

12-2017

# Virtual Reality Based Simulation Testbed for Evaluation of Autonomous Vehicle Behavior Algorithms

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VIRTUAL REALITY BASED SIMULATION TESTBED FOR EVALUATION OF  
AUTONOMOUS VEHICLE BEHAVIOR ALGORITHMS

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A Thesis  
Presented to  
the Graduate School of  
Clemson University

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In Partial Fulfillment  
of the Requirements for the Degree  
Master of Science  
Computer Science

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by  
Vibhor Rastogi  
December 2017

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## ABSTRACT

Validation of Autonomous Vehicle behavior algorithms requires thorough testing against a wide range of test scenarios. It is not financially and practically feasible to conduct these tests entirely in a real world setting. We discuss the design and implementation of a VR based simulation testbed that allows such testing to be conducted virtually, linking a computer-generated environment to the system running the autonomous vehicle's decision making algorithms and operating in real-time. We illustrate the system by further discussing the design and implementation of an application that builds upon the VR simulation testbed to visually evaluate the performance of an Advance Driver Assist System (ADAS), namely Cooperative Adaptive Cruise Control (CACC) controller against an actor using vehicular navigation data from real traffic within a virtual 3D environment of Clemson University's campus. With this application, our goal is to enable the user to achieve spatial awareness and immersion of physically being inside a test car within a realistic traffic scenario in a safe, inexpensive and repeatable manner in Virtual Reality. Finally, we evaluate the performance of our simulator application and conduct a user study to assess its usability.

## ACKNOWLEDGMENTS

I would like to thank my advisors Dr. Sabarish V. Babu and Dr. Andrew Robb for their close guidance throughout this project, Dr. Pierluigi Pisu for ideating and making this all possible and all the team members from Automotive Engineering for their important contributions to this project.

I would also like to thank Dr. Jim Martin for his valuable feedback and help with the project, team members from Networking Lab for their vital contributions and all members of the VE group for their feedback, support and appreciation for my work. I want to express my sincere gratitude to The Graduate School and School of Computing at Clemson University for giving me the opportunity and resources to work on this project.

Finally, I would like to thank my family for their support and encouragement that kept me motivated and going.

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## CHAPTER ONE

### INTRODUCTION

An Autonomous Vehicle (AV) can be broadly defined as a vehicle that use a combination of sensors to sense the physical environment around it and makes decisions to navigate in its environment without the need for human input. Although AVs may include industrial robots, planetary rovers and unmanned aerial vehicles, the past few years have seen a surge in interest in developing AVs for the consumer market within the automobile industry. The terms ‘self-driving car’ and ‘driverless car’ are commonly used to refer to the AVs fitting in this category. In this manuscript, the term ‘Autonomous Vehicle’ or the shorthand ‘AV’ refers to such a self-driving car unless specified otherwise.

Autonomous Vehicles Technology has rapidly progressed in the last decade, partly because of the advancements in super-computing and AI capabilities and partly because of strong competition and heavy investments within the Automotive as well as Information Technology Industries. Advanced Driver Assist System (ADAS) features have been part of vehicles on the road for a fair amount of time already. Some examples of these features are Dynamic Cruise Control, Lane Departure Assist, Emergency Braking Systems, Parking Assist etc. Vehicles with such features are classified as Level 1 Autonomous Vehicles. This classification comes from the specifications formulated by SAE International [1] and accepted by United States Department of Transportation’s National Highway Traffic Safety Administration (NHTSA) in 2016. According to the

specification, there are 6 levels of Driving Automation for on-road vehicles ranging from “No Automation” to “Full Automation”. Table 1-1 summarizes each level of automation.

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/Deceleration	Monitoring of Driving Environment	Fallback Performance of Dynamic Driving Task	System Capability (Driving Modes)
<b>Human driver monitors the driving environment</b>						
<b>0</b>	<b>No Automation</b>	the full-time performance by the <i>human driver</i> of all aspects of the <i>dynamic driving task</i> , even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
<b>1</b>	<b>Driver Assistance</b>	the <i>driving mode</i> -specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the <i>human driver</i> perform all remaining aspects of the <i>dynamic driving task</i>	Human driver and system	Human driver	Human driver	Some driving modes
<b>2</b>	<b>Partial Automation</b>	the <i>driving mode</i> -specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the <i>human driver</i> perform all remaining aspects of the <i>dynamic driving task</i>	<b>System</b>	Human driver	Human driver	Some driving modes
<b>Automated driving system (“system”) monitors the driving environment</b>						
<b>3</b>	<b>Conditional Automation</b>	the <i>driving mode</i> -specific performance by an <i>automated driving system</i> of all aspects of the dynamic driving task with the expectation that the <i>human driver</i> will respond appropriately to a <i>request to intervene</i>	System	<b>System</b>	Human driver	Some driving modes
<b>4</b>	<b>High Automation</b>	the <i>driving mode</i> -specific performance by an automated driving system of all aspects of the <i>dynamic driving task</i> , even if a <i>human driver</i> does not respond appropriately to a <i>request to intervene</i>	System	System	<b>System</b>	Some driving modes
<b>5</b>	<b>Full Automation</b>	the full-time performance by an <i>automated driving system</i> of all aspects of the <i>dynamic driving task</i> under all roadway and environmental conditions that can be managed by a <i>human driver</i>	System	System	System	<b>All driving modes</b>

Table 1-1: SAE International’s Levels of Driving Automation

For a little under 5 years now, Level 2 and Level 3 Autonomous Vehicles have been present on the road in the form of cars with advanced features like dynamic cruise control with lane keeping assistance and cars with “self-pilot” mode that operate on limited access highways. Some automobile companies that have launched such cars include Tesla and Mercedes. Although, it may be long before we’re able to see Level 5

fully autonomous cars that can operate in all conditions without any dependency on a human for driving tasks, several industry experts and leaders believe that SAE Level 4 autonomous vehicles will become commercially available as early as by the year 2020 [2][3][4][5]. For the past few years, several companies that have been developing their own AVs have also been conducting on-road tests in the real world with their in-development test vehicles. All of this has contributed to peaked interest and expectations from self-driving cars across the board and pushed enterprises to produce AVs and soon bring them into the hands of the consumers.

With such rising interest in Autonomous Vehicles, it has become more important than ever to be able to test them for accuracy and ensure predictable behavior in all expected as well as unexpected road conditions and traffic scenarios. It is neither safe nor financially and practically feasible to conduct these tests entirely in a real world setting. Simulation testing within a computer generated virtual environment is something that can greatly benefit such testing of AVs. In the little amount of time that SAE Level 3 vehicles with conditional automation and Level 4 test vehicles have been out and on the roads, we have already seen a few crashes [6] occur, including a fatal car crash involving the death of one individual. One may argue that many of these accidents occurred not because of the failure of the AV's system or its decision making algorithms but due to other reasons. In some cases, it may have been due to the human driver not taking over the control of the autonomous vehicle in a timely manner after being prompted by the system to do so. In other cases, an accident may have been the result of an error made by the human driver of another vehicle involved in the crash. However, none of these arguments can justify an

autonomous vehicle being involved in an accident. An AV that is truly ready for the roads should make no mistakes, communicate its intentions to other vehicles on the road and understand theirs – manual or autonomous, allow for seamless transition of control between manual and autonomous operation, be mindful of errors made by other vehicles and be resilient to misuse from its own users. Therefore, an AV has to be tested not just to account for functional operation without errors but also to incorporate robustness against human factors issues.

Virtual Reality based simulation testing platforms can allow for complex scenario recreation and evaluation of AV behavior algorithms in a safe, inexpensive and repeatable manner as well as provide a testbed for human factors studies and assessment of vehicles. Immersive Virtual Reality is an effective means to conduct social sciences, usability and human factors studies as it makes for experiment setups that allow for high presence and ecological validation. [20][21][22] The VR testing platform described in this research can significantly speed the rate of technology development by providing a platform that can provide an accurate depiction of an actual roadway test scenario to one or more system components under evaluation. Further, the platform allows human-in-the-loop feedback that could potentially provide invaluable system design feedback, without which might require years of transportation trials to identify unexpected design flaws. Although, we limit the scope of this work to presenting the details of the testbed, a performance evaluation and a pilot user study, our future efforts will be in the direction of using the Virtual Reality testbed for more elaborate human centered research studies.

In the sections that follow, we discuss the design and implementation of such a VR based simulation testbed that allows such testing to be conducted virtually, linking a computer-generated environment to the system running the autonomous vehicle's decision making algorithms and operating in real-time. We also discuss the design and implementation of a simulator application that is built upon the VR simulation testbed to create a realistic traffic scenario within an immersive Virtual Reality setting. Our simulator application allows a user to visually evaluate the performance of a Cooperative Adaptive Cruise Control (CACC) System on a virtual AV against a leading actor vehicle. The actor vehicle's behavior within the simulation is controlled by driving a real-world vehicle and streaming live navigation data from real traffic in Clemson University's campus using DSRC based Vehicle to Infrastructure communication capabilities.

## CHAPTER TWO

### RELATED WORK

Taheri et al[9] use an immersive VR based driving simulator to study driver behavior, techniques and adaptability. Meuleners et al[10] conduct a validation study to compare and study the error between on road real driving and driving in a Driving Simulator environment. Although, these are not studies involving Autonomous Vehicle simulators but look at human factors issues in driving simulators.

Other works have looked into studying the issues between humans and autonomous vehicles including perception. Llaneras et al[27] study the drivers' allocation of visual attention to the forward roadway in a limited ability autonomous vehicle. They use a real world autonomous vehicle for the study. Rodel et al[28] conducted an online questionnaire study in which they investigated how factors such as perceived ease of use, attitude towards using the system, perceived behavioral control, behavioral intention to use a system, trust and fun in existing modern vehicles differ with varying degrees of autonomy.

Zhang et al[11] propose an environment modeling approach using image sequences and road GIS data for Autonomous Vehicle simulators. Their work is in making AV simulator environments that are modeled based on the real world, to be more realistic and therefore more effective. Other works[12][13][14] have discussed the design and implementation of their own AV Simulators. [12] discuss the distributed simulation platform, [13] discuss implementation of intelligent actors in simulation and [14] discuss ways to control the weather, sensing and traffic control. We discuss a novel system that

allows for realistic virtual traffic scenario creation in a VR AV simulation with real time traffic data controllable by driving the actor car on a real world road.

Gechter et al[15] discuss a hybrid AV Simulator that is closest to our work. They use a RTK GPS device to record data for actors, however it is not a real time data streaming system with support for immersive visualization in Virtual Reality.

In this work, we present a novel system that allows for realistic virtual traffic scenario creation in a VR AV simulation with real time traffic data controllable by driving the actor car on a real world road. To the best of our knowledge, there are no other testbeds that have integrated each of the following components-

- 1) The use of VR in the simulation platform to visualize the response of a vehicle Control System from the vantage point of a rider in the test vehicle
- 2) A system that allows actor control by driving a real vehicle on actual roads and seeing the actor navigate in real time, in a replicated virtual world that is co-located with the real world
- 3) blended seamlessly with real cars that are using standards-based V2X technology.



## CHAPTER THREE

### VR SIMULATION TESTBED

#### Overview

We set the following goals for the system-

- 1) Allow visualization of the AV behavior algorithms response with high accuracy.
- 2) Have low communication latencies across various distributed parts of the system.
- 3) As an immersive VR system, maximize the presence and minimize simulator sickness for the users

In order to discuss a system that can allow testing and evaluation of AVs within a virtual environment, it is helpful to discuss the components and working of an AV first. An AV is fundamentally a combination of an automobile and a powerful computing cluster with the latter making the decisions that would be made by a human driver in a conventional vehicle and finally giving the command for mechanical actuation to the automobile. The computing cluster itself is composed of a combination of sensors and computational modules. The main components of a typical AV computing cluster are summarized in Fig. 1-1 in a simplified manner.

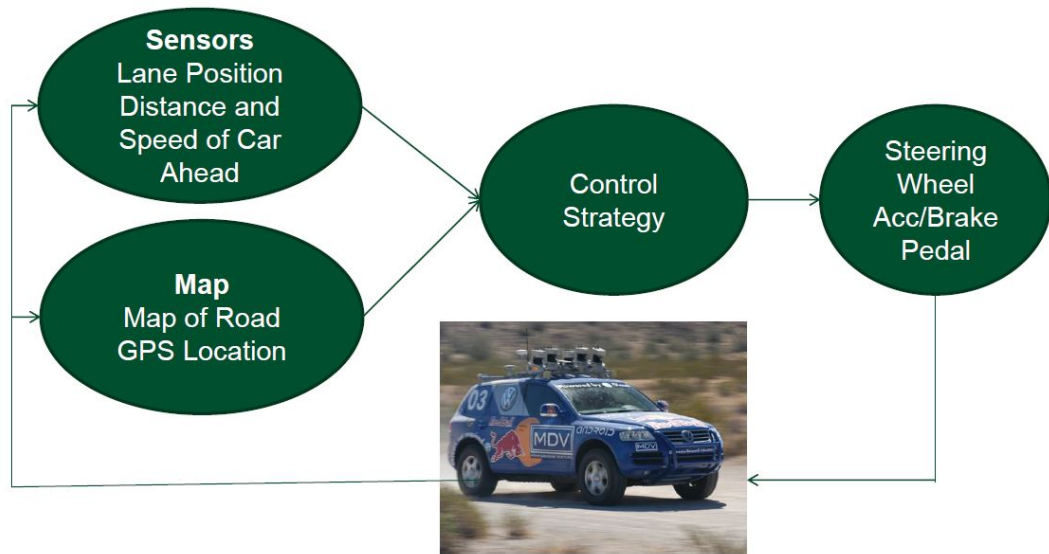


Fig. 3-1 : Autonomous Vehicle Computation Cluster [7][8]

The Control Strategy module is a collection of AV behavior algorithms. The input to this Control module is data from the Sensors and Maps. The Sensor module is a combination of sensor hardware that can “see” the physical environment around the AV together with perception algorithms that “understand” what the sensors see and pass this information to the Control module. The Maps module is a collection of reference maps and hardware for Inertial Measurement and Global Positioning using GPS along with SLAM algorithms that help an AV locate itself in the world while simultaneously updating self-created maps. The input from these modules is used to solve problems such as route planning, obstacle avoidance and responding to traffic signals and rules, all constituting the behavior algorithms. The output from the Controls module is the steering angle and throttle that is used to actuate the mechanical controls of the automobile.

An example of a typical scenario would be the AV having to maneuver itself along the center of a lane from a planned trajectory while avoiding obstacles and following traffic rules. In this example, to evaluate the behavior of the AV, the simulation system should provide information about lane markings and obstacles from the known virtual environment to the AV behavior algorithms module and expect a response output. Visualizing the response by moving the simulated AV within the virtual environment will allow a user to visually evaluate if the response was appropriate for the given input from the environment. In this way, by bypassing the input from the Sensor module from a real environment, any test input may be supplied to the Control module of a simulated AV hosted within a virtual computer generated 3D environment.

### System Architecture

The System consists of two components –

- 1) Control Module
- 2) Visualization Module

Fig. 3-2 illustrates the system architecture. The Control Module runs the AV behavior algorithms and may be implemented on any real-time Operating System (OS). The Visualization Module hosts the simulated AV in a computer generated virtual environment and facilitates immersive visualization of the Control Module's response on the simulated AV in Virtual Reality using a stereoscopic Head Mounted Display (HMD). The Control Module and the Visualization Module are located within the same Local Area Network and exchange information with each other over a bi-directional network

socket link using User Datagram Protocol (UDP). The Visualization Module sends messages to the Control Module containing the state of the simulated AV as well as a description of the environment and its actors as “sensed” by the simulated AV at each instance of time. We call such a message Basic Safety Message (BSM).

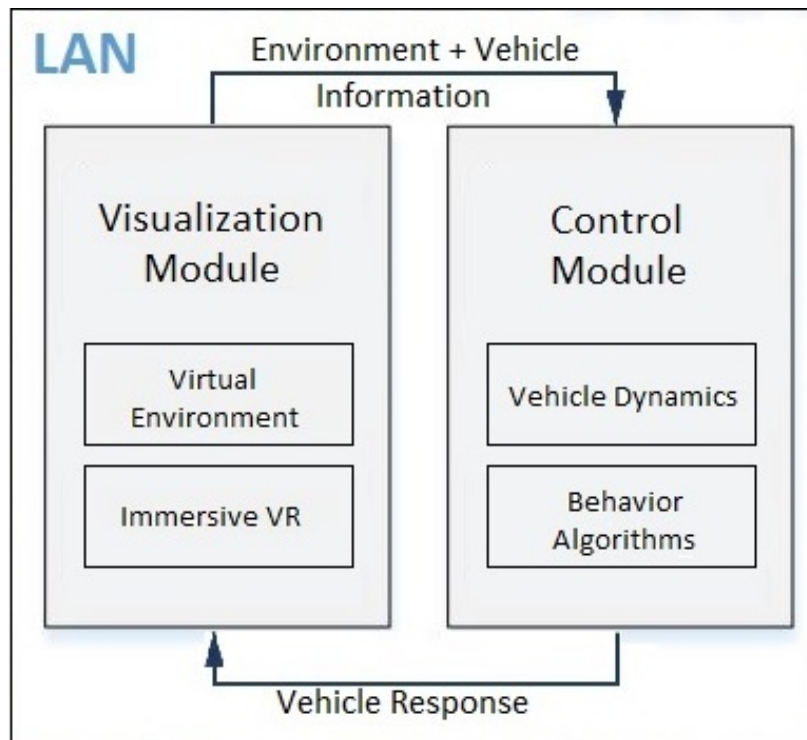


Fig. 3-2: Simulation Testbed - System Architecture

The virtual “sensors” in the simulated AV pass only the information that lies within the range and field of view of the combined simulated sensor package at a particular instance of time. Since we know all the information about the virtual environment, we simply pass the relevant information about the AV and its environment to the Control Module essentially bypassing the perception algorithms in the AV. This allows the testing of the simulated AV’s behavior algorithms essentially with the

assumption that the Perception algorithms work perfectly. The Control Module sends a Response Message (RM) each time it receive a BSM from the Visualization Module. The RMs contain the response for the simulated AV based on the BSM which needs to be visualized in the form of an updated pose and state of the AV. The next BSM the Visualization Modules sends will be computed after the AV has updated its state based on the previously received RM.

## Design and Implementation

We implement our Visualization Module in Unity3D which is a widely used game engine. The Control Module is implemented as a suite of MATLAB Simulink Desktop Real-Time and Carsim Vehicle Dynamics simulation software. To emulate the sensors in the AV, a virtual camera is fixed on the car looking into the surrounding virtual environment which keeps a record of any objects appearing and disappearing within its view. The virtual camera specifications, namely field of view and range are matched with the combined target sensor module's field of view and range. Multiple cameras can be fixed on the car, each with its own field of view and range, looking in different directions to account for upto 360 degrees field of view in total. Fig. 3-3 shows the concept of an AV having a surround view with various sensors for various purposes, each with a different range and field of view.

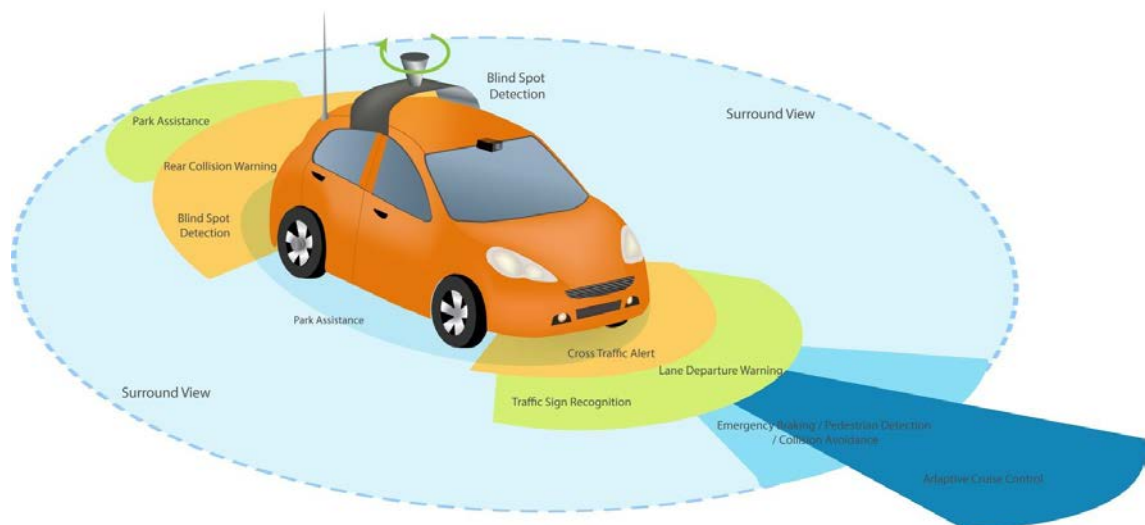


Fig. 3-3: AV sensors with various specifications

The BSMs containing information about the virtual environment around the hosted AV are communicated from the Unity3D application to the Control module serialized using JSON. Within MATLAB Simulink, this message is processed and passed as input to the Vehicle Controls System model under test and a response is computed in the form of a steering angle and throttle value. CarSim is able to process the response and calculate an updated pose and state of the vehicle. Simulink passes an RM to the Unity3D application containing the target position, orientation and speed of the vehicle based on the computed response. This message is used by the Unity3D application to update and visualize the new position of the vehicle. Fig. 3-4 illustrates this process.

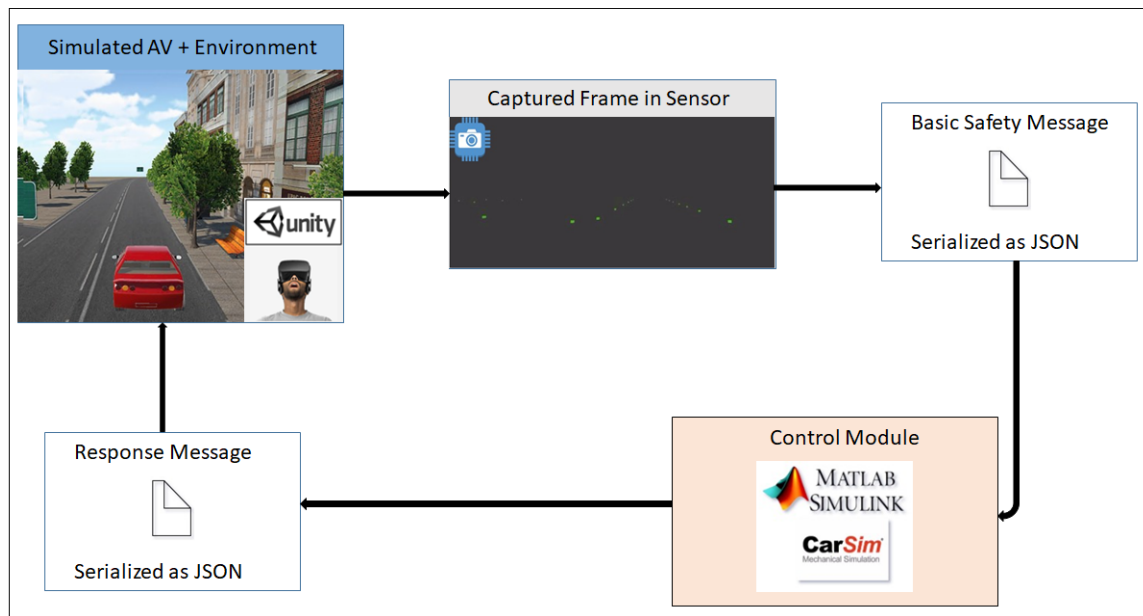


Fig. 3-4: AV Simulation Flow Diagram

The message exchange frequency is set to 30Hz both ways but can be varied. Each BSM contains position and orientation of STOP signs, position, heading velocity of

each moving obstacle such as another car or pedestrian, along with description of the actor i.e. whether it is a STOP sign, obstacle, moving vehicle etc. Each RM from the Control Module contains vehicle target position, orientation, speed and acceleration. This information is sufficient to recreate the motion of the car. At a sufficiently high message streaming rate, we can actually make do without passing the acceleration information in the response messages because as each message contains the required speed of the vehicle at a particular time instance, acceleration is implicitly specified with the continuous stream of messages. The backend system and the Unity application run in real time and asynchronously with each other.

### **Recreating motion of car along a trajectory**

The control module specifies a trajectory for the vehicle to follow in the form of response message communicated in JSON formatted strings. It is worthwhile to reiterate here that the Visualization Module does not actually control the dynamics of the car. Within the Control module, the behavior algorithms will output a steering angle and throttle. A mechanical simulation engine such as CarSim which simulates vehicle dynamics maintains the state of the vehicle as it moves. The final state of the vehicle as obtained after applying the resulting steering and throttle in the next frame is obtained from CarSim and communicated to the Visualization Module. The reference coordinates of Carsim's internal map of the track are different from the coordinates system of Unity3D, thus appropriate transformations are needed.



Once Unity3D has a response message, it is used to animate the motion of the vehicle. To this end, we use a waypoint animation system. Fig. 3-5 illustrates this. The consecutive messages received form corresponding consecutive waypoints. The target position in the message is set as the waypoint's position. The target speed is set to the 'New Mover Speed' of that waypoint, which is the speed the animating object (AV here) will acquire as it leaves that waypoint. The orientation specified in the message is set as the orientation of the vehicle as it leaves that waypoint. For animation, each rendered frame in the graphical simulation needs to show an updated position of the vehicle after it is moved a certain distance towards the next waypoint. The distance through which the vehicle needs to be moved each frame is calculated using the speed and the time it takes for the current frame to be rendered starting from the previous frame.



Fig. 3-5: Waypoint Animation System

## Testing AV Behavior Algorithms

We use the simulation testbed to test the behavior algorithms of an autonomous utility motion board vehicle built by students of Automobile Engineering at Clemson University's International Center for Automotive Research. For the purpose of testing the DO8 vehicle, a test track was chosen to test its operation in the real world. In simulation, we model the track from the real world test track. The virtual environment of the test track has been augmented with buildings, trees and other props for visual appeal. The figures 3-6 and 3-7 below show snapshots of the virtual environment. With the simulation, the performance of some of DO8's behavior algorithms were tested namely, response to STOP signs, route planning and lane keeping algorithms



Fig. 3-6: Top view of test track's virtual environment



Fig. 3-7: View from virtual environment showing lane markers

Figures 3-8 and 3-9 show the frames captured by the simulated camera sensor of the AV at two instances of time T1 and T2. At time instance T1, only the lane markers that appear within 20m in front of the vehicle appear in the frame. This is the information that is sent to the control module at this instance. Following a response from the Control module to move the vehicle forwards at a given rate, we see that a STOP sign now appears within 20m from the vehicle as captured in the frame at the next time instance T2. The information in the frame at T2 will now be communicated to the control module. This ensures that we are not flooding the behavior algorithms with irrelevant and unnecessary information. More importantly this ensures that the input data to the behavior algorithms is realistic. In the real world setting, not all of the information about the environment is already present. Information is presented to the control module as it is obtained through the limited range of the sensors.

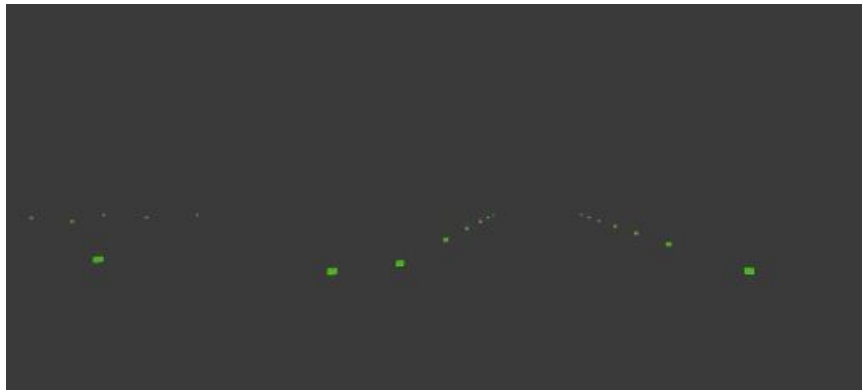


Fig. 3-8: Frame from camera sensor at time T1

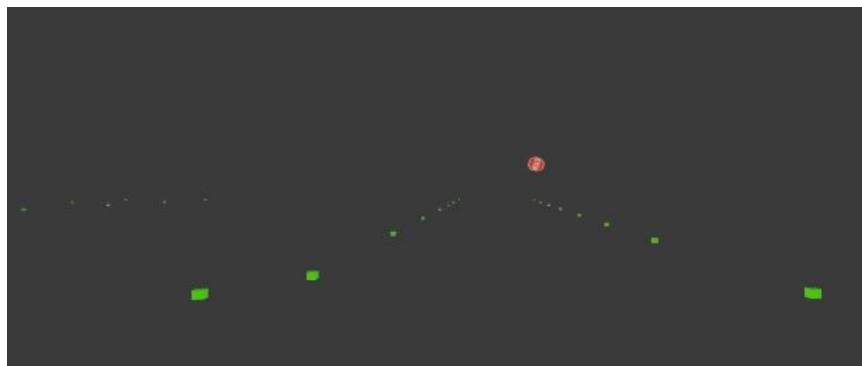


Fig. 3-9: Frame from camera sensor at time T2

The structure of a BSM that is sent from the Visualization Module to the Control Module is illustrated in Fig. 3-10. Each message contains information about the lane through intermittent lane markers along the left and right boundaries of the lane that are visible within the range of the sensor camera. Fig. 3-7 illustrates lane markers in the virtual environment. The lane markers need to be close enough to be interpreted as a continuous lane. Within the virtual environment, these lane marker objects are small cubic primitives that are placed along the boundaries of the lanes as a step in setting up the environment. The lane markers are as such invisible objects with no colliders and are visible only to the sensor camera on the AV. This technique is implemented through the

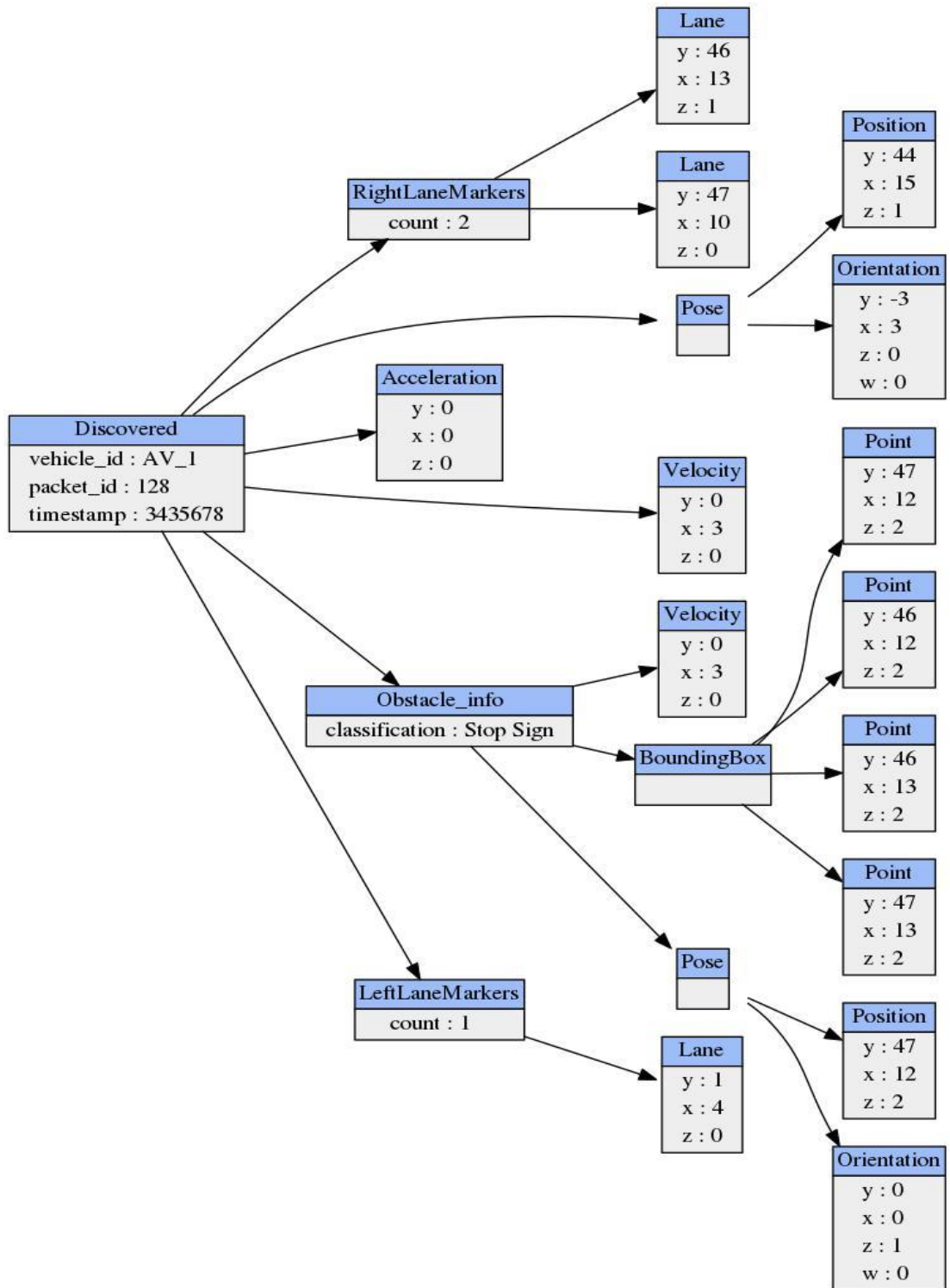


Fig. 3-10: Structure of Basic Safety Message

provision of ‘Layers’ within Unity3D. The message also contains information about all obstacles along with their position, their size as specified by a convex bounding box along the camera 2D plane, their approaching velocities, orientation and a classification. Stationary obstacles have a zero velocity. Traffic signs such as STOP signs are stationary objects. Pedestrians and other vehicles are examples of non-stationary obstacles.

Fig. 3-11 shows the structure of a response message that is communicated from the Control Module to the Environment as response for the AV. Each message specifies the information needed to supply to a target waypoint to animate the motion of the car.

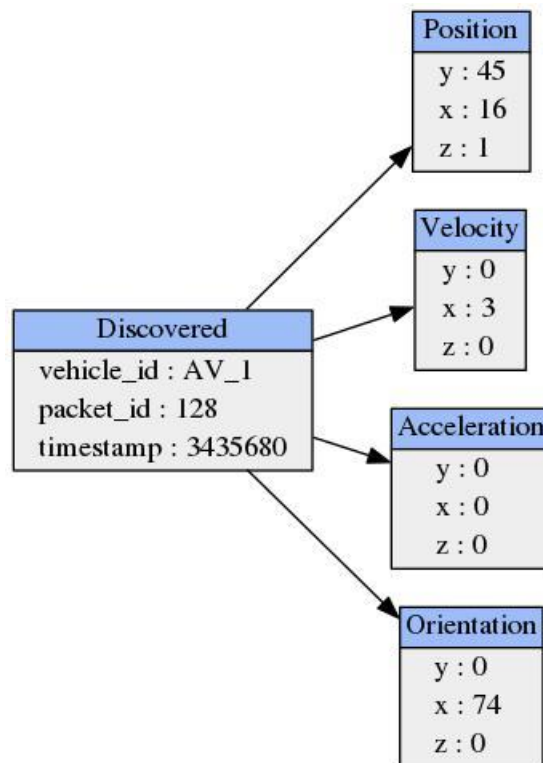


Fig. 3-11: Structure of Response Message

We run our simulation on a high-end graphics machine powered by NVIDIA GTX 1080, enabling it to render an immersive stereoscopic view of the interior of the car and surrounding environment. The users experience the simulator through the use of HTC's VIVE which is a commercial head mounted display (HMD) virtual reality device. The users get to perceive the autonomous vehicle from the perspective that they would have if they were actually riding in the vehicle.

## CHAPTER FOUR

### CACC EVALUATION APPLICATION

#### System Architecture

This application has been built on top of our simulation testbed presented in the previous chapter. The objective of this setup is to simulate a vehicle with Cooperative Adaptive Cruise Control (CACC) System. An upcoming section gives more information on CACC. The use of our simulator will allow us to test the autonomous vehicle with CACC while engaged in this type of cooperative control without the risk associated with real-world testing. To present a leading vehicle actor for the car under simulation, we integrate a vehicle in the simulation that gets vehicular navigation data from real-traffic adding a higher level of realism to the simulation. A real-world vehicle may be driven within Clemson University's campus to control the behavior of the leading vehicle actor. The simulator not only allows to test the system in nominal conditions, but also under adverse situations which can be network delays and breakdowns or even cyber-attacks.

We integrate real world vehicular navigation data from a human driven car in two different ways-

- 1) Recorded data using a high accuracy Real Time Kinematic GPS device
- 2) Live streaming of data while a car is driven in the real world by making use of DSRC network communication

In the first approach, we drive a car installed with Swift Navigation Piksi Multi GNSS RTK GPS device. It provides centimeter scale accuracy (fixed mode) of location at best and regular GPS precision accuracy (floating mode) at worst depending on the



satellite signal strength in the area of operation. We record this data onto a csv file and format and play back the data from the file into the simulation after passing it through a Kalman filter to clean noise. The results of data capture using this method are presented in the results section.

Next, we present the system for live streaming of data.

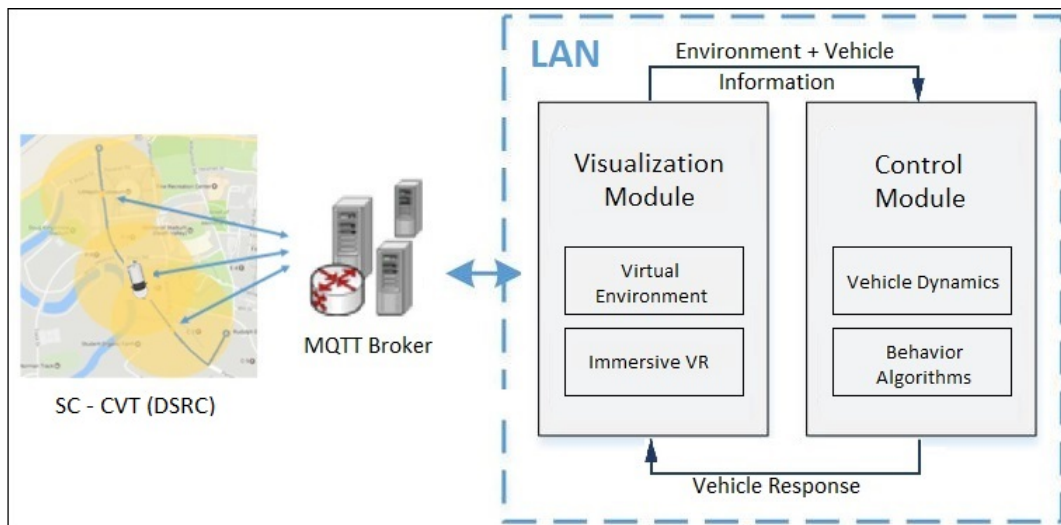


Fig. 4-1: CACC setup - System Architecture

To facilitate the transmission of a real world vehicle's data to the simulation testbed's core modules, we integrate our simulation testbed with the the South Carolina – Connected Vehicle Testbed (SC-CVT)[24] deployed at Clemson University's main campus.<sup>1</sup> The SC-CVT is a Dedicated Short Range Communication (DSRC) infrastructure setup that allows for Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communication capabilities. DSRC is short-range to medium-range wireless communication technology specifically designed for automotive use.

<sup>1</sup> Refer to SC-CVT website for further information

Some key functional attributes of DSRC are:

1. Low latency: The delays involved in opening and closing a connection are very short, on the order of 0.02 seconds.
2. Limited interference: DSRC is very robust in the face of radio interference. Also, its short range (~1000 m) limits the chance of interference from distant sources.
3. Strong performance during adverse weather conditions.

The DSRC infrastructure of SC-CVT comprises of communication nodes of two types – ones that are installed along a 1-mile stretch of road (Fixed Edge Nodes) within the university's campus and those that are placed inside vehicles (Mobile Edge Nodes). Each Mobile Edge Node consists of an On-board Unit (OBU) that facilitates communication with Fixed Edge Nodes using DSRC technology. The OBU also supply the required GPS location and estimated speed data for a vehicle as it is driven on the road. The Fixed Edge Nodes are linked to the university campus's Local Area Network via Optical Fiber and Wi-Fi backhaul links. Fig. 4-2 illustrates the architecture of SC-CVT.

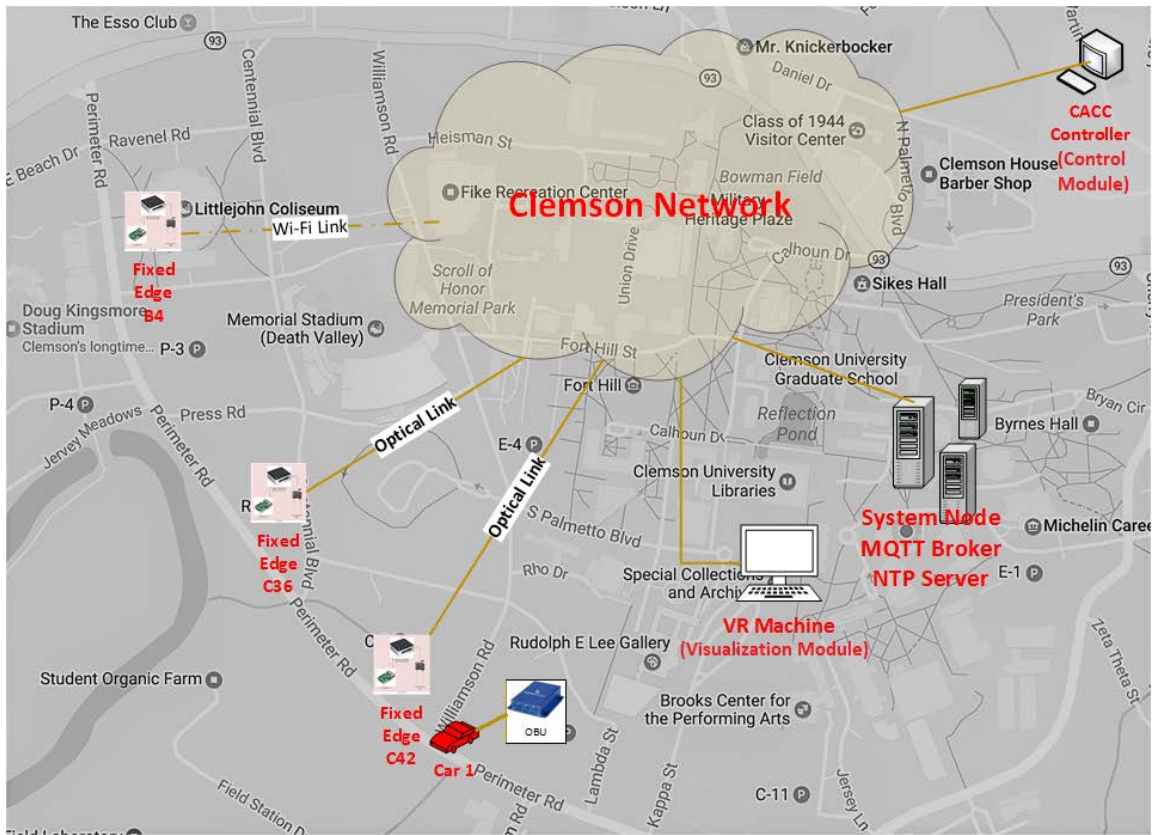


Fig. 4-2: SC – CVT and VR Simulation Testbed components

Data collected from the real world vehicle is published to a Communication System Node[16] running an MQTT broker. MQTT is a lightweight publish-subscribe based messaging protocol. The Visualization Module subscribes to the MQTT broker to receive the vehicle’s published information. This allows real-time data communication from the vehicle to the simulation platform with low latency.

## Design and Implementation

The virtual environment for this application is replica of Clemson University's campus. The road network and the models of the buildings has been laid out in such a way that they are co-located with the real version. The mapping between the location of roads in the real world and Unity3D's co-ordinate system is done using a function that maps GPS coordinates to Cartesian planar system and then add an appropriate offset to match within Unity3D. The altitude is ignores as the terrain is projected onto and modeled as a flat plane. The transformations below summarize this.

$$latitude = base_{lat} + \frac{y}{arc} \quad (1)$$

$$longitude = base_{lon} + \frac{x}{(arc * \cos(base_{lat} * \frac{\pi}{180}))} \quad (2)$$

$$altitude = z \quad (3)$$

Where,

$$arc = 2\pi * \frac{Radius_{earth} + z}{360}$$

$$base_{lat} = 34.67209 \quad base_{lon} = -82.83974$$



Fig. 4-3: Virtual Environment of Clemson University's campus



Fig. 4-4: Platoon of cars within the virtual CU environment

The BSM and RM communication methods are similar to that mentioned earlier. The Fig. 4-5 and 4-6 show the respective messages for these communication. We only pass the information of the vehicle in question in each case. No other environment information or obstacle is communicated as the algorithm under test is only CACC and not able to avoid obstacles or follow traffic rules. Also, for the CACC Evaluation application, we do not use interpolation while animating the trajectories of vehicles and make updates based only on the high frequency stream of messages for the sake of accuracy of visualization.

Discovered
vehicleID : 1
mesgID : 0
timestamp : 489696
latitude : 28
longitude : -43
altitude : 172
velocity : 15
gps_track : 172
acceleration : 0

Fig. 4-5: CACC setup – Basic Safety Message

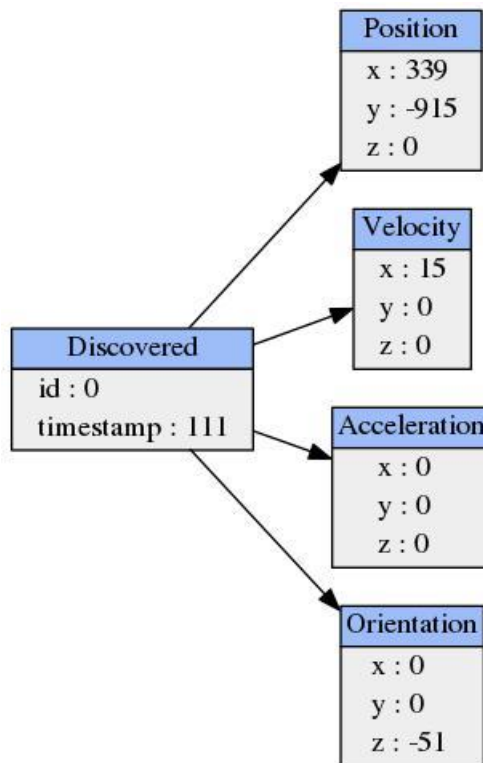


Fig. 4-6: CACC setup – Response Message

### Co-operative Adaptive Cruise Control (CACC)

CACC allows a platoon of cars to move one after the other in a smooth and flow such that each car is “well informed” of the intentions of the car ahead of itself. A car following another car maintains a desired relative distance from the latter. CACC is an extension of Adaptive Cruise Control, but using wireless communication to inform the other of the GPS location and acceleration information besides traditional sensors like radar. With CACC, vehicle platoons are able to maintain lesser distance between each other without compromising safety. As a result, CACC leads to better traffic flow and reduced congestion. Another benefit of CACC, as illustrated in the figure 4-7 is that with added wireless network communication such as DSRC, a vehicle does not depend on line of sight of leading vehicle to get its information. This helps especially during lane changing and turning maneuvers.

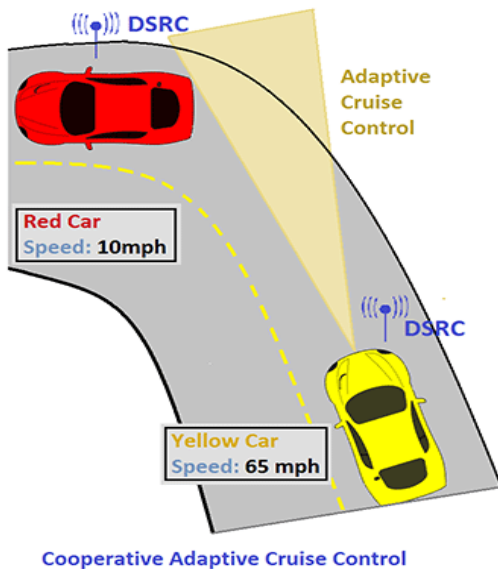


Fig. 4-7 CACC helps during turns<sup>[16]</sup>

### System Performance Metrics

In trying to meet our specific system goals listed in Chapter III - Overview, we test the system for the following performance measures-

*Frame Rate* – The frame rate is the frequency at which the consecutive images in the VR scene are displayed to the user. Frame rate is a particularly important metric for VR systems. A low frame rate may induce cyber sickness in users causing problems such as feeling of nausea, headache and disorientation. Higher values of frame rate positively affect presence in virtual environments. [25] A frame rate of 90fps or more is widely accepted as a gold standard for VR systems.

*Communication delays between various parts of the system* - We refer to the communication delay from the Visualization Module to the Control Module as *Sensing Latency*. Similar latency from the Control Module to the Visualization Module is termed as the *Feedback Latency*. The average time in seconds it takes for a BSM to reach from RSUs to the Visualization Module is called as the Network Latency. We would like to have these values as low as possible. Any communication delays between the various components of the system could potentially add to inaccuracies in visualization of the Control System's response. Low communication delays are key to making the system operate smoothly in a closed loop real-time manner.

*Error in perceived distance between Leading Car and simulated AV* – With this metric we would like to evaluate how well the Simulation testbed is able to preserve the accuracy of the CACC control system's response together with the motion of the leading actor vehicle. We calculate the distance between the Leading Vehicle and the simulated



AV at corresponding timestamps separately within the Control Module and the Visualization Module. Here the distance calculated by the Control Module is taken as the reference. Any difference in the distance measured within the Visualization Module from that of the distance measure within the Control Module is an error. We would like to keep this error at a minimum. A large error would alter the perceived following behavior of the CACC Controlled AV within immersive VR in the Visualization Module.

### Usability Study

We record the data from RTK GPS on a file and use that to recreate the motion of a vehicle that represent the Leading Vehicle (LV) actor. The virtual car which is under test is controlled by the CACC controller algorithm within Carsim/Simulink Control Module, and follows the Leading Vehicle. We present this simulation in Virtual Reality to 10 participants and ask them to fill questionnaires (see Appendix A). The user group consisted of 7 males and 3 females in the age range of 18 to 25. Our users were all students of Clemson University. One such questionnaire measures the Simulator Sickness score [17], another measures presence within the Virtual Reality Experience using the IPQ [18] and another questionnaire asks several subjective questions. With the subjective questionnaire, we seek to measure users' quality of experience [19] and evaluate the human factors aspects of the CACC controller's response.

## CHAPTER FIVE

### RESULTS AND DISCUSSION

#### System Performance

Frame rate - The Unity3D application is able to keep up an average frame rate of over 90 frames per second consistently as reported by Unity3D statistics dump. This is in line with the widely accepted recommended benchmark for a smooth VR experience not prone to causing sickness. The maximum refresh rate of the HTC Vive head mounted display being 90, this is what the users effectively observe.

Communication Delays - The latency due to communication delay was found out across various parts of the system by timestamping exchanged messages between the source and destination at the time they were sent and received respectively. The two machines involved were time synched using a remote NTP server located in Clemson. Any time synch offset between the two machines was adjusted in calculations. The offset was calculated by querying system times using appropriate time commands on the two systems simultaneously, repeating this process 10 times and finally taking the mean of obtained values.

The network latency related to data transmission from the vehicle to the Visualization Module was found out. The channels involved in this path were DSRC and a reliable and high-speed optic fiber communication link. DSRC offers communication capabilities that make its performance robust to extreme weather conditions and independent of vehicle running velocity [26][24]. To measure the network latency, we

conducted a trial sending about 3000 Basic Safety Messages carrying a timestamp based on unix-time and message ID from an On Board Unity (OBU) within the SC-CVT to the machine running the Visualization Module over a duration of 1 minute. The unwavering and reliable nature of DSRC and optic fiber backhaul channel eliminated the need to conduct multiple tests in different conditions. Fig. 5-1 shows the probability distribution of latency measured between the times of data being published from the vehicle and the moment they are received at the Visualization Module. The average network latency was found to be about 37 milliseconds and this enveloped data path from vehicle to MQTT broker and from the broker to the simulator.

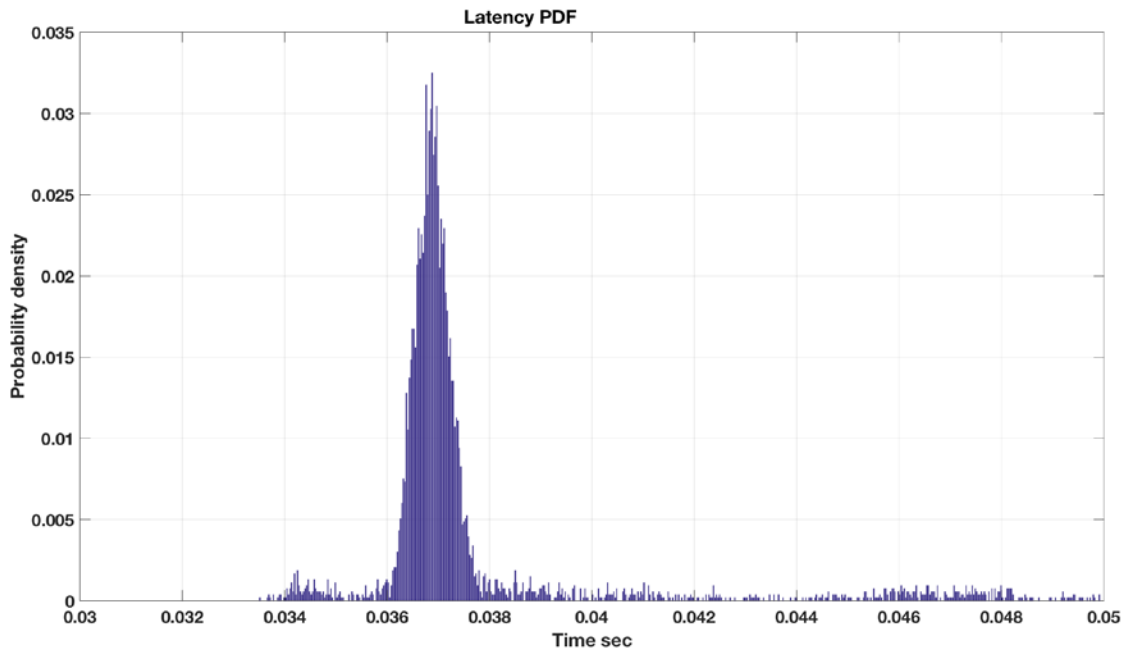


Fig. 5-1: Network Latency

The communication delays between the Unity3D Visualization Module and Carsim + Simulink suite Control Module were also found out. The average Sensing Latency was obtained to be 107.892ms and Feedback Latency was obtained to be 82.36ms. Fig. 5-2 and Fig. 5-3 show the latency histogram of the exchanged messages over the duration of the simulation as the actor vehicle drove on the mile long stretch of the Perimeter Road in the virtual environment as the AV followed it.

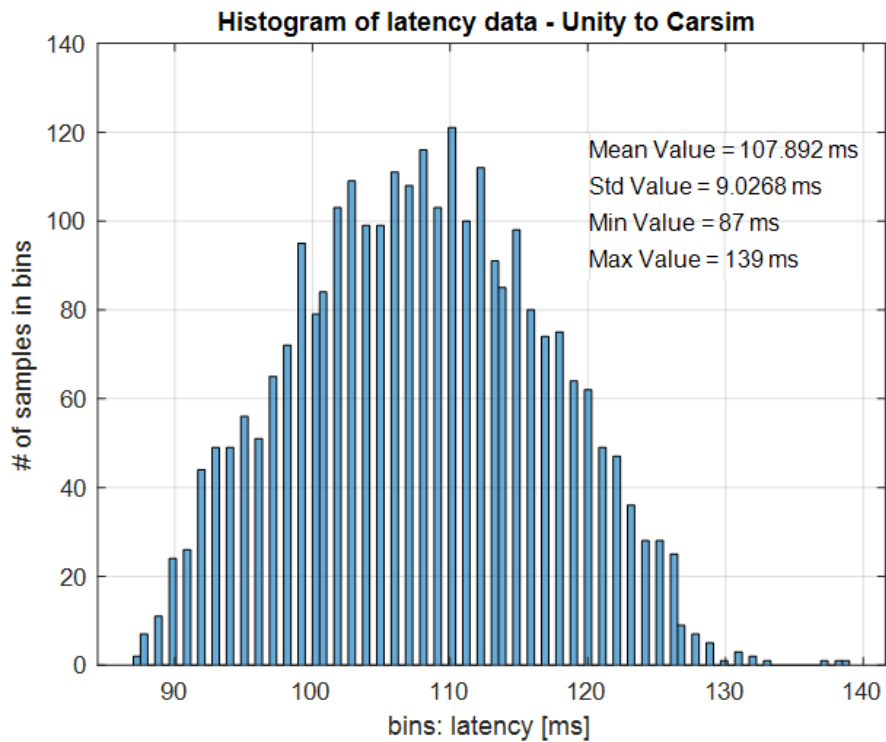


Fig. 5-2: Sensing Latency

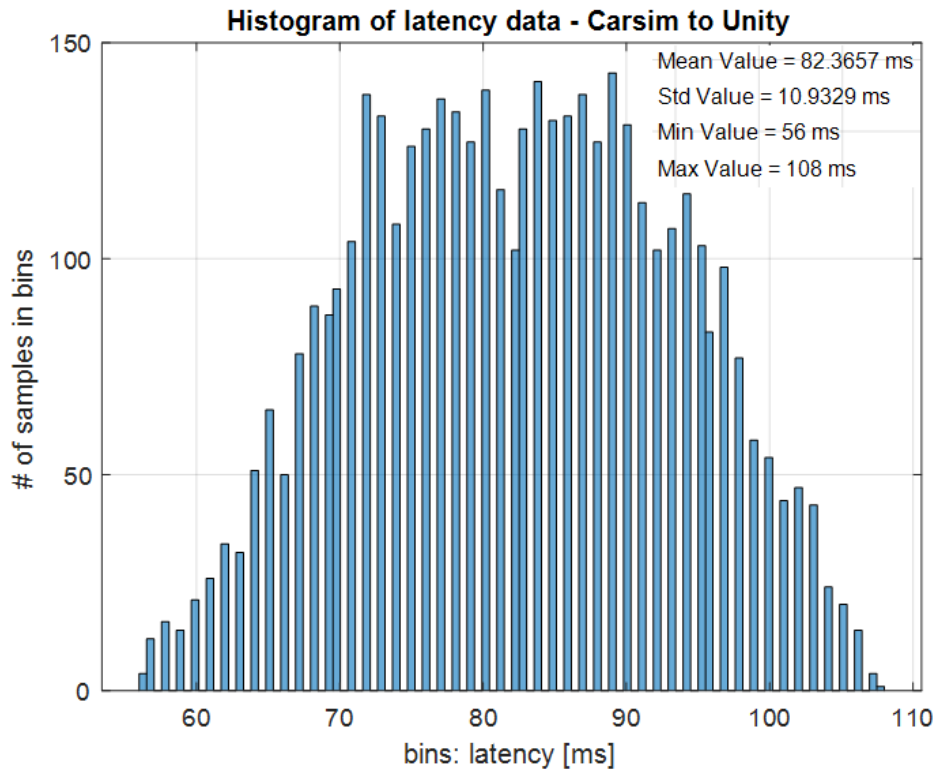


Fig. 5-3: Feedback Latency

In our setup, we considered the Sensing and Feedback latency values to be high and limiting especially because the Visualization and Control Module were on the same local area network. One probable cause of the high latency is identified to be the added layers of software on the Network Socket links for Unity3D and CarSim + Simulink suite.

### Recording GPS Data

In these results we discuss the accuracy with which we are able to record the GPS trail data as the real world car was driven along the mile long stretch of Perimeter Road. In a real world vehicle driving with assistance from CACC, the sensors such as radar and lidar report accurate position of any vehicles in front it. The primary purpose of any wireless communication network channel such as DSRC in such a scenario is to communicate acceleration information of the leading vehicle. However in a simulation such as ours, with a virtual vehicle operating on CACC and no real world sensors it is important to obtain accurate position of the leading vehicle using GPS data. The RTK GPS device reports estimated accuracy of each GPS data sample in the form of an error in meters. The accuracy of GPS position recorded of the real world vehicle while it was driven on Perimeter Road using the RTK GPS device is shown in Fig. 5-6.

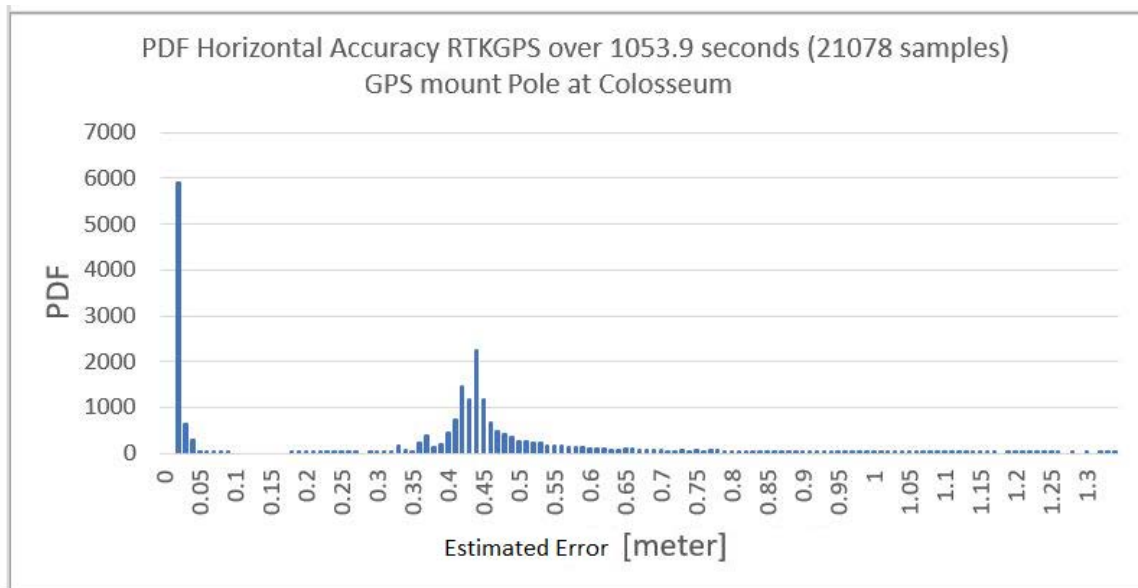


Fig. 5-4: PDF of accuracy of RTK GPS data

We see two distinct aggregates in the plot as seen in Fig. 5-4. The higher accuracy aggregate of samples corresponds to the ‘Fixed’ mode of RTK GPS. In ‘Fixed’ mode, the device is able to establish connection with multiple satellites and operates on centimeter level accuracy. In order for the device to work on this mode, it needs to be free from any obstructions such as tall building and trees. If the RTK GPS device cannot operate on Fixed mode it operated on ‘Floating’ mode that reports position data with about the same accuracy as that of a regular GPS device. Fig. 5-5 shows path taken by the vehicle color coded to indicate the regions that correspond to various levels of accuracy as reported in Fig. 5-4.

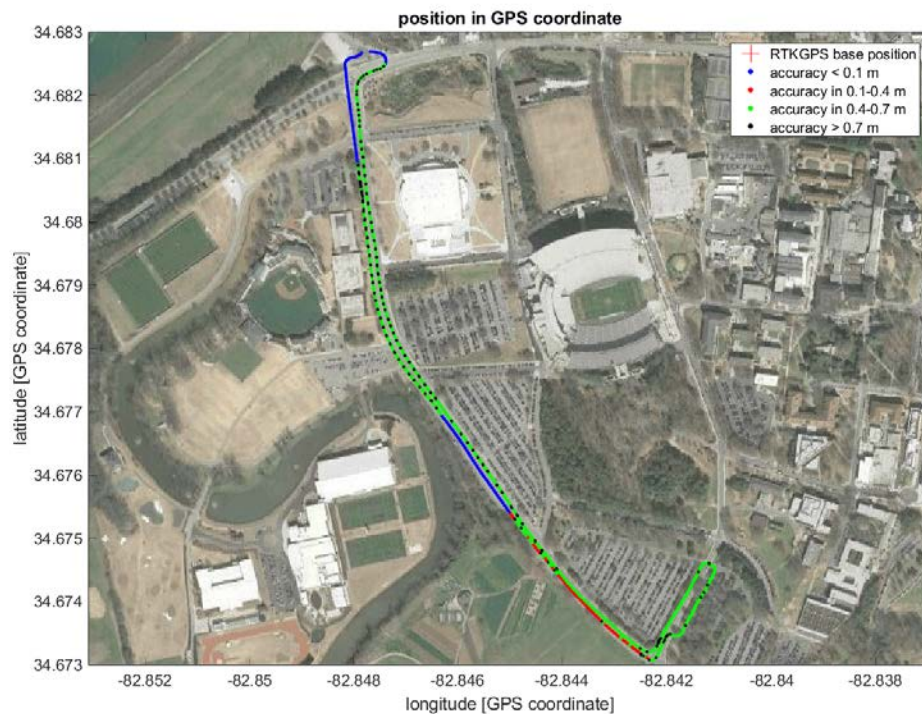


Fig. 5-5: GPS Accuracy data plotted on the map

### Error in Perceived Distance in CACC Response

Fig. 5-6 illustrates the plot of Euclidean distance measured between the actor leading vehicle and the simulated AV separately in the Control Module (black) and the Visualization Module (red) along the time axis. The two modules are time synced with a remote NTP server located in Clemson.

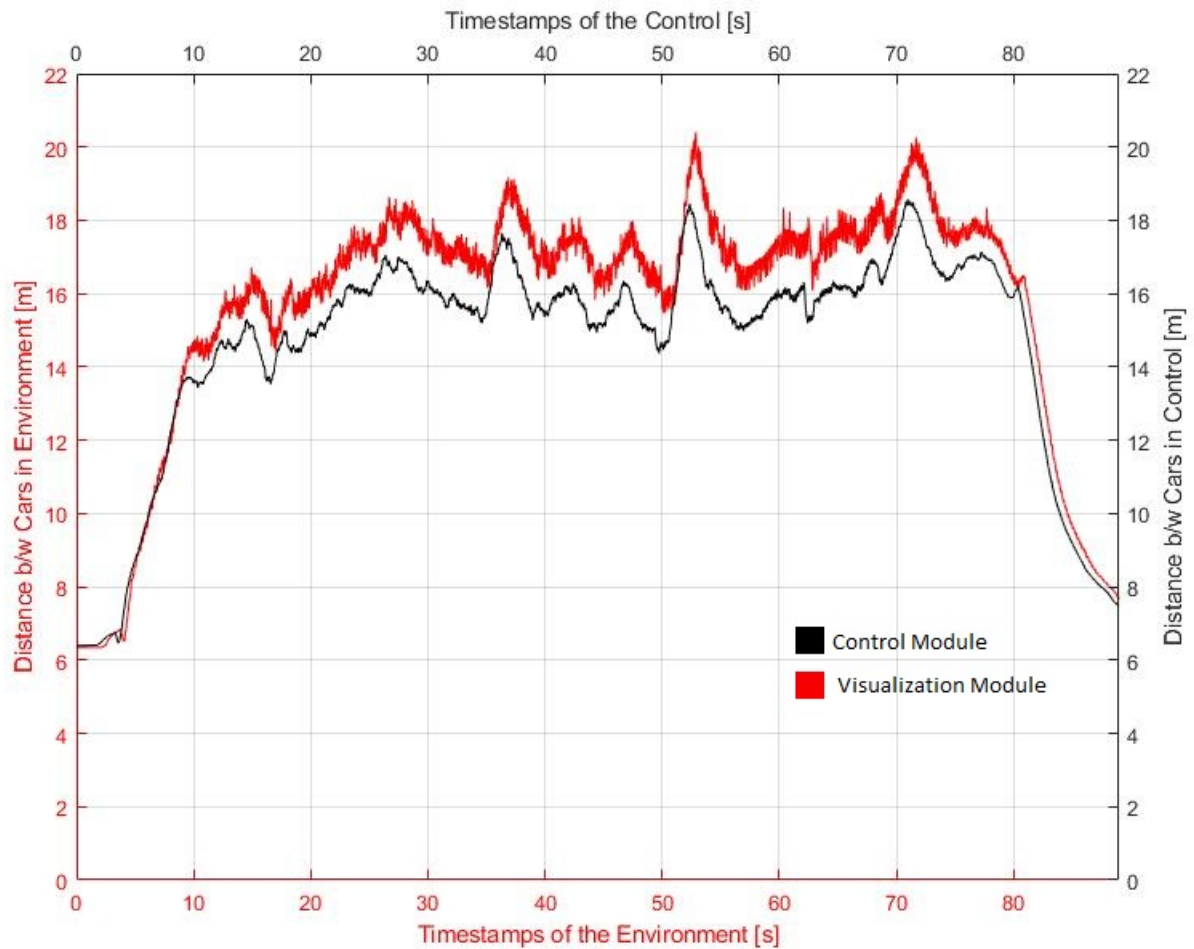


Fig. 5-6: Error in Perceived Distance b/w vehicles

The average value of the distance maintained was 15.45 meters in the Control Module and 16.7 m in the Visualization Module. The mean distance error is 1.25m and



the mean percentage of error is calculated as  $1.25 / 15.45 * 100$  giving 8.9 per cent. This translates to an accuracy of 91.1 per cent in visualization of CACC's response.

The probable causes for this error is identified to be the transmission delay between the two modules. The error can be corrected by compensating for the distance travelled by vehicles during the time elapsed in communication by means of prediction. Besides the error, the Visualization Module plot also shows some amount of jitter of a sawtooth pattern. The cause for this is identified to be non-interpolated updates of the vehicles' positions within the Visualization Module based only on the receipt of messages. We would like to update their positions more frequently by accurate interpolation based on vehicle speed and acceleration in the future to address this problem. This will likely also improve the user experience.

## Usability Study

The users view the simulation in Virtual Reality from the vantage point of a rider in the AV following a leading actor vehicle in the virtual environment of Clemson University's campus. The experience lasts for about 6-8 minutes.

Fig. 5-7 shows the simulator sickness scores of the participants. They were presented the pre and post Simulator Sickness Questionnaire (SSQ) [17] before and after experiencing the simulation respectively.

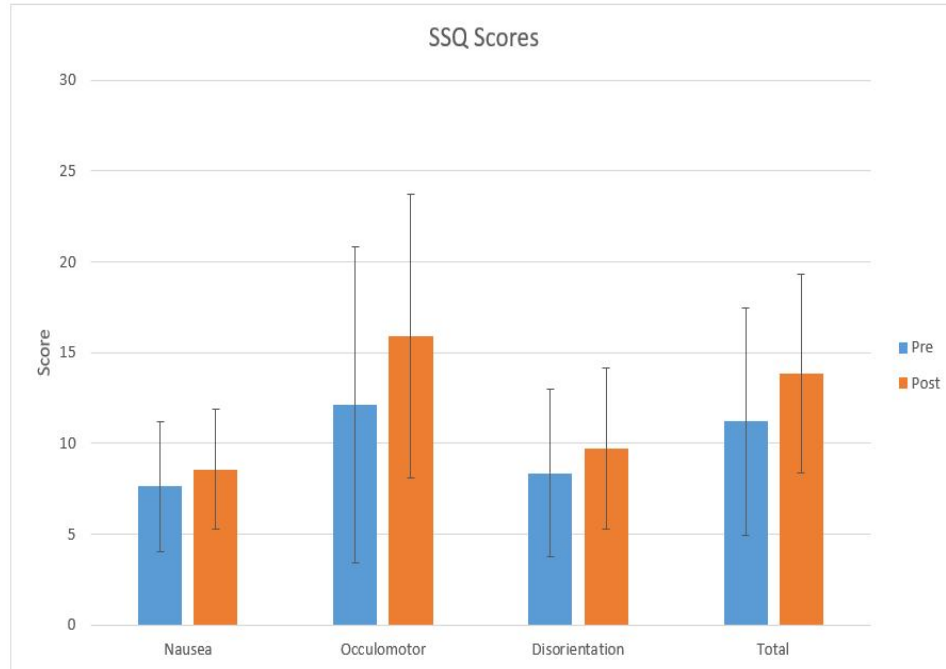


Fig. 5-7: Simulator Sickness Scores<sup>[17]</sup>

The mean total SSQ score in the Post condition was 14.2. This is lower than the 15.5 threshold for a low SSQ score qualifying such a system in the top 75<sup>th</sup> percentile of Simulator Systems across VR or non-VR operation [23].

Fig. 5-8 shows the Presence scores of the participants as calculated from the Igroup Presence Questionnaire [18] and methodology.

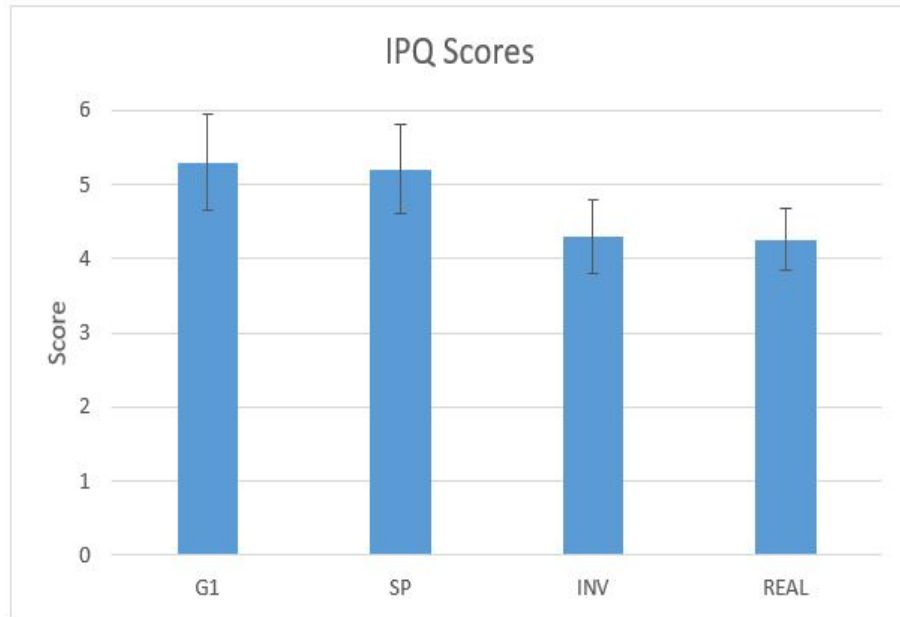


Fig. 5-8: Presence Scores – IPQ<sup>[18]</sup>

The presence scores for General Presence (G1), Spatial Presence (SP), Involvement (INV) and Realism (REAL) are as reported in Fig. 5-8. On the IPQ, a score of 3 indicates neutral, less than 3 indicates negative and greater than 3 indicates positive presence scores. We found moderate to high overall presence in the Virtual Reality simulation.

Fig. 5-9 through Fig. 5-11 show the results of the subjective questionnaire presented to the users during the study. The subjective questions were designed to evaluate CACC by asking users to rate the most important traits relevant to CACC such as starting and stopping behavior, following distance etc. The questions also seek to

gather insights on the user experience of AV ridership in the designed AV with regards to traits such as trust and confidence.

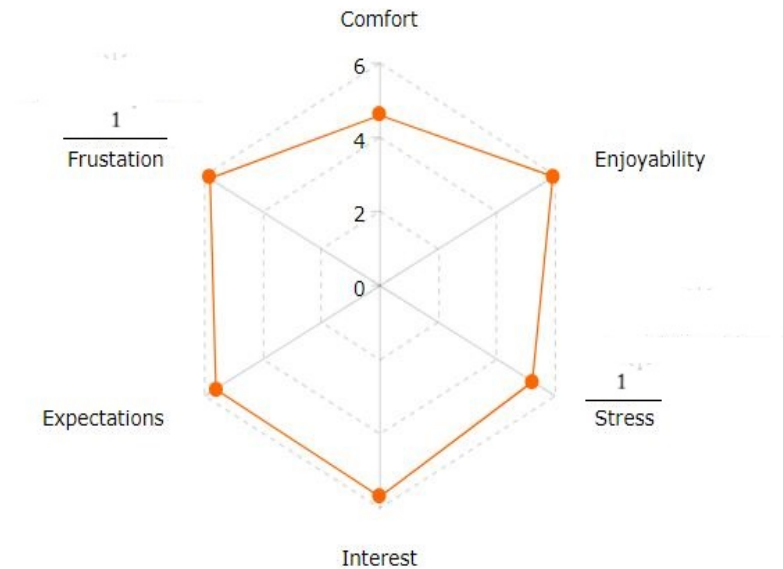


Fig. 5-9: Quality of Experience

The 6 most relevant qualities to ridership in an AV in an immersive virtual reality setting were chosen from the standard Quality of Experience (QoE) measures listed in [19]. The two negative traits namely Frustration and Stress are reported as inverse because a low absolute score on a 0 to 6 rating scale for them indicates a high quality of experience whereas a high absolute score on the 4 positive traits namely Comfort, Enjoyability, Interest and (meets) Expectations indicates a high quality of experience. Thus, the web plot indicated the overall quality of experience with the amount of spread. The QoE result indicates a positive user experience with the immersive VR simulation system of riding in the AV under control.

Fig. 5-10 shows the web plot of user's evaluation scores for questions that asked them to evaluate the response of the CACC response of the behavior algorithms under test within the Control Module.



Fig. 5-10: CACC controller Response

The results indicate that the response of the CACC controller was good from the point of view of four of the six relevant metrics of interest. The acceleration behavior and the following of Traffic Rules such as staying within lanes had some concerns, relatively speaking. The simulated AV was not expected to follow all the traffic rules because the behavior algorithms did not incorporate that aspect and focused on only following behavior. However, the acceleration was reported as being slightly sudden and rapid by some participants. This is a useful insight which indicates that there is a scope for improvement in the implementation of this aspect of the behavior algorithms.

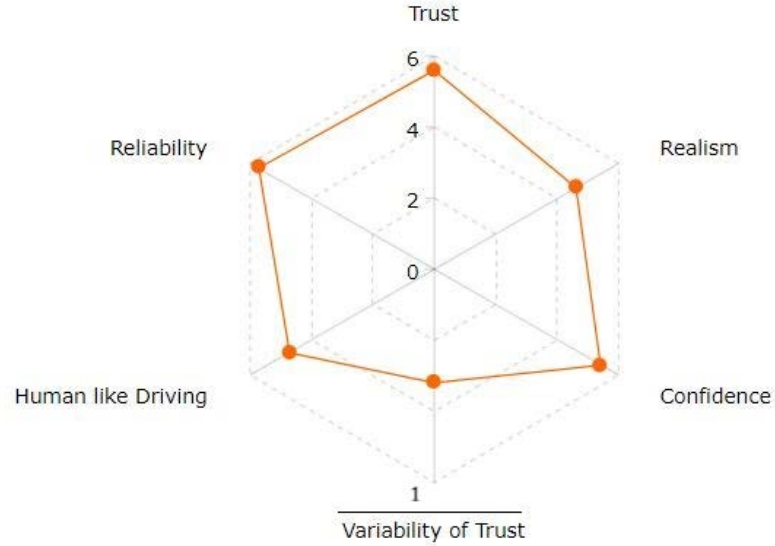


Fig. 5-11: CACC controller human factors aspects

Fig. 5-11 shows the web plot of the human factors aspects of the CACC controller as reported by users' response to questions. The variability of trust is a parameter that indicates that users had varying levels of trust in the AV. A probable reason for this result could be that the AV violated road marking at times because the controller was designed only to handle lateral and longitudinal control behind the leading vehicle and not obey traffic laws. Other results indicate that the users had trust, confidence and thought the AV behaved reliably. However, the users noticed that it behaved slightly differently than a conventional human driven vehicle. This may not necessarily be a bad thing, but just the way AV will work. In fact the driving dynamics that they exhibit could be different but safer for the riders than conventional human driven vehicles.

## CHAPTER SIX

### CONCLUSION AND FUTURE WORK

The work presented discusses the design and implementation of a novel approach to building driving simulators for the testing of autonomous vehicles. The main differentiator from other simulators is the ability to integrate live or recorded real-world driving data for actors into a virtual reality simulation, allowing for scenario creation and a more realistic simulation.

The performance results reveal that there is scope of improvement in terms of the communication latency between the Visualization and Control Modules as these can affect the fidelity of the simulation testbed and perceived performance of the behavior algorithms. For automobile engineers designing AV behavior algorithms, such a VR based simulation testbed could be a useful tool to find areas of improvement within designed algorithms especially from a usability perspective. The use of virtual reality for displaying the events in the simulation allows one to investigate the user experience offered by the autonomous vehicle and allows researching human factors aspects associated with it. The DSRC based communication also opens up the possibilities to the test cyber attack and DOS attack investigation in smart and connected vehicles.

As future work, we would like to implement a better performing network communication solution between the Visualization Module and Control Module. This will also minimize the perceived distance error observed in CACC response. Calculation of end to end latency in time elapsed between the movement of real world vehicle and

when the actor vehicle is rendered in the similar state using a camera based tracking and timestamping approach would be another work in the pipeline.

As future work, we would also like to take the realistic virtual scenario creation to the next level by also providing feedback of the autonomous vehicle's response to the driver of the real vehicle as they drive the vehicle on the road. We would like to achieve this by adding a tablet on the dashboard of a car that simulates the rear-view mirror and renders a computer generated virtual car on the tablet in real time. This will also make use of the MQTT broker to subscribe to the virtual car's information onto the tablet. We would further like to have a car behind the real car and the virtual car's virtual position and have the tablet act as a dash cam. Human drivers on the test track are then able to see the position of virtual car through the tablet as if they were really following or preceding it.



Fig. 6-1: Platoon of cars target experience



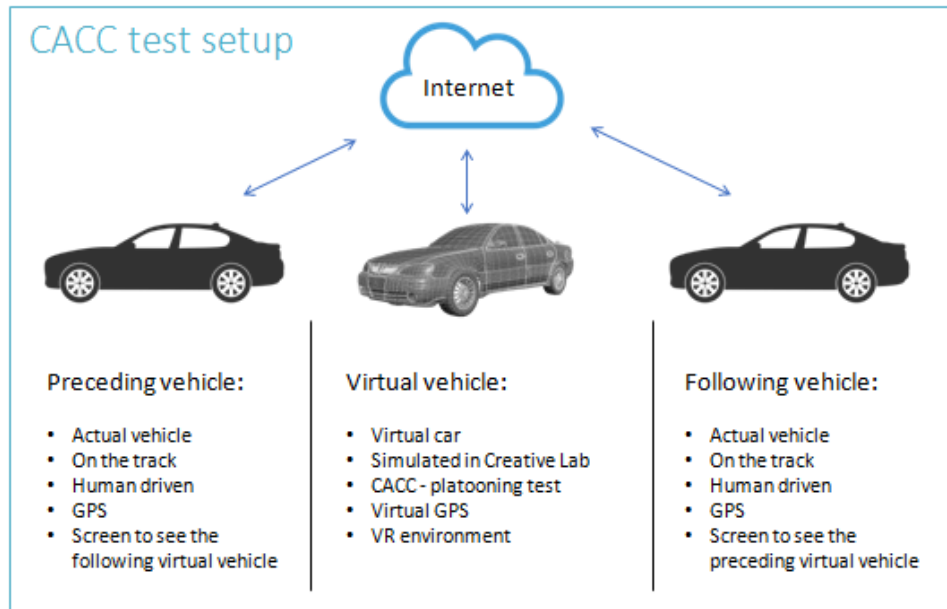


Fig. 6-2: Platoon of cars setup

The feedback of the simulated car data back to the real-world allows to examine the reactions of the human drivers to the autonomous virtual car behavior. Fig. 6-1 and 6-2 illustrate this scenario.

## APPENDICES

Appendix A

User Experience Study – Simulator Sickness Questionnaire (Pre)

No \_\_\_\_\_

Date \_\_\_\_\_

**SIMULATOR SICKNESS QUESTIONNAIRE**

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

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

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

\*\* Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

User Experience Study – Simulator Sickness Questionnaire (Post)

No \_\_\_\_\_

Date \_\_\_\_\_

**SIMULATOR SICKNESS QUESTIONNAIRE**

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

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

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

\*\* Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

User Experience Study – Subjective Survey

No. \_\_\_\_\_

**Subjective survey**

**1) The car I was in responded well to the vehicle in front of it.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**2) The car I was in maintained safe distance behind the other vehicle.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**3) The car I was in maintained appropriate speed while following the other vehicle.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**4) The car I was in stopped smoothly & safely when the other vehicle stopped.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**5) The car I was in picked up well from being stationary when the other vehicle began to move.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**6) The car I was in would be prone to rapid acceleration and deceleration.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**7) At times I felt like I was going to crash into the vehicle in front of me .**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**8) I could trust the car I was in to deal with unforeseen circumstances while following the other vehicle.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**9) The car I was in remained within lane markings while moving.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree

6-Moderately Agree  
7-Strongly Agree

**10) The vehicle in front of me remained within lane markings while moving.**

1-Strongly Disagree  
2-Moderately Disagree  
3-Slightly Disagree  
4-Neither Agree nor Disagree  
5-Slightly Agree  
6-Moderately Agree  
7-Strongly Agree

**11) The car I was in followed the other vehicle reliably.**

1-Strongly Disagree  
2-Moderately Disagree  
3-Slightly Disagree  
4-Neither Agree nor Disagree  
5-Slightly Agree  
6-Moderately Agree  
7-Strongly Agree

**12) My trust in the car I was in remained constant throughout the simulation.**

1-Strongly Disagree  
2-Moderately Disagree  
3-Slightly Disagree  
4-Neither Agree nor Disagree  
5-Slightly Agree  
6-Moderately Agree  
7-Strongly Agree

**13) The car I was in was self-driving similar to how a human would generally drive while following the vehicle in front of it.**

1-Strongly Disagree  
2-Moderately Disagree  
3-Slightly Disagree  
4-Neither Agree nor Disagree  
5-Slightly Agree  
6-Moderately Agree  
7-Strongly Agree

**14) The car I was in behaved like it was simulated by a computer.**

1-Strongly Disagree  
2-Moderately Disagree  
3-Slightly Disagree

- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**15) The vehicle in front of me behaved like it was driven by a human.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**16) The vehicle in front of me behaved like it was simulated by a computer.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**17) My ride in the car was comfortable and did not make me nervous.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**18) The behavior of the car I was in was unpredictable.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**19) The behavior of the vehicle in front of me was unpredictable.**



- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**20) Sitting in the car, I felt like I was physically moving through the environment.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**21) Sitting in this simulator gives me a good idea of riding in a car with autonomous driving behavior in real life.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**22) My experience of riding in this car was dull.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**23) Riding in this car was frustrating.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree

- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**24) My riding experience was enjoyable.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**25) My riding experience meets expectations.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**26) My riding experience was comfortable.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**27) My riding experience was stress inducing.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

Additional comments -

User Experience Study – Post Experiment Questionnaire (Presence and General)

No. \_\_\_\_\_

**Post-experiment questionnaire**

You'll see some statements about your experience. Please rate them according to how much you agree with each.

**1) I was aware of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people etc.)**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**2) The virtual world seemed completely real to me.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**3) I had a sense of acting in the virtual space, rather than operating something from outside.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**4) The experience in the virtual environment seemed consistent with my real world experience.**

- 1-Strongly Disagree
- 2-Moderately Disagree

- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**5) The virtual world seemed only as real as an imaginary world to me as opposed to something indistinguishable from the real world.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**6) I did not feel present in the virtual space.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**7) I was not aware of my real environment.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**8) In the computer generated world, I had a sense of “being there”.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree

6-Moderately Agree  
7-Strongly Agree

**9) Somehow I felt that the virtual world surrounded me.**

1-Strongly Disagree  
2-Moderately Disagree  
3-Slightly Disagree  
4-Neither Agree nor Disagree  
5-Slightly Agree  
6-Moderately Agree  
7-Strongly Agree

**10) I felt present in the virtual space.**

1-Strongly Disagree  
2-Moderately Disagree  
3-Slightly Disagree  
4-Neither Agree nor Disagree  
5-Slightly Agree  
6-Moderately Agree  
7-Strongly Agree

**11) I still paid attention to the real environment.**

1-Strongly Disagree  
2-Moderately Disagree  
3-Slightly Disagree  
4-Neither Agree nor Disagree  
5-Slightly Agree  
6-Moderately Agree  
7-Strongly Agree

**12) The virtual world seemed more realistic than the real world.**

1-Strongly Disagree  
2-Moderately Disagree  
3-Slightly Disagree  
4-Neither Agree nor Disagree  
5-Slightly Agree  
6-Moderately Agree  
7-Strongly Agree

**13) I felt like I was perceiving pictures.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**14) I was completely captivated by the virtual world.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**15) I felt like I was riding through Clemson University's campus.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**16) The road network in the virtual world was an accurate representation of the roads in that part of the university's campus.**

- 0-Don't know
- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**17) Sitting in this simulator, I will be able to tell the difference if the behavior of the car was slightly tweaked.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree

- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**18) The automated following feature would be a good addition to my vehicle in real life provided I'm able to regain control at will.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**19) I would invest in a vehicle with such automated features either now or in the near future (5-7 years).**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**20) I consider myself well informed about the state of the availability of autonomous vehicles in the consumer market.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**21) I trust Automobile Companies with bringing autonomous vehicle to the market when they do.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

**22) The option to experience such simulations for autonomous vehicle at Automobile Trade shows will increase my trust in such vehicles.**

- 1-Strongly Disagree
- 2-Moderately Disagree
- 3-Slightly Disagree
- 4-Neither Agree nor Disagree
- 5-Slightly Agree
- 6-Moderately Agree
- 7-Strongly Agree

Finally some demographic questions,

Your age –

Your gender –

Any additional comments –



## IRB Approval

Information about Being in a Research Study  
Clemson University

### **VR Driving Simulation for Evaluation of Autonomous Driving Behavior Algorithms**

#### **Description of the Study and Your Part in It**

You are invited to participate in a research study conducted by Dr. Sabarish Babu, Dr. Andrew Robb and their graduate students. Dr. Babu and Dr. Robb are faculty in the department of Human Centered Computing at Clemson University. The purpose of this research is to evaluate a VR Driving Simulator designed to test Autonomous Driving behavior algorithms in a realistic virtual driving environment. We would also like to collect feedback and gather insights on the user experience of being engaged in such a driving simulator in Virtual Reality.

Your part in the study will be to experience a driving simulation in VR with autonomous driving capabilities. You will be asked to fill out a presence questionnaire, answer questions regarding your experience with the simulator and report any discomfort potentially arising due to simulator sickness through a standard Simulator Sickness Questionnaire (SSQ).

It will take you about 40 minutes to participate in this study. This will include about 10 minutes of briefing, 15 minutes of experiencing Virtual Reality and 15 minutes filling out questionnaires.

#### **Risks and Discomforts**

During your participation in this study, you may encounter some discomforts like disorientation, nausea, headache and feeling weak in the stomach for a short interval. You are welcome to try out a simpler VR experience before you experience the driving simulation in order to gauge your level of comfort. Other labs that have used driving simulators have suspected that nausea may be more likely in participants who have a history of motion sickness or are pregnant. If you have a history of motion sickness or are pregnant, you may not want to participate in this research study. If at any point you feel you do not want to continue due to any sort of discomfort, you are welcome and encouraged to come out of VR by removing the headset from your face.

Clemson University students may contact the Redfern Health Center at 656-2451 if you continue to feel badly after the study. Other participants may contact the Sullivan Center at 656-3076 or your preferred healthcare provider.

#### **Exclusion Requirements**

As a user of the simulator, you will be required to look around and observe the scene clearly and answer questions based on your experience. You will also be required to use a motion tracked joystick to provide input. Therefore, the participant needs to have a normal 20/20 or corrected normal vision and full use of their neck, arms and hands in order to qualify for the research study.

**CLEMSON**  
RESEARCH CORPORATION

IRB Number: IRB2017-372  
Approved: 10/31/2017  
Expiration: 10/30/2018

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### **Possible Benefits**

If you have not experienced Virtual Reality (VR) before this will be a novel experience that you may enjoy. Most people respond favorably to VR. This research may help us understand the effectiveness and usability of our system. This will enable us to report guidelines on the design of such a driving simulator to the scientific and industrial community in the form of research publications.

### **Protection of Privacy and Confidentiality**

We will do everything we can to protect your privacy and confidentiality. We will not tell anybody outside of the research team that you were in this study or what information we collected about you in particular. Any data collected during the course of the study will only be used in aggregate.

We might be required to share the information we collect from you with the Clemson University Office of Research Compliance and the federal Office for Human Research Protections. If this happens, the information would only be used to find out if we ran this study properly and protected your rights in the study.

### **Choosing to Be in the Study**

Your participation in this study is voluntary. You may choose not to participate and you may withdraw your consent to participate at any time. You will not be penalized in any way if you decide not to participate or if you withdraw from this study.

If you choose to stop taking part in this study, the information you have already provided will be used in a confidential manner.

### **Contact Information**

If you have any questions or concerns about this study or if any problems arise, please contact Vibhor Rastogi at (484) 477-2716 or Dr. Sabarish Babu at (864) 656-5089.

If you have any questions or concerns about your rights in this research study, please contact the Clemson University Office of Research Compliance (ORC) at 864-656-0636 or [irb@clemson.edu](mailto:irb@clemson.edu). If you are outside of the Upstate South Carolina area, please use the ORC's toll-free number, 866-297-3071.



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**Consent**

**I have read this consent form and have been given the opportunity to ask questions. I give my consent to participate in this study.**

Participant's signature: \_\_\_\_\_ Date: \_\_\_\_\_

Print Name: \_\_\_\_\_

A copy of this form will be given to you.



IRB Number: IRB2017-372 Approved: 10/31/2017 Expiration: 10/30/2018
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## REFERENCES

- [1] On-Road Automated Driving Committee. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, *SAE International, Standard J3016*.
- [2] Philip E. Ross (2017, Jan 5). CES 2017: Nvidia and Audi Say They'll Field a Level 4 Autonomous Car in 3 Years. Retrieved from <https://spectrum.ieee.org>.
- [3] Luca Ciferri (2016, Feb 27). Ford's Nair: Sensors, software are self-driving cars' main obstacles. Retrieved from <https://www.autonews.com>.
- [4] Becca Caddy (2015, Oct 8). Toyota to launch first driverless car in 2020. Retrieved from <https://www.wired.co.uk>.
- [5] Dan Bigman (2013, Jan 14). Driverless Cars Coming To Showrooms By 2020, Says Nissan CEO Carlos Ghosn. Retrieved from <https://www.forbes.com>.
- [6] Nilesh Christopher (2017, Jan 13). Mishaps: A brief history of driverless car crashes. Retrieved from <https://economictimes.indiatimes.com>.
- [7] Richard Romano. Driving Simulators to support the design of Autonomous Vehicles. *Institute of Transport Studies, Faculty of Environment, University of Leeds*.
- [8] Stanford Autonomous Vehicle. Stanford University. Retrieved from <http://stanford.edu/~cpiech/cs221/apps/driverlessCar.html>.
- [9] Taheri, S.M., Matsushita, K. and Sasaki, M. (2017) Virtual Reality Driving Simulation for Measuring Driver Behavior and Characteristics. *Journal of Transportation Technologies*, 7, 123-132. <https://doi.org/10.4236/jtts.2017.72009>.
- [10] Lynn Meuleners, Michelle Fraser. A validation study of driving errors using a driving simulator, *Transportation Research Part F : Traffic Psychology and Behaviour*, Vol. 29, Feb 2015, 14-21, <https://doi.org/10.1016/j.trf.2014.11.009>.
- [11] Chi Zhang, Yuehu Liu, Danchen Zhao, Yuanqi Su. RoadView: A traffic scene simulator for autonomous vehicle simulation testing, *IEEE International Conference on Intelligent Transportation Systems (ITSC), 2014*.
- [12] Jie Tang, Shaoshan Liu, Chao Wang, Quan Wang. *Distributed Simulation Platform for Autonomous Driving, arXiv:1705.10948*.

- [13] Tianyu Gu, John M. Dolan. A Lightweight Simulator for Autonomous Driving Motion Planning Development, *Proceedings of the International Conference on Intelligent Systems and Applications (INTELLI)*, 2015, 94-97)
- [14] Andrew Best, Sahil Narang, Lucas Pasqualin, Daniel Barber, Dinesh Manocha. A AutonoVi-Sim: Autonomous Vehicle Simulation Platform with Weather, Sensing, and Traffic control. *Neural Information Processing Systems (NIPS 2017)*
- [15] Franck Gechter, Baudouin Dafflon, Pablo Gruer, Abderrafiaa Koukam. Towards a hybrid Real/Virtual Simulation of Autonomous Vehicles for Critical Scenarios, *SIMUL 2014 : The Sixth International Conference on Advances in System Simulation*
- [16] Clemson University Vehicles Electronics Lab, Retrieved from <http://www.cvel.clemson.edu/auto/systems/dsrc.html>.
- [17] Simulator Sickness Questionnaire (Kennedy et al. 1993), Retrieved from [http://www.cybersickness.org/Simulator\\_Sickness\\_Questionnaire.htm](http://www.cybersickness.org/Simulator_Sickness_Questionnaire.htm).
- [18] Igroup Presence Questionnaire Schubert, T., Friedmann, F., & Regenbrecht, H, Retrieved from <http://www.igroup.org/pq/ipq/index.php>.
- [19] User Experience Questionnaire Online, Retrieved from <http://www.ueq-online.org/>.
- [20] Parsons, T.D.; Gaggioli, A.; Riva, G. Virtual Reality for Research in Social Neuroscience. *Brain Sci.* 2017, 7, 42.
- [21] L.F. Hodges et al. Virtual Environments for treating the fear of heights. *Computer*, Vol. 28, Issue 7, July 1995.
- [22] Thomas D. Parsons. Virtual Reality for Enhanced Ecological Validity and Experimental Control in the Clinical, Affective and Social Neurosciences. *Frontiers in Human Neuroscience* 2015; 9: 660.
- [23] Champney R., Salcedo J.N., Lackey S.J., Serge S., Sinagra M. (2016) Mixed Reality Training of Military Tasks: Comparison of Two Approaches Through Reactions from Subject Matter Experts. In: *Lackey S., Shumaker R. (eds) Virtual, Augmented and Mixed Reality. VAMR 2016. Lecture Notes in Computer Science*, vol 9740. Springer, Cham
- [24] Rayamajhi et al. "ThinGs In a Fog: System Illustration with Connected Vehicles", *Proceedings of the IEEE Vehicular Technology Conference (VCT'17)*, (Sydney AU, June 2017).

- [25] M. Meehan et al. Effect of Latency on presence in stressful Virtual Environments. *IEEE Virtual Reality, Proceedings. March 2003*
- [26] Zhigang Xu, Xiaochi Li, Xiangmo Zhao, Michael H. Zhang, and Zhongren Wang, “DSRC versus 4G-LTE for Connected Vehicle Applications: A Study on Field Experiments of Vehicular Communication Performance,” *Journal of Advanced Transportation*, vol. 2017, Article ID 2750452, 10 pages, 2017. doi:10.1155/2017/2750452.
- [27] Robert E. Llaneras et al. Human Factors Issue associated with Limited Ability Autonomous Driving Systems: Drivers’ Allocation of Visual Attention to the Forward Roadway. *Proceedings of the Seventh International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*
- [28] Christina Rodel et al. Towards Autonomous Cars: The Effect of Autonomy Levels on Acceptance and User Experience. *Proceedings of the 6th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*.