<table>
<tr><td>1. Report No.
446</td><td>2. Government Accession No.</td><td>3. Recipient’s Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle

Safety through Agility: Using Mixed Reality to tune shared autonomy systems</td><td>5. Report Date
October 29,2024</td></tr>
<tr><td>6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
Helen Loeb: https://orcid.org/0000-0001-5762-2044</td><td>8. Performing Organization Report No.
446</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
University of Pennsylvania/Jitsik
276 Barwynne Rd, Wynnewood PA, 19096</td><td>10. Work Unit No.</td></tr>
<tr><td>11. Contract or Grant No.
Federal Grant No. 69A3552344811</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Safety21 University Transportation Center
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213</td><td>13. Type of Report and Period Covered
Final Report (July 1, 2023-June 30, 2024)</td></tr>
<tr><td>14. Sponsoring Agency Code
USDOT</td></tr>
<tr><td colspan="3">15. Supplementary Notes
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.</td></tr>
</table>

16. Abstract

Over the past decade, self-driving capability for all variants of on-street vehicles have promised safer and more efficient transportation. This remains “work in progress” with large unfilled gaps in addressing user-acceptance, safety, ethics, regulation, technology and the business model. Our goal is to develop the Open-source Autonomous Vehicle (AV) software for Open-standard Electric Vehicle (EV) platforms, ie. AV4EV paradigm, to help realize safe, reliable, and efficient autonomy for off-street use cases. We focus on developing the AV4EV Autonomy Essentials Kit (AV4EV-Kit) for known controlled application domains: logistics (in-warehouse mobile robots), material handling (autonomous forklifts) and airside cargo (autonomous ground support equipment). The AV4EV business model addresses these many smaller domains through simplification and modularity. The EV ‘skateboard’ chassis is orders of magnitude simpler than on-street vehicles (~20 moving parts compared to nearly 2,000 in contemporary vehicle architectures) - supporting standardization of interfaces for autonomous driving. Modularity allows AV4EV to address autonomous vehicle market sizes of 50K-250K vehicles/year for each use case by enabling component re-use and efficient customizability to meet specific segment needs. If successful, the AV4EV Kit will create a new business category for Autonomy-as-a-Service with plug-n-play hardware and software for rapid prototyping and deployment. Autonomous machines have a serviceable market of $2.9B with a 15.5% growth rate.

The AV4EV Autonomy Essentials Kit enables logistics customers to kickstart their journey of autonomous machines for safe and efficient movement of people and goods, even if their companies have little prior autonomous system development experience. Using the AV4EV-Kit, customers can rapidly prototype EV platforms into autonomous machines in 10 days for brownfield deployments.

The AV4EV Autonomy Essentials Kit is dedicated to lowering the entry barrier of autonomous driving development and deployment. AV4EV-Kit consists of (1) a plug-in-play hardware platform with sensors and compute, (2) an autonomy software stack to achieve essential autonomous driving functions of perception, sensor fusion, mapping, localization, path planning, obstacle avoidance, traffic light recognition and safe control; and (3) a new Software Defined Vehicle approach for autonomous machine software development and testing in the cloud to lower cost of mixed-criticality software and over-the-air upgrades to enhance safety across the vehicle lifecycle and customize for different deployment scenarios. The AV4EV-Kit conforms to the open-source Autoware autonomous vehicle software standard to interface with the EV’s drive-by-wire system for users to easily integrate navigation functions with vehicle control. The AV4EV-Kit incorporates energy-efficient machine learning-based perception, planning and control algorithms developed by the PI’s and Co-PI’s labs and will be tested by commercialization partners on a variety of EV platforms.

17. Key Words		**18. Distribution Statement**	
Autonomous vehicles, robotics, computational thinking, machine learning, control, simulation		No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161. Enter any other agency mandated distribution statements. Remove NTIS statement if it does not apply.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 24	22. Price Refers to the price of the report. Leave blank unless applicable.

Safety through Agility: Using Mixed Reality to tune shared autonomy systems

Rahul Mangharam (https://orcid.org/0000-0002-3388-8283)
Helen Loeb (https://orcid.org/0000-0001-5762-2044)

FINAL RESEARCH REPORT

Grant Program: US DOT BIL, Safety21, 2023 - 2028 (4811)

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the U.S. Department of Transportation's University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

Federal Grant No. 69A3552344811

Contents

1. Problematic

The high costs of elder care, both to the individual and the government, combined with the demographic shift towards an increasing number of older adults as a percentage of the overall US population is creating a major healthcare crisis. The number of senior citizens in the US in 2030 will be twice that of 2000, leading to a shortage of working-age caregivers and putting increased pressure on labor costs. Equally important is maintaining, or preferably ameliorating, the quality of life of a growing elderly population. Maintaining elders' autonomy is correlated with increasing quality of life and autonomy enhancement is correlated with improving functionality. Driving is typically a symbol of autonomy. The revocation of driving privileges is often the first step taken by families worried about cognitive decline and emerging dementia of the older adult. Dementia including Alzheimer's disease is a chronic, progressive syndrome that is characterized by a reduction in the ability to perform daily activities, e.g. a cognitive decline with increasing unpredictability and psychological symptoms. Dementia affects about 5 million people in the USA and 35 million worldwide. Coincidentally, Autonomous Vehicles (AVs) are a game-changing AI and robotic solution that can enable older people to maintain independence. For this technology to be effectively deployed, Safety and Trust are however key. Older people, but also caregivers and clinicians need to view the technology as safe and trustworthy. To realize this potential, a robust shared autonomy strategy is needed. The term shared autonomy is an oxymoron, but it embodies the tension observed as caregivers, clinicians, and patients negotiate the need to trust the autonomous system and the desire to stay in control. This research project aims to address the question on how to mediate autonomy between participating actors to allow the human control of the system up to their level of performance and autotune the degree of intervention by the machine to maintain safety.

1.1. The approach

To these ends, we propose the development of an interactive imitation learning system for safe human autonomous systems. The system is trained by an expert for multiple levels of performance following a curriculum. When the system is deployed with a human non-expert user (e.g. an older driver), the safe by construction neural network controller ensures safety at any level of performance. This enables the system to personalize its capabilities to suit the human partner while ensuring safety from any mismatches in the expectations of the controller and that of the human user. The AVs will therefore learn how the user desires to share autonomy and ensure the system does not reach an unsafe state under all operating conditions and inputs from the human.

1.2. The proposed development

With this research project, we investigate the development of a hybrid driving system that is intuitive and can let people drive realistic immersive environments. This system will also be capable of automated functions so as to offer Guardian Angel features to the human driver. Ideally the system will operate in a real car, so as to offer an environment that is familiar to older people. It is indeed important that older people, who have been driving for years, recognize a familiar interface through the vehicle pedals and steering wheel. This complete hybrid system will provide an ideal environment to study various impairments, whether cognitive or physical in a safe way. The next paragraphs develop the hardware and software specifications of such a system.

2. The driving simulation landscape

2.1. Hardware considerations

As a stepping stone towards our in-car simulation, we used off the shelf equipment to develop the controls of our driving simulator. The hardware used for our simulation is based on the Logitech G29 set of pedals and steering wheel. 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.

Fig. 1. Logitech G29 wheel explanation. Left: functions for buttons and switches. Right: physical and simulation wheel correspondence.

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. This helped reduce any sensing discrepancy between the physical wheel and the simulation while minimizing the discontinuity during a driving mode switch.

2.2. Digital Twin

In order to provide realistic driving scenarios that offer a robust environment for imitation learning, hybrid systems with shared autonomy, it is important that the driving scenarios be realistic. To that extent, our research team built a semi-automated pipeline for Digital Twin development. A Digital Twin of a city can be obtained by leveraging the vast quantity of digital images of our streets, to develop a drivable 3D model. A large number of resources can contribute to this work. Such tools include Google 3D Earth, Cesium Unreal and Unity 3D API, OpenStreetMap, Matlab and its RoadRunner toolbox.
As a first step towards the development of this semi-automated pipeline, our team focused on the Roosevelt Blvd in Philadelphia. Our results were published in Conference and Journals papers (see bibliography below).
Once the 3D model of the Digital Twin has been built, traffic flow can be generated. We explored the development of stochastic model based on the NGSIM database. Other traffic models such as Apollo, Autoware, or Carla may be used to generate traffic. After the traffic flow model get integrated, it becomes possible to bring the Human back in the loop through a Human Study.

2.3. Human Study

For our research project, we identified 3 parts for the Human Study itself. The first part, which is developed as our Research Core, aims at identifying Human Features that can recognize deteriorated skills in a Human Driver. These features can be head or eye movements. For this technical study, no participants were included, since the feasibility of the system needs to be established. For the second part of the Human Study, we chose to reach out to a cohort of young drivers to test the simulator. The experiment, which included 23 participants, was developed through an IRB protocol with the University of Pennsylvania. Our participants were introduced to the concept of Mixed Reality. The last but not least component of the study consists in bringing older people with and without cognitive or physical impairments. The use of a driving simulator is a safe place to study Shared Autonomy and hybrid systems. This last step, still needs to be completed as we continue our research.

3. Research Core

3.1. Objectives

This research project, *Interactive Imitation Learning* for Safe Shared Autonomy Systems aims at developing a framework that can teach drivers of all ages how to trust and efficiently use Advanced Driver Assistance Systems. Our system, which uses the latest Mixed Reality technology provides a high level of visual and mechanical immersion which is necessary for the Symbiotics Learning aspects of the Machine Learning process and the development of the resulting controller.

3.2. Core Research Development

Our initial results were published in Guardian Angel — Shared Autonomy Safety System for Drivers with Compromised Cognitive Capabilities. The "Guardian Angel" — an autonomous driving safety system was developed at the University of Pennsylvania's X-Lab and Jitsik. We initially focused on post stroke and early-stage dementia patients, acknowledging their cognitive and motor skill limitations. The primary challenge lies in diagnosing the extent of cognitive decline reliably. To tackle this, we set to develop a system that employs Vision based driver monitoring, combined with radio frequency based physiological indicators. By testing patients in the CARLA Simulation Environment, we can assess distraction, disengagement, and risk levels whenever the vehicle is under manual control. Our ultimate objective is to build an anomaly detection model. This model will leverage distraction, driving patterns, and health parameters as features to predict whether the driver is experiencing an impairment event.

3.2.1. Overview of the Driver Monitoring System

One of the system's primary functions is to gauge distraction levels. It assesses where the driver's attention is directed — whether on the road, a smartphone, or something else entirely. By tracking head movements, blink patterns and facial expressions with landmarks, it can pinpoint moments when the driver's focus drifts away from the task at hand.

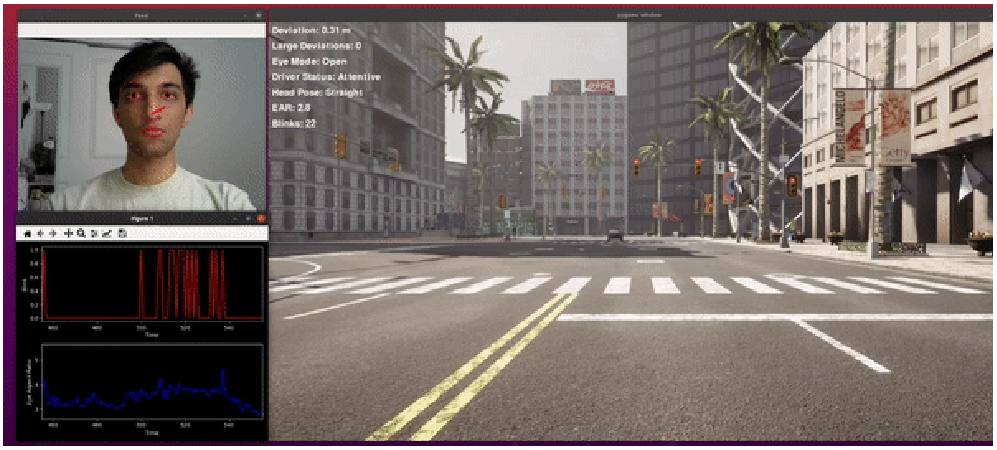


Fig. 2. Facial tracking.

3.2.2 Driver Monitoring System for tracking Visual Cues

The Following Cues are tracked in real-time for anomaly detection model:
1) *EAR*: Measures eyelid openness, indicating focus and alertness shifts.
2) Number of Blinks: Reflects vigilance and potential distraction or fatigue.
3) Head Pose: Maps visual focus, assessing alignment with the road.
4) Sleep Detection: Identifies drowsiness and sleep.
5) MAR: Detects speech and offers insight into drowsiness and distractions

Picture a scenario where the driver's head faces forward, but their eyes are fixated on a potential hazard like a pedestrian. It can be difficult for the system to infer if the driver is distracted. This precise challenge finds its solution in the integration of an eye tracker . By incorporating an eye tracker into our system, we are able to detect these subtle eye movements, fixations and saccades ensuring that the system reliably understands where the driver's attention is directed. Remarkably, our system achieves this without the necessity of virtual reality (VR) headsets. This technology offers improved accuracy in interpreting the visual focus of older patients, without the need for bulky VR headsets as shown in the illustration below.

3.2.3 Eye Gaze Estimation for Behavioral Understanding

One can imagine a driver whose gaze is fixed on the road, seemingly attentive, but in reality, their thoughts are wandering elsewhere. Similarly, someone who appears fidgety and distracted might actually be multitasking effectively, maintaining awareness of their environment despite their seemingly scattered demeanor. This illustrates the intricate challenge of accurately deducing cognitive states solely through visual indicators. Therefore, there arises a pressing need to delve deeper and assess not only the external manifestations but also the underlying driving patterns.

Is the driver maintaining their lane discipline? Are they stopping at red lights and obeying traffic signals? Are they maintaining a safe following distance from the vehicle ahead? These driving behaviors provide crucial insights into the driver's level of engagement with the task at hand. While visual cues offer valuable information, they can sometimes be deceptive. By analyzing the broader context of driving behaviors, we can better understand the cognitive states and intentions of individuals behind the wheel. As a result, we designed various scenarios in the CARLA simulator to comprehensively evaluate these driving patterns and behaviors. The primary scenario is described below.

3.2.4. Beyond Visual Cues: Cognitive Assessment Test Scenarios
In our base test scenario, we construct an environment where the driver is instructed to keep a lane within a dynamic obstacle setting. Our focus extends beyond tracking mere visual cues; we also monitor steering patterns, average brake and pedal force, deviations from the "ideal" centerline trajectory, occurrences of jumping signals, and waiting at stop signs. Throughout these tests, we plan to diligently record these values and track instances where drivers significantly deviate from the optimal state.

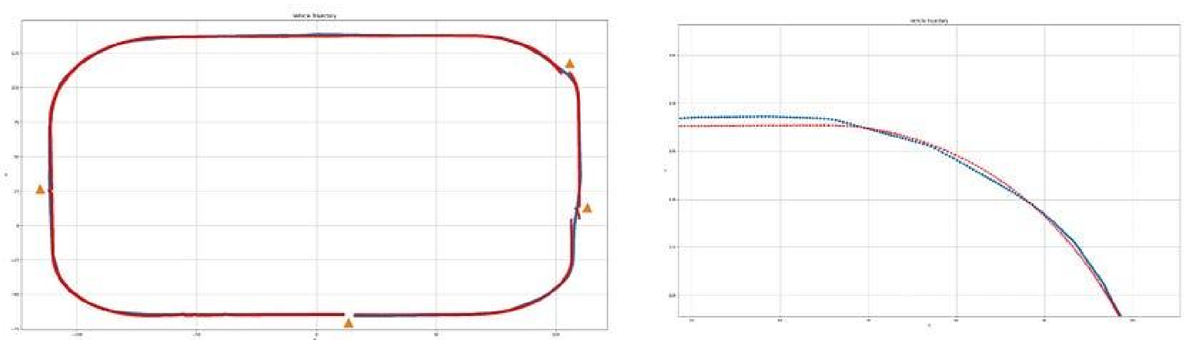


Fig. 3 Test Findings: Highlighting Vehicle Trajectory with Significant Deviations from the Optimal State

These tests can encompass a diverse range of participants, including both those with a history of cognitive impairments and those without. The collected features from these tests can subsequently be fed into our anomaly detection model. By training the model with driving patterns and visual cues, we hope to predict a range of scenarios — from identifying cognitive impairment events to assessing the driver's attentiveness levels. This predictive capability marks a significant stride in enhancing road safety for all drivers, regardless of cognitive limitations. Moreover, the simulation recordings serve as a valuable resource for later reconstruction and review, facilitating in-depth analysis and insights.

Our simulator setup integrates the Logitech G290 steering wheel and pedals, Intel's Realsense D435i with the CARLAUE4 0.9.13 on Nvidia GeForce 4070 GPU. Despite Linux lacking native force feedback support, we incorporated the lg4-ff package to achieve realistic steering experiences. The communication between the DMS, Health Sensor Nodes and the CARLA Simulator is facilitated by the Robot Operating System (ROS2).

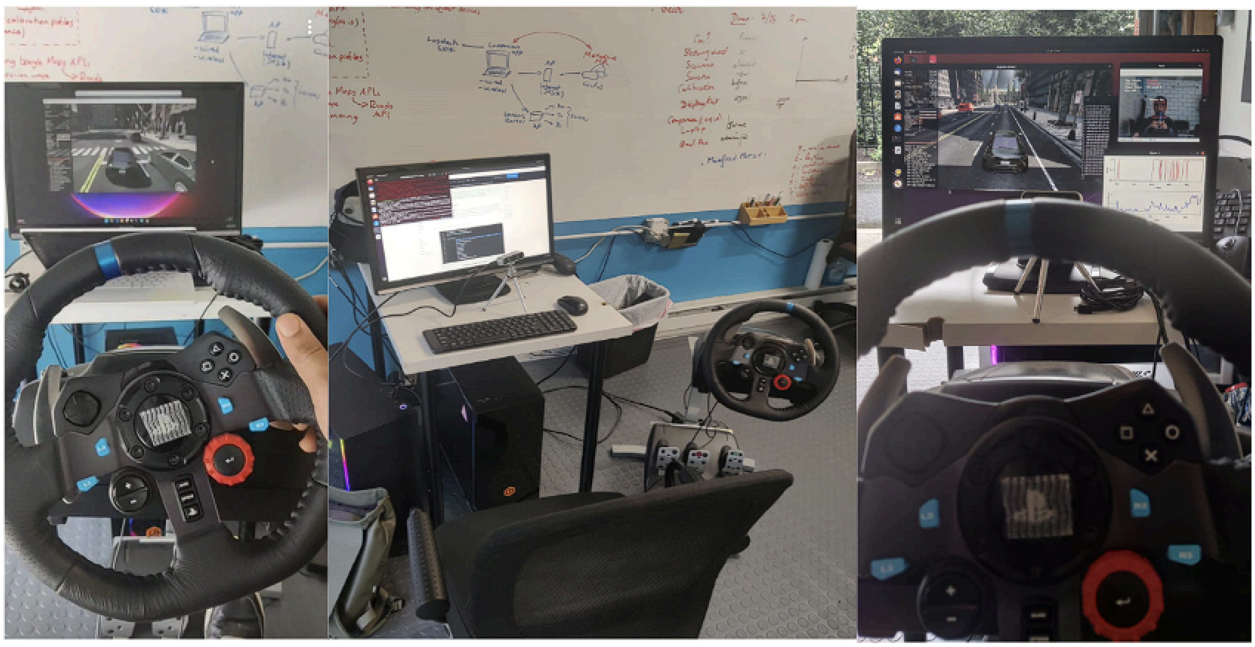
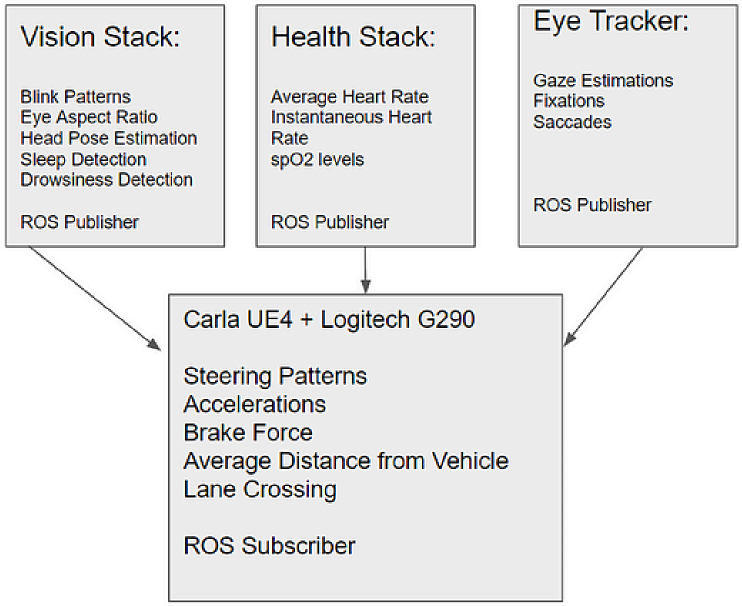


Fig. 4. Simulator demonstration: left monitor shows Carla server first person driver's seat view; right monitor shows the Carla client third person tracking view.

The chart below shows the technical overview of our system:



Tailoring Scenarios:
Utilizing the Carla Scenario Runner tool, we can craft custom scenarios encompassing diverse driving situations. This includes monitoring braking distances, simulating pedestrian interactions, introducing various vehicles, and more. Critical events such as collisions, lane deviations, acceleration patterns, and speed limit violations can be detected, providing comprehensive insights into driving behavior.

3.2.5 Further developments

Our next step will be to integrate the system in a native environment, e.g., a real instrumented vehicle. To that effect, we are developing sensors that can be affixed in a vehicle's pedals and steering wheel to better simulate driving. A Mixed Reality display system will allow drivers to feel truly immersed in the driving scenario.

The support of the URF funding allowed the team to seek additional federal funding to continue the project. Specifically, we applied for the US Department of Transportation Complete Street SBIR 2024.2 initiative through a proposal titled *StreetSavvi: your AI Digital Twin companion to Complete Street design for safe, efficient multimodal traffic*. In addition, we applied to the Rural Autonomous Vehicle Program, a US DOT grant opportunity through a proposal entitled Center For Rural AV Research, Development and Deployment (RAV-READY), *Realizing Affordable, Resilient and Accessible Mobility in Rural America (RAx3).* We anticipate several federal applications in months to come. Specifically, we will submit STTR applications to the National

Science Foundation (NSF), to the National Institute of Health (NIH) and to the Department of Education.

4. Experiment Design

4.1. Introduction

Motor vehicle crashes continue to be one of the primary causes of preventable death for US teenagers. Per the National Safety Council, 5,565 people died on US roads in accidents involving a young driver in 2021–a 9.8% increase from the 2020 total of 5,069. A primary cause for these statistics is the inexperience of teenage drivers. Current training methods are unable to adequately expose teenagers to dangerous driving scenarios in a safe manner. Technological innovations offer new opportunities to solve this problem. The emergence of Mixed Reality at a low cost can help place students in dangerous situations so as to accelerate their exposure to risky situations and train awareness and muscle memory. Driving simulators can be traced back to the 1950s with Aetna's Drivotrainer, a motion picture training system. Several generations of simulators have followed which used multiple monitors to deliver a workable Field of View. Yet, the lack of realism and affordability has, until recently, restricted the use of driving simulation technology to manufacturers and universities. New Virtual Reality (VR) and Mixed Reality (MR) technologies present an opportunity to affordably place students in high-pressure scenarios. The work we highlight below covers a pilot experiment in a driving school where a cohort of 23 student drivers experimented with Jitsik's MetaDrive XR simulator.

4.2. Methodology

Fig. 5. Simulator demonstration: left monitor shows Carla server first person driver's seat view; right monitor shows the Carla client third person tracking view.

Our research team built a driving simulator consisting of a Meta Quest 3 MR headset paired with a Logitech 920 steering wheel and pedal set. The goal of the study was to assess the perception of Mixed Reality in the context of driving education. A parallel parking scenario was chosen for its interactive nature to test the usability, intuitiveness, and efficacy of the simulator. The task required the driver to check mirrors, turn his/her head in all directions, and change between forward and reverse gears. The task of parallel parking is often the first skill assessed on state driving tests. It is often feared by students. The simulator's MR technology lets participants see their hands, feet, and steering wheel while driving, while a virtual gear stick lets participants intuitively switch gears.

The test was administered at the Bala Cynwyd location of the Driven2Drive driving school to a cohort of 23 participants aged 16-30 (12 males, 11 females). Following the simulation, participants completed a 5-point Likert scale survey, asking how much they agreed or disagreed with a series of statements (1: strongly agree, 5: strongly disagree). The questions assessed how immersive the simulator was, how intuitive it was, how useful it was, how fun it was, how helpful it was to driving education, and whether or not it would be more effective if delivered in a vehicle.

4.3. Findings

Likert Scale Mean Scores

	Immersive	Intuitive	Useful	Fun	Helpful
Mean score	2.21	2.29	2.08	1.75	1.63

The mean score for each statement landed in the "somewhat agree" category, with participants agreeing most strongly that the simulator would be helpful in drivers' education. 86% of participants agreed or strongly agreed that the simulator would be helpful in education. Conversely, only one participant disagreed. The modes for how useful the simulator was, how fun it was, and how helpful it would be were all "strongly agree." A correlation matrix shed more light on which factors of the simulation were interrelated and how strongly they influenced each other.

Correlation Matrix

	Immersive	Intuitive	Useful	Fun	Helpful
Immersive	1.00	0.71	0.79	0.52	0.63
Intuitive	0.71	1.00	0.78	0.62	0.54
Useful	0.79	0.78	1.00	0.76	0.67
Fun	0.52	0.62	0.76	1.00	0.55
Helpful	0.63	0.54	0.67	0.55	1.00

How useful the simulator was perceived, was strongly correlated with its immersivity, intuitiveness, and degree of fun, with correlation coefficients of 0.79, 0.78, and 0.76 respectively. A moderate correlation was found between all other variables. The strongest average correlation (0.71)was found between how useful the simulator was and all other metrics.

4.4. Discussion

The findings from this experiment shed light on the efficacy of driving simulation in education. The Likert scale data revealed that most participants strongly agree that it would be helpful in driving education. The lowest scores were averaged under "agree," in how immersive and intuitive the simulator was. These two scores were strongly correlated with how useful the simulator was. As the simulation improves in those areas, its efficacy will also improve. Designing simulators with that in mind will be imperative in the future.

4.5. Conclusion

The facts presented in this pilot deployment of the Jitsik MetaDrive XR simulator at the Driven2Drive driving school help us assess the perception of Mixed Reality simulation among driving school students. Qualitative data obtained from post-simulation surveys show that students anticipate the MetaDrive XR simulator can be effective in driving training. The correlation analysis shows how improvements in immersion and intuitiveness will further improve the simulator's efficacy.

5.0 Conclusion

As life expectancy increases, a growing number of seniors reach the age of 90 and it is no longer uncommon to see people become centenarians. As a consequence, it is paramount that our society offers ways for these people to continue to be independent. It is paramount that our elders continue to be mobile for their daily lives. The incidence of Automated Vehicles offers phenomenal opportunities. At the same time, older people who have driven for decades mistrust automation. It is therefore important to develop hybrid systems, or shared autonomy systems where older drivers are empowered through systems that prolong their routines, yet provide a guardian angel so automation takes over when necessary.

We explored in our research, how driving simulation can play a part in the design and test of these systems. We explored ways to design driving simulators that can be effective and realistic. We explored through a pilot study of human drivers, how driving simulators can contribute to research and assessment of driving abilities. Our results showed that the incidence of Mixed Reality is an asset for driving simulation. They showed that simulation can indeed help educate people whether they are novice or more mature drivers. We anticipate these tools will greatly help the transition to AV in years to come, so all generations can reap the benefits of the technology.

6.0 Appendix

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

A. Consent Form

UNIVERSITY OF PENNSYLVANIA
RESEARCH SUBJECT
INFORMED CONSENT FORM

Protocol Title: Evaluating the Effectiveness of a Driving Simulator for Teaching Student Drivers

Principal Investigator:
Rahul Mangharam
COMP INFO SCI-269 MOORE
200 S 33RD ST
Philadelphia
215-898-2442
Emergency Contact: Helen Loeb
610-731-3960

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 as a way to teach new drivers without the safety risks involved with driving on a road.

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

Through this study, you will gain experience using a driving simulator and potentially expand your understanding of the technology and its potential uses for new and inexperienced drivers. This study involves no more than minimal risk.

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 people learn how to drive while minimizing risk of injury and damage. 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: 18-30.
- Have normal or correct-to-normal vision and hearing (contact lens allowed).
- No pregnancies, history of migraine headaches, claustrophobia, or motion sickness.

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 spending 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 experience with driving and opinions of the use of Virtual or Mixed Reality for learning to drive.

- You will drive through a few testing scenarios we have designed 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 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 students or inexperienced drivers while minimizing risk of injury or damage.

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 Helen Loeb at helensloeb@gmail.com.

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 in 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 or JitSik 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?

There will be no compensation for this study.

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

B. Surveys

B1 Pre-Simulator Survey

Pre-Simulator Survey

metadrive companion v.0.4.1, metadrive xr v0.6.11

* Indicates required question

1. How old are you? *

2. What gender do you identify as? *

   Mark only one oval.

   - Male
   - Female
   - Nonbinary
   - Prefer not to say
   - Other: ______

3. Have you ever driven a car before? *

   Mark only one oval.

   - Yes
   - No
   - Other: ______

4. Do you have a driver's license? *

   Mark only one oval.

   - Yes
   - No
   - Other: ______

5. When did you first get your driver's license? (If unsure of month or day, put 01)

   Example: January 7, 2019

6. How old were you when you first got your driver's license?

   Mark only one oval.

   - 15
   - 16
   - 17
   - 18
   - 19
   - 20
   - 21
   - 22+
   - I don't have a license

7. Are you currently learning to drive?

Mark only one oval.

- Yes
- No
- Other: ____________

8. Did you practice driving with a family member?

Mark only one oval.

- Yes
- No
- Other: ____________

9. How many hours did you practice with your family?

Mark only one oval.

- 0
- 1-10
- 10-20
- 20-30
- 30-40
- 40-50
- 50+

10. Did you practice driving through a driving school?

Mark only one oval.

- Yes
- No
- Other: ____________

11. How many hours did you practice with a driving school?

Mark only one oval.

- 0
- 1-10
- 10-20
- 20-30
- 30-40
- 40-50
- 50+

12. Have you ever used VR (virtual reality) before? *

Mark only one oval.

- Yes
- No
- I've used something similar (augmented reality, mixed reality, etc) but not VR

13. If you have used VR before, what have you used it for?

Check all that apply.

- Gaming
- Learning
- Socializing
- Other entertainment (ie. watching videos)
- Other: ____________

14. Do you own a VR headset? *

Mark only one oval.

- Yes
- No
- Other: ____________

15. Do you anticipate owning a VR headset in the next 2 years?

Mark only one oval.

- Yes
- No
- Other: ____________

16. What do you hope to get out of using this simulator? *

____

B2 Post-Simulator Survey

Post-Simulator Survey

* Indicates required question

1. Please list any issues that you encountered during the simulation (software, hardware, etc.) *

2. Did you experience any motion sickness from using the driving simulator?

   Mark only one oval.

   - Yes
   - No
   - Other:

3. What would you like to see improved in the simulation? *

4. How do you think this software could benefit you or others?

5. Which driving situations could most benefir from a driving simulator?

   Mark only one oval.

   - Parallel parking
   - City driving
   - Highway driving
   - Inclement weather
   - Tunnels and bridges
   - Other:

6. Have you ever had an accident?

   Mark only one oval.

   - Yes
   - No

7. If you've had an accident, when was your last accident?

8. Describe a stressful driving situation.

____
____
____
____
____

9. Do you think driving education should be done by

Check all that apply.

- [ ] Family Members
- [ ] Driving Schools
- [ ] High Schools
- [ ] Other: _______________

Rate on level 1 (strongly agree) to 5 (strongly disagree) the following statements.

10. The driving simulation was immersive.

Mark only one oval.

- 1) Strongly Agree
- 2) Somewhat Agree
- 3) Neutral
- 4) Somewhat Disagree
- 5) Strongly Disagree

11. The driving simulation was intuitive.

Mark only one oval.

- 1) Strongly Agree
- 2) Somewhat Agree
- 3) Neutral
- 4) Somewhat Disagree
- 5) Strongly Disagree

12. The driving simulation was useful.

Mark only one oval.

- 1) Strongly Agree
- 2) Somewhat Agree
- 3) Neutral
- 4) Somewhat Disagree
- 5) Strongly Disagree

13. The driving simulation was fun.

Mark only one oval.

- 1) Strongly Agree
- 2) Somewhat Agree
- 3) Neutral
- 4) Somewhat Disagree
- 5) Strongly Disagree

14. Driving simulators could help with driving education.

Mark only one oval.

- 1) Strongly Agree
- 2) Somewhat Agree
- 3) Neutral
- 4) Somewhat Disagree
- 5) Strongly Disagree

15. The driving simulation is more effective if delivered in a vehicle.

Mark only one oval.

- 1) Strongly Agree
- 2) Somewhat Agree
- 3) Neutral
- 4) Somewhat Disagree
- 5) Strongly Disagree

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).
9. Guerra, E., Dong, X., Wu, Z., Diaz, R., Hernandez, J., Gupta, R., Mangharam, R., Loeb, H., *Digital Twin of the Philadelphia's Roosevelt Boulevard: a microsimulation based on real life traffic*, Submitted to the 2025 TRB Annual Conference.

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.
4. Wu, Z., Zhang, L., Hernandez, J., Leibowitz, C., Loeb, H., Dong, X., Guerra, E., Mangharam, R. *Pipeline for fast Digital Twin development and Integration in Driving Simulation*, Proceedings of the 2024 Road Safety and Simulation Conference, Lexington, Kentucky, October 28-31 2024.
5. Loeb, H., Hernandez, H., Loeb B., Mangharam, R., *Driving simulator for driving education: can Mixed Reality do it?* Proceedings of the 2024 Road Safety and Simulation Conference, Lexington, Kentucky, October 28-31 2024.

c. 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. Xiaoxia Dong
2. Erick Guerra
3. Mike Coraluzzi, Project Manager
4. Ronit Tehrani, CEO Driven2Drive
5. Mike Peretz, Marketing Consultant
6. Jaime Hernandez, Virtual Reality Developer
7. James Megarioris, Hardware Engineer

University of Pennsylvania

1. Raj Anadkat
2. Rajnish Gupta
3. Luying Zhang
4. Zhanqian Wu

Drexel University

1. Benjamin Loeb
2. Minhal Vakil
3. Ramon Diaz
4. Abhiskek Raj
5. Kartikeya Yadav
6. Prashanna Subedi

Other

1. Chase Leibowitz, The Shipley School

D. Bibliography

1	“Autopilot and Full Self-Driving Capability.” Tesla, https://www.tesla.com/support/autopilot. Accessed 31 August 2023.
2	“AVIA data shows 44 million+ autonomous miles driven and outstanding safety record.” Autonomous Vehicle Industry Association, https://theavindustry.org/resources/blog/data-44million-miles. Accessed 31 August 2023.
3	“Category I/II/III ILS Information.” Federal Aviation Administration, 2 December 2021, https://www.faa.gov/about/office_org/headquarters_offices/avs/offices/afx/afs/afs400/afs410/cat_ils_info. Accessed 31 August 2023.
4	“Fatality Facts 2021 State by state.” IIHS, https://www.iihs.org/topics/fatality-statistics/detail/state-by-state. Accessed 31 August 2023.
5	“PAVE Poll: Americans wary of AVs but say education and experience with technology can build trust | PAVE Campaign.” Pave Campaign, 18 May 2020, https://pavecampaign.org/pave-poll-americans-wary-of-avs-but-say-education-and-experience-with-technology-can-build-trust/. Accessed 31 August 2023.
6	Americans cautious about the deployment of driverless cars.” Pew Research Center, 17 March 2022, https://www.pewresearch.org/internet/2022/03/17/americans-cautious-about-the-deployment-of-driverless-cars/. Accessed 31 August 2023.
7	Geospatial World, “What are different levels of Autonomous Vehicles?”, YouTube, May. 2018 [Video file], Available: https://www.youtube.com/watch?v=6592pKyQfyE [accessed Feb. 2022].
8	Guerra, E., Dong, X., Wu, Z., Diaz, R., Hernandez, J., Gupta, R., Mangharam, R., Loeb, H., Digital Twin of the Philadelphia’s Roosevelt Boulevard: a microsimulation based on real life traffic, Submitted to the 2025 TRB Annual Conference.
9	Guerra, E., Dong, X., Wu, Z., Diaz, R., Hernandez, J., Gupta, R., Mangharam, R., Loeb, H., Digital Twin of the Philadelphia’s Roosevelt Boulevard: a microsimulation based on real life traffic, Submitted to the 2025 TRB Annual Conference.
10	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.
11	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).
12	Loeb, H., Hernandez, H., Loeb B., Mangharam, R., Driving simulator for driving education: can Mixed Reality do it? Proceedings of the 2024 Road Safety and Simulation Conference, Lexington, Kentucky, October 28-31 2024.

13	Loeb, H., Hernandez, H., Loeb B., Mangharam, R., Driving simulator for driving education: can Mixed Reality do it? Proceedings of the 2024 Road Safety and Simulation Conference, Lexington, Kentucky, October 28-31 2024.
14	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).
15	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.
16	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.
17	SAE International, "Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles", https://www.sae.org/standards/conten t/j3016_202104/ (Accessed Jan. 2022).
18	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.
19	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.
20	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.
21	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.
22	Wu, Z., Zhang, L., Hernandez, J., Leibowitz, C., Loeb, H., Dong, X., Guerra, E., Mangharam, R. Pipeline for fast Digital Twin development and Integration in Driving Simulation, Proceedings of the 2024 Road Safety and Simulation Conference, Lexington, Kentucky, October 28-31 2024.
23	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.
24	Qiao, Z., Loeb, H., Venkata, G., Lebermann, M., Betz J., and Mangharam, R., "Drive Right: Autonomous Vehicle Education Through an Integrated Simulation Platform", SAE Journal of Connected and Automated Vehicles, vol. 5, no. 4, April, 2022, doi:10.4271/12-05-04-0028.
25	Berducci, L., Yang, S., Mangharam, R., & Grosu, R. (2024, May). Learning adaptive safety for multi-agent systems. In 2024 IEEE International Conference on Robotics and Automation (ICRA) (pp. 2859-2865). IEEE.
26	Yang, S., Black, M., Fainekos, G., Hoxha, B., Okamoto, H., & Mangharam, R. (2024, July). Safe control synthesis for hybrid systems through local control barrier functions. In 2024 American Control Conference (ACC) (pp. 344-351). IEEE.
27	Betz, J., Krovi, V., Mangharam, R., & Behl, M. (2024). Special Issue on Opportunities and Challenges with

	Autonomous Racing. Field Robotics, 4(1).
28	Zheng, C., Jarecki, A., & Lee, K. (2023). Integrated system architecture with mixed-reality user interface for virtual-physical hybrid swarm simulations. Scientific Reports, 13(1), 14761.
29	Xu, M., Niyato, D., Chen, J., Zhang, H., Kang, J., Xiong, Z., ... & Han, Z. (2023). Generative AI-empowered simulation for autonomous driving in vehicular mixed reality metaverses. IEEE Journal of Selected Topics in Signal Processing.