CCAT | CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

Development of an Augmented Reality Environment for Connected and Automated Vehicle Testing

by
Henry Liu, Professor
Yiheng Feng, Assistant Research Scientist
University of Michigan

UMTRI · The University of Akron · ILLINOIS CENTER FOR TRANSPORTATION · PURDUE UNIVERSITY · Washtenaw Community College · Central State University

DISCLAIMER

Contacts

For more information:

Dr. Henry X. Liu
University of Michigan
2350 Hayward, Ann Arbor, MI, 48109
Phone: (734) 647-4796
Email: henryliu@umich.edu

Dr. Yiheng Feng
University of Michigan
2901 Baxter Rd, Ann Arbor, MI, 48109
Phone: (734) 936-1052
Email: yhfeng@umich.edu

Center for Connected and Automated Transportation
University of Michigan Transportation Research Institute
2901 Baxter Road
Ann Arbor, MI 48152
umtri-ccat@umich.edu
ccat.umtri.umich.edu
(734) 763-2498

Technical Report Documentation Page

1. Report No. 2019-UMTR-4	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Development of an Augmented Reality Environment for Connected and Automated Vehicle Testing Identifier: http://hdl.handle.net/2027.42/149453		**5. Report Date** January 2019
		6. Performing Organization Code
7. Author(s) Liu, Henry, Ph.D., https://orcid.org/0000-0002-3685-9920 Feng, Yiheng, Ph.D., https://orcid.org/0000-0001-5656-3222		**8. Performing Organization Report No.**
9. Performing Organization Name and Address UMTRI 2901 Baxter Road Ann Arbor, MI 48109		**10. Work Unit No.**
		11. Contract or Grant No. Contract No. 69A3551747105
12. Sponsoring Agency Name and Address Center for Connected and Automated Transportation University of Michigan Transportation Research Institute 2901 Baxter Road Ann Arbor, MI 48109		**13. Type of Report and Period Covered** Final Report January 2017 – December 2018
		14. Sponsoring Agency Code

15. Supplementary Notes

Conducted under the U.S. DOT Office of the Assistant Secretary for Research and Technology's (OST-R) University Transportation Centers (UTC) program.

16. Abstract

Currently closed Connected and Automated (CAV) testing facilities, such as Mcity, merely provide empty roadways, in which test CAVs can only interact with each other and the infrastructure (e.g. traffic signals). However, a complete testing environment should also include background traffic to interact with the test CAVs. Involving real vehicles as background traffic is not only costly, but also difficult to coordinate and control. To address the limitation, in this project we develop an augmented reality testing environment in which background traffic is generated in microscopic simulation and provided to test CAVs to augment the functionality of the test facility. The augmented reality combines the real-world testing facility and a simulation platform, in which movements of test CAVs and traffic signals in the real-world can be synchronized in simulation, while simulated traffic information can be provided to test CAVs' communication system. Test CAVs "think" they are surrounded by other vehicles and adjust behaviors accordingly. This technology provides a realistic traffic environment to the CAVs, so that test scenarios which require interactions with other vehicles or pedestrians can be performed. Compared to using real vehicles, simulated vehicles can be easily controlled and manipulated in generating different scenarios with much less cost in a safe environment.

17. Key Words Connected vehicles, automated vehicles, augmented reality, acceptance testing and evaluation	**18. Distribution Statement** No restrictions.		
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 24	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Table of Contents

List of Figures

Project Summary

Testing and evaluation are critical steps in the development of connected and automated vehicle (CAV) technology. Closed test facilities serve as the intermediate step between simulation and public road testing. One limitation of closed test facilities is that they merely provide empty roadways, in which test CAVs can only interact with a limited number of other CAVs and infrastructure. This project develops an augmented reality environment for CAV testing and evaluation. A real-world test facility and a simulation platform are combined. Movements of the test CAVs in the real world are synchronized with the simulation and the information of background traffic is fed back to the test CAVs. The test CAVs can interact with virtual background traffic as if in a realistic traffic environment. The proposed system mainly consists of three components: a simulation platform, physical CAVs (test CAV's), and a communication network. Test scenarios that have safety concerns and/or require interactions with other vehicles can be performed safely in this environment. Three exemplary test scenarios were designed and implemented to demonstrate the capabilities of the system: red-light running, railway crossing, and traffic signal priority. A demo video of the testing platform and scenarios can be found at:

https://www.youtube.com/watch?v=-DQ4dGo-Nxs

1. Introduction

Connected and automated vehicles (CAVs) need to be tested extensively before they can be deployed and accepted by the general public. Currently, CAV testing and evaluation is mainly conducted by the following steps: testing in a simulation environment, testing at a closed test facility, and testing on public roads. Simulation is a cost effective way to test this new technology, but it is very difficult to model exact vehicle dynamics and driving behaviors in the simulation. Therefore, some studies developed hardware-in-the-loop (HIL) or vehicle-in-the-loop (VIL) simulation platforms, which incorporate either part of a vehicle (e.g., a real engine with a virtual powertrain model) [1] or an entire vehicle [2] into the simulation. To model real vehicle behaviors observed in the field, a parallel traffic system was proposed, which set up a mirror of the real world in virtual space [3][4]. The parallel system can be used to design different test scenarios and evaluate how vehicles perform in these scenarios [5]. Companies such as Google have been demonstrating their self-driving cars for a few years on public roads, although the debate of whether or not to allow test CAVs to run in conjunction with general traffic will never end [6]. Safety has been an important issue since the technology is still in the development stage. A number of accidents have been reported regarding self-driving functionality including several fatal accidents, one occurring in 2016 [7].

Closed test facilities serve as the intermediate step between testing in simulation and on public roads. They not only improve efficiency but also provide a more controllable and safer environment. To encourage CAV testing in closed test facilities, U.S. Department of

Transportation (DOT) designated 10 pilot CAV test facilities around the U.S in 2016. The main disadvantage of a closed test facility is that it merely provides empty roadways. Test CAVs can only interact with a limited number of other test vehicles and infrastructure (e.g., traffic signals). However, a complete test environment should include background traffic as much as needed to interact with test CAVs. Including real background vehicles in a closed test facility is not only costly, but also difficult to coordinate and control. In addition, without real traffic interactions, scenarios that can be designed and tested are limited.

To address the limitations, we developed an augmented reality testing environment. Background traffic is generated in microscopic simulation and provided to test CAVs to augment the functionality of a test facility. The augmented reality environment combines a real-world test facility and a simulation platform together. Movements of test CAVs in the real world is synchronized with simulation and information of background traffic is fed back to test CAVs. Test CAVs can interact with virtual background traffic as if in a realistic traffic environment. As a result, test scenarios that require interactions with other vehicles or modes of travelers (e.g. pedestrians, cyclists, or trains) can be performed. Compared to using real vehicles, simulated vehicles can be easily controlled and manipulated in generating different scenarios with reduced cost and safety concerns. For instance, when the test CAV fails in a safety related test and hits a simulated pedestrian, no one will actually be hurt. Such tests can be repeated over and over again. The augmented reality environment can serve as a pre-step before involving real vehicles to ensure algorithms are thoroughly examined and parameters are fine tuned. The proposed system is extremely beneficial to testing and evaluating CAV technologies in a cost-effective fashion.

2. System Description

The overall architecture of the augmented reality test environment is shown in Figure 1. The real world consists of test CAVs, infrastructure equipment, and roadside processors (RSP). The infrastructure equipment includes roadside units (RSUs), traffic signal controllers and vehicle detectors. Test CAVs broadcast vehicle information and communicate with RSUs through Dedicated Short Range Communication (DSRC). The RSP is responsible for receiving and processing data from the infrastructure equipment and sending processed information to the Simulation Platform and the Data Management Component. It also receives data from the simulation platform and forwards that to the Infrastructure Equipment. The same traffic network in terms of road geometries and traffic signals are built into the simulation platform as well as in the real-world test facility. Virtual CAVs are generated and updated in the simulation based on the vehicle information received from the test CAVs. Their behaviors are synchronized with real vehicles. Similarly, virtual traffic signals in the simulation are also synchronized with real-world

traffic signals. Background traffic in the simulation is broadcasted by the Infrastructure Equipment (i.e., RSU) to the test CAVs. The Data Management Component is responsible for collecting and managing data generated in both the real world and in the simulation platform, so that performance measures can be evaluated. In the following subsections, three major components of the system, namely, the simulation platform, the test CAV and the communication network will be presented.
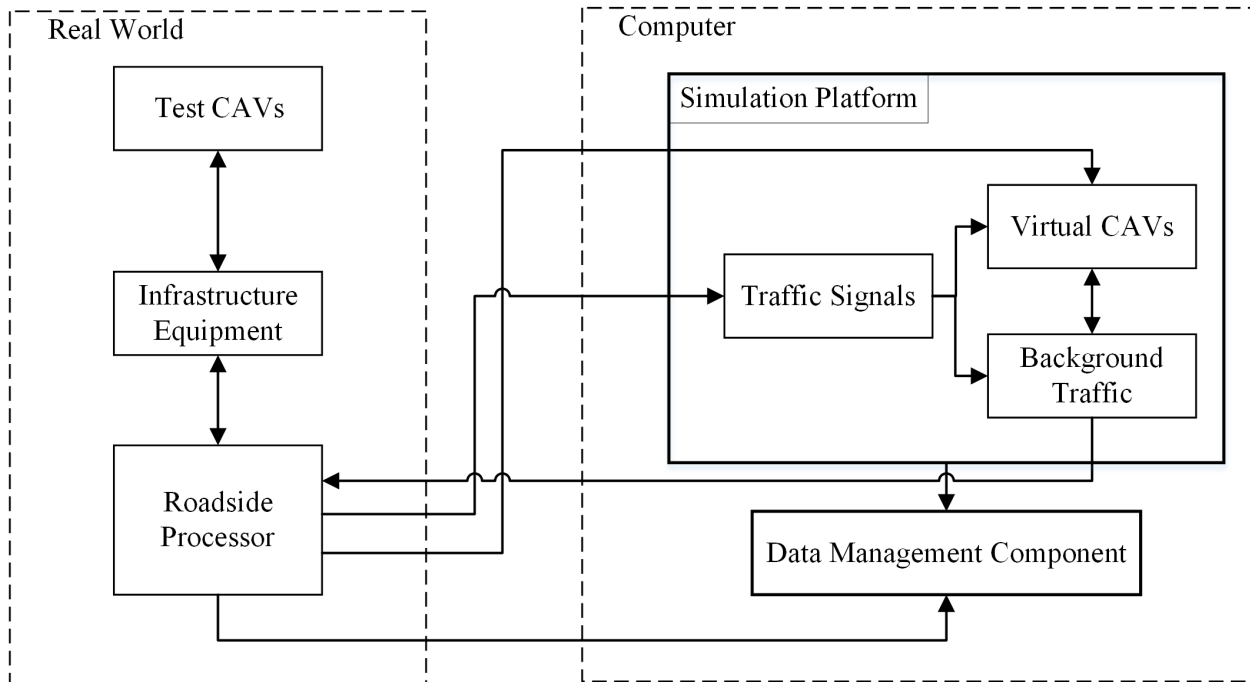

Figure 1 Overall Design of the Augmented Reality Environment

2.1   Simulation Platform

The framework of the simulation platform is shown in Figure 2. It consists of two parts, namely, VISSIM simulator [8] and a simulation managing application. VISSIM provides various APIs as add-on modules to integrate VISSIM with user's own applications. SignalControl.DLL, DriverModel.DLL, and COM interfaces in VISSIM are used for interactions with the real-world environment and the simulation managing application. Traffic signals in VISSIM are synchronized with those in the real world by the SignalControl.DLL. Information from simulated traffic is encoded and sent out by the DriverModel.DLL. The simulation managing application receives information from test CAVs and transforms GPS coordinates to local coordinates [9], which are used to update the locations of virtual CAVs in VISSIM via the COM interface.

Furthermore, the simulation managing application also builds test scenarios via COM.

The workflow of the simulation platform is shown in Figure 3. Each test scenario is constructed as a VISSIM project. Different test scenarios may include different CAV routes, background vehicle inputs, and signal timing plans. Before running the simulation, the simulation platform needs to load one scenario through the COM interface. After initialization, it begins to receive test CAV and traffic signal information from the real world. Upon receiving the first message from the test CAV, the simulation platform creates a virtual CAV in the VISSIM network at the same location as it is in the testing facility. When a new message is received, the virtual CAV's position is updated. A trigger-based interaction mechanism has been implemented. The update of the virtual CAV location may trigger a testing event in VISSIM. The testing events include generating a virtual vehicle at a certain speed or force off the current signal phase. The advantage of using a trigger-based mechanism is that it guarantees the testing can be repeated under exactly the same conditions. Similar to virtual CAVs, virtual signals are updated when new signal status messages are received. VISSIM then executes a simulation step to update and broadcast the information of background traffic.
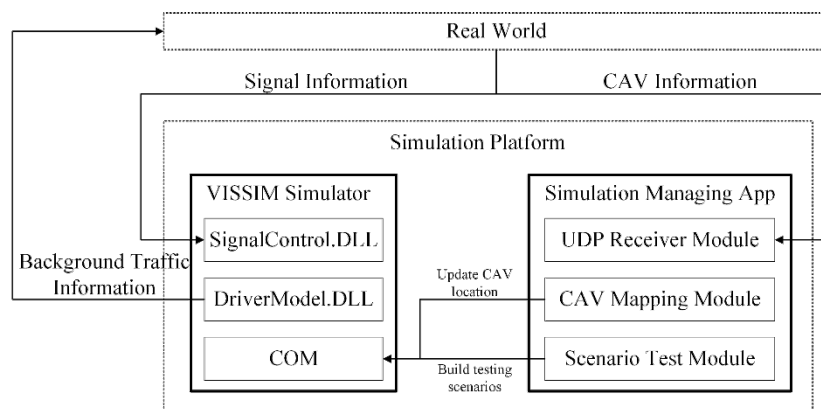

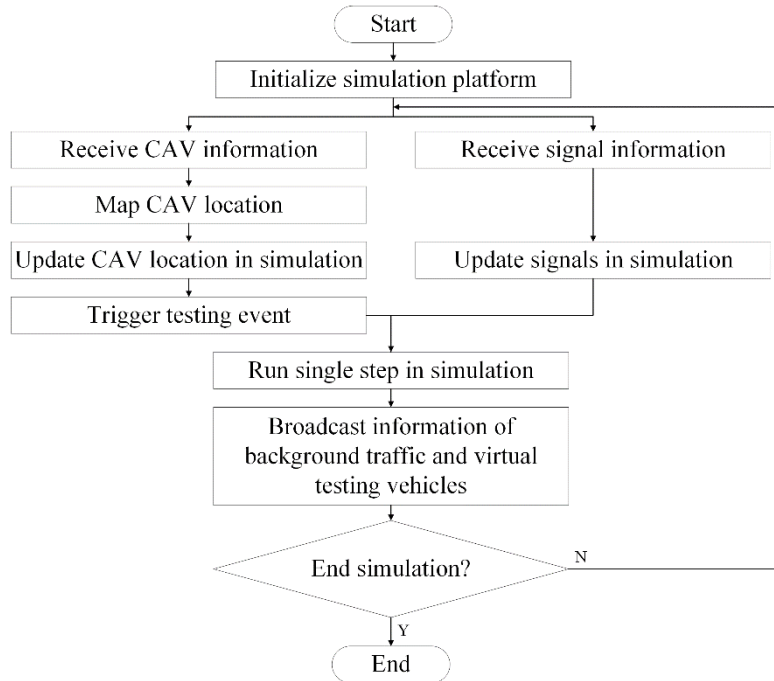Figure 2 Simulation Platform Framework

Figure 3 Workflow of the Simulation Platform

2.2 Test CAV

A Lincoln MKZ Hybrid is used as the test vehicle in the proposed augmented reality environment as shown in Figure 4. The Lincoln MKZ is fully connected and automated and equipped with various sensors. The sensors include:

- 16-channel Velodyne LiDAR on the roof

- Ibeo fusion system (two four-layer LUX LiDAR modules in the front, and one in the rear)

- Long-range RADAR in the front

- Four short range RADARs at the corners

- Mobileye 560 vision system

- Pointgrey camera

- High precision (about 2 cm) GPS module, called Real Time Kinematic (RTK) 3003 from Oxford Technical Solutions

- Inertial Measurement Unit (IMU)

These sensors enable accurate positioning and 360-degree obstacle perception. By-wire control allows us to command the steering wheel, throttle, brake, and transmission by software. An On-Board Unit (OBU) from Cohda Wireless is installed as the DSRC communication device to transmit

messages to/from the simulation environment. The OBU has three main tasks. First, it receives Signal Phase and Timing (SPaT) messages, which are broadcast by the RSU located at the intersections in the testing facility. Second, it receives Basic Safety Messages (BSMs) from both real vehicles (e.g., other test vehicles) and simulated vehicles. Finally, it generates BSMs for the test CAV and broadcasts them to the RSUs. With the received SPaT and BSM data, the CAV can interact with real traffic signals and simulated vehicles automatically. The underlying path planning, vehicle speed control, and steering control were developed by the OpenCAV project from the University of Michigan. Different algorithms were developed to perform basic capabilities such as speed planning/control, path planning/following, and obstacle avoidance. For example, when following a simulated vehicle, the behavior of the CAV follows the Gipps car following model [10].
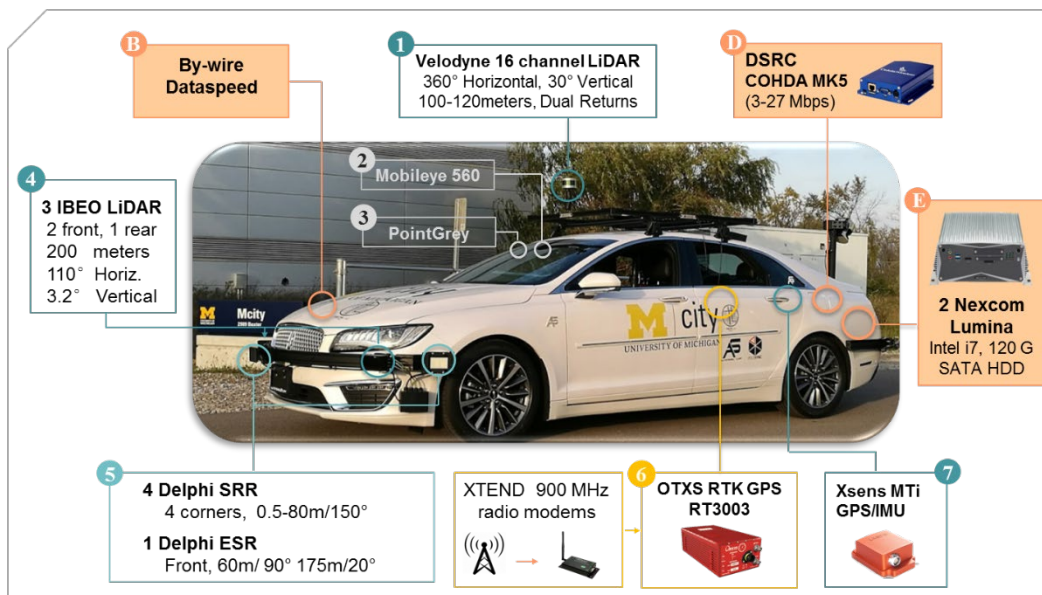

Figure 4 Vehicle Platform (Lincoln MKZ Hybrid)

2.3   Communication Network

The communication network transmits data between the simulation platform and test CAVs. The information flow is shown in Figure 5. The Signal Controller at each intersection broadcasts signal data including current status and remaining time of each phase to the RSP located in the signal cabinet, where SAE J2735 SPaT messages are generated. The SPaT messages are forwarded to both the RSU at the same intersection and the Master RSP. The RSU broadcasts SPaT messages to test CAVs and receives BSMs from test CAVs through DSRC. The received BSMs are forwarded to the Master RSP. Both SPaT and BSM are sent to the Simulation Platform to update virtual signals and virtual CAVs in the simulation. Both BSM and SPaT are broadcasting at a frequency of 10Hz.

Simulated vehicles in VISSIM generate simulated BSMs (sBSM) through the DriverModel.DLL API and send to the Master RSP. Based on the vehicle ID, as broadcast in the BSM, the Master RSP distributes the sBSMs to different RSUs to balance the communication load.
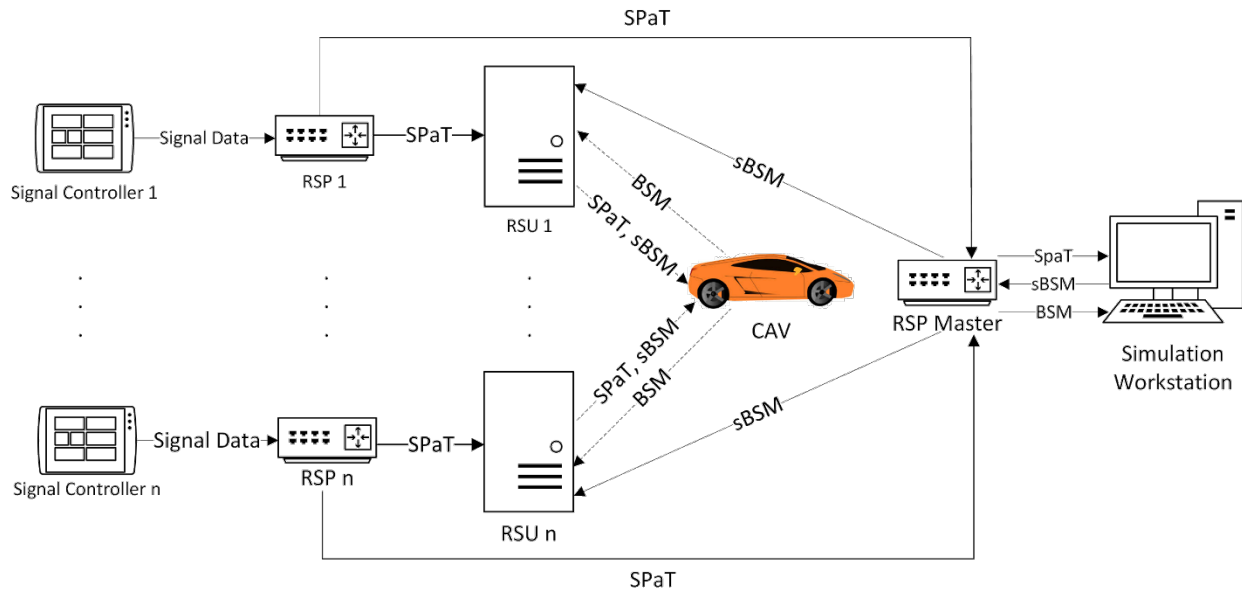

Figure 5 Communication Network and Data Flow

3. System Implementation

The augmented reality testing environment is implemented at Mcity, a newly established closed CAV test facility at the University of Michigan. To setup the simulation platform, Mcity traffic network is built and calibrated in VISSIM through a high resolution map. One critical question for implementing the system is the communication quality between the simulated environment and the real world. This section will first give a brief introduction to Mcity. Then, the results from a communication test are presented. Finally, two of the exemplary test scenarios that were designed and demonstrated are discussed.

3.1 Mcity introduction

Mcity is a small scale high-fidelity simulated urban environment for CAV testing. Occupying 32 acres at the University of Michigan's North Campus Research Complex, Mcity includes approximately five lane miles of roadways with different attributes such as a highway segment, multilane arterial roads, intersections, and traffic signals. Mcity is the world's first full-scale "test city" designed solely for testing the performance of CAVs.

Mcity has eight signalized intersections including six low speed intersections in the downtown area, one high-speed intersection in the highway segment, and one intersection near the

entrance. Four RSUs are installed at four downtown intersections. The RSUs radio ranges cover the entire testing facility as shown in Figure 6.
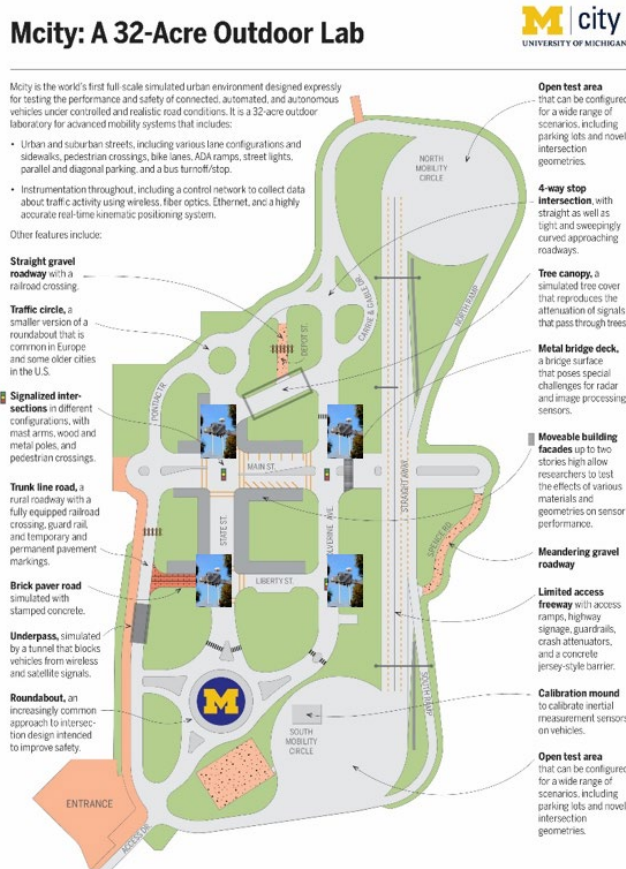

Figure 6 Mcity Test Facility

(Source: https://mcity.umich.edu)

3.2 Communication Test

A communication test is conducted to ensure that the system can meet real-time performance requirements. Since the communication delay is at a millisecond level, it is very difficult to synchronize the clocks between the simulation environment (e.g., a computer) and the test CAVs. To address the problem, we applied an alternative way to test the delay. When a simulated BSM (sBSM) is generated in VISSIM, the first timestamp is created. The sBSM is sent to the master RSP (Figure 5) and broadcast through RSU1. RSU2 receives the sBSM and then sends it back to the master RSP. Finally, the master RSP forwards the BSM back to the computer that runs VISSIM and the second time stamp is created. In this test configuration, the OBU in a test CAV acted as RSU2. The delay is calculated as the time difference between the two timestamps. This implementation

guarantees that the system time to create timestamps comes from the same source, so that the delay calculation can be accurate. The test is conducted under five different cases with numbers of simulated vehicles from one to 100. Each case is performed for a period of 300s in real time. Figure 7 shows the delay histograms under different numbers of vehicles and corresponding package loss rates. The average delay is about 31 ms with 1 vehicle and 102 ms with 100 vehicles. Both the average delay and package loss rate increase with the number of vehicles. The percentage of delay that is below 100ms under each case is calculated. The percentages are 99.71%, 99.16%, 95.81%, 91.52%, and 73.66% for 1, 10, 20, 50, and 100 vehicles respectively. Note that 100 ms is the shortest transmission interval between DSRC messages according to the SAE standard. If a message can be received and processed before the next message is received, the delay can be considered sufficiently short. The test results show that, with the exception of the 100 vehicles case, more than 90% of packages can be transmitted and processed within this interval. Although about 30% of packages in 100 vehicles case have delays of more than 100 ms, test scenarios that require 100 vehicles are also very rare.

(a) 1 vehicle

(b) 10 vehicle

(c) 20 vehicle

(d) 50 vehicle

(e) 100 vehicle

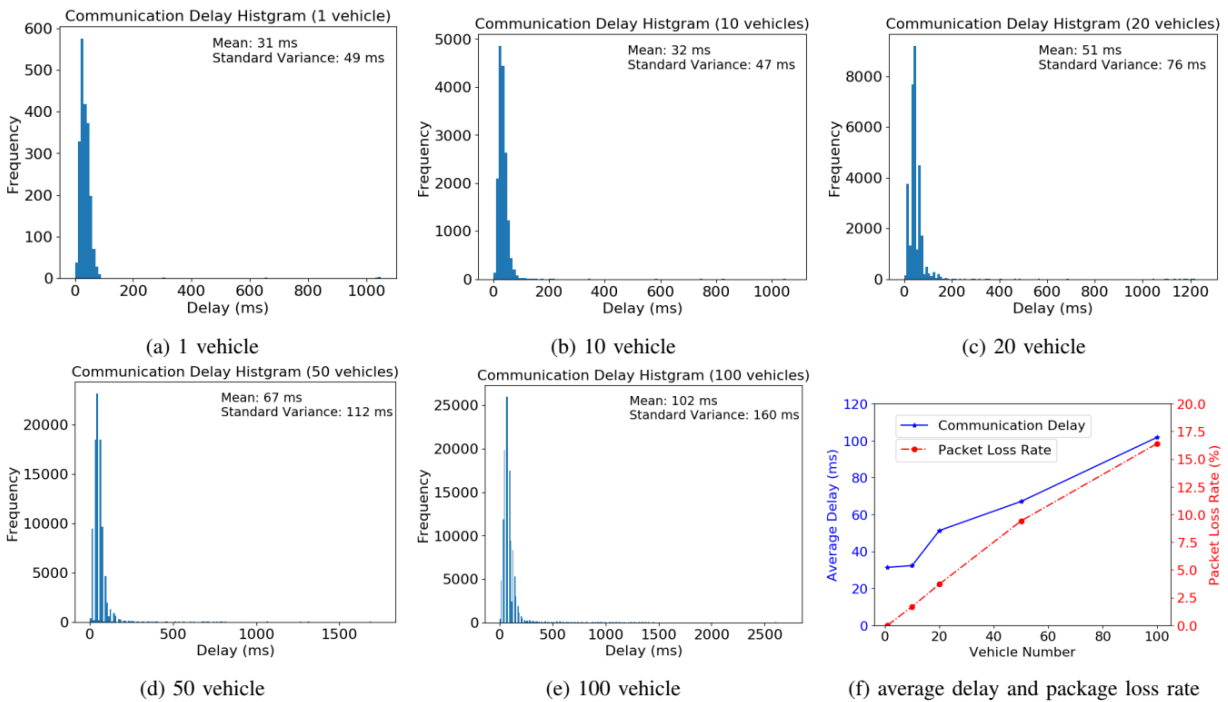(f) average delay and package loss rate

Figure 7 Communication Delay and Package Loss Rate with Different Number of Virtual Vehicles.

3.3 Test Scenarios

In this section, three test scenarios are presented, namely, railway crossing, red-light running, and traffic signal priority.

3.3.1 Railway Crossing

In the railway-crossing scenario, a simulated train is generated in VISSIM when the test CAV is approaching the rail crossing located at Mcity. The test CAV should stop before the rail crossing and wait for the train. Figure 8 shows the views from both the simulation and the test CAV. The simulation network of Mcity is presented in the left part of the figure. A blue train is generated and traveling on the track. Several vehicles are waiting behind the rail crossing including the test CAV (the red vehicle in the circle). The upper right part of the figure shows the view from the test CAV's windshield as well as from inside the vehicle. It can be seen that the test CAV stopped before the rail crossing, although there is no real train in front of it. A virtual train in the simulation blocks the way of the test CAV. The lower right part of the figure shows the view from the test CAV's control system. The big green rectangle is the test CAV and all smaller rectangles represent simulated vehicles. The small red rectangle in front of the test CAV indicates a potential crash scenario.
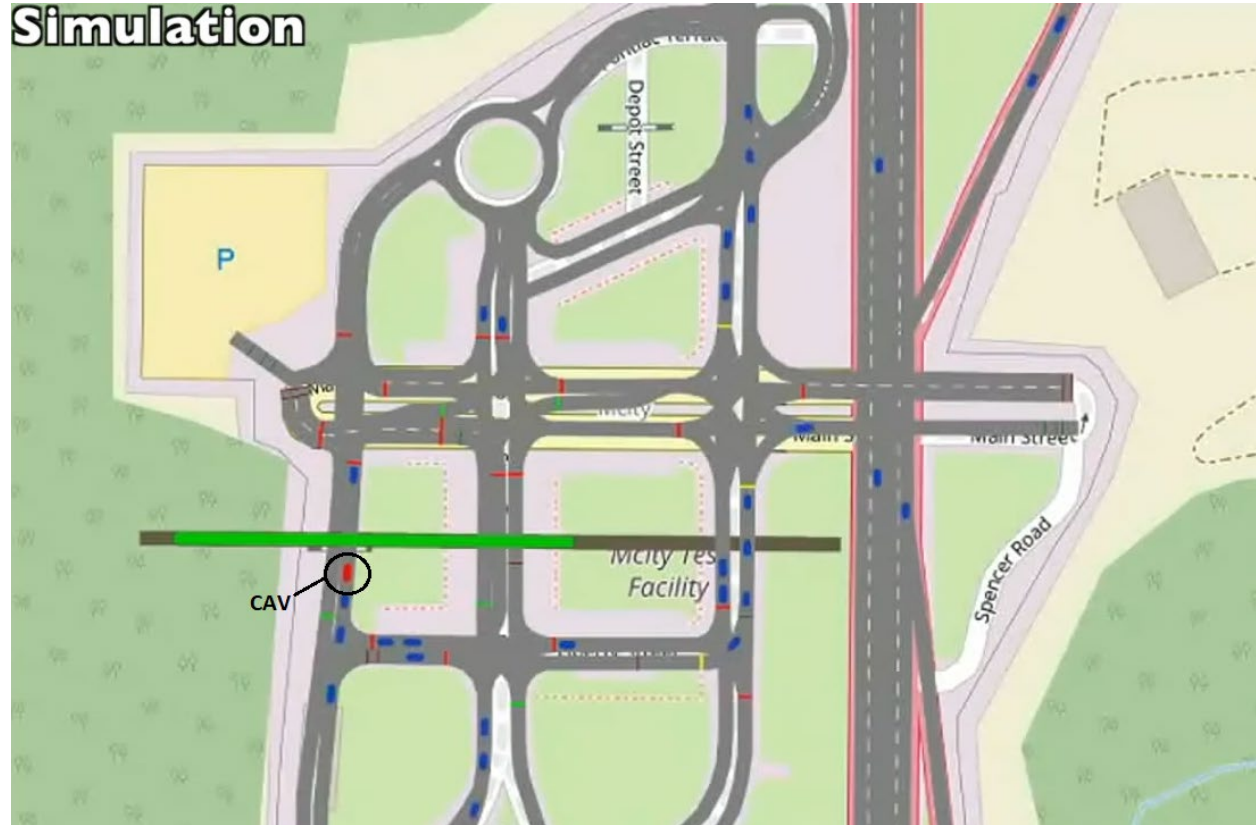
(a) VISSIM Simulation View

(b) CAV Outside and Inside View

(c) CAV Control System View

Figure 8 Railway Crossing Test Scenario

3.3.2 Red-Light Running

Red-light running is a dangerous driving behavior and accounted for about 26.5% of total signalized intersection fatalities in 2014. The purpose of this scenario is to evaluate how a test CAV reacts to a red-light running vehicle and avoids collision under different situations. The scenario design is shown in Figure 9. The intersection at Wolverine Ave. and Main St. in the downtown area of Mcity is chosen to be the test intersection. The test CAV travels westbound on Main St. and tries to make a left turn. A simulated vehicle is generated in the simulation at Wolverine Ave. and travels northbound, as the test CAV is close to the intersection. The signal status indicates that the test CAV has the right of way. The signal timing of the intersection is adjusted so that the test CAV meets the green light every time when it approaches the intersection.
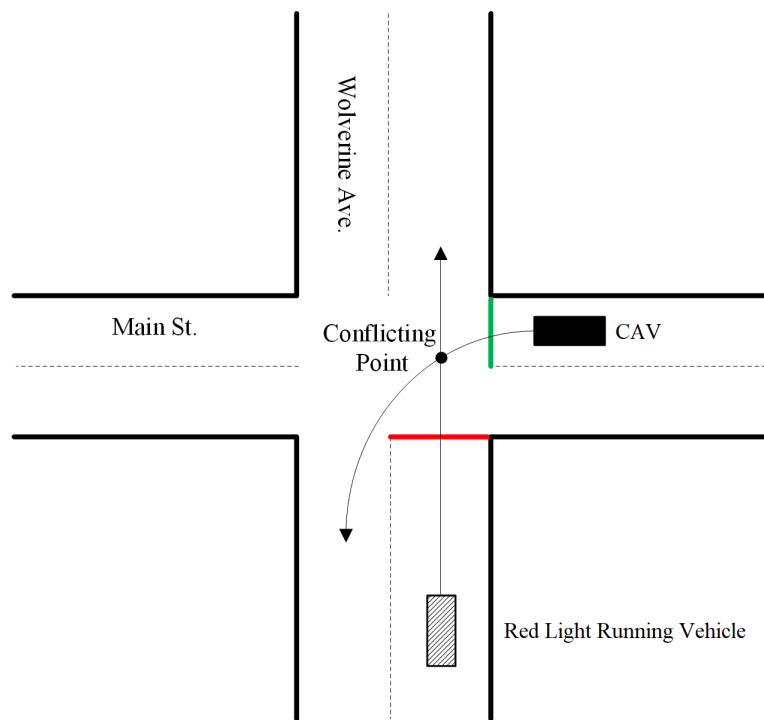
Figure 9 Red-Light Running Test Scenario Design

Figure 10 illustrates how the test CAV responds to the red-light running vehicle in two situations. The horizontal axis represents time steps (0.1s per time step), and the vertical axis represents the distance to the conflicting point of each vehicle. The trajectory of the virtual red-light running vehicle is represented as the red dotted curve. It travels at a constant speed. The trajectory of the test CAV is represented in three different formats. The dark blue curve shows the test CAVs coordinates in the VISSIM simulator. The light blue curve shows the test CAVs coordinates from the OBU GPS. The black curve shows the test CAVs coordinates from the RTK GPS installed on the

vehicle. Currently, the OBU GPS is used to generate and send BSMs to the simulation. Due to the high accuracy of the RTK GPS (2 cm accuracy), coordinates from the RTK GPS are considered as the ground truth. Therefore, the difference between the black curve and the light blue curve represents the GPS error. The difference between the light blue curve and the dark blue curve represents two types of errors from the simulation. The first type is due to the vehicle mapping algorithm. The second type represents the deviation of the VISSIM road network from the real-world road network.

The test CAV calculates the collision threat by comparing the time gap of the arrival times at the conflicting point between itself and the red-light running vehicle. A three second threshold is used to determine whether a potential collision may happen. Figure 10(a) shows the situation that the test CAV detects a potential collision and made a full stop. Figure 10(b) illustrates the situation that the two vehicles are far enough away so the CAV to does not stop.

In Figure 10(a) during the deceleration period (time step 30- 50), the deviation between RTK GPS and OBU GPS remains small, but the deviation between OBU GPS and VISSIM coordinates are large. It is mainly due to the inconsistency between the actual Mcity roadway and the Google Earth map. When the test CAV is stopped (time step 50-80), the three trajectories match well except that the OBU GPS has drifted for about 1s. The same phenomenon is observed in all of our tests. However, the vehicle mapping algorithm is designed to be insensitive to the fluctuations so that the virtual CAV does not move in the simulation because of GPS coordinate fluctuations. When the test CAV begins to accelerate, the VISSIM coordinates and the OBU GPS match well but have a larger deviation from the RTK GPS. The non-stopping situation depicted in Figure 10(b) shows a similar pattern except that the OBU GPS does not have obvious fluctuations.
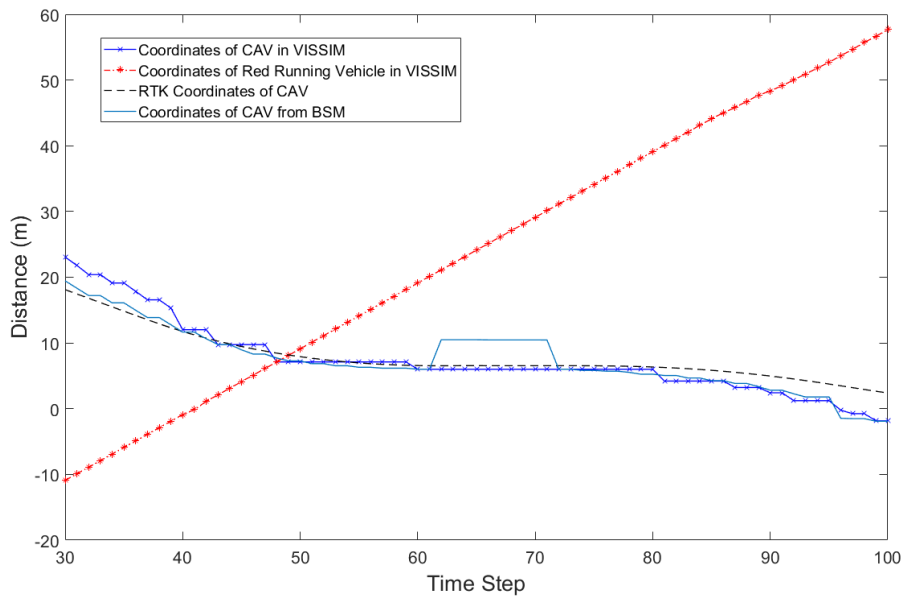
(a) with potential collision
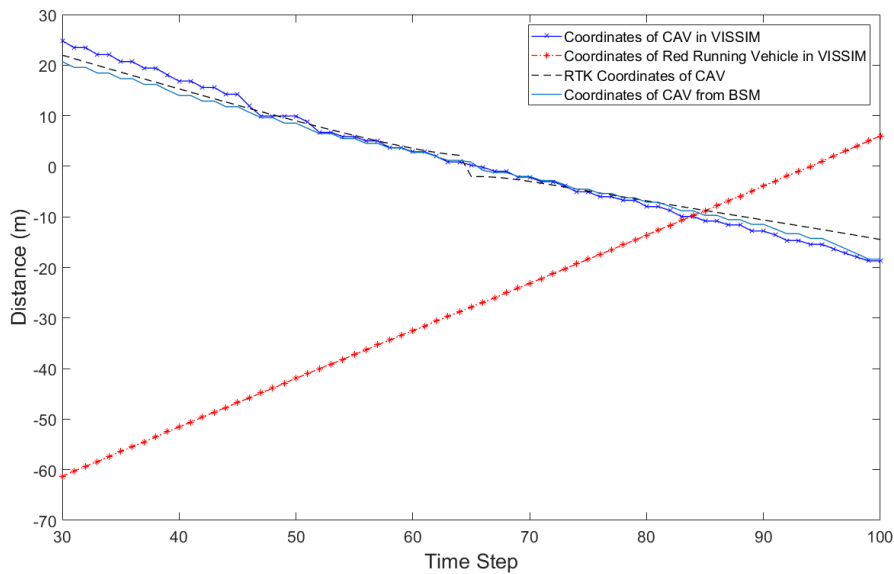
(b) without potential collision

Figure 10 Vehicle Trajectories Under Different Situations.

3.3.3   Traffic Signal Priority

Providing signal priority or preemption is a common practice for special purpose vehicles. For

example, ambulances, police cars or transit vehicles can request signal priority when they are approaching a signalized intersection. Based on the priority level and other operational constraints (e.g., minimum green time, pedestrians in the crosswalk), traffic signals can be modified to accommodate priority vehicles' request.

The signal priority scenario is implemented in Mcity's infrastructure and the test CAV through vehicle-to-infrastructure (V2I) communications. Figure 11 shows the system framework. The whole process can be summarized into four steps. First, the priority vehicle sends priority request messages to the RSU. We embedded the priority request into unused data elements in the BSM, which contains requested intersection ID and desired phase. When the RSU receives request messages, it immediately forwards the request to the RSP for further processing. The RSP generates an optimal signal control plan including force off phases in advance, skip or hold desired phases, with consideration of minimum green time requirement and phase sequence. This new signal timing plan ensures the shortest delay for the priority vehicle based on the condition of vehicle and signal status at this moment. Finally, the RSP sends the signal timing plan to the signal controller for implementation. After the priority vehicle passes through the intersection, the control algorithm resets the controller and returns to the original timing plan. During this control process, the system continues to monitor the status of the priority vehicle to generate the most appropriate plan and minimize the impact on other vehicles.
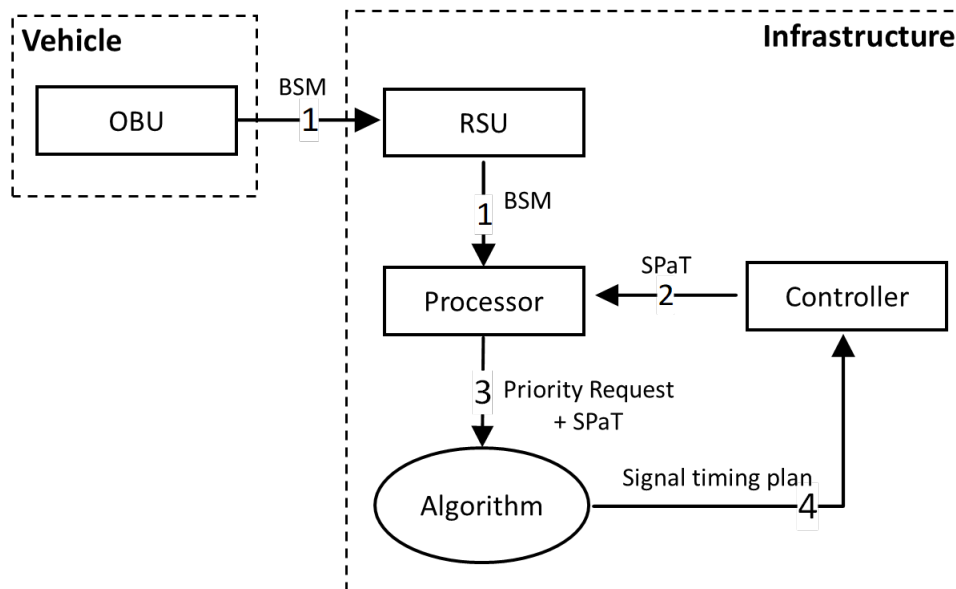

Figure 11 Signal Priority Test Scenario Design

4. Findings

This project developed and implemented an augmented reality environment for CAV testing at Mcity, which greatly enhances the capabilities of closed test facilities. In the augmented reality environment system, movements of test CAVs and status of traffic signals in the real world are synchronized with a simulation platform in real time. Information on background traffic in the simulation platform is fed back to the test CAVs through wireless communications. The augmented reality environment provides a realistic traffic environment to test CAVs for testing scenarios that require interactions with other vehicles or modes of travelers (e.g. pedestrians, bicycles, and trains) can be performed safely. Two test scenarios, railway crossing and red-light running, were designed to demonstrate the capabilities of the system. The augmented reality environment serves as a reliable platform for CAV testing and evaluation. Based on the platform, numerous test scenarios can be implemented. However, it is impossible to enumerate all scenarios that a vehicle may encounter on the roadway. How to design test scenarios efficiently and comprehensively to cover various traffic conditions becomes a critical question. It is important that CAVs be evaluated thoroughly before they can be sold to the public. The augmented reality environment can be used to generate different scenarios with the involvement of real CAVs, with some accelerated evaluation approach that can speed up the testing process.

5. Outputs

The following outputs were generated during the performance of this project:

- USDOT UTC Spotlight Newsletter (Dec, 2017): Augmented Reality and Connected Automated Vehicles, University of Michigan

- Mcity white paper: Real World Meets Virtual World: Augmented Reality Makes Driverless Vehicle Testing Faster, Safer, and Cheaper. Authors: Henry Liu and Yiheng Feng

- Conference Presentations: 2018 TRB Annual Meeting and 2018 IEEE Intelligent Vehicle Symposium

- Conference Paper: Feng, Y., Yu, C., Xu, S., Liu H.X., and Peng, H.. An Augmented Reality Environment for Connected and Automated Vehicle Testing and Evaluation. The 29th *IEEE Intelligent Vehicle Symposium*, Changshu China, 2018.

6. Outcomes

The project work generated intellectual property that can be used for technology transfer:

- Patent: Simulated Vehicle Traffic for Autonomous Vehicles (US Provisional Serial No. 62/500,299) Authors: Henry Liu and Yiheng Feng

7. Impacts

The impacts from the development of an augmented reality test environment are significant. First, this has the potential to save automobile manufacturers and their suppliers millions of dollars in testing – *per vehicle platform*. This cost savings can be cascaded to consumers, making the cost of a CAV more affordable. In turn, this may increase the penetration of CAVs faster. Second, using an augmented reality test environment will result in a more robust CAV design, a design that is safer for consumers. Third, the augmented reality test environment provides a safe venue to conduct testing. Lastly, the augmented reality test environment for connected and automated vehicles has greatly increased the body of knowledge through the outputs above and the media articles below:

- Forbes:

  https://www.forbes.com/sites/samabuelsamid/2017/06/22/university-of-michigan-deploys-augmented-reality-system-to-aid-testing-of-automated-vehicles/#7ec1f4c1e48a

- Engadget:

  https://www.engadget.com/2017/06/24/self-driving-cars-mcity-augmented-reality/

- Detroit News:

  https://www.detroitnews.com/story/business/autos/mobility/2017/10/31/mcity-car-test-site-gets-boost-industry/107210346/

- Mlive:

  https://www.mlive.com/news/ann-arbor/index.ssf/2017/06/avoiding_crashes_virtual_reali.html

- NBC News:

  https://www.nbcnews.com/mach/science/fake-city-promises-real-change-transportation-ncna809136

- Xconomy:

https://www.xconomy.com/detroit-ann-arbor/2017/11/03/with-11m-in-new-funding-mcity-looks-ahead-to-2018-and-beyond/

- IEEE Spectrum:

https://spectrum.ieee.org/cars-that-think/transportation/self-driving/riding-in-a-robocar-that-sees-around-corners

References

[1] M. A. M. Zulkefli, P. Mukherjee, Z. Sun, J. Zheng, H. X. Liu, and P. Huang, "Hardware-in-the-loop testbed for evaluating connected vehicle applications," *Transportation Research Part C: Emerging Technologies*, vol. 78, pp. 50–62, 2017.

[2] S. Sunkari, "A platform for change: TTI provides FHWA a new way to test CV/AV technologies," *Texas Transportation Researcher*, vol. 52, pp. 12–13, 2016.

[3] F. Y. Wang, "Parallel control and management for intelligent transportation systems: Concepts, architectures, and applications," *IEEE Trans. Intell. Transport. Syst.*, vol. 11, no. 3, pp. 630–638, Sept 2010.

[4] L. Li and D. Wen, "Parallel systems for traffic control: A rethinking," *IEEE Trans. Intell. Transport. Syst.*, vol. 17, no. 4, pp. 1179–1182, April 2016.

[5] L. Li, W. L. Huang, Y. Liu, N. N. Zheng, and F. Y. Wang, "Intelligence testing for autonomous vehicles: A new approach," *IEEE Transactions on Intelligent Vehicles*, vol. 1, no. 2, pp. 158–166, June 2016.

[6] D. J. Fagnant and K. Kockelman, "Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations," *Transportation Research Part A: Policy and Practice*, vol. 77, pp. 167–181, 2015.

[7] A. Singhvi and K. Russel, "Inside the self-driving tesla fatal accident," *The New York Times*, 2016.

[8] PTV, *VISSIM 6.0 User Manual. Karlsruhe*, Germany, 2013.

[9] J. Farrell and M. Barth, *The Global Positioning System & Inertial Navigatio*. McGraw Hill Professional. New York, NY, USA., 1999.

[10] P. Gipps, "A behavioural car-following model for computer simulation," *Transportation Research Part B: Methodological*, vol. 15, no. 2, pp. 105–111, 1981.