Connected/Automated Vehicle and Infrastructure Research
[Michigan Mobility Transformation Facility (MTF)]

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UMTRI TRANSPORTATION RESEARCH INSTITUTE UNIVERSITY OF MICHIGAN

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16. Abstract

The concept of the Michigan Mobility Transportation Facility, now known as Mcity, formed from a recognized need for a safe, controlled environment in which to develop various connected and automated vehicle (CAV) components that included interaction with real-world infrastructure. Therefore, one could say Mcity grew out of necessity; but it has also spawned enormous amounts of invention. Since completion, the test facility has supported research and development by vehicle manufactures, Tier 1 suppliers, start-up companies, and various educational uses.

An investment on the part of the University of Michigan and the Michigan Department of Transportation (MDOT), multiple measures of success and its value are demonstrated by how Mcity has become world-renowned, digitally modelled, copied, and has spawned countless research projects that could otherwise not be conducted in a real-world environment due to safety or security concerns.

The testing performed at Mcity has supported numerous research projects interested in understanding the modeling of traffic control networks, evaluating CAV and infrastructure technologies, and evaluating CAV applications. Additional research which could not be practically performed in Mcity; such as the real-world examination of LiDAR detection of lane marking materials. was included in the project and performed on US23 in Washtenaw and Livingston counties to support a broader understanding of how CAV technologies could be supported by roadway infrastructure and for consideration by roadway owner/operators in future planning.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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Acronyms

AACE	Ann Arbor Connected Environment (formerly AACVTE)
AD	Aftermarket Device
ADAS	Advanced Driver Assistance Systems
AR	Augmented Reality
ARPA-E	Advanced Research Projects Agency-Energy
ASD	Aftermarket Safety Devices
AV	Automated Vehicle
BSM	Basic Safety Message
CAMP	Crash Avoidance Metrics Partnership
CAV	Connected and Automated Vehicle
CCI	Clarifications for Consistent Implementations
CDA	Cooperative Driving Automation
CV-CP	Connected Vehicle Co-Processor
C-V2X	Cellular-Vehicle-to-Everything
DSRC	Dedicated Short-Range Communications
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
GPS	Global Positioning System
HSM	Hardware Security Module
IMA	Intersection Movement Assist
IPv6	Internet Protocol version 6
I2V	Infrastructure to Vehicle
LED	Light-Emitting Diode
LiDAR	Light Detection and Ranging
LTAP	Left Turn Across Path
MAP	Map
MDOT	Michigan Department of Transportation
MTL	Michigan Traffic Lab
NADE	Naturalistic and Adversarial Environment
NDD	Naturalistic Driving Data
NR	New Radio
OBU	On-Board Unit
OEM	Original Equipment Manufacturer
OS	Operating System
PSM	Personal Safety Message
RLVW	Red-Light Violation Warning
RRFB	Rectangular Rapid Flashing Beacon
RSU	Road-Side Unit
RTK	Real-Time Kinematic
SCMS	Security Credential Management System
SPaT	Signal Phase and Timing
SPMD	Safety Pilot Model Deployment

UM	University of Michigan
UMTRI	University of Michigan Transportation Research Institute
USDOT	United States Department of Transportation
VAD	Vehicle Awareness Devices
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
3GPP	3rd Generation Partnership Project

Introduction

This report discusses the construction of the Mcity Test Facility at the University of Michigan (UM), as well as associated testing and development in the Ann Arbor Connected Environment (AACE) and surrounding area roadways. This facility (formerly known as the Mobility Transformation Facility) was the first facility in Michigan, and the first public facility in the world, dedicated to the testing and development of connected and automated vehicle (CAV) technologies. This report includes key lessons learned relating to the following:

- Testing of infrastructure-based communications equipment supporting CAVs
- Examination of how conventional roadway infrastructure influences CAV operation
- Deployment (installation, operation, and maintenance) of advanced infrastructure to support CAVs.

The Mcity Test Facility design incorporates a variety of common roadway attributes, including various designs of intersections, roadway markings, lane configurations, traffic control devices, signage, lighting, roadside infrastructure, and the interaction/communication with smart infrastructure via infrastructure-to-vehicle (I2V) and vehicle-to-infrastructure (V2I) communications. The rationale for including specific attributes in Mcity's construction is discussed, as well as modifications that have occurred to the facility since opening in May 2015.

This report also describes how the AACE has evolved since being established in 2012 under the U.S. Department of Transportation (USDOT) funded Connected Vehicle Safety Pilot Model Deployment (SPMD) program. Specifically, how changes in CAV technologies have required changes to the AACE and the role the Mcity test facility played in implementing those changes.

Lastly, the report contains lessons learned from the construction of the Mcity Test Facility, its operation, and the maintenance of Mcity and the AACE since 2012. While thousands of connected vehicles were also tested in Mcity or the AACE environment, the focus of this report is on the roadway infrastructure intended to support CAVs – primarily I2V and V2I communications. The report includes information regarding several research studies that have been conducted to support the development and deployment of I2V and V2I communications.

Background on the Mcity Test Facility

Construction of the Mcity Test Facility (formerly known as the Mobility Transformation Facility) and AACE were significant learning experiences for the university faculty and staff involved. Both projects were unlike any previous projects UM had ever undertaken, and there were no examples of a CAV-dedicated research facility or deployed connected environment elsewhere to use as a model.

First conceived of in the summer of 2013, leadership from the University of Michigan Transportation Research Institute (UMTRI) immediately engaged the Michigan Department of Transportation (MDOT) in discussions about a possible facility and location. Officially opened in May 2015, construction of the Mcity Test Facility was also one of the fastest University construction projects to have taken place at the time. The support and guidance offered by the MDOT director and various staff was essential to the successful completion of the facility, as no one at the University had any experience in the actual process of constructing roadway infrastructure. However, several faculty staff at the university knew that the roadway infrastructure, be it traditional or new technology, would have an increasing impact on the successful development of highly automated vehicles and cooperative driving automation (CDA).

UMTRI faculty had significant experience in fielding numerous studies of advance driver assistance systems (ADAS) in the real-world for the USDOT. These systems relied heavily on the same types of vehicle-based sensing technology that were being designed into prototype automated vehicles, and we were aware of many vehicle-based sensor limitations that would have to be addressed by both vehicle-to-vehicle (V2V) and I2V/V2I technologies. From this real-world experience, we anticipated challenges in deploying I2V/V2I equipment. Armed with our knowledge of vehicle-based sensors and their limitations, and developing an understanding of infrastructure-based technology, we set forth to build a test facility expressly dedicated to conducting research and evaluation of highly automated vehicles and the communications technology that CAVs and CDA would require.

The Mannik and Smith Group was hired by the university to develop the final design of the facility, based upon preliminary sketches and drawings provided by UM faculty, in consultation with MDOT staff. This ensured that the test facility was constructed in accordance with roadway design specifications.

In the end, the total cost of the construction, 4.25 lane miles of roadway surface, and equipment in the Mcity Test Facility, not including the value of the land (which remains property of the UM Health System) was $11.5M. Contractors' bids in early 2014 were 10 – 12% lower than the actual build cost, and as such, the completion of a few minor, and largely aesthetic, facility attributes had to be delayed. In addition, a significant amount of material was "salvaged" from state, county, and local municipalities – essentially items that were destined to be scrapped. These items included an extensive array of surface street and highway signage, fire hydrants, and roadside "furniture" such as newspaper boxes, bicycle racks, and benches.

Still other materials, and a few services, were donated, including crash attenuators, signposts, heads for streetlights, sign trusses, a cantilevered sign, and some streetlight poles. The cost of constructing the facility at the time it opened would have been closer to $13M had the university needed to purchase all of the items and services.

Construction planning lasted from the Fall of 2013 until the Spring of 2014, with construction beginning in the Summer of 2014 at the 32-acre site bounded by Plymouth, Nixon, Huron Parkway, and Baxter on UM's north campus (Figure 1). Ultimately, the test facility also included an eight foot high perimeter fence to keep wildlife out and "black-out" fabric to protect the confidentiality of testing taking place.

Photo provided by
UM Architecture, Engineering & Construction

Figure 1: Aerial photo of Mcity under construction, Summer 2014.

Construction continued until December of 2014 before breaking for the winter (Figure 2). But by December of 2014 all of the concrete and asphalt work was complete, and what remained for the Spring of 2015 (Figure 3) was the installation of the remainder of the physical infrastructure – including traffic control devices, power and communications, building facades, roadway signage, lane markings, and to complete a simulated tunnel and tree canopy.

Construction Drawings

An electronic copy of the construction drawings was provided to MDOT separately. An illustration of the Mcity Test Facility with its original design, and current attributes is provided in Figure 4.

Figure 2: Roundabout under construction, Fall 2014.

Figure 3: Aerial photo of Mcity under construction, Spring 2015.

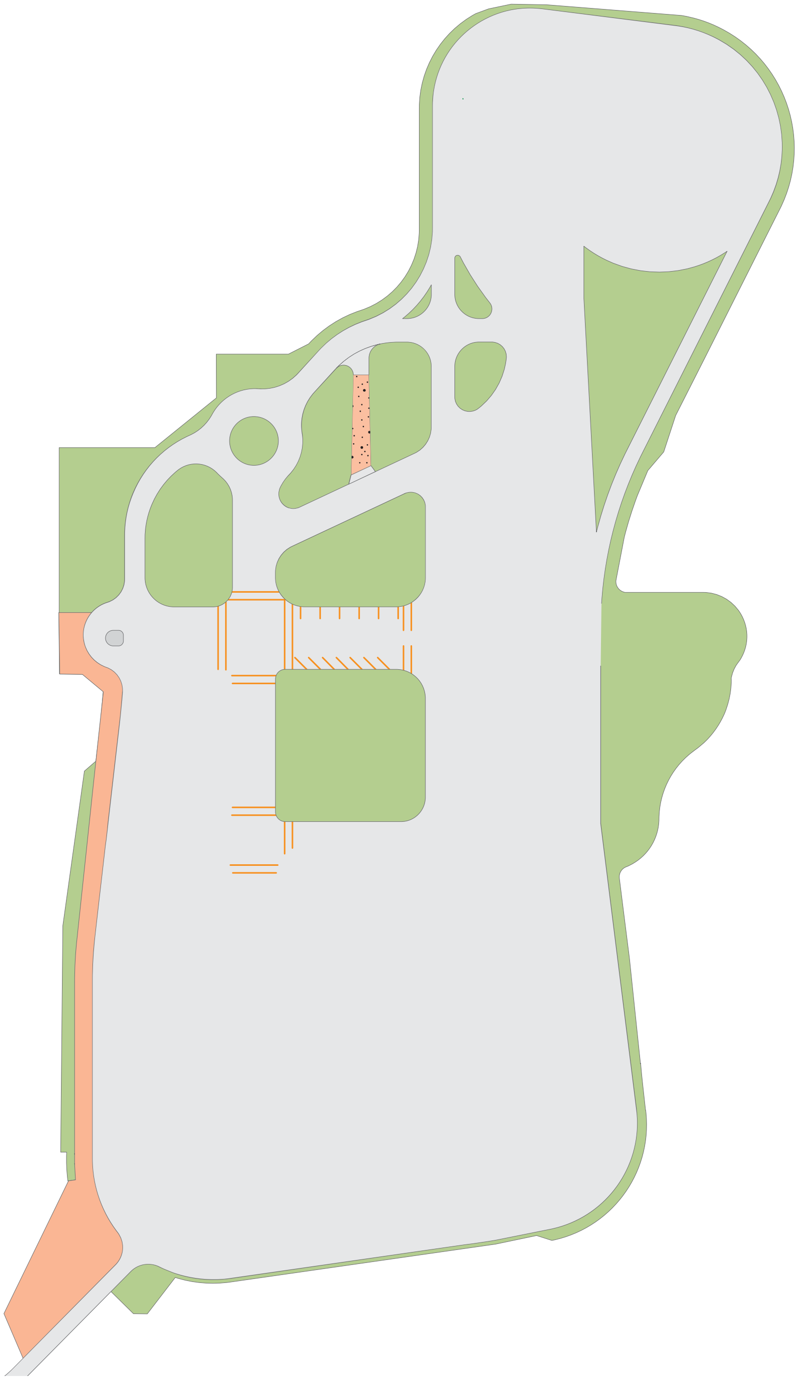


Figure 4: Illustration of the current Mcity Test Facility design and attributes (includes all original attributes).

Deployment of Smart Roadway Technologies in the Mcity Test Facility (Milestones 1 - 5)

Constructed Attributes and Rationale for their Selection

As mentioned previously, UM faculty had extensive real-world experience working with the vehicle-based sensing systems to be used in automated vehicles. These systems included LiDAR (light detection and ranging), radar, image processing, near and far infrared, and ultrasonic sensing. Based on past experience, we were also aware of the types of roadway and environmental conditions that challenge the different sensing technologies. Issues such as camera dynamic range and response to abrupt changes in light level, static objects on the roadside that produced radar returns resulting in "false" collision avoidance warnings. Additionally, how different transitions between the roadway surface and the road edge affects LiDAR and image recognitions, defining the road edge when no lane line is present, variations in LiDAR reflectance as a function of surface materials, etc. As such, many of these known challenges were incorporated into the design and construction of Mcity.

Initially, we considered a multitude of challenging roadway attributes be constructed at the site. However, to minimize cost we decided to limit attributes to those representative of standard roadway environments. As such, we chose to incorporate attributes such as different intersection configurations (including a roundabout), traffic control devices, road classes, road curvatures, changes in grade, road surface materials, lane marking materials, signage styles, pedestrian crossings, building facades, types of roadway lighting, and a gated at-grade rail crossing.

On top of the "traditional" roadway infrastructure, a highly adaptable traffic control and traffic management system was also built (Figure 5). Specific construction elements that were specified based on anticipated need to support future technologies included conduit space (two spare 3-inch conduits), fiber optic cable capacity, power requirements throughout the facility, the size of traffic control cabinets to support research equipment, and even the size of traffic signal pole foundations to support future additional equipment on mast arms. In total, eight traffic signal locations were installed on a dedicated traffic control network, fed to a traffic management center. This is located within UMTRI, which is several hundred yards from the test facility.

The selection of the location to build Mcity next to UMTRI was deliberate. By its location adjacent to UMTRI facilities, access would not require operating vehicles on public roadways between the two. Yet after testing, vehicles could move within minutes to an operational connected vehicle environment (SPMD, later AACE) with nearly 3,000 equipped vehicles by leaving Mcity for the adjacent surface streets and highways.

Figure 5: Mcity Traffic Management Center, which is also linked to the City of Ann Arbor traffic control network at 70+ signalized intersections and specialized roadside installations – overlayed on the lower right-hand display.

Figure 6: Aerial photo of the Mcity Test Facility as originally constructed, at dusk when various types and color temperatures of roadway lighting are evident.

Mcity As-Built Attributes Intended to Challenge Automated Vehicles

As previously mentioned, the scale of Mcity did not permit testing of all types of roadway infrastructure. However, several areas received particular attention to include as wide of a range of material/configurations as possible, particularly if it were known that certain attributes would challenge CAV technology or be required for it to operate successfully. This section of the report includes descriptions of those intentional design attributes.

I2V/V2I Infrastructure

Dedicated short-range communications (DSRC)-based I2V/V2I infrastructure that had been installed on Ann Arbor area roadways as part of the SPMD project were extended into Mcity (Figure 7). Initially this included equipment identical to the deployed equipment. Later, testing was performed in Mcity on equipment upgrades (2016 DSRC standards) destined for Ann Arbor roads. This testing within Mcity supported both the Mcity installations and those in the Ann Arbor connected vehicle environment. Later, as UMTRI served as the national reference for the deployment of connected vehicles and infrastructure, additional pilot locations (New York City, Tampa, and the state of Wyoming) utilized these same test results.

Figure 7: Infrastructure-to-vehicle communication radios and a vehicle detection camera.

Pavement Markings

A range of different pavement marking materials was applied to road surfaces to determine if certain materials were more readily detectable by image processing on CAVs. Some road surfaces were limited to the use of temporary tape to permit lane reconfiguration of particular road segments. The color and retroreflective characteristics of the lane markings were also varied on both concrete and asphalt surfaces, creating different levels of contrast between the pavement and the lane markings to challenge camera recognition. All lane markings in Mcity were applied directly to the roadway surface, and not recessed (Figure 8, Figure 10).

Traffic Signal Location

The infrastructure used and the positioning of traffic signals was intentionally varied across eight signalized locations. Variations included traffic signals that were suspended over the intersection via cable, signals that were post mounted, and signals that were fixed to mast arms. The types of poles were also varied for the suspended signals (steel vs wood). Variation in the signal head location was done to make it more challenging for image processing systems to identify the location of the traffic signal even before recognizing the signal phase. Cable-mounted traffic signal heads also move/sway in the wind (Figure 9, Figure 11).

Figure 8: Various lane marking materials (latex-based paint and thermal plastic) and a traffic circle.

Figure 10: Bicycle lane surface markings and square concrete curb.

Figure 9: Examples of post- and pedestal-mounted traffic signal heads as well as suspended from wooden poles.

Figure 11: Gated railroad grade crossing and traffic signal heads suspended from metal poles.

Roadway Margins

Various combinations of road surface and margin material were included in construction. For both concrete and asphalt surfaces, there were road segments where the margins were either solid (concrete or asphalt), gravel, or the road edge abutted up to grass. A limited amount of gravel road surface was also installed, but its margin always transitioned to grass. In addition, four different sizes/shapes of concrete curb were installed in the urban section of Mcity. All these variations were included to test recognition of the road edge using image processing or LiDAR sensors (Figure 12, Figure 13). A small section of metal grate surface; like the one on the Mackinac Bridge, was also installed (Figure 14).

Figure 12: Examples of pavement transitions (asphalt to gravel and concrete to asphalt) and a low sloping curb.

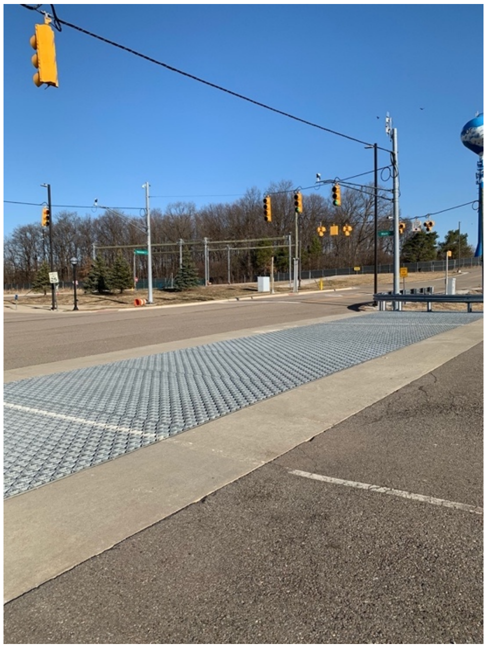


Figure 14: Section of grated metal bridge surface.

Figure 13: Gravel roadway with transition to a grass margin.

Roadway Lighting

A variety of illumination types were installed. These included high-pressure sodium, metal halite, and light-emitting diode (LED) fixtures. Most were mounted such that lamps were directly over the road surface, but some were post-mounted streetlights located on the curb. Different types of fixtures were installed to examine whether the color temperature of the light source at night had an effect on image processing when detecting road/lane boundaries or obstacles in the roadway (Figure 6).

Tunnel and Simulated Tree Canopy

A "tunnel" was constructed with a North-South orientation so that a sharp transition in light level entering and exiting the tunnel is achieved on sunny days. The length of shadows cast depends on the position of the sun as it varies by season. This design allows for testing of the dynamic range and response of cameras used for image processing. The tunnel is fully enclosed in metal to block or attenuate wireless signals, such as signals from global positioning system (GPS), DSRC, cellular, etc. in the same manner experienced in the real-world scenarios. Similarly, a simulated tree canopy was made from military camouflage netting suspended by cables. The use of camouflage simulated flickering light coming through the leaves of a tree canopy. It was also treated with a carbon-based paint to attenuate wireless signals (8dB). Lastly, the proximity of the tunnel walls to the lane and the reflective nature of the metal poses challenges for LiDAR systems (Figure 14 and Figure 15).

Figure 15: Entrance to tunnel producing sharp transitions in light level and attenuating wireless signals.

Figure 16: Simulated tree canopy without its suspended camouflage netting installed.

Pedestrian Crossings

Pedestrian crossings are located at most intersections within Mcity, as well as at some midblock locations. Midblock crossings had two different types of signals indicating that a pedestrian was crossing. One uses post-mounted Rectangular Rapid Flashing Beacon (RRFB), while the other incorporates flashing overhead signals suspended via cable over the road surface. Several pedestrian crossings at intersections use conventional push-button activated pedestrian signal heads. A pedestrian crossing was also included in the facility's roundabout. The different types of crossings, their locations relative to road geometry, the presence or absence of a mid-crossing refuge, and the presentation of signals vary to allow testing of an automated vehicle's ability to correctly interpret the crossings (Figure 16 and Figure 18).

Roundabout and Traffic Circle

Roundabouts and traffic circles can be particularly challenging for automated vehicles given uncertainty relative to a signalized intersection as to when other vehicles might enter. One small traffic circle is located on the north end of the facility's State Street, and a roundabout is located on the south end. Other than its particularly small radius, the traffic circle does not include much that is unusual to challenge automated vehicles (AVs). The roundabout, on the other hand, is intentionally designed to be particularly challenging. It is a two-lane roundabout such that vehicles can change lanes while in it. Built on a compound slope, the entrances/exits are not evenly spaced around the circumference. This uneven spacing poses challenges to automated vehicles because the time available to assess whether another vehicle that is entering or exiting differs based on the approach to the roundabout (Figure 8 and Figure 17).

Figure 17: Mid-block pedestrian crossing with rapid RRFB.

Figure 18: Roundabout on a compound slope with unevenly distributed entrance and exit points.

Figure 19: Pedestal-mounted pedestrian crossing signal.

Building Facades

Building facades are constructed to limit the line of sight that vehicle-based sensors have when approaching urban intersections. While the facades do not substantially attenuate wireless signals, they do limit the range of radar, LiDAR, and camera-based sensing. In addition, the surfaces of most facades are constructed using a range of real-world building materials. Representing how LiDAR reflects off of different materials and affects the quality of the returned signal was the purpose in using the various materials such as glass, metal, baked brick, wood, and aluminum siding, and doors in constructing the surfaces of the building facades (Figure 20).

Roadside Furniture

A variety of elements that could be repositioned anywhere on the test facility were acquired. These included outdoor seating, rural mailboxes, a post box, fire hydrants, bicycles and a bicycle rack, newspaper boxes, etc. These items were usually salvaged from materials the City of Ann Arbor was scrapping. Where these items are positioned, relative to the lane of travel and the roadway geometry, can cause radar-based warning systems to produce false alarms or product “clutter” in LiDAR returns (Figure 21).

Figure 20: Examples of real construction materials used in building facades (brick, glass, aluminum, cement board).

Figure 21: Examples of items regularly found along the roadside (mailbox, fire hydrant) and squared curbing.

Highway Design Attributes

The higher speed section of Mcity includes attributes commonly seen on highways, such as crash attenuators, Jersey barriers, rumble strips, guardrails, on and off ramps, and ramp metering. These are all real-world attributes that must be correctly recognized, and potentially avoided, by CAVs (Figure 22 and Figure 23) operating in a highway environment.

Figure 22: Exit ramp with metering, crash attenuators, Jersey barrier, and truss-mounted signage.

Figure 23: Concrete and asphalt pavement and highway signage on a truss.

Road Signs

Because not all road signs are pristine, Mcity acquired a range of new and well-worn road signs for mounting in the facility. Again, often salvaged out of materials destined for scrap, a “library” of used road signs was assembled such that different signage, including posted speed, could be changed in addition to the quality of the sign condition. Variations in quality included extensive UV exposure, damage due to being struck by a vehicle (missing retroreflective material or bent), and graffiti (Figure 24 and Figure 25). Signs can be rapidly changed, as they are held to their posts using hitch pins rather than rivets, and the entire post can be removed as well by lifting it off a base. Signs can also be added on the roadside or surfaces using temporary bases. On the higher speed section of Mcity, intended to represent a highway environment, there are three overhead signs - one cantilevered and two on trusses (Figure 23).

Figure 24: Examples of signage varying in quality (good condition, graffiti, fading).

Figure 25: Graffiti on a road sign.

Parking

Three types of parking spots are included in Mcity: parallel, diagonal, and stall parking. Each presents their own challenges for automated parking systems. In addition, an accessible parking spot and signage was installed in one location to assess if AVs can differentiate between it and non-accessible spots (Figure 26 and Figure 27).

Figure 26: Parallel parking spots, including an accessible handicapped spot and post-mounted streetlights.

Figure 27: Diagonal parking spots.

Additional Attributes

Additional attributes that can be challenging for AVs that were included in the construction of Mcity include:

- A gated, at grade railroad crossing (Figure 11)
- Metal bridge decking over a small wetland area that produces spurious radar reflections (Figure 19)
- Construction zone channelizers, barricades, water-filled barriers, and cones which can be located anywhere and in any configuration on the facility to simulate construction zones

Descriptions of Activity Conducted in the Mcity Test Facility

Focus of Testing in Mcity

Mcity is used by a wide variety of groups and individuals, including automotive manufacturers, parts suppliers, start-up companies, faculty and students conducting research, and nonprofit events. During certain times of the year, it can be challenging to find available time at Mcity without booking well in advance. Faculty and students also utilize Mcity for educational purposes, and nonprofit events like Square One Educational Network have held robotics competitions for high school students at Mcity. The costs associated with Mcity are based on a recharge rate that is recalculated annually based on the previous year’s utilization and maintenance costs.

Initial testing that was conducted in Mcity after opening was not, for the most part, taking full advantage of all the available attributes built into the facility. In 2015, CAV developers that used Mcity were still working on some basic CAV sensor and algorithm development. Early on, a number of vehicle manufacturers and suppliers used Mcity to test and demonstrate individual attributes (such as driver assistance systems) of what would ultimately become part of a CAV system. Functions such as the use of electronic maps, maintaining a position in a lane, some I2V applications, and object recognition were commonly performed in the facility.

Within a couple of years after opening, Mcity users were examining the precursors to SAE Level 2 and 3 CAV systems. This included operation in stop-and-go traffic, a broader set of I2V/V2V applications, and functions such as automated lane changes. However, not all Mcity users were, or are, at the same level of advancement, and within Mcity basic work on digital mapping, control algorithms, sensing, and I2V/V2V applications continues. However, this type of work tends to be done by start-up companies – including those developing newer mobility options for both people and goods delivery.

Most recently, the more advanced work conducted in Mcity has focused on new I2V/V2V communication protocols such as Cellular Vehicle-to-Everything (C-V2X) and 5G. There is also increased emphasis on a role for I2V equipment and communications as part of the roadway infrastructure. This includes the addition of sensors to the roadway infrastructure to provide information to vehicles when basic I2V, V2V, and vehicle-based sensing technology are not enough to provide a complete understanding of the roadway and all its users. The additional infrastructure-based sensing capability in the form of image processing, LiDAR, and radar is largely being focused on different types of intersections, where sensing and communication provide CAVs with additional information regarding pedestrians, cyclists, and other vehicles. This is particularly important when one assumes that not all road users are broadcasting their location and are not in the line of sight of vehicles’ on-board sensing equipment.

Overall, the types of testing performed have, and will continue, to change with time. As a result, additional equipment, attributes, and facility capabilities are being added to support the needs of Mcity users.

Infrastructure Attributes or Modifications Added since the Facility Opened in 2015

Garage Space

After the opening of the Mcity Test Facility in 2015, one of the most frequent and immediate requests from both academic and industrial users was for garage space: a place to store their vehicles across multi-day testing, a place to perform light work on vehicles between tests, and in some cases, a place for long-term storage. In all cases security, climate control, lighting, power, and network connectivity were critical.

In 2016, three options were explored: a budget option with no central meeting space and reduced mechanic space, an intermediate option with a small central meeting area and additional mechanic space, and a more substantial option with a large central meeting area, a corridor connecting the bays, and ample workspace in all bays. Several industry partners were approached to defray some of the capital costs of construction, but ultimately the plans were put on hold due to the high estimated costs.

By 2018 the need for garage space was even greater, and Mcity explored a cost-reduced version of a garage that would be suitable for storage of vehicles only, and climate controlled to the extent required to keep advanced sensors within their operating ranges - but not necessarily comfortable for people to work in. Again, an industry partner was sought to defray cost, and construction initiated. The 10-bay garage was completed in spring of 2019 (Figure 28, Figure 29, and Figure 30), with Mcity using four of the bays, and the supporting industrial sponsor using the remaining six. The garage has remained at 100% capacity since. There continues to be high-demand for rentable garage space, both from industry and academic partners – the UM as well as other Michigan universities and colleges.

Today, Mcity is working to renovate an adjacent garage/office space left from the previous landowners (ERIM and Bendix Corp.). This facility was originally built to support a small circular test track on the site used by Bendix to test vehicle brake systems. This facility is being called the “Mcity Auxiliary Building”, and is roughly 3500 square feet of usable space, with a single garage bay. Mcity’s renovation was halted due to the COVID-19 pandemic, but it anticipates bringing the building up to minimum code for engineers and researchers to house vehicles for data offload and adjustments between tests, orchestrate and coordinate testing, and for basic office amenities such as climate control and restrooms in 2021.

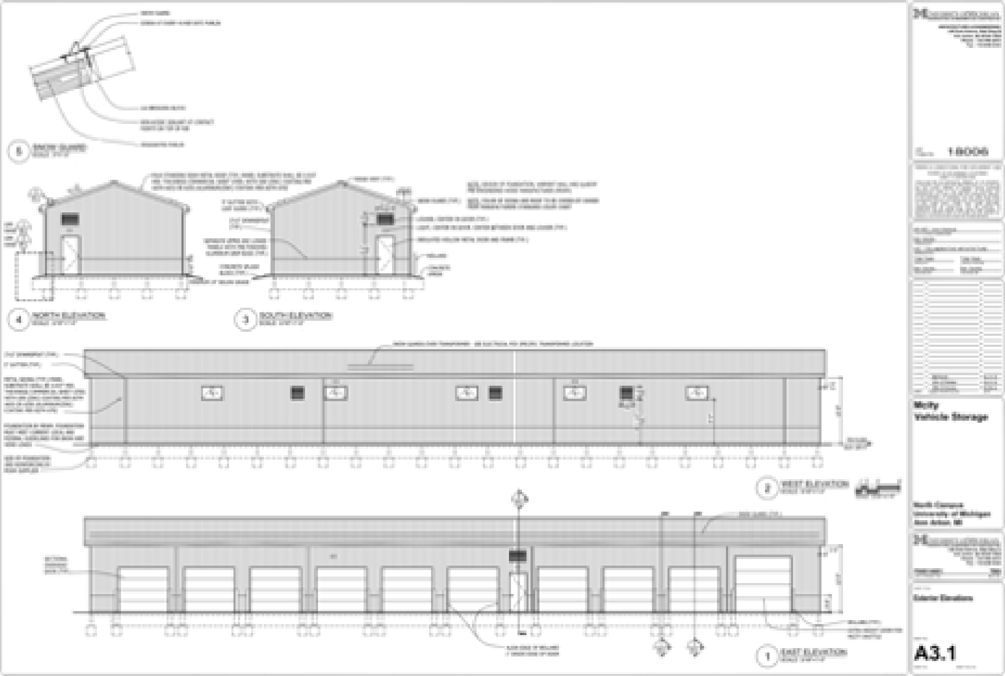


Figure 28: Construction drawing of the Mcity garage.

Figure 29: The exterior of the Mcity garage upon completion.

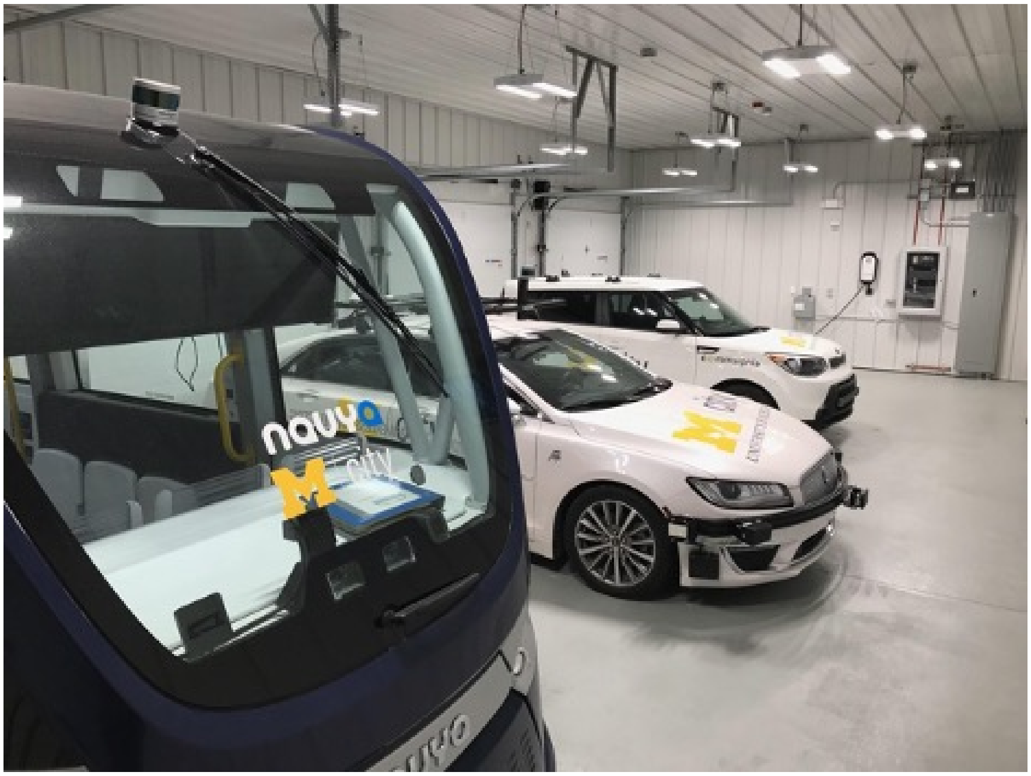


Figure 30: The interior of Mcity garage.

Changes in Lighting

Mcity retains a wide range of lighting sources throughout the testing space designed to reflect various real-world lighting conditions, however much of the lighting has been updated. The hardware and light control are provided by RAB Lighting, an Mcity member company. Mcity currently houses 63 independently controlled light sources within the testing space. Models range from high intensity overhead lights producing up to 16k lumens each to small decorative lighting posts with a warmer color tone. The building-mounted lights found in the downtown block provide dim lighting at regular intervals, while overhead lights posted along the highway provide wider, brighter light pools spaced further apart. While all of the overhead lights are LED, half of the fixtures mimic a narrow, warm color band of high-pressure sodium, and the other half a fuller spectrum “white” of newer streetlights.

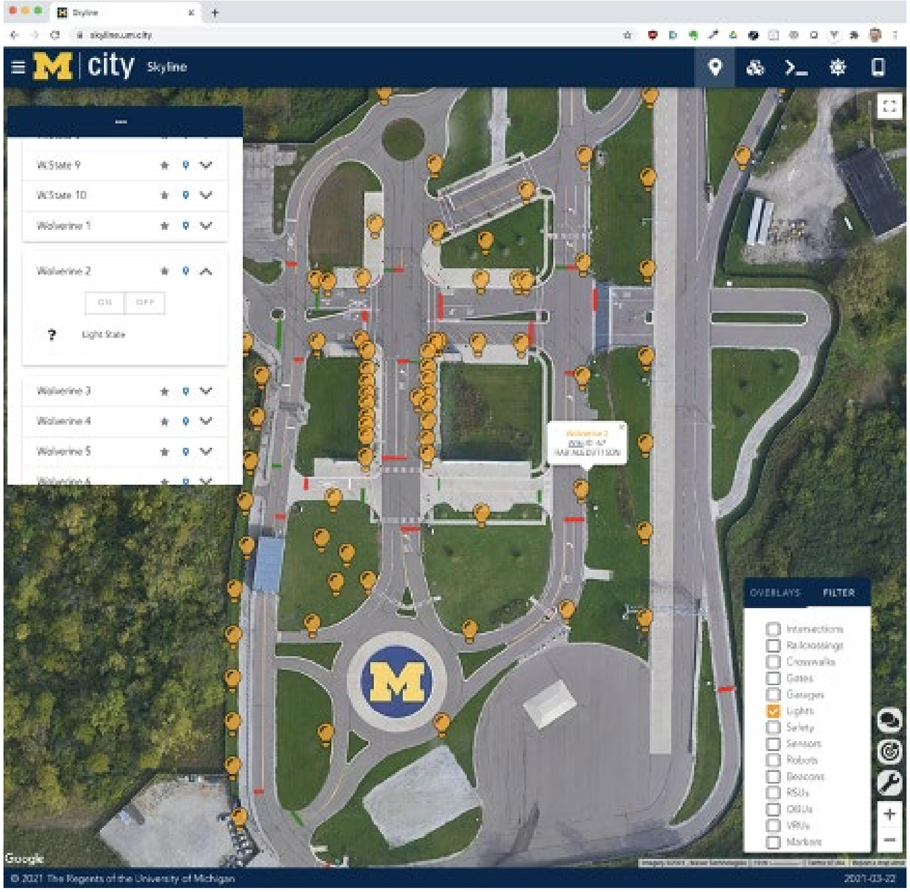
All the lights throughout the facility are scheduled to come on and off at set times throughout the day but can also be directly controlled by facility users via Mcity Operating System (OS) to modulate brightness and activate or deactivate on a per-unit basis. In this way, an Mcity user may create custom lighting scenarios to simulate, for example, low-light or near-dark nighttime country roads, further-spaced light pools with every other light activated, irregular lighting conditions with variable luminosity from different lights, or poorly maintained road settings where certain lights are 'burned out'.

Mcity OS

By 2017 it had become clear from the types of tests and research requests Mcity was receiving that a unified control, data collection, and orchestration system was needed. This would allow facility users to coordinate between various infrastructure elements, moving test systems, and ground truth data collection in order to carry out repeatable, accurate tests quickly, and simply. Mcity hired software engineering staff to build such a system. Today, Mcity OS is capable of assisting in the graphical creation of complex test scenarios (Figure 31), supports new and interesting test methodologies like augmented reality, and integrates with a large variety of infrastructure devices, from custom-built IoT systems to municipal traffic controllers, railroad crossing systems, streetlights, vehicle test robots, and many more. The implementation of Mcity OS is licensable beyond the University, has been licensed and running at our partner facility, The American Center for Mobility.

The specification for Mcity OS is open, and freely available for others to implement.
https://github.com/mcity/octane-api

A white paper on Mcity OS is also available. https://mcity.umich.edu/wp-content/uploads/2021/02/mcity-whitepaper-OS-web.pdf



- ☐ Intersections
- ☐ Railcrossings
- ☐ Crosswalks
- ☐ Gates
- ☐ Garages
- ☑ Lights
- ☐ Safety
- ☐ Sensors
- ☐ Robots
- ☐ Beacons
- ☐ RSUs
- ☐ OBUs
- ☐ VRUs
- ☐ Markers

Figure 31: Interface for the Mcity OS - Skyline.

Augmented Reality

Leveraging vehicle-to-everything (V2X) technology, several teams have built sophisticated "augmented reality" systems for testing CAV behavior in the simulated presence of other vehicles. The Michigan Traffic Lab has constructed a system that allows for accelerated evaluation of automated vehicles during "normal" driving through the Mcity test facility, using V2X roadside equipment to synchronize a virtual Mcity environment with the real environment. Virtual and real vehicles can "see" each other via V2X communications. This bypasses perception systems in automated vehicles but allows very accurate and repeatable (as well as safe) testing of CAV control strategies.

Other applications include Advanced Research Projects Agency-Energy (ARPA-E) projects that have utilized this technology to create specific traffic patterns that replicate real-world conditions and help achieve accuracy when testing fuel/energy conservation applications. A whitepaper on this approach is available. https://mcity.umich.edu/wp-content/uploads/2018/11/mcity-whitepaper-augmented-reality.pdf

The UM and Mcity are currently funding several projects that are attempting to augment the reality of camera and LiDAR sensors, in real time, to insert different weather conditions, road users, and so on into the live perception stream that a CAV produces.

Changes in Connected Vehicle Communication Protocols and Equipment

Since the facility opened in 2015, there has been a range of new connected vehicle/ infrastructure communication protocols developed in addition to DSRC. These included C-V2X and the use of 5G for connected vehicle applications. While there remains uncertainty as to whether the USDOT will mandate use of one particular protocol, the facility needs to be capable of supporting the testing and development of multiple protocols. Currently, Mcity includes examples of infrastructure equipment that broadcast DSRC, C-V2X, and true 5G. The accompanying vehicle-based transmitters/receivers are also available for use in testing.

Real-Time Kinematic (RTK) Positioning

As part of the desire for highly accurate ground truth, UM runs a redundant reference station next to the Mcity test facility, that provides centimeter level GPS correction data to anyone using the facility, or more broadly in Washtenaw County. Mcity has also developed several low-cost (sub-$1,000) hardware units that leverage this technology to provide instant integration of pedestrian/cyclist proxies, test vehicles, and other road users.

Figure 32: Mcity's RTK unit for vehicles.

Figure 33: Mcity's RTK unit for pedestrians and cyclists.

Vehicle Platforms

Mcity has a variety of vehicle platforms, some for connected/automated vehicle research (Mcity's Open CAV fleet), standard and e-bikes, vehicles for mounting pedestrian and animal proxies (targets), and still others for orchestrated testing. These resources can be reserved as part of a reservation of the test facility, or separately. DSRC-equipped motorcycles can also be obtained from UMTRI when needed.

Lessons Learned during and Shortly after Mcity Construction

One of the most significant lessons learned during the design and construction of the test facility was the limit on the range of roadway configurations and attributes that could be represented in a test facility the size of Mcity. It was quickly realized that the types of roadway infrastructure chosen would be quite limited, and that as many variations of attributes be included as possible. In addition, due to the facility's location, freezing temperatures and snow accumulation needed to be considered. This made it impractical to install items such as raised, reflective lane delineators (Bott's dots) they would be significantly damaged or destroyed, when snow was removed from the facility surfaces.

Related to snow removal: it takes ½ day to remove snow from even just 4.25 lane miles of road surface. This means the facility often cannot be used shortly after a snowfall. However, there have been instances where facility users wanted access prior to snow being removed, including with no existing tire tracks, in order to test vehicle positioning accuracy without lane markings or tire tracks being detectable by vehicle cameras.

In several instances, facility users wished that the roadway surfaces were not a pristine as they were immediately after construction, as they did not represent the condition of real-world road surfaces. With time however, the state of the Mcity road surfaces has degraded – albeit not at the same rate as a typical road surface degrades due to the limited amount of traffic experienced. This includes peeling and fading roadway markings, and cracks in the roadway surface that have been filled with tar. Unfortunately, the only original paved surface on the site prior to construction was a small asphalt parking area, which was retained. Otherwise, all other road surfaces are allowed to degrade until such time they absolutely need replacement.

Another lesson learned was the difference between "as designed" and "as built" construction. While it was rare that "as built" did not meet the design, even slight variations could pose a challenge. One example was the installation of wood traffic signal poles at one intersection. The separation between power/communication conduit and the traffic signal pole were adequate as designed. Slight variation on the part of both the conduit installation and the pole being located resulted in severing of the conduit in one instance.

Lastly, community curiosity with the facility was also a lesson learned. While the facility opened to members of the community to visit the same week of the grand opening, subsequent similar offerings grew increasingly larger crowds. In one particularly year, approximately 1,800 people visited Mcity during a 4-hour open house. There have also been instances of people using drones to see the inside of the facility, as the fencing is covered in black fabric. Early after construction, there were also aircraft that surveyed the facility on occasion. This included a helicopter with a large camera mounted to its underside that hovered overhead – presumably taking photos to use in building a similar facility. Since opening, close to twenty facilities similar to Mcity in purpose have been constructed around the world (China, Japan, India, England, France, as well as several other facilities in the U.S.). Representatives from many of these new facilities have visited Mcity prior to constructing their own.

Descriptions of Activity Conducted in the Ann Arbor Connected Environment and Surrounding Roadways (Milestone 6)

Activities that Support the Mcity Test Facility

Standards Development and Equipment Testing in SPMD

The Safety Pilot Model Deployment (SPMD), and subsequent iterations, was impactful. Lessons learned from this project were incorporated into industry standards including Road-Side Unit (RSU) 4.1, SAE J2935, SAE J2945, and IEEE 1609.x. SPMD also was the starting point for the production security credential management system (SCMS) developed by the consortium of vehicle manufacturers in the Crash Avoidance Metrics Partnership (CAMP) and stood up by Green Hills ISS.

In 2015, the UMTRI-led team began to transition from SPMD to the AACVTE under Federal Highway Administration (FHWA) Cooperative Agreement DTFH6115H00005. A major part of the project was to update the devices to be compliant with the revised industry standards that were developed from the results of SPMD.

The team worked with OmniAir and their certification houses, which was not originally a planned activity in the AACVTE project. The UMTRI-led team was assured that certification testing would be ready when we bought the devices. However, it was not and was still in the development phase. The AACVTE project paid for on-site certification testing for suppliers deploying RSUs and On-Board Units (OBU) in AACVTE. Certification tests involved both bench tests at UMTRI and dynamic vehicle-level tests at Mcity.

During AACVTE, a round of burn in testing for RSUs prior to supplier selection was added to help evaluate the state of industry. AACVTE started with two RSU suppliers, two Aftermarket Safety Devices (ASD) suppliers and two Vehicle-Awareness Devices (VAD) suppliers. A supplier that was selected for both an ASD and RSUs was dropped from the program because they could not deliver functional devices for deployment. The supplier could not or would not correct issues found during interoperability testing. Thus, a lesson previously learned, and confirmed in the AACVTE, is to secure two or more providers per device.

We assumed that only two rounds of interoperability testing would be necessary, but three were needed. After interoperability testing, a phased roll out of devices began so that if issues were identified, corrections could be implemented prior to deploying the full complement of OBUs and RSUs.

Verification Testing

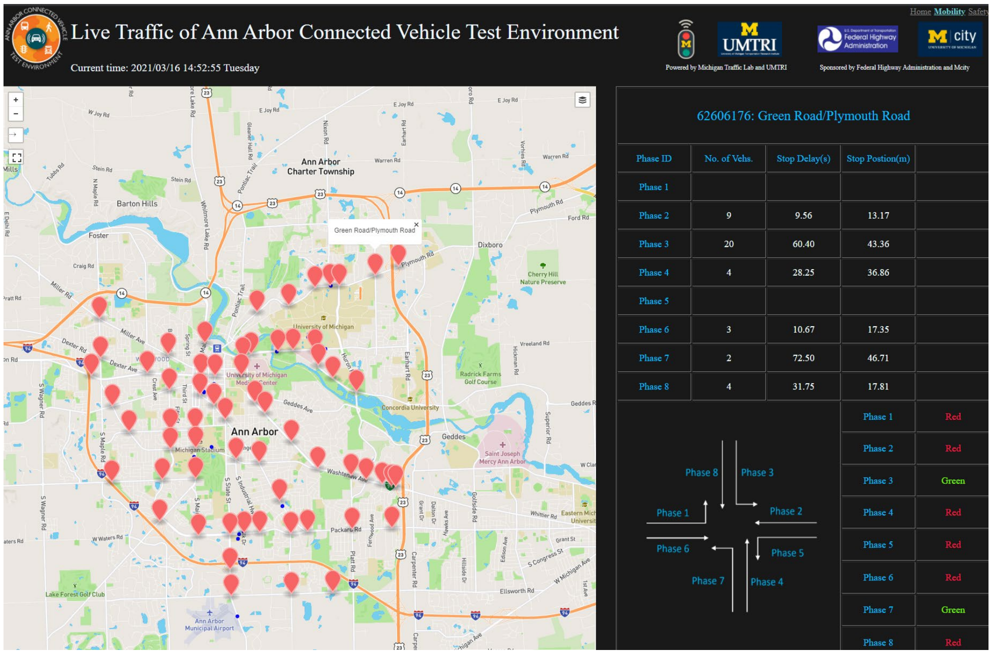
Verification testing was conducted in both AACE and Mcity over time to ensure that installed DSRC hardware was functioning and properly configured. This was primarily done by analyzing broadcasted messages (i.e., Basic Safety Messages [BSMs]) to ensure the following:

- The installed radios were receiving GPS satellite information and broadcasting messages with the proper Device ID (fixed 2 bytes of the 4-byte Temporary ID in the BSM Part 1 structure).

- The broadcast frequency of the messages is nominally 10 Hz.
- The quality of the position and elevation solution is within acceptable accuracy tolerances given the inherent noise associated with non-moving.
- Refinements to the testing procedure included testing in either the East or the North orientation. If the test failed, a technician would verify the following:
    - Antenna offsets in the configuration file on the device
    - All antenna wiring connectors and routing for pinching and poor connectivity
    - The radio has adequate exposure to the satellite constellation
    - Conduct the test a second time before swapping radios and the GPS antenna
- Pass/Fail Algorithm
- Using the results of the verification tests, a multiple part algorithm was developed to judge the following:
    - Absolute error of the latitude and longitude position of the verification vehicle relative to a known and surveyed location
    - Relative error of the verify vehicle position as compared to a reference stationary vehicle that broadcasts indefinitely
    - Similarly, absolute and relative elevation errors are calculated and judged for the verify vehicle
    - The Pass/Fail criteria specified that either the absolute or relative errors must be less than the tolerances specified by SAE J2945/1 for position and elevation accuracy in one of two heading orientations

Michigan Traffic Lab/Real-Time Data from the Ann Arbor Connected Environment

The Michigan Traffic Lab (MTL) at UMTRI does more than just support the Mcity traffic control network. Research conducted at the MTL has focused on cyber-physical transportation systems, particularly related to traffic flow monitoring, modeling, control, and testing and evaluation of CAVs. MTL develops and deploys state-of-the-art advanced traffic management systems using connected vehicle data from the Ann Arbor connected environment. Specifically, MTL developed the world’s first connected vehicle-based traffic signal optimization system and deployed the system in multiple cities in China. MTL has also developed a publicly available web portal to monitor and measure near real-time traffic signal performance using the connected vehicle data from the Ann Arbor Connected Environment, as shown in Figure 34.



Live Traffic of Ann Arbor Connected Vehicle Test Environment

Current time: 2021/03/16 14:52:55 Tuesday

Powered by Michigan Traffic Lab and UMTRI

Sponsored by Federal Highway Administration and Mcity

62606176: Green Road/Plymouth Road

Phase ID	No. of Vehs.	Stop Delay(s)	Stop Postion(m)
Phase 1			
Phase 2	9	9.56	13.17
Phase 3	20	60.40	43.36
Phase 4	4	28.25	36.86
Phase 5			
Phase 6	3	10.67	17.35
Phase 7	2	72.50	46.71
Phase 8	4	31.75	17.81

Phase 1	Red
Phase 2	Red
Phase 3	Green
Phase 4	Red
Phase 5	Red
Phase 6	Red
Phase 7	Green
Phase 8	Red

Figure 34: AACVTE Live Traffic Web-based Interface.

MTL also provides an augmented reality (AR) environment for CAV testing, in which movements of testing vehicles and traffic signals in the real world can be synchronized in simulation, while simulated traffic information can be transmitted to testing vehicles' communication system. The augmented reality environment enables real CAVs to interact with simulated background vehicles, which offers realistic traffic environment in a safe environment (Figure 35). To accelerate the testing process of automated vehicles, MTL has developed a naturalistic and adversarial environment (NADE), in which simulated background vehicles will be trained to perform adversarial maneuvers at selected moments to challenge the automated vehicle under test. It is expected that this approach can accelerate the deployment of CAVs. The NADE and AR based test environment is in the process to be implemented in American Center for Mobility this year.

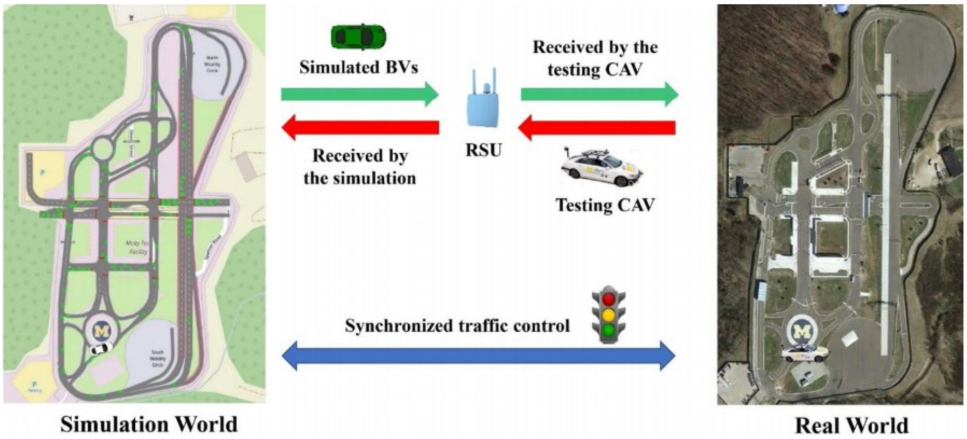


Figure 35: The Augmented Reality Testing Platform.

Research Conducted in AACE or Surrounding Area

Since AACE is an open infrastructure deployment, it is impossible to know exactly how many original equipment manufacturers (OEMs), Tier 1 suppliers and others used the environment to develop and test products. That said, members of the UMTRI-led team have been contacted by individuals and organizations who are doing cybersecurity testing, Signal Phase and Timing (SPaT) and MAP validation, as well as hardware and software solutions to aid in the detection of pedestrians for CAV product development.

Heat Map Project

The heat map project explored the feasibility of conducting on-road testing of two connected vehicle applications, intersection movement assist (IMA) and left turn across path (LTAP), in the AACE. Key findings from the study included that on-road testing of LTAP and IMA applications to ascertain false positive rates is feasible. Furthermore, driving routes can be scaled up to accommodate more test and background vehicles to increase the instances of the application triggering a warning. Lastly, interoperability of OEM and Tier 1 suppliers’ equipment was confirmed in situ.

Longitudinal Degradation of Pavement Marking Detectability for LiDAR Sensing Technology

Recent advancements in vehicle automation and driver assistance systems that detect pavement markings to guide lateral control of CAVs has increased the importance of the detectability of pavement markings through various sensor modalities across weather and road conditions. Among the sensing techniques, LiDAR sensors have become popular for vehicle automation applications because they return accurate distance measurements and can quantify the reflectivity of surroundings for object detection and pavement marking tracking. However, most studies of pavement marking visibility have focused on human or camera-based optical detection. Relatively few studies have investigated marking material performance for LiDAR sensors and none using a range of lane marking materials and conducted longitudinally.

A pavement marking test section on US-23 between exits 45 - 58 was divided into six sections with different marking materials to each section. This was done in close cooperation with MDOT during the planning and construction phases of the US-23 Flex Route. Testing was performed on the US-23 Flex Route, rather than Mcity, because of the very limited amount of traffic in Mcity as compared to actual roadways.

A mid-size sedan was instrumented with a 905-nm LiDAR sensor as well as a high-fidelity camera and a GPS. Data was collected from both the northbound and southbound lanes over a period of 32 months. A total of 210 passes through the Flex Route were analyzed. The LiDAR and GPS data were used to reconstruct 3D point clouds representing the road surface, including the reflectivity at each point. Road surface points were extracted from each test section, and the LiDAR reflectivity data were used to extract lane markings as well as determine the detectability of the marking based on the materials deployed.

Four materials, including HPS-8, polyurea, cold plastic, and sprayable thermoplastic, were analyzed with a variety of marking geometries, color, and wet-reflectivity. Covariates such as measurement angle, weather, time, traffic volume, and surface wetness were examined through in-depth analysis of the LiDAR reflective intensity data. Reflectivity quality was degraded at different rates for the four materials, with the material in recessed surfaces, degrading more slowly than those applied to the top of the roadway surface. The results provide guidance for selecting materials and developing maintenance schedules when marking detectability by LiDAR is a concern. The final report for this project is under MDOT review.

Security Credential Management System 2.0

AACE is a certified environment using a commercial SCMS. To ensure the highest levels of security among communicating connected vehicles, the SCMS must also identify and remove any misbehaving devices – such as vehicles broadcasting inaccurate location information. This project focused on misbehavior detection, incorporating, and testing the following methodologies:

- Proximity overlap – when two vehicles report overlapping positions for an extended period.
- Warning-based – when a warning is issued in a vehicle, but the driver takes no action because the data received was not valid.

The algorithms were developed by leveraging previous federally funded research. Once successful bench testing was completed, several devices were updated and installed on development vehicles. Those vehicles were used to test the misbehavior algorithms first at Mcity and then in AACE. A pilot fleet consisted of about 25 connected vehicles in addition to the development vehicles. All vehicles were driven along a prescribed route in the AACE. At least one vehicle was intentionally sending erroneous BSMs – i.e., misbehaved. The team studied the reaction of the test fleet to vehicles that were misbehaving (true identification) and the reaction of the test fleet to vehicles that are not misbehaving – the pilot fleet (false identification). The final data analyses and final report are pending.

Vehicle-to-Pedestrian (V2P) Warning

AACE was expanded to include equipping four midblock crosswalks along Plymouth Road. Each crosswalk was equipped with a GRIDSMART camera system to detect pedestrians, a Lear DSRC RSU, an Econolite cobalt controller, and connected vehicle co-processor (CV-CP) card. Further, pedestrians who frequently walked along and/or crossed Plymouth Road were recruited to participate in the study by logging their crossings in these four crosswalks. Additionally, some participants downloaded an app on their phones to track these crossings. The RSUs broadcast personal safety messages (PSMs) to aftermarket device (AD)-equipped vehicles within range of the crosswalks whenever a pedestrian was detected by the GRIDSMART system. This project is assessing the technical merits, effectiveness, and benefits of various systems that warn drivers/vehicles about pedestrians in crosswalks. The data analyses and final report are pending. However, the amount of pedestrian crossing data was significantly decreased due to the COVID-19 pandemic and college students not crossing Plymouth Road to/from campus to attend classes.

Clarifications for Consistent Implementation

As more connected signalized intersections are deployed nationwide, there is an increasing desire for these intersections to communicate with on-board applications for transit, emergency, and production vehicle deployments. Connected vehicles should be able to transverse the United States seamlessly, and their onboard applications should work anywhere they go. Specifically SPaT-based applications such as signal priority, signal pre-emption, and red-light violation warning (RLVW) should function the same, regardless of the deploying agency or region. It is understood by deployers that the established standards alone will not ensure open compatibility with production vehicles.

Existing standards often include optional elements or flexibility given the variety of objectives or ways a system may be deployed. In some cases, the optional elements or flexibility may be interpreted differently for different deployments, despite the common objectives and applications of each deployment. These differences can lead to a lack of interoperability that prevents vehicles from using data at connected signalized intersections across different jurisdictions.

Within AACE part of the strategic roadmap is for the RSUs to be tested for conformance to clarifications for consistent implementations (CCIs) to ensure interoperability of connected signalized intersections in AACE. All deficiencies will be documented and shared with stakeholders. The RSUs will be updated, as necessary.

Safe and Efficient Roundabouts by Artificial Intelligence and V2X Technology

This project focuses on improving the safety and efficiency of roundabouts through artificial intelligence (AI) and V2X technology. An infrastructure-based data monitoring and collection solution is proposed to increase the penetration rates at roundabouts by tracking the trajectories of all road users using advanced sensors including GRIDSMART camera, AccuScan radar and FLIR thermal camera. The sensors track and measure the positions and speeds of all road users within the range in real time, including motor vehicles, pedestrians, and bicycles, and generate raw trajectory traces. The roadside processor receives trajectory data from both the RSU and the sensors and perform data fusion. The roadside processor is responsible for generating proxy safety messages and sending to RSU to broadcast. Two types of proxy messages are generated: BSMs for vehicles and PSMs for pedestrians and bicycles. Both message types will follow SAE J2735 standards. Machine learning algorithms are being developed to analyze the naturalistic driving data (NDD) at roundabouts and understand traffic and driver behaviors. Both safety and mobility impacts will be analyzed. An IMA application for roundabouts will be developed and integrate into a real vehicle to send warning messages to the drivers. This system is currently deployed at the intersection of State Street and Ellsworth in Ann Arbor, and is actively collecting data to support machine learning algorithm development.

Real-time Distributed Optimization of Traffic Signal Timing

Leveraging recent advancements in distributed optimization, and the growing connectivity and computational capability of vehicles and infrastructure, this project proposes to revolutionize real-time adaptive signal control via distributed optimization. The proposed research consists of three thrusts. Thrust 1 focuses on advancing distributed optimization and parallel computing techniques for solving network-level signal optimization models with discrete variables, nonconvex/nonlinear objective function and/or constraints. Thrust 2 further distributes the computation task to individual vehicles, by further decomposing distributed intersection-level sub-problems to smaller problems that can be solved at the vehicle level or treating them as fully independent economic agents that negotiate the right-of-way through intersections. In Thrust 3, we conduct simulation to validate our results and deploy the system developed in Thrust 1 in the City of Ann Arbor.

Lessons Learned Deploying Connected Vehicle Equipment in the AACE

Limits on Equipment Providers and Long-Term Support of Products

The RSUs currently deployed in Ann Arbor are operational but require continual intervention to keep them in that state, such as checking the memory and wiping the logs if too full. The device supplier (Lear) no longer supports the units. The team worked with Lear to get a final release that would fix some of the issues to maximize up time of the RSUs, and they agreed to support the rollout of the release. However, when rolled out it was found that the release had unstable Internet Protocol Version 6 (IPv6) communication. Without IPv6, the RSU cannot get new security certificates every two weeks and will quit broadcasting SPaT and MAP. The RSUs will also generate and log so many error messages that the memory fills up and the unit stops working. When it gets in that state, the RSU must be accessed onsite to reset the device. Lear would not fix the issue, so we are back to a previous release which requires a significant maintenance effort.

Changing Infrastructure Equipment and Requirements

Currently, the UMTRI team is planning to deploy C-V2X. These new devices will be first generation cellular. Three rounds of interoperability testing are planned, plus RSU burn-in testing, and a very slow ramp up for deployment.

The AACE team meets with each supplier every two weeks to prepare for testing, track issues, and discuss pre- and post-deployment issues as appropriate. The aim is that these meetings will taper off once we have deployed. However, this is not always the case. In the AACVTE program, the supplier meetings tapered off and eventually stopped with the OBU suppliers but continued indefinitely with the RSU suppliers.

Changes in Protocol Standards (2016 update) and Push for New Protocols (C-V2X)

When the SPMD program was complete, lessons learned were incorporated into the industry standards. A new RSU 4.1 standard was developed. The IEEE 1609.x standards were revised. The SAE J2735 standard was revised. A new standard was developed for the SCMS. Lastly, a new set of test standards were created, namely, SAE J2945/x. This standard set is commonly referred to as the 2016 standard set, even though most were not finished until well into 2017.

When the process started during the AACVTE project, our assumptions were that we could reuse the existing devices (OBUs and RSUs) and merely update them to be compliant with the 2016 standard set. However, that was not the case. In the new standard set the devices were required to have a hardware security module (HSM), and the existing RSU and OBU devices could not be retrofitted to include it. Together, these changes rendered all the SPMD-era devices unusable. As a result, UMTRI had to decommission, and replace, all 2800 OBUs and 25 RSUs.

Now the test environment faces an update yet again. With a recent Federal Communications Commission (FCC) ruling, in one year the deployed equipment will only be able to broadcast DSRC on one channel – 180. Currently, we use all the channels in AACE. To be compliant, we will need to update 2500 OBUs and 75 RSUs. Furthermore, in two years, we will not be able to broadcast DSRC at all – if the recent FCC ruling stands. At that point, we will need to have all our DSRC OBUs and RSUs decommissioned and replaced potentially with C-V2X devices.

For C-V2X, the current state of the industry is much like it was for DSRC 10 years ago. Most suppliers have a prototype device, but not something that is ready for a large-scale deployment. Furthermore, there are planned changes to the C-V2X specification. The first release of C-V2X services was defined during Release 14 and was completed in early 2017. Additional enhancements were introduced in Release 15. A 5G New Radio (NR) was defined by 3rd Generation Partnership Project (3GPP) during Release 15. A 5G NR based C-V2X was defined in Release 16. This standard was completed in June 2020. 3GPP continues to evolve the technology during Release 17, which is currently ongoing. Unfortunately, the NR is not backwards compatible. The best-case scenario is that the applications that we are testing today with the release 15 C-V2X radio will remain as is, and new applications for CAVs will be done with the NR. Both would be required for a full CAV solution. In that scenario, deployment would go from one radio to two installations per vehicle or infrastructure location.

Summary

The recognized need for a facility such as Mcity resulted from various rounds of equipment testing and validation that were needed for the Connected Vehicle SPMD program. Prior to the opening of Mcity, UM and its many partners lacked a safe environment in which to develop various CAV components that included interaction with real-world types of infrastructure. A type of infrastructure of particular interest at Mcity is a traffic control network with connected vehicle capabilities. Therefore, one could say Mcity grew out of necessity; but it has also spawned enormous amounts of invention. This has been true for all test facility users. Since construction completion, the test track has supported research and development by vehicle manufactures, Tier 1 suppliers, start-up companies, and various educational applications. As a facility, open to any party wishing to test there, Mcity provides a service to any CAV developers.

An investment on the part of the UM and MDOT, multiple measures of success and its value are demonstrated by how Mcity has become world-renowned, digitally modelled in numerous software applications, copied in numerous other locations, and has spawned countless research projects that could otherwise not be conducted in a real-world environment due to safety or security concerns. Both the Mcity test facility and the current AACE build off each other and complement one another.

The testing and research performed at Mcity has supported multiple USDOT sponsored programs, and the data from the connected environment, which had been proven out in Mcity, has been used by hundreds of researchers interested in understanding travel behavior, modeling traffic control networks, and evaluating CAV applications. Nearly eight years since its inception, and 6 years since opening, Mcity remains a highly sought after and utilized facility that supports the broader CAV development community.