestrians, other drivers, or passengers in an unavoidable accident is a fixture in people’s minds. Concerns about the economic impacts of AVs, mainly job loss and industry shifts, also hinder their acceptance. In addition, the risk of overdependence on technology and the degradation of human driving skills is a valid concern. As with all emerging technology, significant regulatory and legal concerns need to be solved. Questions as to who would be liable in the case of injuries and deaths are still unsolved issues.

2.2. Benefits of Widespread Autonomous Vehicle Usage

Despite these concerns, there are a great number of reasons to advocate for widespread AV use. There have been vast AV technological improvements in the past few years, including improved sensors, algorithms, AI models, etc. High-level 4 AV systems, such as Waymo and Cruise are currently being deployed with great success. Despite concerns, autonomous vehicles are incredibly safe. According to data from the AVIA (Autonomous Vehicle Industry Association), AVs have driven 44 million miles during a 2-year period on U.S. public roads with only 1 serious injury [10]. Statistically, one can expect 1.37 deaths per 100 million miles with human driving [11]. In 2022 alone, 43,000 lives were lost on U.S. roads as a result of human driver accidents [10]. There are great economic advantages to the widespread use of AVs as well. Traffic congestion will be greatly reduced resulting in far greater driving efficiency. Transportation times will be reduced, resulting in reduced transportation costs. New jobs will be created in this emerging autonomous vehicle industry. AVs offer greatly increased mobility for those who are unable to drive, such as the elderly and disabled.

Altogether, the benefits of AVs heavily outweigh the detriments. The technological concerns about AVs are natural. All new, disruptive technologies come with concerns from the general public in their early stages. As AV technology progresses, public concerns will gradually reduce. Basic autonomous features have already been highly successful and adopted by the public, including automated lane change, automated collision avoidance, automated parking, etc. Ful autonomous driving faces great challenges in becoming widely adopted but the technology will evolve heavily and improve greatly, absolving technological concerns.

Autonomous technology has been vital to safety in the aviation industry. Since autopilot was widely adopted in aviation, air travel safety has increased drastically. One of the greatest technologies, the ILS, or instrument landing system, has greatly increased the safety of landing airplanes in poor conditions. ILS CAT III [12] allows airplanes to land automatically by communicating with various ground entities. Auto Landing capabilities allow pilots to land safely in bad weather with poor visibility. Many airports that frequently have low visibility would barely be able to operate if planes were not outfitted with auto-landing capabilities. During an automated landing, pilots still need to monitor the systems and be ready to intervene at any time. Although the pilots need to be attentive, the instrument systems are significantly safer than the pilots when in poor conditions. Autonomous systems have been widely adopted in the aviation industry and add a lot to safety. It is likely to evolve in the same way in the automotive industry.

As autonomy gets deployed, every single autonomous crash is heavily investigated, just like for airplanes. The vast amount of data recorded by the car allows for a thorough investigation after a crash. Each crash results in improvements made to the AV software which then gets retrofitted to all vehicles. It is therefore easy for AVs to improve – something that cannot be done by human drivers.

The ethical concerns will always remain, but they are no less than that of regular driving. Humans need to make the same split-second decisions. With AVs, there will be far fewer unavoidable crashes when those decisions even need to be made.

Going back to obvious regulatory concerns with AVs, this is typical of all new technology. The legal system will need to evolve, and precedent will be put in place to allow for widespread AV usage.

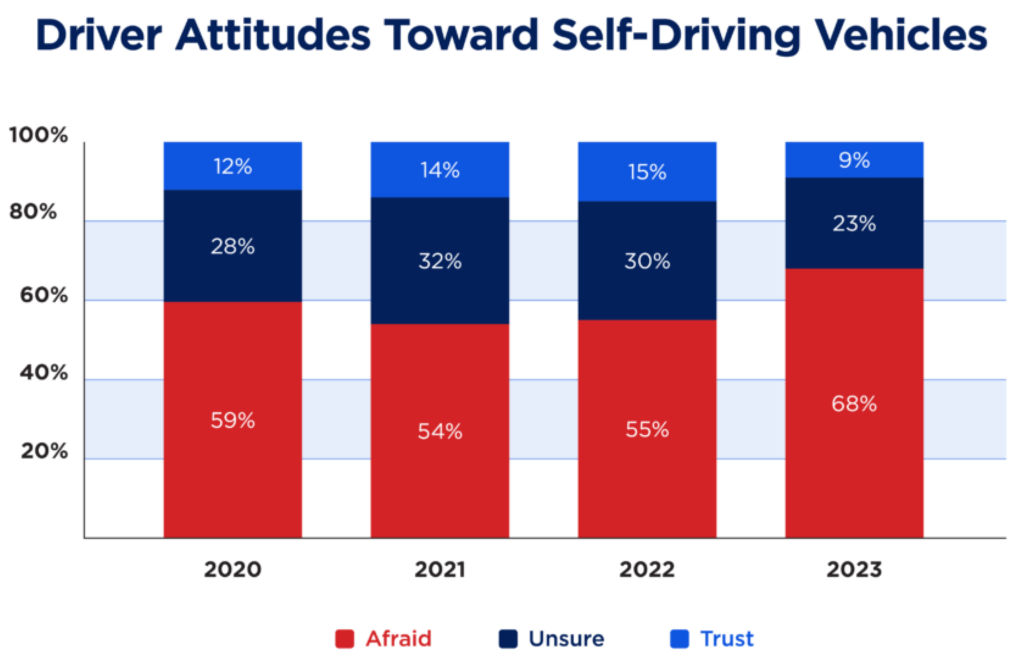
We anticipate the greatest challenge we, as a society face for widespread AV adoption, is the human factor: people do not want to give up control and simply do not trust AVs. AVs will not get far past the drawing board, no matter how safe they are, unless people begin to trust and use them. As AVs continue to improve, people need to be trained to trust and use them so that we, as a society, achieve our Vision Zero objective, a world in which we eliminate all traffic fatalities and serious injuries.

2.3. Driver Perception of Autonomous Vehicles

Various studies have shown that despite the benefits to AV usage, drivers are incredibly apprehensive about adopting them. The majority of this apprehension is caused by a lack of knowledge about how AV systems work.

2.3.1. AAA Metrics:

AAA recently compiled survey data from 2020-2023 on the public perception of AVs [3].



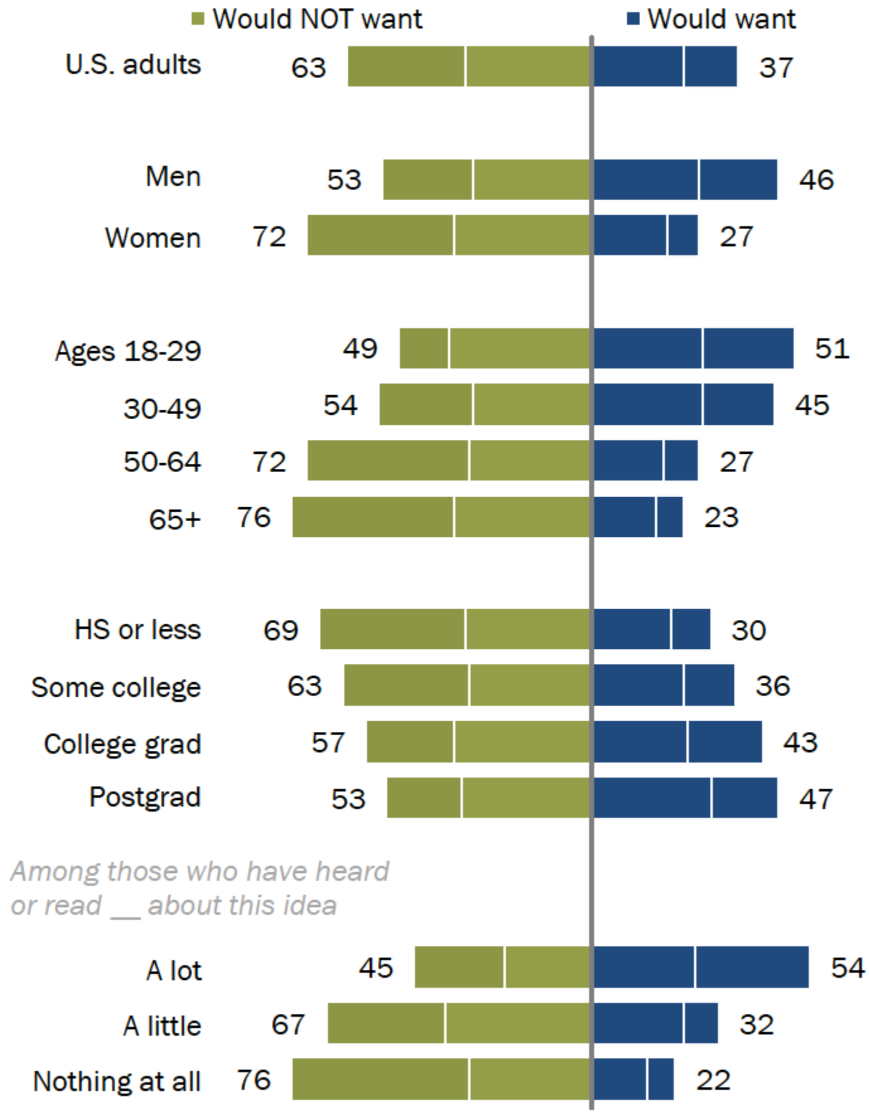
In 2020, 12% of Americans trusted AVs, 28% were unsure, and 59% did not trust them [3]. The numbers improved for AVs in 2021, to 14% who trusted, AVs 32% unsure, and 54% afraid [3]. Metrics were similar in 2022, with a record-high 15% of Americans trusting AVs, 30% being unsure, and 55% not trusting them [3]. AV trust declined significantly in 2023, with only 9% of Americans trusting them, 23% being unsure, and an astounding 68% of Americans not trusting them [3]. This data shows the stagnant and even decreasing trust in AVs in Americans even though AV technology is improving and evolving greatly. This illustrates the disconnect between AV innovation and AV trust. Additionally, the large number of “unsure” responses reflects the lack of AV education in America.

2.3.2. Pew Research Metrics:

Pew Research did a similar study, with strikingly similar results [2].

Majority of Americans say they wouldn't want to ride in a driverless vehicle, but men, adults under 50 and those with a college degree are more open to the idea

% of U.S. adults who say they definitely or probably __ to ride in a driverless passenger vehicle if they had the opportunity



Note: Respondents who did not give an answer are not shown.
Source: Survey conducted Nov. 1-7, 2021.
"AI and Human Enhancement: Americans' Openness Is Tempered by a Range of Concerns"

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Pew Research found that 44% of adults believe that widespread AV use would be bad for society with only 26% thinking that it would be good [2]. 29% of respondents were unsure, another reflection of the lack of AV education. 63% of adults would not want to ride in an AV, with just 37% being willing to. Pew concluded that younger men with higher education were more willing to ride in AVs. Following the trend of younger people embracing emerging technology, they found that 51% of people 18-29 would ride in AVs. Only 19% of those with a high school education or less think that widespread AV use would be good for society, compared to 34% of college grads and 39% of those with a postgraduate degree, highlighting that educated individuals are more likely to embrace AVs. The greatest insights come from the AV education levels of the respondents. Just 11% of individuals with zero knowledge about AVs thought that widespread use would be good for society, compared to 22% of those with some knowledge and 45% of those with significant AV knowledge. 50% of those with zero AV knowledge were unsure of whether it would be good for society, compared to 29% of those with some knowledge and 20% of those with significant AV knowledge. These numbers highlight the effects of AV knowledge on the willingness to accept AVs and the need for high-quality AV education. The fact that 50% of those with little knowledge do not know whether AVs would be good or bad for society underscores the need for widespread AV education. Additionally, 54% of those knowledgeable about AVs would ride in one compared to just 22% of those with no AV knowledge, continuing to support the need for AV education to obtain widespread use.

2.3.3. PAVE Metrics:

Partners for Automated Vehicle Education (PAVE Campaign) developed its own polls regarding public perception of AVs and the need for AV education [5]. They concluded that 48% of Americans would NEVER get in an autonomous taxi or ride-share vehicle but 60% of Americans would have greater trust in AVs if they better understood how the technology worked. 49% of those surveyed had no knowledge of AVs, something that according to Pew Research data would contribute to their unwillingness to ride in AVs. PAVE also concluded that 58% of Americans would have greater trust in AVs if they could experience a ride in one while 24% would not. This illustrates the need for AV education to include riding in an AV [5].

The simulation experiment developed with this research project leverages VR technology. It provides a hands-on immersive experience of what riding in an AV feels like. The PAVE data suggests that this type of experience should increase driver trust in AVs. 45% of PAVE respondents felt that AVs could save lives, while just 19% thought they couldn't and 36% were unsure [5]. This underscores the fact that, even if drivers understand how safe AVs are, they are still not willing to use them because of an apprehension to relinquish control to a machine. Tara Andringa, the executive director of PAVE, concluded "The results of this survey confirm that autonomous vehicles face major perception challenges and that education and outreach are the keys to improving trust. These insights provide both motivation and direction to our effort to confront this educational challenge" [5].

2.4. Conclusion

Despite the illustrated benefits of AVs, people are incredibly apprehensive about using them. The societal benefits of self-driving technology will not come to full realization unless widespread AV can be achieved. This creates a phenomenal challenge for educators, technologists, policymakers, and our larger society.

The roadblocks to widespread AV popularization are human factors – a lack of trust. Studies have shown that this lack of trust is due to a lack of understanding of AVs, which can only be solved through education. It should be our goal as a society to achieve Vision Zero – a world in which there are no serious injuries due to traffic accidents. The research protocol presented below suggests techniques to precisely educate people about AVs through an immersive hands-on simulation.

3. Research Core Introduction

3.1. Background & Motivation

Autonomous vehicles (AVs) have been gaining unprecedented attention and popularity as society eagerly expects the next revolution in the transportation industry. Taking advantage of ever more sophisticated artificial intelligence models, the increasingly reduced cost of hardware, and the newly renovated road infrastructure, AVs are being increasingly deployed into cities and towns. However, the concept of autonomous driving (AD), or self-driving, still sounds mysterious and even scary to many people. Research has shown that the public has a natural tendency to resist AVs and often requires them to be significantly safer than human-driven vehicles [13]. Similarly, AV-related malfunctions and accidents tend to be overly dramatized in the media which further jeopardizes public trust [14].

As we are still experiencing the stage of rapid development of AVs, it is unlikely that in the near future, AVs will completely eliminate traffic accidents and outperform humans in every aspect. However, they have the potential to: significantly reduce traffic accidents, increase traffic efficiency, consume less energy, and provide an alternative way of transportation [15]. In order for society to fully accept AVs and enjoy their benefits, work must be done to increase the public's understanding of these innovative technologies [16]. The best way to do this is for someone to step into an AV with a safety expert behind the wheel. However, such demonstrations can be expensive and time-consuming. In addition, the test drive is subject to traffic, weather, and geographical conditions and may not provide the most comprehensive evaluation. Further, one may not feel comfortable riding in an AV before establishing any trust on it [17]. Finally, riding with an instructor does not provide the first-person experience needed to be comfortable with the technology.

As a solution to these problems, a driving simulator stands up as a cost-effective, time-efficient, and completely safe platform to demonstrate the capabilities of AVs. Driving simulators can support the testing of different scenarios that might be dangerous or risky to attempt in the real world [18]. They are also accessible to people from all age groups with varying driving backgrounds. The work described here is a continuation of the previous Drive Right research effort which aimed at increasing the public's trust and understanding of AVs using an integrated driving simulation platform [19]. Our previous study has shown that simulator education can effectively decrease participants' perceived risk and increase the perceived usefulness of AVs. In this study, we took one step forward and used the open-source Carla driving simulator for its flexibility, compatibility, and openness [20]. Our modified Carla simulator in the Virtual Reality (VR) environment mimics the control of a Level 4 AV [21] and is capable of handling most circumstances. The software system is coupled with the Logitech G29 steering wheel & pedal set to further increase the simulation fidelity.

3.2. Target Population

The target population of this study is drivers who have had experience with conventional vehicles but lack knowledge of AVs. For Level 4 AVs, it is reasonable to argue that the driver can take control of the vehicle at any time, either due to safety concerns or simply to enjoy the driving fun. The key point is that as long as these vehicles are below Level 5, drivers should have the option to decide their preferred driving mode and be informed on how to interact with an autonomous system. Our VR simulator fulfills that goal by providing first-hand, in-person experience in controlling an AV, which is generally not available on the market. We hoped that this direct experience would help participants understand what it feels like to ride in an AV, how they should interact with it, and if an AV is a good fit for them. Note that while the main focus of this study is drivers who look forward to using an AV, the public in general can still benefit from the simulator either from a passenger point of view or to gain some understanding of the autonomous system.

Note that the author does not intend to make the claim that the simulator proposed in this study is a faithful representation of any AVs on the road and is a ready-to-use commercial product. We only wish to show the application of a driving simulator and its potential application in the AV field. It is well-known that driving simulators have been adopted by leading AV industries to test and validate the AD system, and therefore, can be easily extracted for a standalone user interface. The methodologies and findings in this study should provide some information for the policymakers, auto dealerships, and driving schools in terms of AV education and demonstration.

3.3. Research Questions

With this work, we would like to address some quantitative and qualitative research questions, and the main method for data collection is survey instruments.

3.3.1. Quantitative

1. *Does a VR driving simulator decrease drivers' perceived risk towards AVs?*
2. *Does a VR driving simulator increase drivers' perceived usefulness towards AVs?*
3. *Does a VR driving simulator increase drivers' perceived ease-of-use towards AVs?*
4. *Does a VR driving simulator increase drivers' trust towards AVs?*
5. *Does a VR driving simulator increase drivers' behavioral intentions towards AVs?*

3.3.2. Qualitative

6. *Should driving simulators be used at auto dealerships for AV demonstration?*
7. *Should driving simulators be used at driving schools for AV training?*
8. *Should AV training and qualification be made mandatory for everyone?*

3.4. Contribution

This work contributes to existing literature in the following ways:

1. It is the first systematic approach to deploy the Carla driving simulator into the VR framework while extending its driving algorithm validation purpose with the human factor consideration. Our development provides an easy-to-follow approach to use Carla on any VR headset and the full instructions are available on GitHub (Fig. 1).
2. It is the first attempt to take the AD system as a whole and focus entirely on user experience and interaction. To our best knowledge, previous literature on driving simulators generally focused on specific information, features, or user responses to help improve the system design from a manufacturer's standpoint. In our study, we set the simulator close to real life and present everything from a user standpoint. We believe that users will be able to form a mental model of AVs and refresh their impression of the technology as they actively engage in the driving task and make their own informed decisions.
3. We present the rationale for using a driving simulator and show why it could be such an effective tool for AV training and demonstration. The results from our study suggest that

policymakers should use legislative processes to reduce the misuse of AVs and promote a safe AV environment. This can be achieved in many different forms and a driving simulator stands up as a cost-effective and time-efficient way.

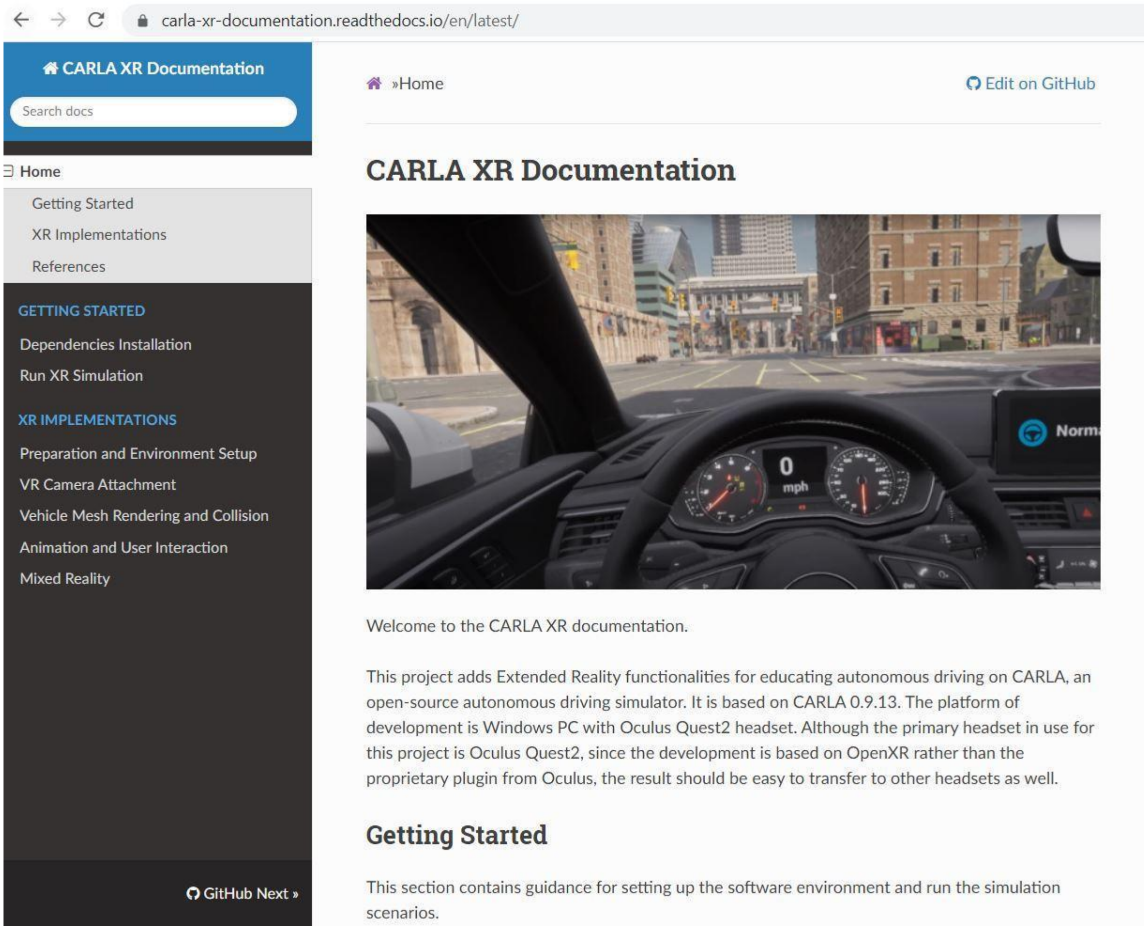


Fig. 1. Instruction Page on GitHub for Carla VR Configuration.

4. Literature Review

4.1. Overview

Extensive efforts have been made by academia and industry to increase people's understanding and trust towards AVs. A large portion of these attempts involved some real or simulated AV riding experience, with different design and focus. In a general sense, the author summarized existing literature on AV trust development into four groups: information delivery, takeover improvement, risk analysis, and riding experience.

4.2. Information delivery

Research has been done to explore what kind of information should be displayed by an AV, and in what form it should be displayed. One popular choice is anthropomorphism, which is to design the vehicle interface to mimic human tones and facial expressions, hoping to reduce human mistrust by depicting the machines as more "human" [22]-[25]. Another technique, which has been adopted by many designers, is to display a complete set of information about the vehicle's surroundings (vehicles, traffic signs, pedestrians) as well as its planned movement. This technological transparency will portray the AV as both intelligent and capable [26], [27]. A similar idea is to use sound, lighting, animation, and other feedback to indicate the vehicle's current status and try to raise the driver's attention, which is generally found useful [28], [29].

4.3. Takeover Improvement

In a simulated takeover training experiment, the AV is perceived as either Level 2 with advanced driver's assistance or Level 3 with conditional automation. In either case, the researchers deliberately add system failures and try to measure the participant's takeover response. In [30], the difference was measured between no training, video training, and the monitor simulator training group, while in [31], it was the video, low-fidelity VR, and high-fidelity VR training group. In all cases, training has a positive impact on the takeover response while the more immersive tools tend to achieve better results. Trust is improved by assuring drivers that in the case of a real system failure, they have been prepared to handle the situation smoothly.

4.4. Risk Analysis

Researchers have been trying to understand the root of people's mistrust towards AVs, and much work can be summarized as an investigation of the "internal" and "external" risks. The internal risk is associated with the AD system's perceived reliability, while the external risk is about the environmental conditions [32]. Studies have shown that external risk, regardless of traffic or weather, is not a major factor [33]. Rather, the internal risk, which is linked to people's fear and bias, affects the evaluation of the technology. In multiple experiments, researchers found that the participants consistently degraded the performance of AVs when compared to human-driven vehicles even though the driving style was exactly the same [34]. Based on such observations, it is reasonable to argue that work should be done to help people reduce bias and judge AVs wisely.

4.5. Riding Experience

The most effective way to change people's attitude towards AVs is to let them ride in one in traffic. However, due to safety concerns and legal restrictions, such an attempt is not always feasible. As a result, researchers have come up with several alternatives to provide close-to-real AV experience. One choice is to provide AV riding in a closed testing field at a relatively low speed. For instance, Paddeu et al's measured comfort and trust on a shared autonomous shuttle [35], while Liu & Xu demonstrated the capabilities of an AV to change the ambivalent group to be more positive [36]. Another option is to let a human driver control the vehicle but create the illusion of AD. In [37], the driver was physically hidden from the passenger, and in [38] the passenger wore a VR headset, which received the vehicle movement information and got the corresponding update in the digital twin.

4.6. Previous Simulator Research

Our previous Drive Right research utilized an integrated simulation platform that leveraged the SVL Simulator, Apollo 5.0, and Autoware Auto. Five short scenarios were designed that involved challenging traffic conditions, and a human versus AD driving experiment was conducted. The objective was to show that AD was capable of handling complex traffic conditions and might yield better performance than humans in some circumstances. During the AD demonstration, a set of environmental information was displayed on the user interface to help explain the vehicle's behavior. A study with 28 participants showed that this educational demonstration could effectively decrease participants' perceived risk and increase the perceived usefulness of AD.

Compared to the previous study, our new design adopts an interactive approach with several improvements. First, the simulation environment is enhanced from the flat screen display to Virtual Reality. Consequently, the vehicle's view is changed from the third-person bird-eye to the first-person driver's seat. In addition, participants now have the freedom to turn on and off the autopilot mode at will, which was not available in the past study. The five short scenarios are replaced by three extended ones to provide a more in-depth driving experience. In general, the focus has been changed from the low-level demonstration and explanation to the high-level interaction. We hope this will help the participants form a good understanding of AVs and gain transferable knowledge about real vehicles.

5. Experiment Design

5.1. Carla

Carla is an open-source driving simulator introduced for AD algorithm development and validation research. Its rigorous environmental assets, complete sensor suite, and full control over all actors make it a suitable platform to conduct AV-related experiments. The research team chose to use Carla to take advantage of its well-designed mainframe so that significant work can be saved from developing a new simulator and more focus can be put on designing the study and exploring the research questions.

5.1.1. Carla VR

While the standalone Carla package was built in the 3D environment using Unreal Engine 4 (UE4), it did not come with VR capability. As a result, the research team had to add the OpenXR plugin and rebuild the project to enable rendering on an Oculus Quest 2 headset. To achieve this, the Carla project source code and a Carla-customized fork of UE4 were first downloaded from the official platform. Then, the UE4 was built using Visual Studio 2019, Windows 8.1 SDK, x64 Visual C++ Toolset, .NET framework 4.6.2, and the Carla server & client were compiled using the x64 Native Command Tool. To set the OpenXR, the plugin was first enabled inside the Carla UE4 project and then activated through the Oculus Link in the Meta Oculus application. Finally, the OpenXR runtime for Oculus was installed and added to the environmental variables. In this way, if the project requires another headset in the future, it can be easily implemented by replacing the path and re-compiling the project.

5.2. Server-Client Configuration

The Carla simulator has a server and a client. The server is responsible for the construction and maintenance of the Carla world, which includes but is not limited to displaying and updating the 3D model, creating vehicles and pedestrians, collecting simulated data, and handling all collision events. The server communicates with the client, which is a Python-based backend program built upon the Pygame package. The Python client receives the vehicle sensor data from the server, executes the corresponding planning, control, and prediction module, and sends back the vehicle control command (steer, acceleration, brake). Meanwhile, the client displays an animation window to keep track of the player's vehicle in the third-person view. After receiving the control information, the server updates the vehicle's update and calls off an execution cycle. The communication between the server and the client as well as the data transmission is handled by Carla's internal protocol and cannot be easily accessed by the third-party developers.

Rendering high-quality VR simulation in real-time was very computationally intensive, even with high-performance CPUs and GPUs. To maximize the quality of the simulation, we separated the server and client into two machines, which were connected using an ethernet cable, and communicated via the TCP port. A Cat6 Ethernet cable was used in this case to support the data transmission to a maximum rate of 150Mbps. This configuration shared the computational pressure and allowed each machine to run at a smooth state. In our setup, the server machine was a desktop equipped with an i7-11th CPU and an Nvidia 3070 GPU with 12GB of dedicated memory, while the client machine was a laptop with an i7-9th CPU and an Nvidia 1080 GPU with 8GB of dedicated memory.

5.3. Vehicle Mesh Rendering

Since Carla is designed primarily for AD algorithm research validation, it shows vehicles in the third-person view, and all vehicles have a mesh and texture with a low Level of Detail (LOD). To use Carla in the VR application in the first-person view, a high LOD vehicle with interior modeling must be imported from an outside source. After searching and comparing a variety of models, an Audi A6 model was selected from the Car Configurator Project and cleared of irrelevant nodes (Fig. 2, Fig. 3). This model was developed by Epic Games and supports a free license when working with the Unreal Engine.

Fig. 2. Audi Vehicle Model Exterior View.

Fig. 3. Audi Vehicle Model Interior View.

5.4. AutoAttachCamera

Since Carla contained no event handling for our newly imported Audi A6 model, a handler was created based on its internal Tesla Model 3 as the two vehicles shared approximately the same dimension and hitbox. In addition, a Blueprint class called *AutoAttachedCamera* was developed, which actively looked for a player-controlled Tesla Model 3 (Fig. 4) and then automatically disabled its LOD mesh rendering and replaced that with the high LOD Audi A6 rendering (Fig. 5). View was also attached to the Audi vehicle's driver's seat as in first person. If a previous player's vehicle was destroyed and a new one had been generated, the camera would automatically move to the new vehicle. In this way, the spawning event was properly handled between the server and the client. This method would not only help avoid potential conflicts among the mesh, skeleton, and sensors but also optimize the performance by showing the high-fidelity model and calculating the collisions using considerably fewer polygons (Fig. 6).

Fig. 4. Low Level of detail Tesla Model 3 third-person tracking view in Carla client.

Fig. 5. High level of detail Audi Model third-person tracking view in Carla client.

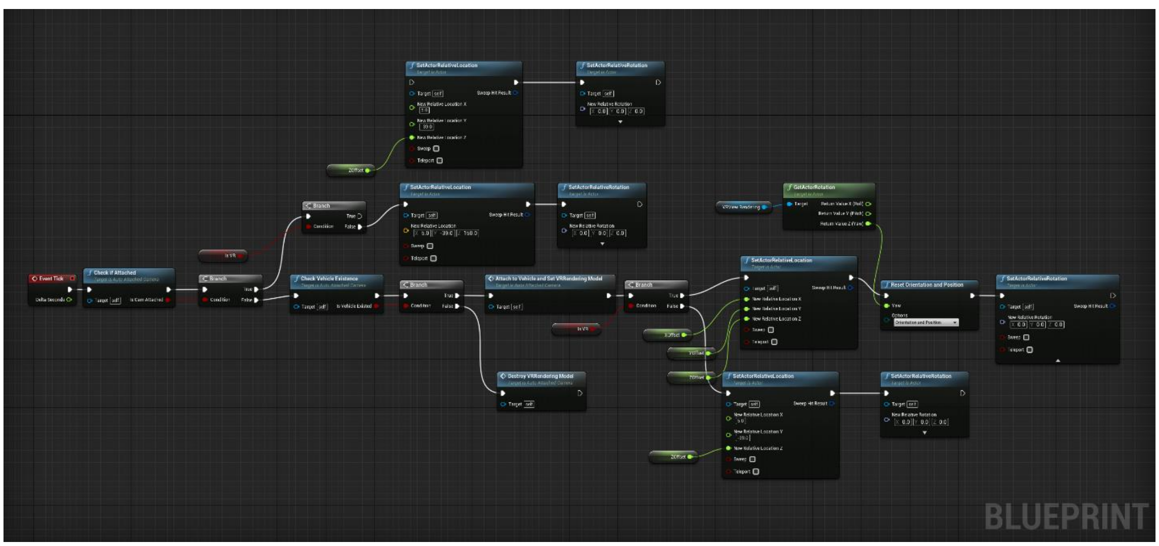


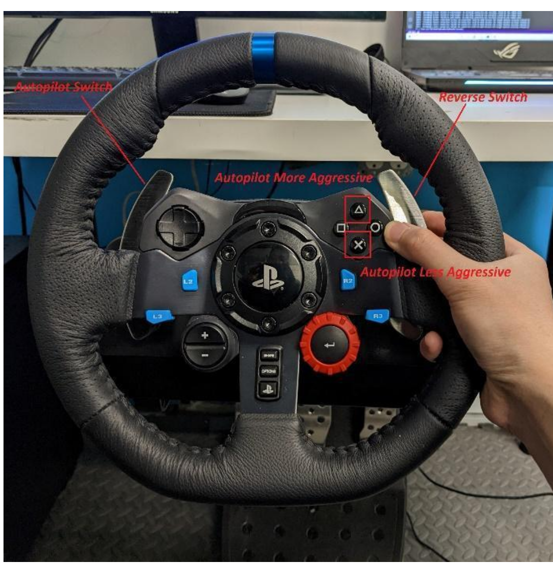
Fig. 6. AutoAttachedCamera Blueprint design elaborated.

5.5. Animation and User Interaction

The animation of the steering wheel, speedometer, and tachometer was handled by ControlRig, an animation object inside the UE4. Notice that since the vehicle's interior was not part of Carla's original design, information could not be accessed through its internal server-client protocol. Therefore, a standalone Flask server was created as an additional platform to allow the storage and exchange of data. At each control iteration, data was posted from the Python client to the Flask server and read by the Carla server as JSON files. The Carla server then exacted the values and applied them to the ControlRig object to update the animation of the steering wheel, speedometer, and tachometer. The vehicle could also produce dynamic engine sound as the velocity changes. The original sound wave was extracted from the Car Configurator project and edited using Audacity and FL Studio to derive audio files for different states. Then, the audio of different states was mixed using SoundCue, an audio profile object inside UE4, to support continuous velocity change.

5.6. Logitech G29

Logitech G29 is a racing force steering wheel & pedal set that is suitable for various driving tasks. In our simulator, G29 played two different roles. In the manual mode, the user uses the steering wheel to control the direction of the vehicle, and the throttle and brake pedals to adjust the speed. The vehicle is assumed to have an automatic gear shift so that no input from the clutch or the shifter is required. Systematic tests have shown that the processing time from the user input to the simulator response takes less than 100 microseconds, and therefore could be safely neglected.



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In our human study, drivers could drive manually or engage the autonomous mode by pulling the switch on the left side of the steering wheel. To exit the autonomous mode, they could pull the switch again or lightly press the brake pedal. The switch on the right side of the wheel was used to toggle the reverse mode. Note that in both the manual and autonomous modes, the physical steering wheel of the simulator perfectly mimicked the virtual wheel in the simulated car model (Fig. 7). This helped reduce any sensing discrepancy between the physical wheel and the simulation while minimizing the discontinuity during a driving mode switch.

5.7. Wheel Match

The wheel position match was easy to implement in the manual mode, as the controller could simply read the physical wheel input and reflect that on the simulator. In the autonomous mode, however, it was the physical wheel trying to match the simulated wheel position. In addition, G29 contained no support to command the wheel position directly, and the rotation was achieved by controlling its internal motor's rotational force and friction using NodeJS. The implementation came from the guidance on [39], which itself referred to the Linux kernel on-wheel support. Force could be adjusted on a scale of 0 to 1 in either direction, while friction had a minimum of 0 and a maximum of 1 to counter the movement. With direct access to the force and friction, the next step was to implement a PID controller which took in the difference between the simulated steering angle and the actual physical steering angle and output the desired force and friction. To keep the control system clean, friction was kept constant while the magnitude and the direction of the rotation force were adjusted to counter the position error. Fig. 8 drawn from an extended data collection period shows that the physical wheel could match the position of the simulated wheel with negligible delay and overshoot.

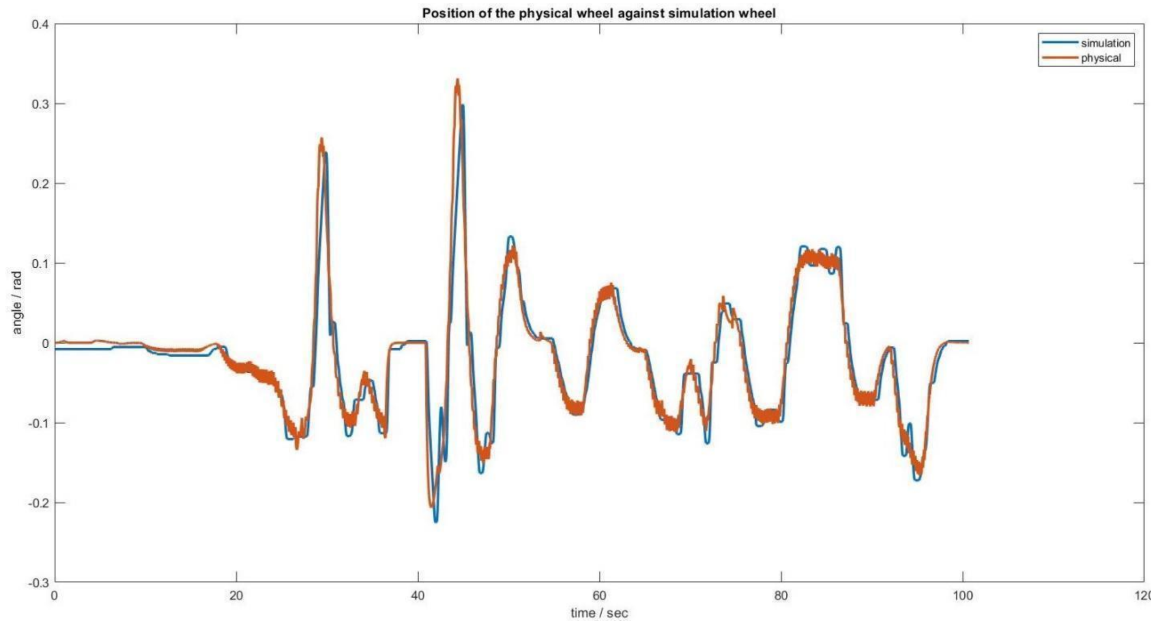

Fig. 8. Position of the physical wheel against simulation wheel.

5.8. Scenarios

Three scenarios were introduced in this study: rural, city, and highway. All scenario maps were imported directly from Carla environmental assets with no further modification. In addition, they were designed to guide users to gradually get used to the interaction with the AV, understand its capabilities, and start building confidence in it.

5.8.1. Rural

The rural scenario was a representation of the suburban environment, consisting mostly of trees, shrubs, one-lane country roads, and stop signs at intersections. This scenario served as a familiarization step, in which the participants tried to actively control the vehicle with the steering wheel and pedals in the manual mode, and let the vehicle drive itself in the autonomous mode. Since the rural scenario enforced simple road conditions and low vehicle speed, participants could get used to the simulation environment and vehicle controls in a relaxed setting. No other vehicles were added to the map to help keep the tutorial clean and simple (Fig. 9).

Fig. 9. Rural scenario in the first-person driver's seat view

5.8.2. City

The city scenario was populated with buildings, traffic lights, and complex road crossings. In this scenario, participants were not required to drive and were asked to turn on the autonomous mode and watch the vehicle navigate by itself. The predefined route would guide the AV to go through several conditions such as sharing the road with conventional vehicles, merging at an unprotected intersection, waiting for traffic signals, and yielding to pedestrians. Participants could resume manual control at any time if they felt unsafe or would like to handle an emergency situation. The goal of this scenario was to show the capabilities of an AV in a complex city environment to help participants further increase understanding and trust (Fig. 10).

Fig. 10. City scenario in the first-person driver's seat view.

5.8.3. Highway

The highway scenario was a three-lane express road with no crossings and cyclists (Fig. 11), and several NPC vehicles were added with varying velocities and driving behaviors. In this scenario, participants had the ability to switch freely between manual and autonomous driving. In addition, the AD supported three different behaviors: cautious, normal, and aggressive. In the cautious mode, the vehicle had a speed limit of 55 mph, contained soft acceleration & brake, and stayed in the rightmost lane. In the normal mode, the vehicle had a speed limit of 65 mph, contained normal acceleration & brake, and stayed in the middle lane. In the aggressive mode, the vehicle had a speed limit of 75 mph, contained hard acceleration and brake, and also stayed in the middle lane. In all three modes, the AV could automatically take over another vehicle that was driving at a lower speed. Takeover response was prioritized to use the left lane but could be changed to the right lane if the left lane was blocked. Participants were encouraged to actively use AD to experience its different driving behaviors, and they could change the behavior using the up & down buttons on the steering wheel e.g., from cautious to normal to aggressive (Fig. 7). The three AD driving behaviors were not available in the previous scenarios primarily for two reasons. First, in the rural and city scenario, the vehicle had a relatively low speed limit and different driving styles would not show much difference. Second, we wanted to increase the complexity of control one step at a time so that participants did not get overwhelmed and withdraw from the study.

Fig. 11. Highway scenario in the first-person driver's seat view. Current autonomous driving mode is set to cautious, other available options: normal, aggressive.

6. Experiment

6.1. Participants

We recruited 36 participants to join the study via email and social media. To qualify for the study, the participant must meet all of the following requirements: be older than 18 years old and less than 75; have a valid driver's license and at least three months of independent driving experience; not have a police-reported crash within the last year; have normal or correct-to-normal vision and hearing (contact lens allowed); does not have a history of migraine headsets, claustrophobia, or motion sickness; is not currently pregnant; and has no prior riding experience with autonomous vehicles (which does not include cruise control, lane keeping assist, forward collision warning, emergency brake, and other ADAS features). In addition, participants were carefully selected so that most of them do not have a solid engineering background or understanding of AVs.

Our participant group consisted of 18 males, and 18 females and had a mean age of 25.5 years. The participants were compensated with a $25 Amazon gift card for taking part in the study. If they decided to quit in the middle of the study for any reason, they still got compensated. This study was approved by the Institutional Review Board (IRB) at the University of Pennsylvania and all participants gave their informed written consent.

6.2. Survey

The effectiveness of our simulator was measured through the survey instrument. Before the simulator, participants were asked to assess their understanding of AVs, and the choices included: “I hear about it from the news and social media but know little about it”, “I know the vehicle uses sensors and artificial intelligence but have no understanding of the technology”, “I have a basic understanding of the sensor data and algorithms running on an autonomous vehicle”, “I have a decent understanding of the algorithms and software stacks running on an autonomous vehicle”. As filtered by our pre-selection process, we expected most participants to select choice one or two, as the benefit of the simulator would not be maximized to those already with a good understanding of AVs. The next part was AV ratings and included questions from five different categories: perceived risk (PR), perceived usefulness (PU), perceived ease of use (PE), trust (TR), and behavioral intention (BI). Each category consisted of three questions while the categorization was not explicitly shown in the survey (Tab. 1). The fifteen questions were adapted from the survey design in [40]-[43] and modified to fit the need of this study. They used the five-point Likert scale ranging from $1 = Strongly\ Disagree$ to $5 = Strongly\ Agree$.

After the simulator study, the fifteen questions were asked again to measure any attitude change. Participants were given a different sheet and could not refer to their previous answers. Given that the gap between the initial survey and the ending survey was about 30 minutes, participants would likely forget what they had answered before and therefore would have to reevaluate the questions. This helped disentangle the connection from the initial survey and made the simulator more accountable for any noticeable difference. The remaining questions were all qualitative, including participants' general idea of using a driving simulator, their preference for AD driving behavior, and their additional questions and comments for the study.

TABLE 1

FIFTEEN QUANTITATIVE SURVEY QUESTIONS

PR 1	I am worried about the safety of autonomous driving technology.
PR 2	I am worried about the interaction of an autonomous vehicle with conventional vehicles.
PR 3	I am worried that autonomous driving system failure or malfunction may cause accidents.
PU 1	Using an autonomous vehicle will allow me to conduct non-driving related tasks.
PU 2	Using an autonomous vehicle will increase my driving safety and efficiency.
PU 3	Using an autonomous vehicle will be useful when I am physically or mentally impaired.
PE 1	Learning to operate an autonomous vehicle would be easy for me.
PE 2	Interacting with an autonomous vehicle would not require a lot of my mental effort.
PE 3	I think it is easy to get an autonomous vehicle to do what I want to do.

TR 1	I believe that autonomous vehicles can take me safely to my destination.
TR 2	I believe that autonomous vehicles can handle most traffic conditions.
TR 3	I believe that autonomous vehicles are as reliable as my own driving.
BI1	I intend to ride in an autonomous vehicle in the future.
BI2	I expect to purchase an autonomous vehicle in the future.
BI3	I plan to introduce autonomous vehicles to my family and friends.

6.3. Procedure

The research team sent out the recruitment information via email and social media. Participants who contacted us and met the requirements were given a brief introduction about the study and invited to come to our research lab. Upon arrival, the researchers greeted them and walked them through the informed consent form. After the participants read and signed the consent form, the researchers asked them to fill in the first part of the survey. Then, we displayed a three-minute video introducing the five levels of automation [44]. The video was a plain explanation of the vehicle’s capabilities at each level and should not have much effect on the participants’ views. The purpose of showing this video was to give the participants some background information so that we could explain to them that our simulator was designed at Level 4. After the warmup, the participants took a seat in the simulator setup (Fig. 12), while we helped them adjust the seat position and calibrate the VR headset. Before they tried the simulator, we gave them a quick walkthrough on the control of the steering wheel and pedals. Since most parts were identical to a real vehicle, participants generally became comfortable very quickly. Then, they put on the VR headset and tried all three scenarios as described in the previous sections. In each scenario, they were asked to drive along a predefined route with a preset destination, but with the freedom to switch between the manual and autonomous mode at any time. After the participants finished all three scenarios, we gave them the second part of the survey and answered any additional questions, comments, or concerns.

Fig. 12. Simulator demonstration: left monitor shows Carla server first person driver's seat view; right monitor shows the Carla client third person tracking view.

7. Analysis

7.1. Initial Analysis

Of the 36 participants, 10 stated that they had a limited understanding of AVs, 17 answered that they knew the vehicle uses sensors and artificial intelligence, and 9 answered that they had a basic understanding of the different sensors and data running on an AV. This result matched our pre-selection process as those with no prior understanding would benefit most from our study. The means and standard deviations of the 5 categorical measurements were computed and shown in Tab. 2. For each category, the value was an unweighted average of its 3 questions. In addition, Cronbach's α coefficient was computed to validate the internal consistency of each category. The results have shown that the average ratings for all categories improved after the simulator demonstration, which means that participants' opinions towards AVs, in general, have shifted towards the positive direction (Fig. 13).

TABLE 2

MEAN, STANDARD DEVIATION, AND CRONBACH'S A

OF THE FIVE CATEGORICAL MEASUREMENTS

	Pre Simulator			Post Simulator		
	M	SD	Cronbach's a	M	SD	Cronbach's a
PR	3.44	0.75	0.69	2.95	0.84	0.82
PU	3.53	0.65	0.03	3.9	0.79	0.67
PE	3.35	0.73	0.57	3.72	0.71	0.52
TR	3.12	0.77	0.75	3.6	0.78	0.75
BI	3.63	0.84	0.78	3.98	0.76	0.82

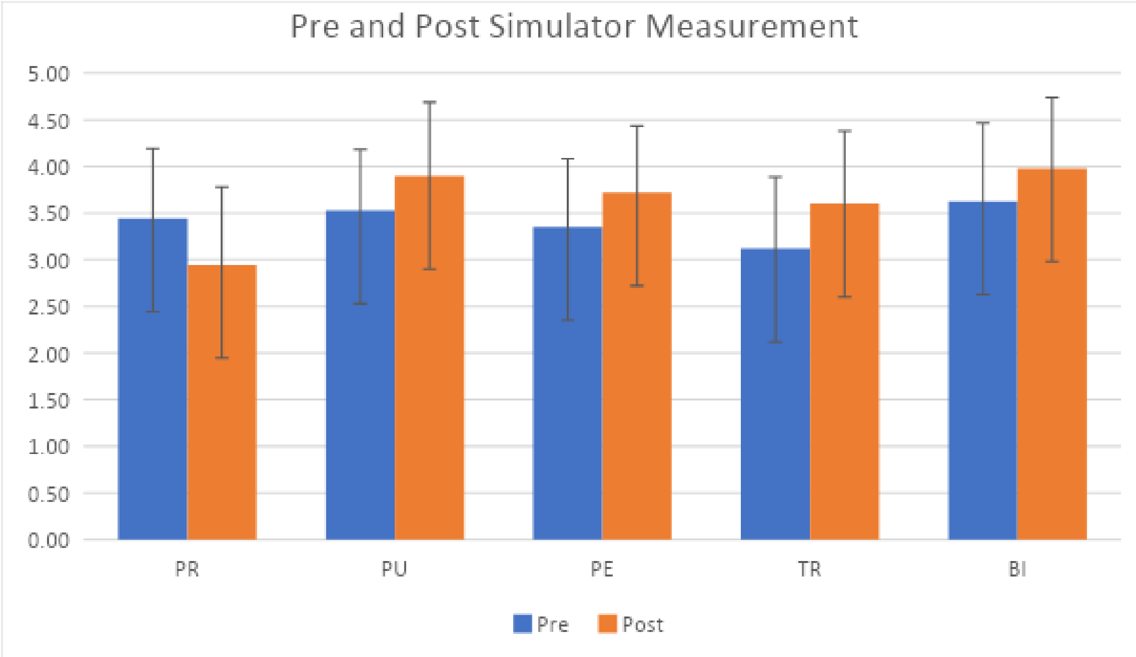

Fig. 13. Pre and Post Simulator Experiment Mean and Standard Deviation Plot.

1.1. Wilcoxon Signed-Rank Test

To verify that the changes in participants' attitudes were statistically significant, a Paired-Samples T Test was proposed. However, a prior Chi-Square Test showed strong evidence ($p < 0.01$) that the difference between the experimental data is not normally distributed for all categories, which violated the test assumption. Instead, a Wilcoxon Signed-Rank Test was applied for the data significance. It was shown that after the simulator experiment, there was a significant decrease in PR ($N = 33, p < 0.05$), a significant increase in PU ($N = 31, p < 0.05$), a significant increase in PE ($N = 28, p < 0.01$), a significant increase in TR ($N = 27, p < 0.01$), and a significant increase in BI ($N = 21, p < 0.01$). The significant improvement in all categories confirmed our question on the effectiveness of the simulator.

7.2. Mediating Effect

There was one interesting observation we described as the "mediating effect": participants who initially held low ratings towards AVs tended to give a better evaluation after trying the simulator, as they were figuring out that AVs had some intelligent decision-making process and could handle most traffic conditions; on the contrary, participants who initially gave high ratings tended to lower their evaluation due to the discrepancy between their expected AV experience and the actual simulated AV experience. In this case, three common reasons were given: the fear of handing over control, the lack of flexibility in the AD system, and the driving style mismatch between an AV and a human. With that in mind, the results in general still moved in the favorable direction of AVs.

7.3. Internal Consistency

The Cronbach's α coefficient showed different results before and after the simulator experiment but remained mostly consistent for each category. PR initially received a score of 0.69 and then increased to 0.82, indicating that the participants' evaluations of risk became better aligned across different perspectives. PE received a score of 0.52 before and 0.57 after, showing that the internal connection among the questions is only moderate and does not change much due to the simulator. TR received a score of 0.75 both before and after the simulator study, meaning that trust is a consistent measure and can be bonded to a certain standard. Similarly, BI received high scores around 0.8, suggesting that participants' opinions were aligned in terms of purchasing, riding, or introducing an AV. The counterintuitive part lied in PU, which initially showed no connections among the questions with a score of 0.03 but increased to 0.67 after the simulator trial. To explain this, we took a deeper look into the data and found that many participants originally gave a score of one for question PU1, which asked about AV assisting them in conducting non-driving-related tasks. In comparison, they gave very high scores for PU2: AV helping them increase driving safety and efficiency, and PU3: AV helping the driver that is physically and mentally impaired. The high inconsistency showed that although participants agreed on AD's assistance function and safety measures, they were very concerned about handing over control. After the simulator, however, participants established a sense of what AD felt like and became more confident in its performance, and this helped align the measures and contributed to a higher Cronbach's α

7.4. Comparison to Previous Study

The results of this study aligned with our previous study in the sense that it significantly decreased PR and increased PU. Furthermore, this study improved over the previous study in the sense that it successfully increased participants' PE of an AV and also BI to use one. TR was not explicitly measured in the previous study but has also shown improvement in this one.

We believed that the overall improved quality of this simulator study was due to the design of our interactive, immersive VR driving environment. In the previous study, participants could only drive entirely using the manual or autonomous mode, and the simulation was displayed on screen in the third-person view. Therefore, participants did not get much chance to experience the interaction and PE side of the system. In the new study, participants' complete control of the vehicle gave them some sense of the usability of the system and potentially contributed to a higher PE score. Furthermore, we conjectured that this novel and exciting simulation experience stimulated participants' interest in an AV and made them more inclined to get into a real one, as reflected in the BI part.

Despite the improvements, this new study did not completely overrun the previous one. First, in our Carla-based driving simulator, all sensor data and driving algorithms were processed in the backend and no system information was presented to the participants. In comparison, the previous study which used Apollo and Autoware always presented a complete picture of the environmental information as well as the vehicle's planned movements. In addition, Apollo and Autoware, being the highly-rated industrially used AD platforms, presented a more trustworthy source of AD than our customized software stacks in Carla. As mentioned before, the design of the previous study was about demonstration and education while the focus of this one was experience and interaction. If we were able to combine the advantages of both, we should be able to achieve a high-fidelity immersive platform that resembles a real vehicle.

8. Discussion

8.1. AD Behavior Choice

After the highway mode, participants were asked whether they like to stick to one AD behavior or use all three behaviors (cautious, normal, aggressive) interchangeably. About half of the participants stated that they preferred the availability of all three behaviors so that they could decide which one to use based on the time, safety, and comfortability requirements. Another group answered that it would be nice to have all three choices, but they would almost always use the aggressive one. The remaining participants said that they just wanted aggressive behavior, and according to them, if the AD was designed to prioritize safety, why not drive as fast as you can?

One interesting point raised here is about the intricacy of Level 4 AD. It is well-defined that at Level 3, the driver must be ready to take over at any time, while at Level, 5 no human intervention is needed. As something in between, the technical definition of Level 4 allows a driver to conduct non-driving related tasks such as taking a nap, replying to a message, or enjoying a movie. However, since Level 4 implies that the system is not one hundred percent self-contained, the mental pressure persists on human drivers. As a result, they may want to travel as fast as possible to end the state of “driving”. Assuming a different context, in which the AD is Level 5, or the person is riding inside the passenger’s seat, they may not feel obliged to monitor the vehicle’s state and can therefore focus on their own tasks. In this case, the riding experience will be like a train or a plane and the duration will become less noticeable.

8.2. Driver’s Background

We found that drivers’ evaluations of AVs were dependent on their own perceived driving skills. Participants who claimed to have a lot of driving experience tended to not trust the AD: they described the AD as safe but rigid, and definitely not a match for their own driving. On the contrary, participants who drove little and were concerned with their driving safety showed higher interest in AD and praised its safety measures. From this observation, we can reasonably infer that people who are more dependent on AD and who can benefit most from it will be more willing to embrace the technology, while people who heavily rely on and enjoy their own driving can be reluctant to accept it.

8.3. Simulator for AV Demonstration

The researchers discussed with the participants about the potential use of the simulator for AV demonstration. A typical example would be at auto dealerships, and most participants stated that they definitely want some simulation experience to help them make the purchase. While it is commonly agreed that driving simulators cannot provide the physical motion and the sense of alertness as in real traffic, they come with their unique advantages. First, a driving simulator is not constrained by the available conditions during a test drive and grants the flexibility to adjust the weather, lighting, traffic, and geographic parameters. Second, the simulator experience can take an extensive period for a thorough evaluation of the system with zero damage and cost, while the real test drive typically lasts for only a few minutes and may require a safety expert behind the wheel. Third, a real test drive may not always be feasible, for instance, during an auto show, a tech exhibition, or an academic conference, while the simulator is much easier to carry around and can be set up at any place. Fourth, an on-road test drive may strictly require the participant to possess a valid driver's license, and even insurance coverage, while a driving simulator is suitable for anyone from any background. Customers who come with their families and friends can have them try the simulator and give constructive feedback.

8.4. Simulator for AV Training

Driving simulators can also be a valuable tool for driver’s training and education. There are two cases: those with a valid driver’s license and those with not. During our study, participants with varying knowledge pointed out that just because someone holds a valid driver's license does not mean they should be legally allowed to use an AV. Currently, due to limited knowledge and experience, the public tends to blindly trust or untrust AVs to the extremes, which means they either use them with overconfidence or not use them at all. The researchers believe that vehicle automation, from driver’s assistance (Level 2) to full automation (Level 5), will undoubtedly reduce the driver’s pressure and workload with each increased level and intelligence. However, as long as these vehicles are not fully automated, some human intervention is still needed and the drivers must be prepared for the unexpected outcomes. Therefore, it is desirable that drivers can fully exploit the benefits of AVs while making intelligent decisions on how to use them. In this case, AV-specified training and qualification are recommended, and the driving simulator can make an excellent platform. For those without a driver's license, a simulator can also be a good tool to practice driving skills, and the users can learn to drive a conventional vehicle and interact with an AV at the same time.

9. Experiment Limitation and Future Work

9.1. Simulation Environment

Our Carla-based simulator, despite its vivid layout, vast selection of vehicles, and controllable environmental parameters, was not an exact capture of the real world. In order to achieve maximum effectiveness in AV training and demonstration, the simulator must have high fidelity, which requires its elements to resemble the real world as much as possible. While such a design can be challenging, it is not unachievable. For example, in the latest release of Unreal Engine 5, games showed an unprecedented level of detail and interactivity that has made it hard to differentiate between the virtual and the real world. Since our Carla-based simulator was built using the Unreal Engine 4, there is a lot of space for extension and improvement.

9.2. User Interaction

As mentioned before, our AD system ran in a black box and no decision information was presented to the driver. This was due to limited development time and the complexity of creating a well-framed user interface. In the future, we would like to add an extra layer of animation and allow the user to use the touch panel like a real vehicle. The touch command can be achieved using the Oculus Quest 2 controller, just like any standard VR application. The vehicle's AD information can be extracted from our backend program and displayed in a user-friendly way. In addition, we could link our simulator platform to Autoware using the official support on ROS bridge. By doing that, we can take advantage of Autoware's well-designed software stacks and user interfaces.

9.3. Steering Wheel & Pedals

The G29 steering wheel and pedal set are good for vehicle control but still somewhat different from a real car. In the next stage, we plan to move from the Virtual-Reality simulation into the Mixed-Reality framework, which means the participants will sit in a real car, wearing a headset, observe everything inside the car, and make control actions using the real steering wheel and pedals. The vehicle will be surrounded by a greenscreen, and the view through the windshield will be replaced by the simulation environment. In this case, users can drive the vehicle in the simulation world but will remain stationary at all times.

9.4. Virtual Reality Headset

The Oculus Quest 2 headset has an affordable price, long-term support, and community popularity, but comes with a low frame rate and resolution. This reduced animation quality can make the VR simulator a less pleasant experience and add gaps between the simulator and the real world. We are looking into more professional headsets such as Varjo to increase the resolution and frame rate and provide a better simulation experience.

9.5. Participants

Our small number of participants cannot faithfully represent all age, gender, and population groups. The future study requires a larger number of participants with varying backgrounds to achieve a more comprehensive and objective analysis.

10. Research Core conclusion

We presented in this work a Virtual Reality driving simulator and an interactive driving experience to improve people's understanding and trust of autonomous vehicles. To that effect, we adapted the open-source driving simulator Carla and designed several driving scenarios. A study with 36 participants showed that our simulator successfully improved participants' attitudes toward autonomous vehicles in terms of perceived risk, perceived usefulness, perceived ease of use, trust, and behavioral intention. We also presented the application of a simulator at driving schools, auto dealerships, and other places. Of course, limitations exist in terms of the hardware, software, and sampling method, and we aim to improve them in the future. Overall, the driving simulator and human study presented in this work acted as an innovative, pioneering effort to promote autonomous vehicle education, testing, and demonstration.

11. Applications

11.1. Further development

While the Virtual Reality development we developed in this research project offers a solid visual immersion in a driving situation, we acknowledge the mechanical immersion will need to be improved for a more realistic experience. Ideally, participants want to feel as if they were in an actual car with an actual steering wheel and actual pedals. As an example, the need to buckle the seat belt, while it is not an important part of the driving simulation scenario, is a psychological trigger that signals to drivers' brains that they are about to start the driving experience.

To address this mechanical immersion, the research team embarked in Year 3 on a translational research project where the driving simulator no longer relies on the Logitech steering wheel and pedals. In this new development, the simulation is transferred to an actual car with real brake and gas pedals and a real steering wheel. Participants then get the correct sensations, in terms of pedal resistance and steering wheel touch, which are what they are accustomed to.

A 2012 Toyota Prius was used for this development. Sensors based on Inertial Measurement Unit technology were developed so they could be strapped to the vehicle.

For this experiment, turnplates were acquired. The Toyota Prius tires were centered on these turn plates prior to the experiment. The experience was also improved by replacing the Meta Quest 2 with a Meta Quest Pro which offers a color video Passthrough. This Passthrough can be used by the simulation, so participants can see their hands, they can see the interior of the car during the driving simulation.

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Fig. 13. Translational Research of the Driving Simulation to an actual car

11.2. Field Deployment

The next logical step in our research will be to repeat the Trust assessment developed by testing participants in the new vehicle simulation. Additional surveys will be developed to assess the ecosystem validity of the enhanced driving simulator. We anticipate this new environment will be more apt at getting participants to react to the concept of automation. One limitation though is that the Logitech steering wheel was motorized while the first iteration of the in-car driving simulation does not provide physical rotation of the steering wheel. Participants are however exposed to a Virtual rotating steering wheel through the headset experience.

To complete the assessment in trust in self-driving, the research team contacted a leading driving school in the Philadelphia area. The owner was interviewed and shared her recent acquisition of two cars with Level 2 automation. She explained how current drivers get intimidated and actively seek training before they decide to try this type of technology. While they could easily try level 2 vehicles through a local dealership, they feel the need to reach out to formal driving instructors who have the experience and expertise to recognize driver anxiety. We anticipate driving schools can effectively deploy driving simulations, like the one proposed in this research, to help develop training and subsequently develop trust in self-driving.

12. Conclusion

12.1. Limitations

Our research project was limited to a cohort of 36 participants. We were however able to develop and test techniques that can be largely deployed to help train drivers to self-driving and subsequently increase their trust. In addition, all our experiments were run in a research lab. Further work, such as the one suggested with the partnership of a driving school, will be needed to establish the trust developed through the experiment.

12.2. Future Work

We anticipate that training in self-driving should be a multi-tier process. The simplest step is also the easiest to deploy. One needs to explain through a curriculum based on reading material and videos the various sensors on the car (camera, lidar, radar) and basic control technology so as to educate drivers and start getting their trust. A second step might be an accompanied ride through a dealership or a driving instructor who can demonstrate the technology on the road. Still, we anticipate that for anxious drivers or mature drivers who feel a need to learn by doing, the presence of an immersive driving simulator will allow them to play with the various controls and understand the car dynamics till they feel comfortable using these same self-driving controls on the road. Future work should explore the deployment of the in-car driving simulator proposed here in driving schools so as to develop a better field test of the technology.

13. Appendix

A. Survey Data
B. Consent Form
C. Research Products for this Project
    a. Journal Publications
    b. Conference Publications
    c. Thesis
    d. Research Students
D. Bibliography

A. Survey Data

The following tables present the data collected from 36 participants in five categories: perceived risk (PR), perceived usefulness (PU), perceived ease-of-use (PE), trust (TR), and behavioral intention (BI). Columns on the left represent the data before the simulator and columns on the right represent the data after the simulator.

	PR1	PR2	PR3	SUM	AVG		PR1	PR2	PR3	SUM	AVG
P1	4.00	4.00	4.00	12.00	4.00		2.00	4.00	3.00	9.00	3.00
P2	5.00	4.00	5.00	14.00	4.67		4.00	4.00	5.00	13.00	4.33
P3	5.00	5.00	5.00	15.00	5.00		2.00	3.00	3.00	8.00	2.67
P4	2.00	3.00	3.00	8.00	2.67		3.00	4.00	4.00	11.00	3.67
P5	3.00	3.00	4.00	10.00	3.33		4.00	4.00	3.00	11.00	3.67
P6	3.00	2.00	4.00	9.00	3.00		2.00	2.00	3.00	7.00	2.33
P7	5.00	5.00	5.00	15.00	5.00		3.00	3.00	3.00	9.00	3.00
P8	3.00	3.00	5.00	11.00	3.67		2.00	2.00	2.00	6.00	2.00
P9	4.00	4.00	4.00	12.00	4.00		1.00	2.00	1.00	4.00	1.33
P10	3.00	4.00	2.00	9.00	3.00		1.00	4.00	3.00	8.00	2.67
P11	2.00	2.00	3.00	7.00	2.33		2.00	2.00	4.00	8.00	2.67
P12	3.00	2.00	3.00	8.00	2.67		2.00	2.00	2.00	6.00	2.00
P13	2.00	2.00	3.00	7.00	2.33		3.00	5.00	4.00	12.00	4.00
P14	4.00	3.00	3.00	10.00	3.33		3.00	4.00	4.00	11.00	3.67
P15	2.00	2.00	3.00	7.00	2.33		2.00	2.00	3.00	7.00	2.33
P16	4.00	4.00	5.00	13.00	4.33		4.00	2.00	3.00	9.00	3.00
P17	2.00	4.00	4.00	10.00	3.33		5.00	4.00	4.00	13.00	4.33
P18	3.00	2.00	4.00	9.00	3.00		3.00	4.00	4.00	11.00	3.67
P19	3.00	4.00	4.00	11.00	3.67		3.00	2.00	4.00	9.00	3.00
P20	4.00	3.00	5.00	12.00	4.00		4.00	3.00	4.00	11.00	3.67
P21	4.00	4.00	4.00	12.00	4.00		3.00	2.00	2.00	7.00	2.33
P22	4.00	4.00	4.00	12.00	4.00		2.00	2.00	3.00	7.00	2.33
P23	4.00	2.00	5.00	11.00	3.67		2.00	2.00	2.00	6.00	2.00
P24	5.00	3.00	3.00	11.00	3.67		2.00	3.00	2.00	7.00	2.33
P25	3.00	1.00	4.00	8.00	2.67		2.00	3.00	2.00	7.00	2.33
P26	5.00	3.00	4.00	12.00	4.00		3.00	2.00	3.00	8.00	2.67
P27	3.00	4.00	3.00	10.00	3.33		2.00	2.00	2.00	6.00	2.00
P28	4.00	4.00	4.00	12.00	4.00		1.00	1.00	1.00	3.00	1.00
P29	4.00	4.00	4.00	12.00	4.00		4.00	4.00	4.00	12.00	4.00
P30	2.00	4.00	2.00	8.00	2.67		4.00	3.00	4.00	11.00	3.67
P31	3.00	3.00	4.00	10.00	3.33		4.00	3.00	4.00	11.00	3.67

P32	3.00	4.00	4.00	11.00	3.67		4.00	3.00	4.00	11.00	3.67
P33	3.00	1.00	4.00	8.00	2.67		4.00	3.00	4.00	11.00	3.67
P34	2.00	2.00	3.00	7.00	2.33		4.00	3.00	4.00	11.00	3.67
P35	2.00	2.00	3.00	7.00	2.33		4.00	3.00	4.00	11.00	3.67
P36	4.00	4.00	4.00	12.00	4.00		2.00	2.00	2.00	6.00	2.00

	PU1	PU2	PU3	SUM	AVG		PU1	PU2	PU3	SUM	AVG
P1	5.00	5.00	4.00	14.00	4.67		2.00	5.00	5.00	12.00	4.00
P2	2.00	4.00	5.00	11.00	3.67		4.00	4.00	5.00	13.00	4.33
P3	5.00	2.00	5.00	12.00	4.00		5.00	3.00	5.00	13.00	4.33
P4	4.00	4.00	2.00	10.00	3.33		1.00	3.00	2.00	6.00	2.00
P5	2.00	4.00	3.00	9.00	3.00		5.00	4.00	3.00	12.00	4.00
P6	4.00	3.00	4.00	11.00	3.67		4.00	4.00	4.00	12.00	4.00
P7	1.00	4.00	3.00	8.00	2.67		4.00	5.00	5.00	14.00	4.67
P8	4.00	4.00	1.00	9.00	3.00		4.00	5.00	5.00	14.00	4.67
P9	3.00	3.00	3.00	9.00	3.00		3.00	4.00	4.00	11.00	3.67
P10	1.00	4.00	4.00	9.00	3.00		2.00	4.00	4.00	10.00	3.33
P11	4.00	3.00	4.00	11.00	3.67		4.00	4.00	4.00	12.00	4.00
P12	2.00	2.00	4.00	8.00	2.67		3.00	3.00	3.00	9.00	3.00
P13	2.00	2.00	4.00	8.00	2.67		5.00	4.00	5.00	14.00	4.67
P14	3.00	2.00	2.00	7.00	2.33		5.00	4.00	4.00	13.00	4.33
P15	1.00	5.00	3.00	9.00	3.00		5.00	5.00	3.00	13.00	4.33
P16	1.00	3.00	3.00	7.00	2.33		1.00	3.00	2.00	6.00	2.00
P17	2.00	5.00	5.00	12.00	4.00		4.00	5.00	5.00	14.00	4.67
P18	4.00	4.00	3.00	11.00	3.67		2.00	4.00	2.00	8.00	2.67
P19	2.00	4.00	5.00	11.00	3.67		4.00	4.00	4.00	12.00	4.00
P20	5.00	4.00	2.00	11.00	3.67		5.00	5.00	4.00	14.00	4.67
P21	4.00	5.00	5.00	14.00	4.67		4.00	2.00	3.00	9.00	3.00
P22	4.00	2.00	3.00	9.00	3.00		5.00	5.00	5.00	15.00	5.00
P23	4.00	4.00	5.00	13.00	4.33		5.00	4.00	5.00	14.00	4.67
P24	2.00	3.00	5.00	10.00	3.33		5.00	5.00	5.00	15.00	5.00
P25	5.00	5.00	5.00	15.00	5.00		5.00	5.00	5.00	15.00	5.00
P26	3.00	4.00	4.00	11.00	3.67		4.00	3.00	4.00	11.00	3.67
P27	3.00	4.00	3.00	10.00	3.33		2.00	3.00	3.00	8.00	2.67
P28	5.00	2.00	3.00	10.00	3.33		5.00	4.00	4.00	13.00	4.33
P29	5.00	3.00	5.00	13.00	4.33		5.00	3.00	5.00	13.00	4.33
P30	4.00	5.00	5.00	14.00	4.67		2.00	5.00	5.00	12.00	4.00
P31	4.00	2.00	4.00	10.00	3.33		3.00	2.00	3.00	8.00	2.67
P32	4.00	3.00	3.00	10.00	3.33		4.00	3.00	4.00	11.00	3.67
P33	2.00	4.00	4.00	10.00	3.33		4.00	2.00	4.00	10.00	3.33
P34	3.00	4.00	5.00	12.00	4.00		3.00	4.00	4.00	11.00	3.67
P35	2.00	4.00	5.00	11.00	3.67		4.00	4.00	4.00	12.00	4.00
P36	4.00	4.00	4.00	12.00	4.00		4.00	4.00	4.00	12.00	4.00

	PE1	PE2	PE3	SUM	AVG		PE1	PE2	PE3	SUM	AVG
P1	4.00	1.00	3.00	8.00	2.67		5.00	4.00	3.00	12.00	4.00
P2	3.00	4.00	3.00	10.00	3.33		4.00	4.00	4.00	12.00	4.00
P3	3.00	2.00	3.00	8.00	2.67		3.00	2.00	5.00	10.00	3.33
P4	3.00	2.00	3.00	8.00	2.67		4.00	1.00	3.00	8.00	2.67
P5	3.00	3.00	3.00	9.00	3.00		5.00	5.00	5.00	15.00	5.00
P6	4.00	4.00	2.00	10.00	3.33		4.00	4.00	4.00	12.00	4.00
P7	1.00	1.00	1.00	3.00	1.00		2.00	1.00	2.00	5.00	1.67
P8	5.00	3.00	3.00	11.00	3.67		5.00	1.00	5.00	11.00	3.67
P9	3.00	4.00	3.00	10.00	3.33		4.00	3.00	4.00	11.00	3.67
P10	4.00	4.00	4.00	12.00	4.00		4.00	4.00	4.00	12.00	4.00
P11	3.00	3.00	4.00	10.00	3.33		3.00	4.00	3.00	10.00	3.33
P12	3.00	3.00	3.00	9.00	3.00		3.00	4.00	4.00	11.00	3.67
P13	4.00	4.00	4.00	12.00	4.00		5.00	5.00	5.00	15.00	5.00
P14	4.00	2.00	1.00	7.00	2.33		4.00	4.00	2.00	10.00	3.33
P15	3.00	4.00	5.00	12.00	4.00		4.00	4.00	4.00	12.00	4.00
P16	3.00	2.00	3.00	8.00	2.67		4.00	2.00	3.00	9.00	3.00
P17	4.00	4.00	3.00	11.00	3.67		5.00	5.00	2.00	12.00	4.00
P18	5.00	2.00	5.00	12.00	4.00		5.00	3.00	5.00	13.00	4.33
P19	5.00	4.00	3.00	12.00	4.00		4.00	2.00	3.00	9.00	3.00
P20	5.00	5.00	5.00	15.00	5.00		5.00	5.00	5.00	15.00	5.00
P21	4.00	3.00	3.00	10.00	3.33		4.00	2.00	3.00	9.00	3.00
P22	3.00	2.00	2.00	7.00	2.33		5.00	4.00	4.00	13.00	4.33
P23	4.00	2.00	4.00	10.00	3.33		4.00	2.00	4.00	10.00	3.33
P24	3.00	1.00	3.00	7.00	2.33		5.00	4.00	4.00	13.00	4.33
P25	5.00	5.00	4.00	14.00	4.67		5.00	5.00	4.00	14.00	4.67
P26	5.00	3.00	3.00	11.00	3.67		5.00	4.00	4.00	13.00	4.33
P27	4.00	3.00	3.00	10.00	3.33		4.00	4.00	3.00	11.00	3.67
P28	3.00	2.00	4.00	9.00	3.00		4.00	4.00	4.00	12.00	4.00
P29	4.00	4.00	3.00	11.00	3.67		5.00	5.00	3.00	13.00	4.33
P30	3.00	4.00	3.00	10.00	3.33		3.00	2.00	3.00	8.00	2.67
P31	5.00	5.00	1.00	11.00	3.67		4.00	2.00	2.00	8.00	2.67
P32	5.00	5.00	3.00	13.00	4.33		5.00	4.00	2.00	11.00	3.67
P33	4.00	4.00	3.00	11.00	3.67		4.00	4.00	2.00	10.00	3.33
P34	3.00	3.00	3.00	9.00	3.00		3.00	4.00	4.00	11.00	3.67
P35	4.00	4.00	3.00	11.00	3.67		4.00	4.00	4.00	12.00	4.00
P36	4.00	3.00	4.00	11.00	3.67		3.00	3.00	4.00	10.00	3.33

	TR1	TR2	TR3	SUM	AVG		TR1	TR2	TR3	SUM	AVG
P1	4.00	3.00	3.00	10.00	3.33		5.00	4.00	4.00	13.00	4.33
P2	4.00	2.00	3.00	9.00	3.00		4.00	2.00	4.00	10.00	3.33
P3	3.00	1.00	1.00	5.00	1.67		4.00	3.00	2.00	9.00	3.00
P4	4.00	4.00	2.00	10.00	3.33		4.00	3.00	1.00	8.00	2.67
P5	5.00	5.00	2.00	12.00	4.00		5.00	5.00	2.00	12.00	4.00
P6	3.00	4.00	2.00	9.00	3.00		4.00	4.00	3.00	11.00	3.67
P7	1.00	1.00	1.00	3.00	1.00		3.00	3.00	3.00	9.00	3.00
P8	4.00	4.00	4.00	12.00	4.00		5.00	5.00	5.00	15.00	5.00
P9	4.00	3.00	2.00	9.00	3.00		4.00	4.00	3.00	11.00	3.67
P10	4.00	4.00	4.00	12.00	4.00		4.00	4.00	4.00	12.00	4.00
P11	3.00	4.00	3.00	10.00	3.33		4.00	4.00	3.00	11.00	3.67
P12	3.00	3.00	3.00	9.00	3.00		3.00	2.00	3.00	8.00	2.67
P13	4.00	4.00	3.00	11.00	3.67		5.00	5.00	3.00	13.00	4.33
P14	4.00	2.00	2.00	8.00	2.67		3.00	3.00	2.00	8.00	2.67
P15	5.00	4.00	4.00	13.00	4.33		4.00	4.00	3.00	11.00	3.67
P16	4.00	3.00	2.00	9.00	3.00		4.00	3.00	3.00	10.00	3.33
P17	4.00	4.00	2.00	10.00	3.33		4.00	4.00	4.00	12.00	4.00
P18	4.00	2.00	3.00	9.00	3.00		5.00	5.00	2.00	12.00	4.00
P19	4.00	3.00	2.00	9.00	3.00		4.00	3.00	2.00	9.00	3.00
P20	4.00	4.00	4.00	12.00	4.00		5.00	4.00	4.00	13.00	4.33
P21	4.00	2.00	3.00	9.00	3.00		3.00	4.00	2.00	9.00	3.00
P22	3.00	4.00	3.00	10.00	3.33		4.00	4.00	3.00	11.00	3.67
P23	3.00	4.00	3.00	10.00	3.33		4.00	5.00	5.00	14.00	4.67
P24	2.00	1.00	2.00	5.00	1.67		5.00	5.00	5.00	15.00	5.00
P25	4.00	4.00	3.00	11.00	3.67		4.00	4.00	4.00	12.00	4.00
P26	2.00	2.00	2.00	6.00	2.00		3.00	2.00	1.00	6.00	2.00
P27	3.00	2.00	3.00	8.00	2.67		3.00	2.00	2.00	7.00	2.33
P28	2.00	2.00	2.00	6.00	2.00		3.00	2.00	3.00	8.00	2.67
P29	3.00	4.00	3.00	10.00	3.33		5.00	4.00	4.00	13.00	4.33
P30	4.00	5.00	5.00	14.00	4.67		4.00	5.00	5.00	14.00	4.67
P31	3.00	3.00	2.00	8.00	2.67		3.00	3.00	2.00	8.00	2.67
P32	3.00	2.00	3.00	8.00	2.67		2.00	3.00	2.00	7.00	2.33
P33	3.00	2.00	3.00	8.00	2.67		3.00	4.00	4.00	11.00	3.67
P34	4.00	4.00	3.00	11.00	3.67		4.00	4.00	4.00	12.00	4.00
P35	4.00	4.00	4.00	12.00	4.00		4.00	4.00	4.00	12.00	4.00
P36	3.00	4.00	3.00	10.00	3.33		4.00	4.00	5.00	13.00	4.33

	BI1	BI2	BI3	SUM	AVG		BI1	BI2	BI3	SUM	AVG
P1	3.00	3.00	2.00	8.00	2.67		3.00	3.00	3.00	9.00	3.00
P2	4.00	4.00	4.00	12.00	4.00		4.00	4.00	4.00	12.00	4.00
P3	4.00	4.00	4.00	12.00	4.00		5.00	5.00	4.00	14.00	4.67
P4	5.00	5.00	5.00	15.00	5.00		5.00	4.00	4.00	13.00	4.33
P5	4.00	4.00	4.00	12.00	4.00		5.00	5.00	5.00	15.00	5.00
P6	4.00	4.00	3.00	11.00	3.67		4.00	4.00	3.00	11.00	3.67
P7	1.00	1.00	5.00	7.00	2.33		2.00	2.00	5.00	9.00	3.00
P8	4.00	3.00	4.00	11.00	3.67		5.00	5.00	5.00	15.00	5.00
P9	3.00	3.00	3.00	9.00	3.00		3.00	3.00	3.00	9.00	3.00
P10	2.00	2.00	3.00	7.00	2.33		3.00	3.00	4.00	10.00	3.33
P11	4.00	4.00	3.00	11.00	3.67		4.00	4.00	3.00	11.00	3.67
P12	2.00	2.00	4.00	8.00	2.67		3.00	3.00	4.00	10.00	3.33
P13	4.00	3.00	4.00	11.00	3.67		4.00	3.00	4.00	11.00	3.67
P14	3.00	3.00	3.00	9.00	3.00		3.00	3.00	3.00	9.00	3.00
P15	5.00	5.00	4.00	14.00	4.67		5.00	5.00	5.00	15.00	5.00
P16	4.00	3.00	3.00	10.00	3.33		4.00	3.00	3.00	10.00	3.33
P17	4.00	4.00	4.00	12.00	4.00		5.00	5.00	5.00	15.00	5.00
P18	5.00	5.00	3.00	13.00	4.33		5.00	5.00	5.00	15.00	5.00
P19	4.00	3.00	3.00	10.00	3.33		4.00	3.00	4.00	11.00	3.67
P20	5.00	4.00	4.00	13.00	4.33		5.00	4.00	4.00	13.00	4.33
P21	4.00	4.00	4.00	12.00	4.00		3.00	2.00	2.00	7.00	2.33
P22	3.00	2.00	2.00	7.00	2.33		4.00	5.00	5.00	14.00	4.67
P23	2.00	3.00	2.00	7.00	2.33		5.00	4.00	4.00	13.00	4.33
P24	5.00	3.00	2.00	10.00	3.33		4.00	4.00	4.00	12.00	4.00
P25	5.00	5.00	5.00	15.00	5.00		5.00	5.00	5.00	15.00	5.00
P26	3.00	3.00	3.00	9.00	3.00		3.00	3.00	3.00	9.00	3.00
P27	4.00	4.00	3.00	11.00	3.67		4.00	4.00	3.00	11.00	3.67
P28	4.00	2.00	2.00	8.00	2.67		4.00	3.00	4.00	11.00	3.67
P29	5.00	5.00	5.00	15.00	5.00		5.00	5.00	5.00	15.00	5.00
P30	5.00	5.00	5.00	15.00	5.00		5.00	5.00	5.00	15.00	5.00
P31	3.00	3.00	4.00	10.00	3.33		3.00	3.00	5.00	11.00	3.67
P32	3.00	2.00	2.00	7.00	2.33		4.00	2.00	3.00	9.00	3.00
P33	4.00	4.00	3.00	11.00	3.67		5.00	4.00	3.00	12.00	4.00
P34	5.00	5.00	4.00	14.00	4.67		5.00	5.00	4.00	14.00	4.67
P35	4.00	4.00	4.00	12.00	4.00		4.00	4.00	4.00	12.00	4.00
P36	5.00	4.00	5.00	14.00	4.67		5.00	4.00	4.00	13.00	4.33

B. Consent Form

UNIVERSITY OF PENNSYLVANIA
RESEARCH SUBJECT
INFORMED CONSENT FORM

Protocol Title:	Evaluating the Effectiveness of a Driving Simulator for Autonomous Driving Education
Principal Investigator:	Rahul Mangharam COMP INFO SCI-269 MOORE 200 S 33RD ST Philadelphia 215-898-2442
Emergency Contact:	Zhijie Qiao 812-236-3725

Research Study Summary for Potential Subjects

You are being invited to participate in a research study. Your participation is voluntary and you should only participate if you completely understand what the study requires and what the risks of participation are. You should ask the study team any questions you have related to participating before agreeing to join the study. If you have any questions about your rights as a human research participant at any time before, during or after participation, please contact the Institutional Review Board (IRB) at (215) 898-2614 for assistance.

The research study is being conducted to explore the effectiveness of a driving simulator to help the public gain understanding and trust in autonomous vehicles, including their advantages and limitations.

If you agree to join the study, you will be asked to complete the following research procedures: answer initial survey questions; drive through three testing scenarios; answer reflection survey questions. Your participation will last for up to **1 hour**.

Through this study, you will gain hands-on experience on autonomous vehicles using a simulator and potentially expand your understanding of the technology. This study involves no more than minimal risk. However, your view towards autonomous driving technology might be affected by today's experience.

Please note that there are other factors to consider before agreeing to participate such as additional procedures, use of your personal information, costs, and other possible risks not discussed here. If you are interested in participating, a member of the study team will review the full information with you. You are free to decline or stop participation at any time during or after the initial consenting process.

Why am I being asked to volunteer?

You are being asked to take part in a research study. Your participation is voluntary which means you can choose whether to participate or not. Before you decide, you will need to know the purpose of the study, the possible risks and benefits of being in the study and what you will have to do if you decide to participate. The research team is going to talk with you about the study and give you this consent document to read. You do not have to make a decision now; you can take the consent document home and share it with friends and family.

If you do not understand what you are reading, do not sign it. Please ask the researcher to explain anything you do not understand, including any language contained in this form. If you decide to participate, you will be asked to sign this form and a copy will be given to you. Keep this form, in it you will find contact information and answers to questions about the study. You may ask to have this form read to you.

What is the purpose of the study?

The purpose of the study is to explore the effectiveness of a driving simulator to help the public gain understanding in autonomous vehicles. The results will be used to complete and publish a research paper with all personal identifiers removed.

What are the criteria to participate in this study?

You must meet all following requirements:

- Fall into the age group: 18-75.
- Have a valid driver's license and three months of independent driving experience.
- Have normal or correct-to-normal vision and hearing (contact lens allowed).
- No pregnancies, history of migraine headaches, claustrophobia, or motion sickness.
- No police-reported crashes within the last year.
- No prior experience with autonomous driving (does not include cruise control, lane keeping assist, forward collision warning, or emergency break).

Why was I asked to participate in this study?

You are being asked because you meet our criteria and volunteer to join the study.

How long will I be in the study?

The study is one-time and will take up to 1 hour.

Where will the study take place?

You will be asked to come to our research lab, located at 34th St & Lancaster Ave, Philadelphia.

What will I be asked to do?

- You will answer questions about your initial view on autonomous driving.
- You will drive through three testing scenarios we have design in the simulator.
- You will answer reflection questions about your simulator experience.

What are the risks?

This study involves no more than minimal risk (the probability and magnitude of harm or discomfort anticipated in the research are not greater in and of themselves than those ordinarily encountered in daily life or during the performance of routine physical or psychological examinations or tests). You might feel slight discomfort when using the virtual reality device, which is a normal side effect. The feelings will disappear in 20 minutes after taking the equipment off.

How will I benefit from the study?

You will gain hands-on experience on autonomous driving using a simulator and potentially expand your understanding of the technology. In addition, your participation could help us understand if a driving simulator is a good way to educate the public on autonomous vehicles.

What other choices do I have?

Your alternative to being in the study is to not be in the study.

What happens if I do not choose to join the research study?

You may choose to join the study or you may choose not to join the study. Your participation is voluntary. There is no penalty if you choose not to join the research study. You will lose no benefits or advantages that are now coming to you or would come to you in the future.

When is the study over? Can I leave the study before it ends?

The study is expected to end after all participants have completed all visits and all the information has been collected. The study may be stopped without your consent for the following reasons:

- You have not followed the study instructions.
- The Principal Investigator, the sponsor, or the Office of Regulatory Affairs at the University of Pennsylvania can stop the study anytime.

You have the right to drop out of the research study at any time during your participation. There is no penalty or loss of benefits to which you are otherwise entitled if you decide to do so. Withdrawal will not interfere with your future care. If you no longer wish to be in the research study, please contact Zhijie Qiao at zhijie@seas.upenn.edu.

How will my personal information be protected during the study?

We will do our best to make sure that the personal information obtained during the course of this research study will be kept private. However, we cannot guarantee total privacy. Your personal information may be given out if required by law. If information from this study is published or presented at scientific meetings, your name and other personal information will not be used. The Institutional Review Board (IRB) at the University of Pennsylvania will have access to your records. After your survey is recorded, all personal identifiers will be removed. The survey questions contain no private identifiable information and cannot be used to re-identify any specific individual.

What may happen to my information collected on this study?

Your information will be used to write a research paper, with all personal identifiers removed.

Future Use of Data
Your information will be de-identified. De-identified means that all identifiers have been removed. The information could be stored and shared for future research in this de-identified fashion. The information may be shared with other researchers within Penn, or other research institutions, as well as pharmaceutical, device, or biotechnology companies. It would not be possible for future researchers to identify you as we would not share any identifiable information about you with future researchers. This can be done without again seeking your consent in the future, as permitted by law. The future use of your information only applies to the information collected on this study.

What happens if I am injured from being in the study?

We will offer you the care needed to treat injuries directly resulting from taking part in this research. We may bill your insurance company or other third parties, if appropriate, for the costs of the care you get for the injury, but you may also be responsible for some of them. There are no plans for the University of Pennsylvania to pay you or give you other compensation for the injury. You do not give up your legal rights by signing this form. If you think you have been injured as a result of taking part in this research study, tell the person in charge of the research study as soon as possible. The researcher's name and phone number are listed in the consent form.

Will I have to pay for anything?

There will be no cost for this study.

Will I be paid for being in this study?

The study will give a $25 Amazon Gift Card as compensation.

Who can I call with questions, complaints or if I'm concerned about my rights as a research subject?

If you have questions, concerns or complaints regarding your participation in this research study or if you have any questions about your rights as a research subject, you should speak with the Principal Investigator listed on page one of this form. If a member of the research team cannot be reached or you want to talk to someone other than those working on the study, you may contact the Office of Regulatory Affairs with any question, concerns or complaints at the University of Pennsylvania by calling (215) 898-2614.

May we contact you in a later time for further information regarding the study? ☐ Yes ☐ No

When you sign this form, you are agreeing to take part in this research study. If you have any questions or there is something you do not understand, please ask. You will receive a copy of this consent document.

______________________ ______________________ ______________________

Printed Name of Subject Signature of Subject Date

C. Research Products for this Project

a. Journal Publications

1. Qiao, Z., Loeb, H., Gurrla, V., Lebermann, M., Betz, J., & Mangharam, R. (2022). Drive Right: Autonomous Vehicle Education through an Integrated Simulation Platform. *SAE International Journal of Connected and Automated Vehicles*, *5*(12-05-04-0028).
2. Jazayeri, A., Martinez, J. R. B., Loeb, H. S., & Yang, C. C. (2021). The Impact of driver distraction and secondary tasks with and without other co-occurring driving behaviors on the level of road traffic crashes. *Accident Analysis & Prevention*, *153*, 106010.
3. Loeb, H. S., Vo-Phamhi, E., Seacrist, T., Maheshwari, J., & Yang, C. (2021). *Vehicle Automation Emergency Scenario: Using a Driving Simulator to Assess the Impact of Hand and Foot Placement on Reaction Time* (No. 2021-01-0861).
4. Tremoulet, P. D., Seacrist, T., Ward McIntosh, C., Loeb, H., DiPietro, A., & Tushak, S. (2020). Transporting children in autonomous vehicles: An exploratory study. *Human factors*, *62*(2), 278-287.
5. Seacrist, T., Douglas, E. C., Hannan, C., Rogers, R., Belwadi, A., & Loeb, H. (2020). Near crash characteristics among risky drivers using the SHRP2 naturalistic driving study. *Journal of safety research*, *73*, 263-269.
6. Seacrist, T., Sahani, R., Chingas, G., Douglas, E. C., Graci, V., & Loeb, H. (2020). Efficacy of automatic emergency braking among risky drivers using counterfactual simulations from the SHRP 2 naturalistic driving study. *Safety science*, *128*, 104746.
7. Seacrist, T., Maheshwari, J., Sarfare, S., Chingas, G., Thirkill, M., & Loeb, H. S. (2021). In-depth analysis of crash contributing factors and potential ADAS interventions among at-risk drivers using the SHRP 2 naturalistic driving study. *Traffic injury prevention*, *22*(sup1), S68-S73.
8. Loeb, H. S., Vo-Phamhi, E., Seacrist, T., Maheshwari, J., & Yang, C. (2021). *Vehicle Automation Emergency Scenario: Using a Driving Simulator to Assess the Impact of Hand and Foot Placement on Reaction Time* (No. 2021-01-0861).

b. Conference Publications

1. Qiao, Z., Sun, X., Loeb, H., & Mangharam, R. (2022). Drive Right: Shaping Public's Trust, Understanding, and Preference Towards Autonomous Vehicles Using a Virtual Reality Driving Simulator. *arXiv preprint arXiv:2208.02939*.

2. Qiao, Z., Loeb, H., Gurrla, V., Lebermann, M., Betz, J., & Mangharam, R. (2023). Drive Right: Promoting Autonomous Vehicle Education Through an Integrated Simulation Platform. *arXiv preprint arXiv:2302.08613*.
3. Yang, C., Liang, O., Ontanon, S., Ke, W., Loeb, H., & Klauer, C. (2018, October). Predictive modeling with vehicle sensor data and IoT for injury prevention. In *2018 IEEE 4th International Conference on Collaboration and Internet Computing (CIC)* (pp. 293-298). IEEE.

c. Thesis

Qiao, Z., Drive Right: Shaping Public's Trust, Understanding, and Preference Towards Autonomous Vehicles Using a Virtual Reality Driving Simulator, University of Pennsylvania, 2022

d. Collaborators and Research Students

This research benefited from the collaboration of numerous collaborators in academia and elsewhere. It supported the work of multiple undergraduate and graduate students from the University of Pennsylvania, Drexel University and other institutions.

Collaborators

1. Mike Coraluzzi, Project Manager
2. Ronit Tehrani, CEO Driven2Drive
3. Mike Peretz, Marketing Consultant
4. Jaime Hernandez, Virtual Reality Developer
5. Danielle Boussel, Financial Advisor
6. James Megarioris, Hardware Engineer
7. Chris Yang, Professor, Drexel University

University of Pennsylvania

1. Zhijie Qiao
2. Xiatao Sun
3. Yash Rajpal
4. Shriyash Upadhyay
5. Lakshay Sharma
6. Xiatao Sun
7. Venkata Gurrala
8. Matt Lebermann

Drexel University

1. Jonathan Loeb
2. Matthew Bauman

3. Christine Kwong
4. Elliott Dickman
5. Allen Wu
6. Amine Mrad
7. Benjamin Naab
8. Quinn Williams
9. Nathalia Gomez
10. Sean McColgab
11. Adin Solomon
12. Benjamin Loeb
13. Elliott Warshowsky

Other

1. Chase Leibowitz, The Shipley School
2. Milena Boussel, Universite Paul Sabatier
3. David Salama, ESME
4. Rachel Loeb, JBHA
5. Olivier Rouanet, ESE

D. Bibliography

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