MnDOT Autonomous Bus Pilot Project

Testing and Demonstration Summary | June 2018

DEPARTMENT OF TRANSPORTATION

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Project Partners: 3M First Transit

COLORADO Department of Transportation

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To better prepare for the operations of an automated shuttle bus in mixed general traffic and in Minnesota cold weather climate conditions, MnDOT is conducting an Autonomous Bus Pilot project. The purpose of the proposed Minnesota Autonomous Bus Pilot project is to define an automated vehicle pilot and solicit technology partners to come to Minnesota to work with the stakeholders in safely demonstrating the technology.

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MnDOT Autonomous Bus Pilot Project Testing and Demonstration Summary

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- MnDOT for its leadership and participation in the testing and demonstrations of the Autonomous Bus Pilot project.
- CDOT for their partnership and financial contributions.
- MnROAD staff for providing guidance and assistance in supporting the testing and demonstration of the automated shuttle bus at the MnROAD facility during the Fall 2017 / Winter 2018 period.
- EasyMile staff for providing technical assistance throughout the testing and demonstration period in the operation of the automated shuttle bus selected for the project.
- First Transit staff for providing technical assistance in staffing and operating the automated shuttle bus during the project’s testing, demonstration, and public tours.
- City of Minneapolis and Hennepin County for providing guidance and oversight of the automated shuttle bus demonstration on Nicollet Mall during the Super Bowl LII week of festivities in January 2018.
- 3M for providing technical assistance, vehicle wrapping, demonstration support, and connected vehicle technology.

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EXECUTIVE SUMMARY

The Minnesota Department of Transportation (MnDOT) authorized testing and demonstration of an automated vehicle (AV) in February of 2017. MnDOT's research into previous AV efforts in other states indicated that testing had not been completed in winter weather conditions. MnDOT also wanted to address the lack of exposure to the AV technology within the state, while increasing Minnesota's influence in AV development nationally. The testing and demonstration goals included the following:

1. Identify the challenges of operating automated vehicle technologies in snow/ice conditions and test potential solutions through field testing.
2. Identify the challenges and strategies of having third parties safely operate automated vehicles on the MnDOT transportation system.
3. Identify infrastructure gaps and solutions to safely operate automated vehicles on the MnDOT transportation system.
4. Prepare transit for improving mobility services through automated vehicles.
5. Increase Minnesota's influence and visibility on advancing automated & connected vehicles.
6. Enhance partnerships between government and industry to advance automated & connected vehicles in Minnesota.
7. Provide opportunities for public demonstrations of automated vehicles and obtain public feedback.

MnDOT tested an automated shuttle bus supplied by EasyMile at the MnROAD facility in December 2017 and January 2018 under the direction of MnDOT staff with support from project consultants. The testing methodology can be found in Chapter 2. Public tours and demonstrations of the automated shuttle bus were held for select transportation professionals in December 2017 and January 2018 at MnROAD. This was followed by public demonstrations of the automated shuttle bus between January 24th and January 28th in conjunction with community activities that preceded Super Bowl LII in Minneapolis, Minnesota. Five additional demonstrations were held between February and April of 2018 at 3M, the City of Rochester, the University of Minnesota, Hennepin County, and Bismarck, North Dakota. The overview of these additional demonstrations can be found in Chapter 5.7.

Figure ES-1 Automated Shuttle Bus Operation at MnROAD Facility

The results of the automated shuttle bus testing at MnROAD can be found in Chapter 3. The findings of the winter weather testing indicated that

- The automated shuttle bus operated well under dry pavement conditions with no precipitation. The vehicle kept a safe operating distance from other vehicles, pedestrians, bicycles and other roadway obstructions on the track, performing slowdowns and stops as needed. Daytime and nighttime light conditions did not impact the shuttle performance.
- Falling snow, blowing snow, or loose snow on the track was often detected as obstructions by vehicle sensors, causing the vehicle to slow down or stop to avoid a collision.
- Snow banks alongside the vehicle routes caused issues with pre-programmed paths. Snow banks had to be removed at the Minnesota Capitol demonstration and the Hennepin County demonstration was delayed a week from plan to allow the snow banks to melt.
- At times, compacted snow and patches of ice or slush on the track caused the wheels to slip, which in turn created issues with the bus not responding to its exact location on the track.
- Salt spray from treated sections of roadway that collected on the vehicle sensors did not appear to significantly degrade performance. While some minor anomalies were observed, the reason could not be confirmed. Cleaning dirt accumulation from the sensors due to normal operations appeared to improve the automated shuttle bus performance.
- Because of the rural nature of the MnROAD site, the vehicle required installation of localization infrastructure. Signs posts were installed approximately every 100 feet around the test loop.
- As the core temperature of the battery dropped significantly, automated shuttle bus operations were negatively impacted. Charging times during colder temperatures increased compared to charging times during warmer temperatures.

Based on survey data taken during the Super Bowl demonstration in downtown Minneapolis, public opinion was favorable towards the Minnesota Autonomous Bus Pilot project. Over 1,300 participants rode the automated shuttle bus on Nicollet Mall from January 24th to January 28th, 2018. Public concerns focused on vehicle safety and security of the automated shuttle bus operating system. Full details of the public demonstration can be found in Chapter 5. Statewide, a total of 3100 participants rode the automated shuttle bus at public demonstrations including the Super Bowl, State Capitol, 3M, the University of Minnesota, Hennepin County, and the City of Rochester.

The Autonomous Shuttle Bus testing and demonstrations was a good first step in understanding the impacts of Minnesota's winter climate on automated technology. Future steps for Minnesota's AV program will likely focus on the following:

1. Continue to test and assess how AV technology works in winter weather conditions.
2. Continue to grow partnerships with vendors of AV technology.
3. Work with transit partners to find opportunities to use AV technology to enhance transit services, including full size buses.
4. Work with persons with disabilities on how AV technology can improve mobility.

CHAPTER 1: INTRODUCTION

This chapter briefly describes the Minnesota Autonomous Bus Pilot Demonstration overview and purpose.

1.1 Project Overview and Purpose

MnDOT and the statewide Minnesota stakeholder agencies procured an automated vehicle and provided a testing and demonstration environment for the fast-emerging technology area of automated vehicles. The testing and demonstrations conducted by the project team furthered Minnesota's Autonomous Bus Pilot project goals listed in section 1.2.

Minnesota cold and snowy winter weather conditions create several unique challenges for automated vehicle operations. To better understand operations of an automated shuttle bus in in Minnesota winter weather conditions, MnDOT conducted an Autonomous Bus Pilot project. A key outcome of this project was to work with an automated vehicle technology vendor to demonstrate the automated technology and identify roadway infrastructure improvements necessary to operate an automated technology in Minnesota winter weather conditions. Three phases of this project included:

1. MnROAD Testing – This phase provided a controlled environment in which to test the automated shuttle in a variety of winter weather conditions.
2. Downtown Minneapolis Demonstration – This phase allowed the key stakeholders and public to ride the automated shuttle and give feedback on their experience.
3. Additional Demonstrations – This phase allowed a wider variety of stakeholders to ride the automated shuttle and demonstrate its capabilities in a variety of environments.

This report describes the observations made by project staff during the demonstration of the vehicle's operation at the MnROAD facility near Albertville, Minnesota. It also summarizes details from stakeholder tours conducted at MnROAD and the Super Bowl showcase conducted in Minneapolis, Minnesota.

1.2 Project Goals

Autonomous Bus Pilot project efforts include the following project goals that have been discussed with MnDOT project team members:

1. Identify the challenges of operating automated vehicle technologies in snow/ice conditions and test potential solutions through field testing.
2. Identify the challenges and strategies of having third parties safely operate automated vehicles on the MnDOT transportation system.
3. Identify infrastructure gaps and solutions to safely operate automated vehicles on the MnDOT transportation system.
4. Prepare transit for improving mobility services through automated vehicles.
5. Increase Minnesota's influence and visibility on advancing automated & connected vehicles.

6. Enhance partnerships between government and industry to advance automated & connected vehicles in Minnesota.
7. Provide opportunities for public demonstrations of automated vehicles and obtain public feedback.

1.3 Demonstration Scope

The demonstration of the automated shuttle bus was conducted by EasyMile, the vendor chosen by MnDOT, and oversight of the demonstration was performed by WSB and AECOM staff.

In September 2017, WSB and AECOM prepared and shared a demonstration plan with EasyMile for review and comment. The demonstration plan outlined various operational scenarios and described automated shuttle bus behaviors that WSB and AECOM staff planned to observe in various weather conditions at various times of the day. Previous documentation prepared for MnDOT for further details.

The demonstration plan guided initial discussions between the EasyMile project team and WSB and AECOM staff on how the automated shuttle bus would be tested and demonstrated at the MnROAD facility.

1.4 Project Staff and Demonstration Participants

Several project team partners participated in the automated shuttle bus demonstrations. A list of agencies and associated responsibilities is summarized in Table 1-1 below.

Table 1-1 Agencies and Responsibilities in Automated Shuttle Bus Demonstrations

Agency	Responsibilities
MnDOT	Lead Public Agency • Provided overall project management and direction to all team members • Provided testing facilities at MnROAD for the demonstration • Communicated project activities with media and the general public
EasyMile	• Provided the automated shuttle bus for demonstrations • Coordinated with MnDOT on the delivery and operation of the automated shuttle bus • Provided operations and maintenance troubleshooting to address issues discovered during the demonstration
First Transit	• Operated the automated shuttle bus for demonstrations • Provided staff trained on the technical operation of the automated shuttle bus • Managed the operation of the automated shuttle bus at all demonstrations
3M	• Partnered with MnDOT on the automated shuttle bus demonstrations

	• Coordinated with EasyMile on delivery of the automated shuttle bus to the 3M campus for custom vehicle wrap • Coordinated with the project team during stakeholder tours and demonstrations • Provided Minneapolis demonstration support • Provided connected vehicle demonstration technology
WSB and AECOM	Project Consultants for the automated shuttle bus demonstration • Coordinated weekly meetings with all project team members • Provided oversight of all demonstration-related activities and stakeholder tours

CHAPTER 2: METHODOLOGY

This chapter briefly describes the methodology followed by agencies involved in the demonstration.

2.1 **Demonstration Site**

Demonstration and observations of the automated shuttle bus operations occurred on a portion of the 2.5 mile closed low volume loop at MnROAD. The total track distance utilized for testing was 4,370 ft. (0.83 miles) as shown in Figure 2-1. The preprogrammed route established for the automated shuttle bus allowed for movement in a counter-clockwise direction utilizing the right travel lane. The test track consisted of pavement, except for a short gravel crossover path located on the northwest end of the track between the programmed Intersection Stop and Platform Stop.

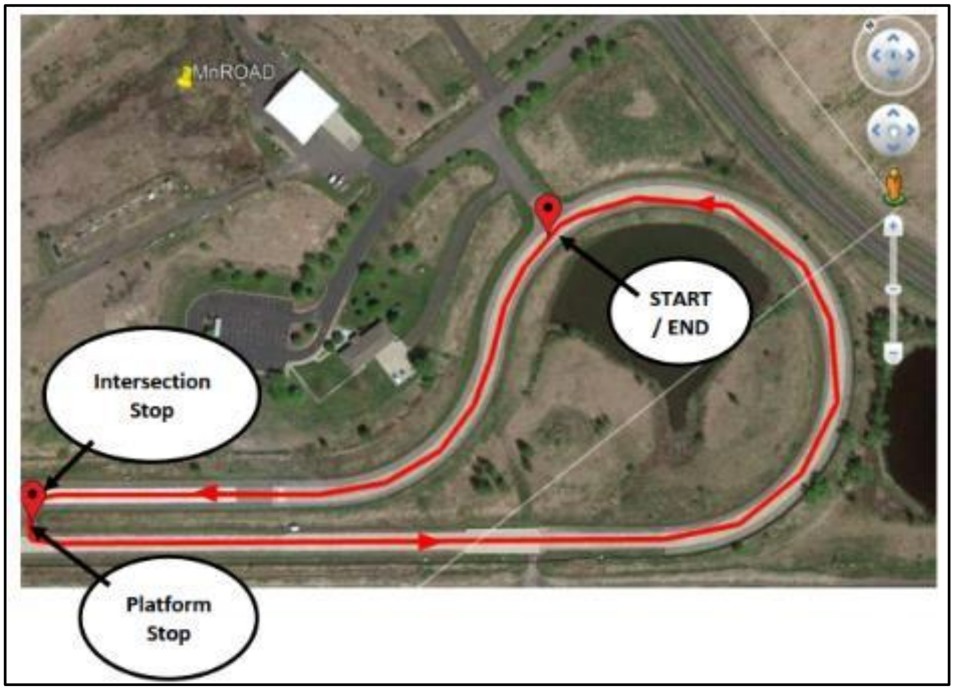


Figure 2-1 MnROAD Automated Shuttle Bus Test Track

The test track required vertical sign posts spaced every 100 feet, along with small blank sign panels placed on the sign posts every 700 to 800 feet. This was necessary to enhance the automated shuttle bus route localization in an environment that lacks buildings, trees, and other vertical infrastructure along the test track. Previous identified infrastructure typically serves as landmarks detected by the vehicle sensors. Orange cones were placed adjacent to the MnROAD pond as safety indicators for the automated vehicle's sensors to mitigate the risk of the automated vehicle going off course into the pond. Figure 2-2 below presents the infrastructure installed.

Figure 2-2 MnROAD Infrastructure for Automated Shuttle Bus Demonstration

A preprogrammed route was created for stakeholder demonstrations. Stakeholders loaded the shuttle bus at the MnROAD facility main entrance, rode the bus along the route to a programmed stop at the rear of the building, and then returned to the main entrance to end their tour. The route included programmed stop locations and is shown in Figure 2-3.

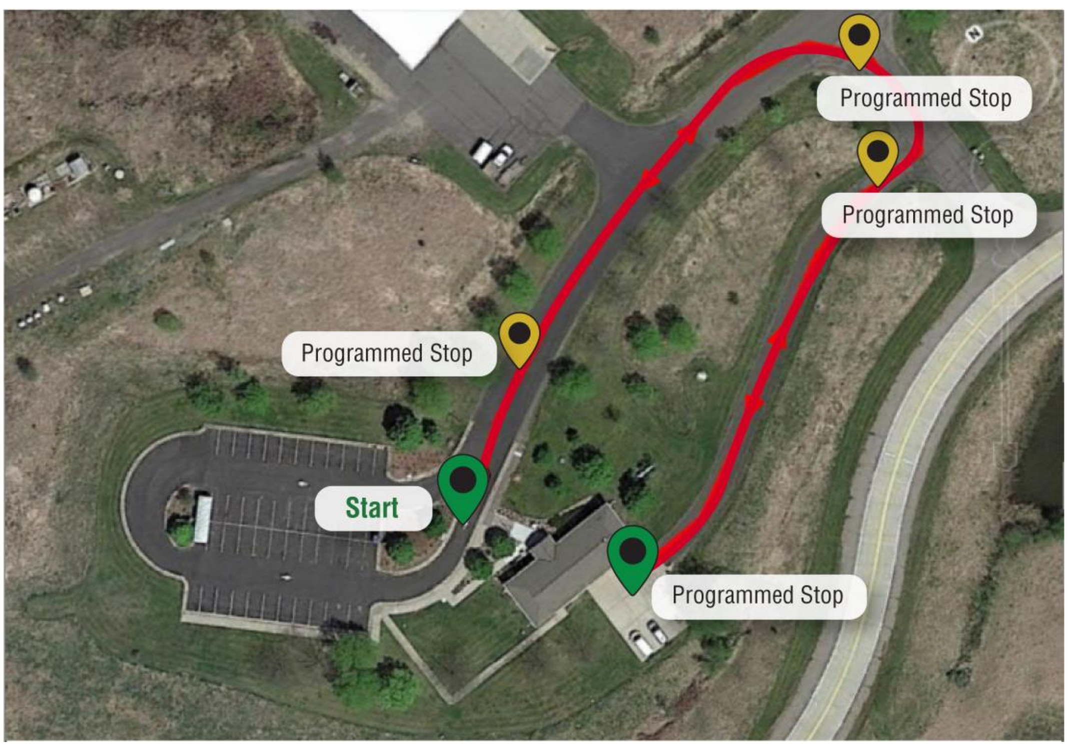


Figure 2-3 MnROAD Route Diagram for Automated Shuttle Bus Stakeholder Tour

The automated shuttle bus required climate controlled storage with a minimum entrance height of 9.2 feet and charging facilities. MnROAD provided garage space adequate for storage and maintenance activities needed throughout the testing period as well as charging of the internal batteries.

2.2 **Automated Shuttle Bus**

The automated shuttle bus provided by EasyMile was the EZ10 model. This is shown in Figure 2-4 below. The vehicle is a driverless, electric shuttle bus (13.13 feet long) that can transport up to 12 people (six people seated, six people standing) but could be equipped with different seating allowing up to 15 people to be transported. It also includes an accessibility ramp for passengers with reduced mobility. The EZ10 has no steering wheel or brake pedal and navigates autonomously using pre-mapped routes. It has a maximum speed of 25 miles per hour, but the typical operating speed is 12 to 15 miles per hour. For the MnROAD demonstration route, variable speed settings were utilized, depending on the test scenario ranging from about 2 to 11 miles per hour. The vehicle has a Society of Automotive Engineers (SAE) Level 4 autonomy classification.

The EZ10 is equipped with high-accuracy GPS and eight separate LIDAR sensors. The LIDAR sensors include four 270-degree single-layer sensors mounted at each lower corner of the vehicle. There are two sixteen-layer sensors, one in the front and one in the back of the vehicle, designed to detect an obstacle in a cone-shaped zone in the front and back of the vehicle. Also, two 180-degree roof-mounted sensors are designed to detect landmarks in the surrounding environment for localization. See Figure 2-4. The localization system includes the GPS, LIDAR sensors, odometry and inertial measurement unit allowing the automated shuttle bus to operate accurately on the pre-programmed route. The EZ10 was equipped with four-wheel drive, winter tires, and an interior heater.

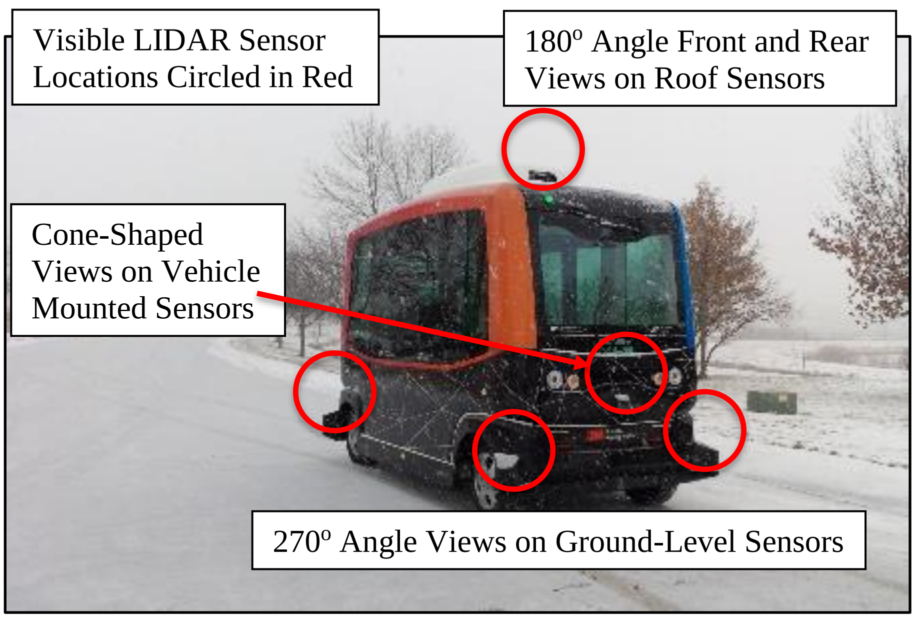


Figure 2-4 EasyMile EZ10 Full Electric Automated Shuttle Bus

2.3 Demonstration Procedures

The demonstration plan included conducting observations of the automated shuttle bus performance by introducing test case scenario variables in a variety of weather conditions. Many of the scenarios were an attempt to replicate the performance of the automated shuttle bus in a low-speed, low-volume public roadway environment. The conditions and variables are presented in Table 2-1 below.

Table 2-1 Types of Demonstration Observations	
Weather Conditions	**Variables**
Clear Weather / Bare Pavement	Automated Shuttle Bus Only
Uncontrolled Winter Weather	Obstacles (Work Zone Barrel)
Controlled Winter Weather	Other Cars, Pedestrians, Bicycles

Prior to vehicle testing, WSB and AECOM prepared a set of bus operator procedures. These procedures were prepared for the First Transit staff who operated the vehicle and conducted test scenarios. The procedures were derived from the operational scenarios included in the demonstration plan. An example of the procedures is shown in Figure 2-5 below.

Bus Operator Procedures		
Scenario:	3.1.1 Clear Weather Operational Scenario 1 – Operation with no vehicles / bicyclists / pedestrians	
Date: Day 1	Start: 2:00pm (Shift 1) / 5:30pm (Shift 2)	End: 2:45pm (Shift 1) / 6:15pm (Shift 2)
Test Purpose:		
Observe autonomous bus operations in closed environment.		
Test Description		
The autonomous bus will Travel up to 15 MPH and operate autonomously by driving in both directions within each lane of traffic around a portion of the 2.5-mile track. An operator will be present in the vehicle at all times ready to assume control of the vehicle as needed, and to confirm the autonomous operation of the vehicle. The operator will confirm acceptable operations prior to proceeding to other operational scenarios on the track.		
Demonstration		
Set origin and destination points along track for scheduling short trips. Travel up to 15 MPH on straight segments in both directions around the loop. Allow operator to take control of bus and turn control over to the bus as needed. Operate in dry pavement/clear weather conditions. Demonstrate the following behavioral competencies:		
#	Requirement	
1	Detect and Respond to Static Obstacles in the Path of the Bus (Staff Person A / B)	
2	Perform Vehicle Stops at Designated Stations (Vehicle Operator)	
3	Perform Wheelchair Ramp Deployment (Vehicle Operator)	
4	Navigate Intersections and Perform Turns (Vehicle Operator)	
5	Bus localization, lane keeping and path trajectory (Vehicle Operator)	

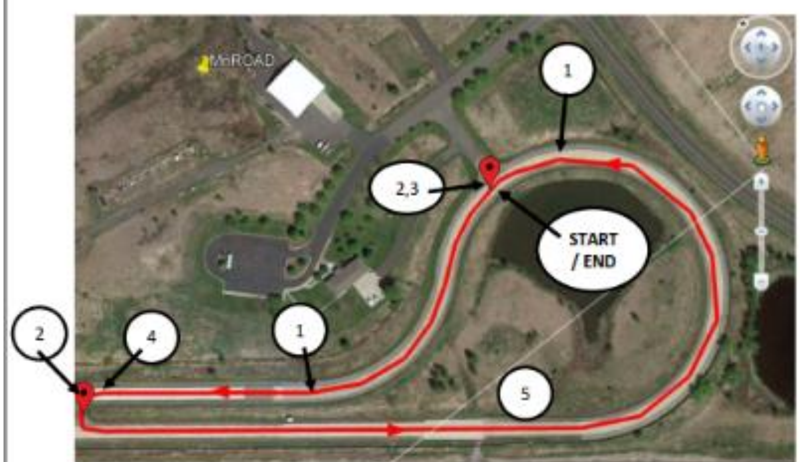


Figure 2-53 Sample of Bus Operator Procedures for Demonstration

2.4 Testing Observations

WSB and AECOM project staff followed the testing and demonstration procedures with project team members at the MnROAD facility in December 2017 As WSB and AECOM staff members made initial observations while following the procedures, they determined that it would be beneficial to digitally record many of the numerical observations, such as temperature, wind, and time of day among other measures for future analysis. A Google Forms survey application was created to record the observations for review in a separate worksheet. Table 2-2 below shows the types of observations recorded by WSB and AECOM staff.

Table 2-2 Types of Observations Recorded During Vehicle Demonstration		
Testing Notes	**Vehicle Events**	**Weather Details**
Time of Day	Sensor Activated Slow	General Observations
Date	Emergency Stop	Temperature
Person Completing Form	Intersection Stop	Feel Like Temperature
Lap Number	Manually drove vehicle	Wind
Testing Scenario	Battery charging issue	Dew Point
Start Time	Planned Start	Pressure
End Time	Planned End	Sky Conditions
Battery Temperature (in Celsius)	Planned Obstacle (i.e. vehicle, bicyclist, pedestrian, barrel, etc.)	Precipitation
Battery Charge Level	Planned stop	Humidity
Heater On/Off	Platform Stop	Weather Source
Lights On/Off	Other events	Visibility

Digitally recording observations allowed for timestamps to be recorded of instances where the automated shuttle bus stopped moving due to obstructions that the vehicle sensors identified. Timestamps were recorded for the beginning and ending of many vehicle events, as noted in Table 2-2 and for the start and end times of conducted test laps. WSB and AECOM project staff also manually recorded the locations of sensor-activated slowdowns or emergency stops on pre-printed route maps and could upload photos of the maps or other photos to the Google Forms application.

CHAPTER 3: RESULTS

This chapter describes the results observed by WSB and AECOM during testing at MnROAD.

3.1 Testing Dates

Testing at MnROAD was conducted on the dates and under the general types of conditions described in Table 3-1. Testing began on December 1st, 2017 and ended on January 12th, 2018. During this time, vehicle tests were conducted at various times of the day in a variety of weather, temperature, and pavement conditions as noted in Table 3-1. A more detailed summary of conditions, testing, and observations for each test day is provided in Appendix A of this report.

Table 3-1 Types of Weather Conditions and Pavement Coverage During Testing

Day	Time of Day	Temps / Sky Conditions	Pavement Conditions
12/11/17	Morning / Day	Low 30s (feels like 25) / Cloudy	1" Snow on Pavement
12/18/17	Afternoon / Night	36 (feels like 30) / Cloudy	Mostly Bare Pavement
1/2/18	Afternoon / Night	13 (feels like -3) / Light Snow, Cloudy	Compacted Snow / Ice Patches
1/3/18	Afternoon / Night	-3 (feels like -14) / Mostly Clear	Compacted Snow / Ice Patches / Loose Snow
1/4/18	Morning / Day	-4 (feels like -4) / Mostly Cloudy	Pavement Plowed
1/5/18	Morning / Day	-13 (feels like -23) / Sunny	Compacted Snow
1/8/18	Day	22 (feels like 14) / Cloud & Sun	Snow Making
1/9/18	Morning / Day	40 (feels like 33) / Sunny	Road Salt
1/10/18	Afternoon / Night	37 (feels like 30) / Misty Rain & Fog	Bare Pavement
1/11/18	Afternoon / Night	6 (feels like -10) / Wind Gusts 30	Bare / Snow Drifts
1/12/18	Day	- 9 (feels like - 24) / Sunny	Snow Making

3.2 Testing Time Periods

Tests at MnROAD were conducted during morning, mid-day, and night-time periods as shown in Figure 3-1. The background shading on the Time of Day Testing Performed graph reflects periods of sunlight observed during the testing period.

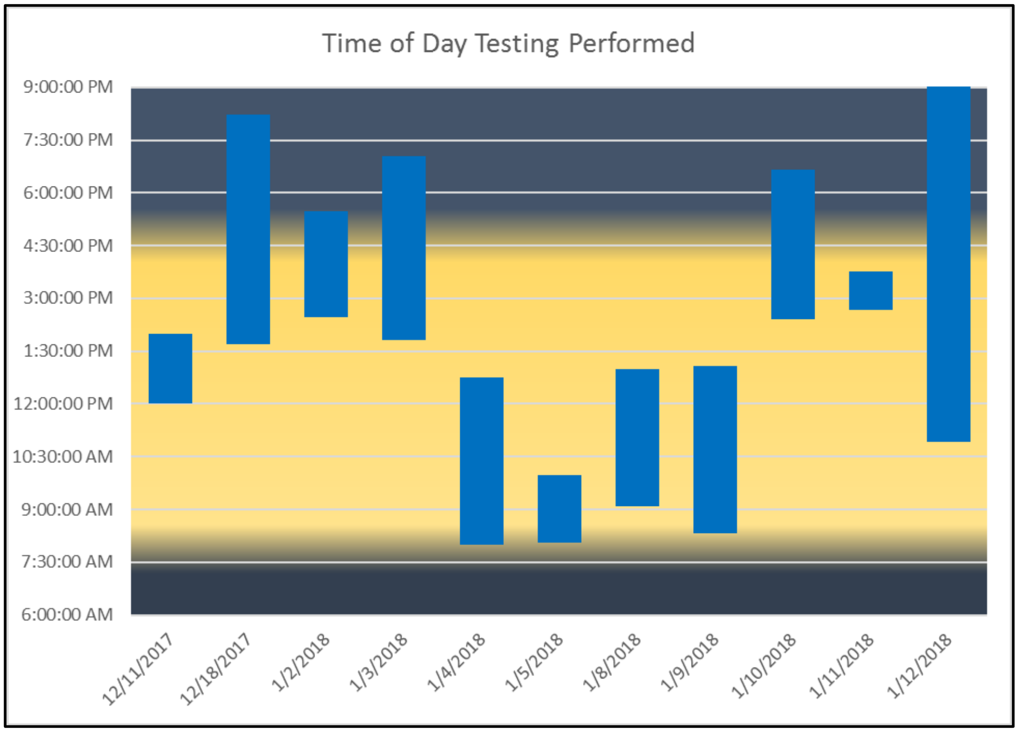


Figure 3-1 Time of Day Testing Performed at MnROAD Facility

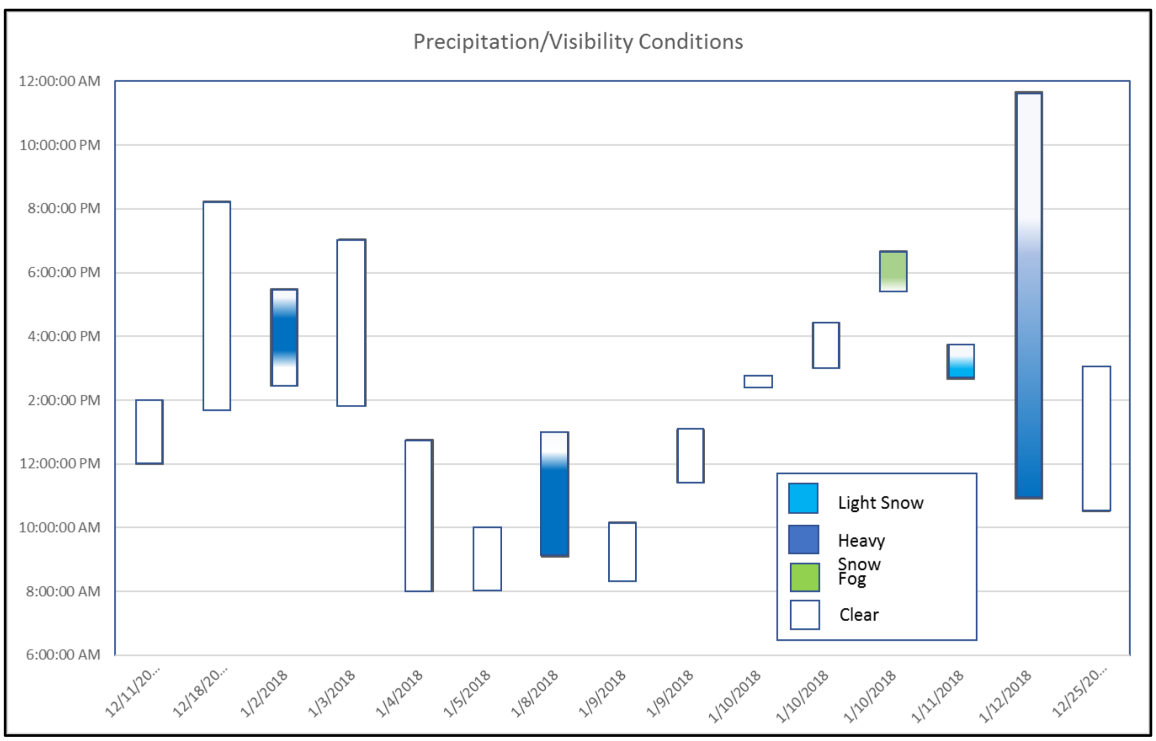


Figure 3-2 Weather Condition Summary for MnROAD Facility

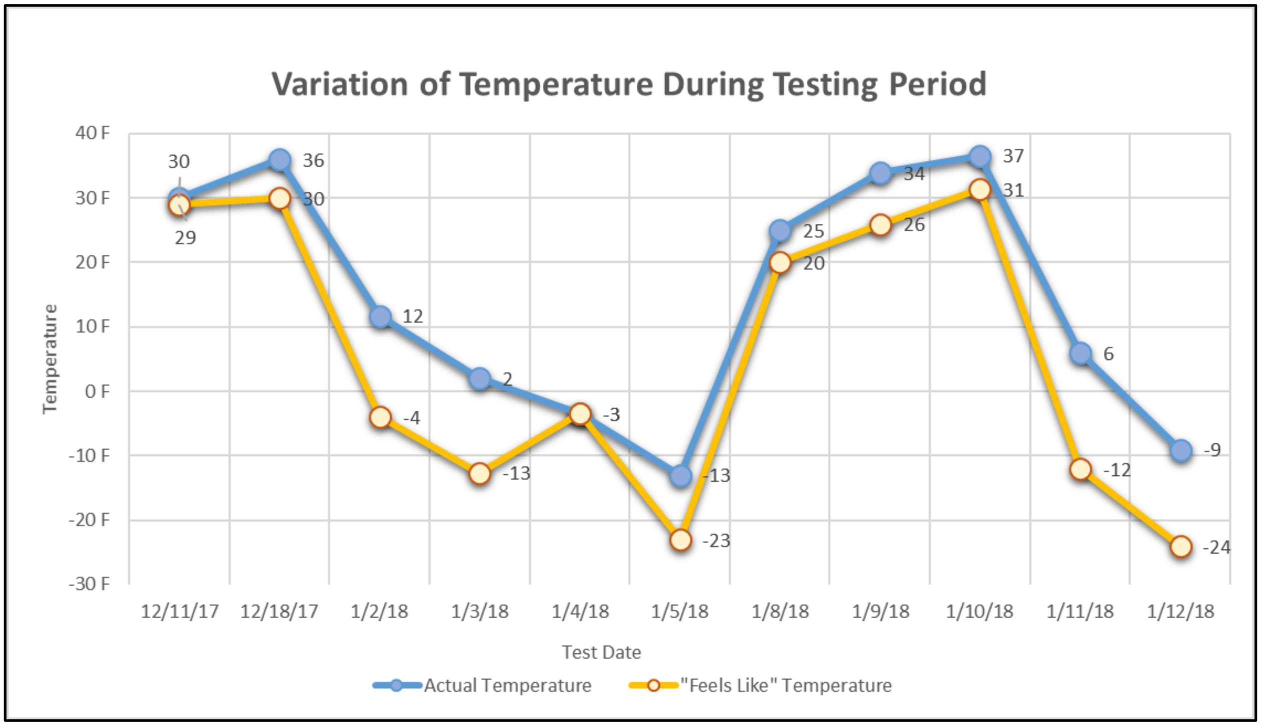


Figure 3-3 Temperature Condition Summary for MnROAD Facility

Testing speeds of the automated shuttle bus ranged from approximately 2 to 11 miles per hour, depending on the testing scenario and conditions. A summary of automated shuttle bus testing speeds is presented below.

Table 3-2 Automated Shuttle Bus Testing Speeds

Top Testing Speed	Top Testing Speed	Top Testing Speed
18 KPH = 11.2 MPH	14 – 17 KPH (8.7 – 10.6 MPH)	1 MPS = 2.2 MPH 2 MPS = 4.5 MPH 3 MPS = 6.7 MPH 4 MPS = 8.9 MPH 5 MPS = 11.2 MPH

3.3 Testing Conditions and Variables

WSB and AECOM performed tests using a mix of variables in several types of weather and pavement conditions, generally summarized in Table 3-3. Clear, foggy, light snow, and heavy snow conditions were encountered during the 11 days of testing. Figure 3-4 illustrates the weather conditions encountered on each of the testing days. Figure 3-5 illustrates the temperature conditions and wind chills.

Table 3-3 Types of Testing Conditions and Variables		
Clear / Dry / Mild Weather	Winter / Cold Weather	Snow / Rain / Fog
Loose / Compacted Snow	Slush / Ice / Road Salt	Bare Pavement
Varying Visibility	Various Lighting	Obstacles
On-coming Vehicles	Slow / Stopped Vehicles	Car-in-Front / Following
Intersection Turns	Stop / Yield Signs	Varying Speeds
Pedestrians	Bicycles	Right-of-Way Decisions
Parking	Transit Stops	Pick-up / Drop-off Passengers

3.4 Observation Summary

A summary of general demonstration observations is presented on the following pages for the vehicle testing at MnROAD. Additional information and graphs derived from collected data are included in Appendix A of this report.

3.4.1 Clear Weather / Bare Pavement

The automated shuttle bus performed well in periods of clear weather and bare pavement as shown in Figure 3-4. Observations confirmed optimal route localization and ability to accurately navigate stops, starts, turns, curves, and intersections. The automated shuttle bus interacted well and as expected when introducing test scenarios with other cars, pedestrians, bicycles and obstructions. Some sensor activated slowdowns and emergency stops occurred due to the detection of blowing dust, weeds or snow from the shoulder area.

Figure* 3-4 *Clear Weather / Bare Pavement Conditions

3.4.2 Light Snow Conditions

Observations conducted during a period of calm winds, low 30^{o} F temperatures, and after a light one-inch snow fall that covered the entire test track showed similar automated shuttle bus navigation performance as was seen with bare pavement. Some sensor activated slowdowns and emergency stops occurred due to the detection of blowing snow or snow kicked up from the tires.

Obstruction testing with a work zone barrel showed similar results as seen during bare pavement. Figure 3-5 illustrates the light snow conditions.

Figure* 3-5 *Testing During One Inch of Snow

3.4.3 More Severe Snow Conditions

Falling, blowing, or loose snow on the track (shown in Figure 3-6) was often detected as obstructions by vehicle sensors causing sensor activated slowdowns or emergency stops to avoid perceived collisions. The number of emergency stops was generally lower when no snow was present on the roadway such as after snow plowing and when there was no blowing snow present.

Figure* 3-6 *Snow / Blowing Snow Conditions

3.4.4 Rain and Fog Conditions

A night test was conducted when the temperature was above freezing (32^{o} F) but with a light fog and misty rain turning to snow. Those mild and wet conditions, as shown in Figure 3-7, did not appear to impact the vehicle's performance.

Figure* 3-7 *Light Misty Rain / Edge of Snow

3.4.5 Controlled Snowmaking Conditions

Arrangements were made for the use of two snowmaking systems that allowed for controlled testing on two separate days: one with mild temperatures near freezing and one bitterly cold day with -20^{o} F wind chills. Figure 3-8 contains images of testing on these days. Snowmaking machines provided varying pavement conditions on over 500 feet of test track. The warmer day allowed for the creation of up to four inches of slush on a small segment of the roadway and the bitterly cold day provided a range of accumulated snow amounts, from a trace to six inches in one area.

A key finding from the controlled testing found that the automated shuttle bus performed sensor activated slowdowns stops when trying to navigate through the manmade falling/blowing snow, but it was able to recover its automated function and proceed on the route once the snowmaking blower was turned off and the snow settled from the air. Performance in the varying pavement conditions is included in the section below. Figure 3-8 below shows the automated shuttle bus in controlled snowmaking and various pavement conditions.

Figure 3-8 Controlled Snowmaking Conditions

3.4.6 Varying Pavement Conditions

The automated shuttle bus performed well on both uncontrolled and controlled pavement conditions; however, falling snow, compacted snow, and patches of ice or slush on the track led to wheel slippage. Figure 3-9 shows images of testing on these days.

Slippage occurred more frequently at higher speeds and during variable speeds when the vehicle was near obstacles, following other cars, and maneuvering at some stops. These conditions caused the automated shuttle bus to lose track of its exact location on the track, leading to sensor-activated slowdowns or emergency stops and disengagement of the automated mode due to localization issues.

Figure 3-9 Ice, Snow, and Slush Pavement Conditions

3.4.7 Varying Environmental Conditions

The vehicle's operational performance did not appear to be impacted by varying lighting conditions (morning, day, evening or night), by temperature conditions that varied from -20^{o} F (wind chill) to 40 ^{o}F or by varying wind conditions as shown in Figure 3-10.

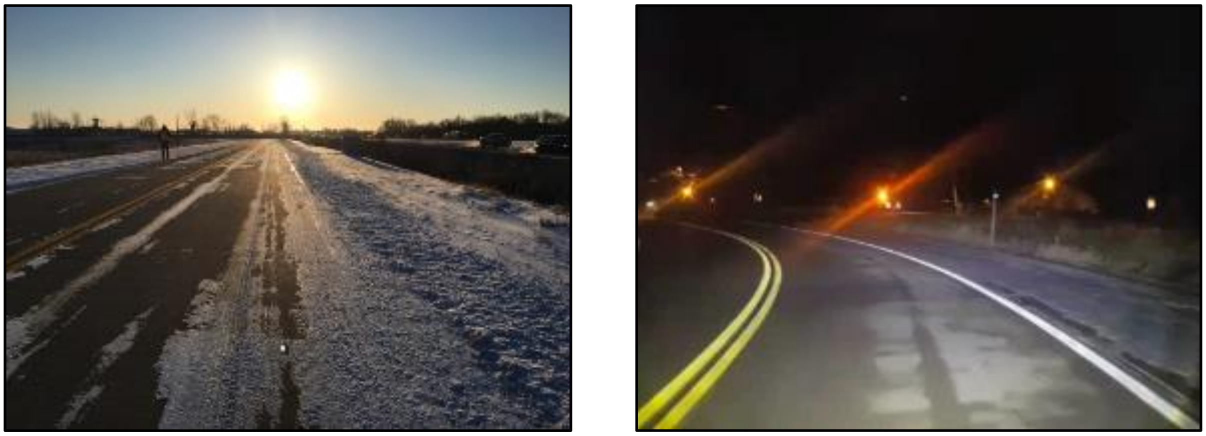


Figure 3-10 Varying Lighting Conditions During Sunset and Night

3.4.8 Interaction with Obstructions

Test scenarios included the automated shuttle bus interaction with roadway obstructions by positioning work zone barrels at various locations, including the edge line, center line, and center of the travel lane. Observations were made during day and night while operating the automated shuttle bus at varying speeds to determine the following: 1) stop distances from automated shuttle bus to obstruction in center of lane, and 2) distances off the wheel path where the obstruction would slow or stop the automated shuttle bus. There was consistent observed interaction and the automated shuttle bus performed controlled slowdowns and stops when necessary. Findings from the tests are presented in Table 3-4 below. Figure 3-11 presents some of the obstructions used in the testing.

Table 3-4 Scenarios and Findings from Vehicle Interactions with Obstructions

Scenario	**Findings**
Work zone barrel in center of travel lane	Obstruction detected, automated shuttle bus did controlled slowdown and stopped. Bumper to obstruction stop distance = 5.7 – 6.0 ft.
Work zone barrel placed off wheel path and had no impact to automated shuttle bus approach speed	Distance = 5.0 – 6.0 ft. off wheel path. Distance increased with higher speeds and more slippery pavement conditions.
Work zone barrel placed off wheel path and stopped automated shuttle bus	Distance = 2.2 ft. This distance was consistent with varying speeds and pavement conditions.
Work zone barrel placed off wheel path and did slow automated shuttle bus approach speed	Distance = 2.2 ft. – 6.0 ft.
Repeated testing during night conditions	Same results as during day

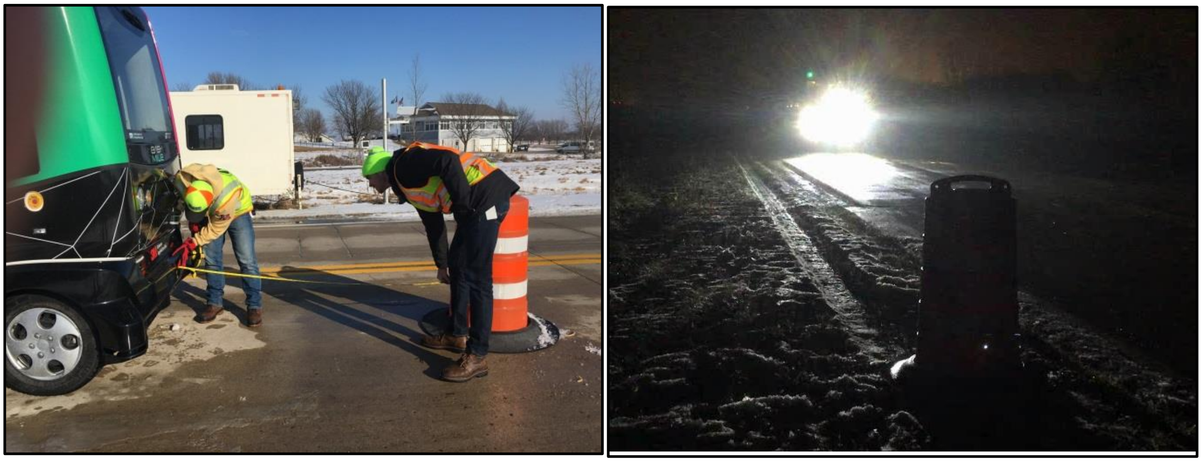


Figure 3-11 Roadway Obstruction Testing

3.4.9 Interaction with Other Vehicles

Test scenarios included introducing one or two other cars on the test track to observe interaction between the automated shuttle bus and cars. Several different conditions were created including the cars following, ahead, ahead and stopping, ahead at consistent or variable speeds, in parallel/adjacent lane, passing, parked at intersections, traveling in opposing directions, stalled across travel lane, etc. The automated shuttle bus performed well and kept a safe operating distance from the other vehicles performing slowdowns or stops as needed. Stop distance measurements were taken and are presented with other key findings in Table 3-5 below. A key finding observed on a clear day with bitterly cold temperatures was the detection of exhaust fumes as an obstruction from a car traveling in the same direction in the parallel lane, causing an unplanned sensor activated slowdown and emergency stop. Figure 3-12 presents some of the images the other vehicles used in the testing.

Table 3-5 Scenarios and Findings from Vehicle Interactions with Other Vehicles

Scenario	Findings
Car ahead slows and stops	Car detected. Automated shuttle bus did controlled slowdown and stopped. Bumper to bumper stop distance = 5.6 – 7.6 ft. Distance increased with higher approach speeds and more slippery pavement conditions.
Car ahead traveling at varying speeds	Automated shuttle bus keeps safe distance and varies speed but localization issues with sensor activated stops appeared to increase with the varying travel speeds and more slippery pavement conditions.
Car ahead traveling at consistent 5 MPH or 10 MPH speed	Automated shuttle bus reacts appropriately and travels at safe operating distance.
Car stopped and creeping out into intersection in opposing direction as automated shuttle bus is making left turn	Stop impact distance from the car creep = 5.6 ft. bumper to bumper.

Table 3-5 Scenarios and Findings from Vehicle Interactions with Other Vehicles

Scenario	Findings
Car traveling in same direction in parallel lane adjacent to automated shuttle bus or passing	Good interaction. Performed slowdowns or stops when necessary.
Car traveling in opposite direction in opposing lane at varying distances from center line	Good interaction. Performed slowdowns if opposing car was detected too close to automated shuttle bus.
Car stalled across travel lane	Car detected, automated shuttle bus did controlled slowdown and stopped.
Exhaust fumes visible from car traveling in same direction in parallel lane and passing automated shuttle bus	Car exhaust was detected as an obstruction if fumes were blown into automated shuttle bus path/detection zone and caused automated shuttle bus to slow/stop.

Figure 3-12 Testing of Other Vehicle Interaction

3.4.10 <u>Interaction with Pedestrians</u>

Testers observed pedestrian interaction with the moving automated shuttle under varying approach speeds. The automated shuttle bus detected the pedestrian, slowed and stopped as necessary. Testers recorded stop distance measurements. These are included in Table 3-6. Stop distance from pedestrian to bumper of the automated shuttle bus increased slightly with higher approach speeds. Figure 3-13 shows the pedestrian interaction testing.

Table 3-6 Scenarios and Findings from Vehicle Interactions with Pedestrians	
Scenario	**Findings**
Pedestrian in center of travel lane and automated shuttle bus approach speed = 1 MPS (2.2 MPH)	Stop distance from pedestrian shins to automated shuttle bus bumper = 5.3 ft.
Pedestrian in center of travel lane and automated shuttle bus approach speed = 2 MPS (4.5 MPH)	Stop distance from pedestrian shins to automated shuttle bus bumper = 6.0 ft.
Pedestrian in center of travel lane and automated shuttle bus approach speed = 3 MPS (6.7 MPH)	Stop distance from pedestrian shins to automated shuttle bus bumper = 6.6 ft.
Pedestrian approaches the side of moving automated shuttle bus making it stop	Stop distance from pedestrian shins to wheel path varied from 1.6 to 1.8 ft.

Figure 3-13 Testing of Pedestrian Interaction

3.4.11 Interaction with Bicycles

Interaction with a bicycle was conducted on the test track on a mild day with bare pavement. The automated shuttle bus interaction with the bicycle was similar to the interaction observed with other vehicles where the automated shuttle bus kept a safe operating distance from the bicycle, performing slowdowns or stops as needed. Test scenarios included the bicycle traveling at varying speeds ahead of or behind the automated shuttle bus on shoulder/edge line, center of lane, or near center line. Tests were also conducted with the bicycle riding in the parallel/adjacent lane in the same or opposite direction, passing or being passed, crossing the roadway, etc. The stop distance measurements taken when the bicycle stopped in front of the approaching automated shuttle bus are presented in Table 3-7. Figure 3-14 shows some of images the other vehicles used in the testing.

Table 3-7 Scenarios and Findings from Vehicle Interactions with Pedestrians

Scenario	Findings
Bicycle ahead at varying speeds traveling in shoulder, near edge line, in center of lane or near center line	Good interaction. Bicycle detected, automated shuttle bus did controlled slowdowns as needed.
Bicycle traveling in same direction in parallel lane adjacent to automated shuttle bus or passing or being passed	Good interaction. Performed slowdowns or stops when necessary.
Bicycle traveling in opposite direction in opposing lane at varying distances from center line	Good interaction. Performed slowdowns if opposing bicycle was detected too close to automated shuttle bus.
Bicycle crossing travel lane in front of automated shuttle bus	Bicycle detected. Automated shuttle bus did controlled slowdown.
Bicycle crossing travel lane in front of automated shuttle bus and stops in center of travel lane	Bicycle detected. Automated shuttle bus did controlled slowdown and stopped. Stop distance measurement from bumper to bicycle foot pedal = 6.5 ft.

Figure 3-14 Testing of Bicycle Interaction

3.4.12 Road Salt Spray

Road salt applied to the MnROAD track created visible road salt spray residue on the vehicle sensors, as shown in Figure 3-15 below, but overall this did not appear to change the observed automated shuttle bus behavior. There were some minor top speed and stopping distance anomalies during this time but the reason could not be confirmed. At other times when the vehicle sensors were dirty from normal operations and the automated shuttle bus had degraded performance, the vehicle sensors were cleaned and that appeared to improve performance.

Figure 3-15 Road Salt on LIDAR Sensor

3.4.13 Sensor Housing Finding

Loose snow picked up by rear tires accumulated inside the automated shuttle bus sensor housings, as shown in Figure 3-16 , which might have impacted sensor performance. Sensor-activated stops appeared to minimize after sensor housing holes near tires were covered by vendor resulting in less accumulating snow within the housing.

Figure 3-16 Snow Accumulation is Sensor Housing

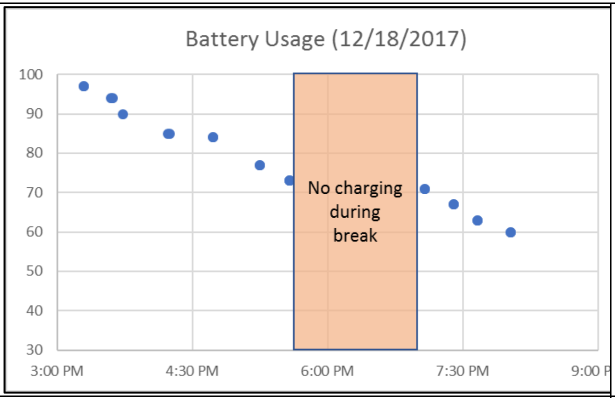
3.4.14 Wheel Wander Accuracy

The navigation and localization system was extremely accurate and we observed anywhere from three mm to one cm accuracy. Wheel path tracks along the programmed route were very apparent as multiple test laps were driven. Wheel rutting along the short gravel crossover road was also observed as shown in Figure 3-17.

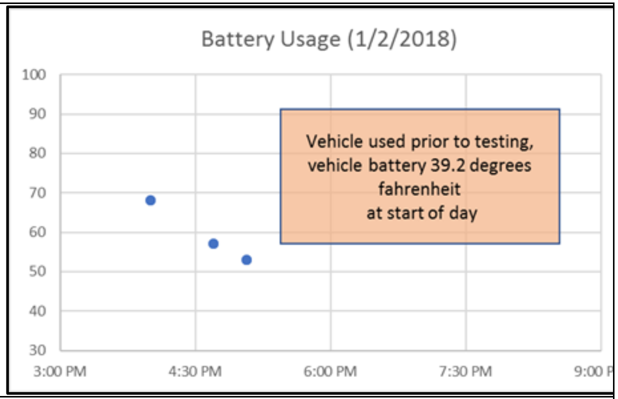
Figure 3-17 ***Observed Wheel Tracks***

3.4.15 Vehicle Battery Performance

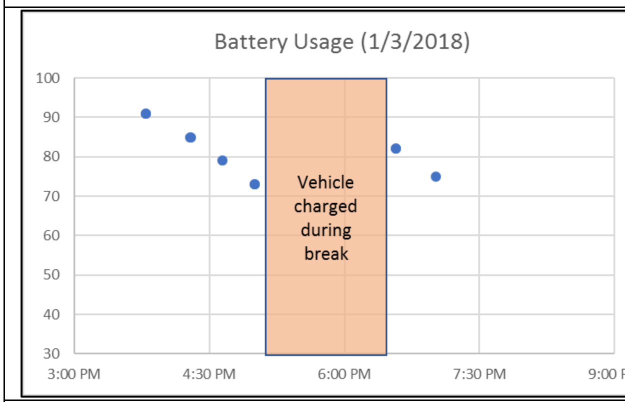
Project testing staff recorded observations on battery charge levels at multiple points in time during the demonstration to better understand how winter weather temperatures affected the charge level of the automated shuttle bus batteries over time. In general, project testing staff observed that colder winter weather temperatures had the effect of discharging the battery faster**.** During periods of subzero temperatures, the vehicle batteries discharged more quickly when the vehicle heater was running. In addition, as the core temperature of the battery dropped significantly it affected automated shuttle bus operations negatively. Figure 3-18 presents a summary of the observations regarding battery charge readings recorded during automated shuttle bus testing over several dates.



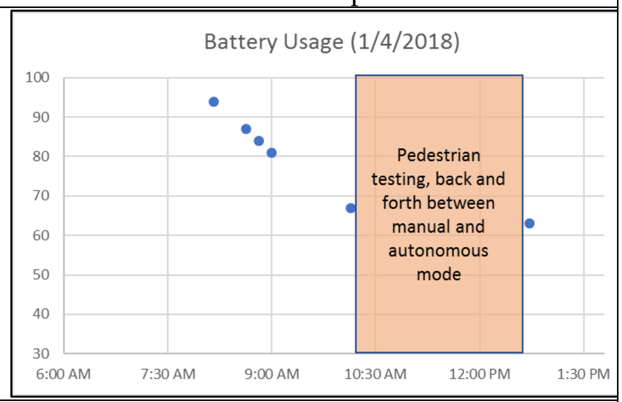
Dec. 18th, 2017 Battery Charge Readings
Start Temp.: 36º F; Wind: S 7 mph



Jan. 2nd, 2018 – Battery Charge Readings
Start Temp.: 12º F; (-4º F wind chill); Wind: SW 13 mph



Jan. 3rd, 2018 Battery Charge Readings
Start Temp.: 3º F; (-13º F wind chill); Wind: WNW 11 mph



Jan. 4th, 2018 Battery Charge Readings
Start Temp.: -4º F; (-4º F wind chill); Wind: ENE 3 mph

Figure 3-18 Battery Charge Readings During Automated Shuttle Bus Demonstrations

CHAPTER 4: MNROAD STAKEHOLDER TOURS

This chapter describes the stakeholder tours conducted by MnDOT, WSB and AECOM during December 2017 at the MnROAD facility.

4.1 Tours' Purpose and Goals

The tours at MnROAD were designed to showcase the abilities of the automated shuttle bus to invited members of state, county, local and transit agencies as well as members of the legislature, academic institutions, local press and private sector interests. The goals of the demonstration were to

- Allow participants to experience an automated vehicle in a controlled environment
- Provide information regarding the automated vehicle program to participants during the demonstration
- Gain acceptance of the automated vehicle program

4.2 Tour Coordination

WSB and AECOM provided support for the MnROAD tours by handling demonstration logistics and schedule, coordinating invitee lists, and developing and distributing informational materials. A summary of the tour support and coordination can be found in the Task 13 Technical Memorandum.

4.2.1 Logistics

The tour dates were scheduled to maximize the amount of demonstration time available at the MnROAD facility. By completing the tours early in the full demonstration schedule at MnROAD, it allowed the automated shuttle bus to complete the demonstrations without the need for interruptions. WSB and AECOM planned nine tours over five days with morning and afternoon sessions available. This provided enough flexibility to accommodate the high invitee turnout.

Coordination of the MnROAD tour staff was essential for a successful outcome. Roles and responsibilities were clearly defined for each team member, and a detailed work schedule was developed to ensure that each of the tour dates had the correct number and type of staff on hand.

The MnROAD facility was configured to accommodate demonstration attendees. Due to the wintry weather, demonstration staff prepared indoor staging areas where groups could wait.

Representatives from local media outlets were invited to a special media day at the beginning of the tour schedule. Project leaders gave a presentation on the Minnesota Autonomous Bus Pilot Program and held a question-and-answer session afterwards.

Figure 4-1 Media Day at MnROAD

4.2.2 Invitations

MnDOT, WSB and AECOM created an invitee list for the tours based on the project stakeholders. The goal was to invite as many high-level transportation policy makers as possible to expose them to automated vehicles first hand and educate them on the possibilities of the emerging technologies. Invitees registered electronically for a specific time to participate in the demonstration, which helped balance participant activity over the nine scheduled tours.

4.2.3 Materials

Information about the automated shuttle bus and Minnesota's AV/CV program were distributed to tour participants. The one-page handout used during the demonstration can be found in Appendix B.

4.3 Schedule and Attendance

The table below contains a high-level summary of the tour dates at the MnROAD facility. Tours were scheduled for a morning or afternoon session. A total of 238 out of 315 registered participants attended the stakeholder tours in December 2017.

Table 4-1 MnROAD Tour Attendee Numbers Per Day			
Date	**Session**	**Attended**	**Registered**
Tuesday, December 12, 2017	PM	26	43
Wednesday, December 13, 2017	AM	35	48
Wednesday, December 13, 2017	PM	14	17
Thursday, December 14, 2017	AM	35	45
Thursday, December 14, 2017	PM	11	18
Tuesday, December 19, 2017	AM	20	38
Tuesday, December 19, 2017	PM	43	49
Wednesday December 20, 2017	AM	21	24
Wednesday, December 20, 2017	PM	33	33
	TOTALS	**238**	**315**

Table 4-2 MnROAD Tour Attendee Numbers by Organization						
Date	Session	Public	Private	Academic	Elected Officials	Transit Agency
Tuesday, December 12, 2017	PM	8	8	1	5	4
Wednesday, December 13, 2017	AM	27	5	0	1	2
Wednesday, December 13, 2017	PM	9	2	0	1	2
Thursday, December 14, 2017	AM	16	8	4	2	5
Thursday, December 14, 2017	PM	8	3	0	0	0
Tuesday, December 19, 2017	AM	11	3	0	1	5
Tuesday, December 19, 2017	PM	33	10	0	0	0
Wednesday, December 20, 2017	AM	14	4	1	1	1
Wednesday, December 20, 2017	PM	14	10	4	3	2
TOTALS		**140**	**53**	**10**	**14**	**21**

CHAPTER 5: DOWNTOWN MINNEAPOLIS DEMONSTRATION

This chapter describes the downtown Minneapolis demonstration conducted in Minneapolis, Minnesota between January 24th and January 28th, 2018.

Figure 5-1 Downtown Minneapolis Demonstration

5.1 Demonstration Purpose and Goals

The purpose of conducting the downtown Minneapolis demonstration during the Super Bowl LII festivities was to introduce the automated shuttle bus to a large public audience and attract interest in automated vehicle technology.

5.2 Demonstration Coordination and Logistics

5.2.1 Planning

The automated shuttle bus demonstration in downtown Minneapolis required permits from several agencies. The City of Minneapolis, Hennepin County, and MnDOT all agreed to the schedule, site plan, and marketing materials. WSB and AECOM facilitated meetings with the stakeholders to reach a consensus on the final plan and then implemented the plan during the demonstration period. The Metropolitan Sports Commission and the Super Bowl Planning Commission were approached to use Super Bowl LII and NFL branding for the automated shuttle bus, but that request was ultimately denied.

5.2.2 Schedule

The public demonstration was held between January 24th and January 28th, 2018. January 24th and January 25th were reserved for private tours. Public tours began January 26th to coincide with the Super Bowl opening weekend events on Nicollet Mall.

5.2.3 Site Location and Setup

The location of the automated shuttle bus demonstration was selected to maximize public exposure and tie into the activities planned for Super Bowl LII. An area of Nicollet Mall was requested to co-locate with Super Bowl LII activities on the same street. The Minneapolis Public Library, owned by Hennepin County, has ample outdoor space along Nicollet Mall that was used as a staging area. This eliminated the need for property use agreements with private entities and expedited the demonstration planning schedule.

WSB and AECOM created a site map that included participant tent layout, automated shuttle bus path, traffic and pedestrian barricades, and event displays for use around the demonstration area. The plan also included wayfinding signs for people navigating from the light rail station on 5th Street and Nicollet Mall to the tour location. The plan was ultimately used to get permits from the City of Minneapolis and Hennepin County to host the demonstration.

5.2.4 Demonstration Route

The demonstration route was along Nicollet Mall between 3rd Street South and 4th Street South as shown in the map below. Passengers boarded the automated shuttle bus near 4th Street South and traveled toward 3rd Street South and then back to the starting point at 4th Street South. This portion of Nicollet Mall was blocked to all vehicle and pedestrian traffic during the demonstration.

Figure 5-2 Super Bowl Demonstration Location

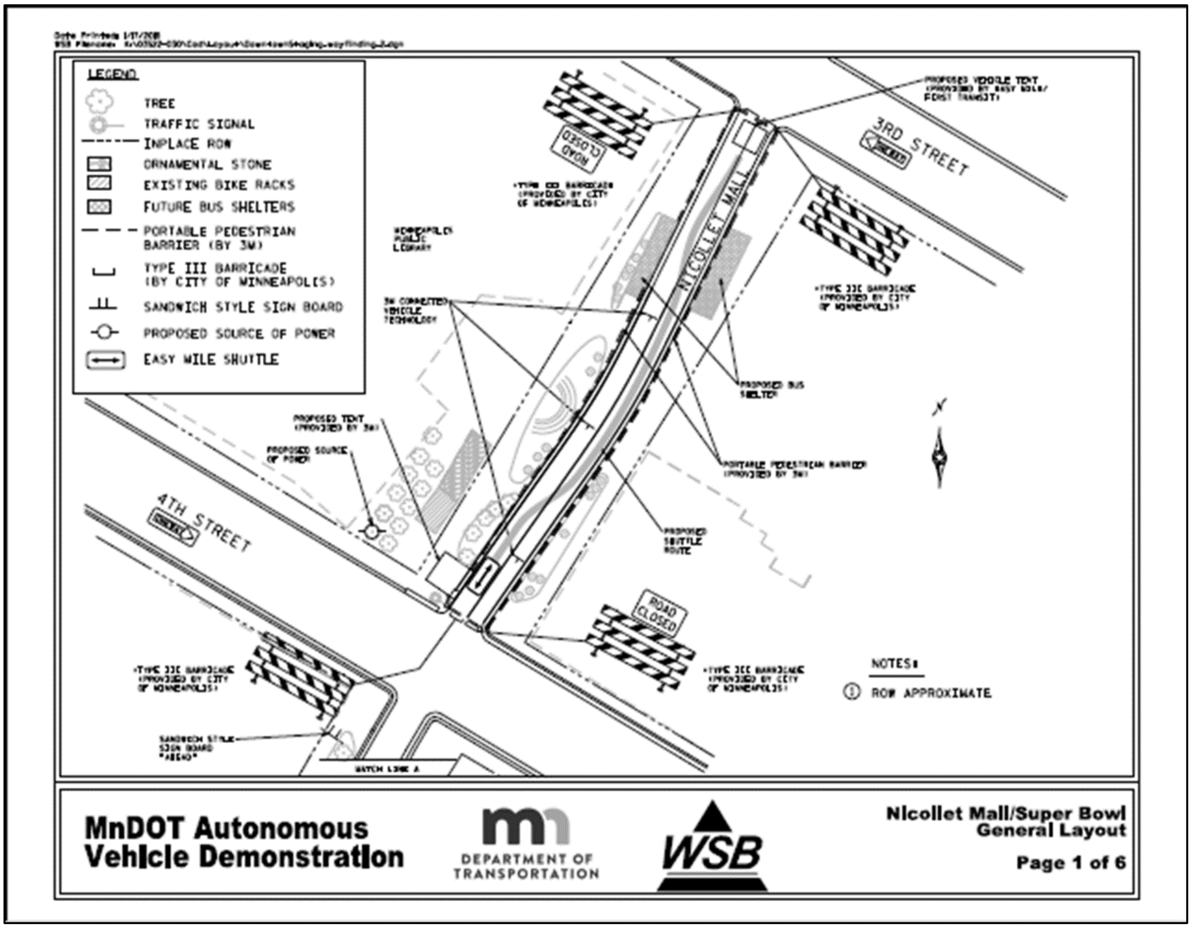


Figure 5-3 Super Bowl Demonstration Site Layout

5.2.5 Materials

A one-page handout developed by MnDOT was available for participants at the Nicollet Mall demonstration. The document explains the purpose and goals of the autonomous vehicle program, gives a description of the automated shuttle bus, and provides language on MnDOT's AV operations into 2018. An example of the handout can be found in Appendix B.

5.3 Schedule

Before the tours were open to the public, WSB and AECOM scheduled private tours for three organizations:

1. January 24th, 2018 – National Federation of the Blind, Minnesota Chapter
2. January 24th, 2018 – Minnesota Safety Council
3. January 25th, 2018 – City of Minneapolis

The public demonstrations began on Friday, January 26th, 2018 and ended on Sunday, January 28th, 2018.

WSB and AECOM provided staff on all five days of the demonstration for both the staging area outside of the Minneapolis Public library and inside the automated shuttle bus to provide education and answer questions from the public.

5.4 Attendance

Attendance numbers for the three days are listed below:

- Friday, January 26th – (303 riders)
- Saturday, January 27th – (465 riders)
- Sunday January 28th – (511 riders)

In all, a total of 1,279 riders participated over the three-day public event.

Figure 5-4 Public Demonstrations

5.5 Key Observations from Public Survey

WSB and AECOM created survey questions to distribute to demonstration participants on the shuttle. These questions assessed the public's level of familiarity with automated vehicles, established a sense of riders' comfort level with a driverless vehicle, and how the public feels about expanding the use of automated vehicle technology. The survey questions are listed below:

- Are you a resident of the State of Minnesota?
- Was this your first ride on a driverless vehicle?
- Were you apprehensive about being safe riding a driverless vehicle before your ride today?
- Having ridden the driverless vehicle, do you think the ride was safe?
- Are you looking forward to having driverless vehicles operate on all roadways in the future?

Most of the responses to the survey questions were positive. Riders commented that they were excited to participate in Minnesota's first public AV demonstration, and in general, looked forward to future developments of AV technology. Some riders commented that they would like to see the shuttle operate outside of such controlled conditions on Nicollet Mall and wondered if all safety concerns have been addressed.

A full list of survey responses can be found in Appendix C.

5.6 State Capitol Demonstration

A separate demonstration was conducted on March 7, 2018 at the Minnesota State Capitol building to provide automated shuttle bus rides for the Minnesota State Legislature. A programmed route was established in the front grounds of the Capitol and rides were given to 216 individuals including a mix of legislators, MnDOT and Department of Public Safety officials, and the public.

The day before the Capitol demonstration, there was enough snow to require plowing the shuttle route. This created snow banks along the route that were not present during the mapping phase of the demonstration. The snow banks detected by the shuttle caused sensor-activated slowdowns, especially in the turns. The snow banks were removed by maintenance vehicles, which eliminated the slowdowns along the route.

A handout related to the Minnesota Autonomous Bus Pilot project and future automated and connected vehicle initiatives was available for the participants. An example of the handout can be found in Appendix B. On this day, a press conference was also held at the State Capitol announcing the new Governor's Executive Order establishing the CAV Advisory Council and support for future AV testing in Minnesota.

A total of 216 riders participated in riding the automated shuttle bus at the State Capitol Demonstration.

5.7 Other Demonstrations

Other demonstrations were also performed during the project for multiple public and private agencies at various locations as presented in the Table below. Attendance figures that were recorded at these demonstrations are also presented in Table 5-1.

Table 5-1 Other Demonstrations Performed and Attendance Figures			
Date	**Lead Agency**	**Location**	**Number of Riders**
2/20/18	3M	Saint Paul, MN	217
2/21/18 – 2/22/18	3M		262
3/22/18	City of Rochester	Peace Plaza - Rochester, MN	267
4/28/18	Hennepin County	Midtown Greenway, Minneapolis, MN	199
4/29/18	Hennepin County		214
4/30/18	University of Minnesota	Washington Avenue Pedestrian / Bicycle Bridge, Minneapolis MN	454
5/11/18	North Dakota DOT	Bismarck, ND	118
5/12/18	North Dakota DOT		919

CHAPTER 6: KEY CONCLUSIONS

6.1 Operations at MnROAD

6.1.1 Clear Weather

The automated shuttle bus operated as expected under clear weather conditions. There were a few sensor activated slowdowns and emergency stops due to external stimuli picked up by the vehicle sensors, but in general the shuttle moved along its intended route and performed controlled stops at locations designated for passenger pick up and at intersections.

6.1.2 Falling and Blowing Snow

The automated shuttle bus experienced sensor activated slowdowns/stops and emergency stops when operating in falling snow, blowing snow (especially during snowmaking operations), and from loose snow kicked up from the test track. The vehicle sensors detected snow particles and performed multiple successive sensor-activated stops assuming there were obstacles in the drive path. Once the shuttle had passed the snow making areas, it resumed normal operations.

6.1.3 Snow Cover on Pavement

The automated shuttle bus navigated through several inches of snow/slush on the pavement but lost its location on the programmed path if the tires slipped. The automated shuttle bus course-corrected once back on dry pavement if conditions caused it to slip from the preprogrammed path.

6.1.4 Temperature/Battery Correlation

Testers observed that temperatures below 0° F drained the battery at a faster rate than temperatures above 0° F. At times, the automated shuttle bus required mid-demonstration battery charges during the MnROAD sessions, and the interior heating system, internal lights, and cold weather drained the battery at a noticeably faster rate. Lower battery levels are directly correlated to a reduction in shuttle system performance.

6.1.5 Vehicle, Pedestrian, Bicycle and Obstruction Detection

The automated shuttle bus performed well in detecting other vehicles, pedestrians, and bicycles on the MnROAD test track. It detected and reacted to static obstacles placed in its path. The automated shuttle bus also showed more conservative braking behavior and increased stopping distances as speed increased or as pavement conditions worsened.

6.2 Downtown Minneapolis Demonstration

6.2.1 Shuttle Performance

The automated shuttle bus performed without major disruptions during the three days of public demonstrations on a closed block in downtown Minneapolis.

6.2.2 Public Opinion

Participants that rode the automated shuttle between January 26th and January 28th, 2018 reacted positively to the experience. The survey responses from the event indicated that most of survey respondents were excited about the advent of automated vehicle technology and would like to see deployment of automated vehicle technology.

6.3 Results of Autonomous Vehicle Demonstration Applied to Project Goals

The goals stated in section 1.2 of the report were addressed throughout the project as described below:

1. *Identify the challenges of operating automated vehicle technologies in snow/ice conditions and test potential solutions through field testing*. The automated shuttle bus was field tested in various winter weather conditions. The results of the testing can be found in Chapter 3 of this report.
2. *Identify the challenges and strategies of having third parties safely operate automated vehicles on the MnDOT transportation system.* The project team learned that this technology has good applications for use throughout the state, and that as AV technology advances, stakeholders will need to address how the transportation workforce would change.
3. *Identify infrastructure gaps and solutions to safely operate automated vehicles on the MnDOT transportation system.* Although the automated vehicle did not rely on signs or pavement markings, the project team learned that it required additional infrastructure at MnROAD. The project team also learned that snow and ice removal may be key to operations in the future.
4. *Prepare transit for improving mobility services through automated vehicles.* Comments from the National Federation for the Blind indicated that they think this technology has a lot of potential for increasing mobility of disabled passengers.
5. *Increase Minnesota's influence and visibility on advancing automated & connected vehicles.* The demonstration in downtown Minneapolis during Super Bowl LII was an effective showcase for Minnesota's AV/CV program and provided exposure to the local and national/international public. It was also a catalyst to the development of MnDOT's CAV-X office.
6. *Enhance partnerships between government and industry to advance automated & connected vehicles in Minnesota*. The project team learned that they need to develop strong non-traditional partnerships with technology and vehicle providers. Additionally, there needs to be a strengthening of traditional partnerships with sister state agencies and local units of government.
7. *Provide opportunities for public demonstrations of automated vehicles and obtain public feedback.* Several demonstrations took place throughout the state and are summarized in Chapter 5 of this report.

CHAPTER 7: FUTURE STEPS

MnDOT will continue to work on the automated vehicle program through various initiatives including strategic planning, additional pilots, and ultimately deployments. Some potential future steps include but are not limited to the following:

1. Testing after software enhancements being done now by EasyMile for better obstruction filtering and operations in winter weather. The enhanced software will not be available before the end of May 2018 based on the last update from EasyMile. Future testing of the new software in winter weather is encouraged to see if the updated software enhances performance in snow.
2. Testing conditions such as more extreme road salt spray on sensors, battery performance while implementing strategies to keep battery warm/extend charge during cold weather, limits of operations on roadway inclines/grade, and operations with other sensor integration products.
3. There is a need for continued technology enhancements by the vendor to fully address winter operations and testing in different roadway environments. For example, further development work is required for interfacing automated shuttle bus operations with traffic signals and stop/yield signs
4. MnDOT could establish its process for giving approval to operate automated vehicles on public roads which meets federal requirements. This process can build on lessons learned from Contra Costa County, CA and other areas that may have already completed an exemption process to operate on public roads.
5. Possible integration and more formal pilots of 3M's connected roads smart sign sensors to bring in a connected corridor element to the automated vehicle program.
6. Pursue future phases originally envisioned at the start of the Minnesota Autonomous Bus Pilot project. This would include a phase where testing is taken out of the completely controlled environment and performed on a bus rapid transitway (BRT) or other public roadway and the ultimate phase of transit agencies deploying AV shuttle bus fleets.
7. Look for opportunities to perform additional demonstrations with other local partners like Minnesota Valley Transportation Authority (MVTA), Hennepin County, University of Minnesota, Duluth Transit Authority (DTA), Southwest Transit, a Greater Minnesota transit agency, etc.
8. Look for opportunities to perform demonstrations involving the private sector like 3M, FedEx, Mayo Clinic and others who may be looking to enhance business campus transportation options for employees.
9. Pursue new partnerships to allow testing of a full-size bus with the AV technology to allow for higher passenger capacities and speeds and to allow deployment on other types of roadway environments.
10. Leverage the new Governor's Executive Order establishing the Connected and Automated Vehicle (CAV) Advisory Council to set the stage for other AV testing in Minnesota.
11. Take on-going opportunities for additional outreach to Minnesota stakeholders as MnDOT performs the CAV strategic planning and executes the Governor's Executive Order.

APPENDIX A

MnROAD Data

Table A-1 Observations During Automated Vehicle Demonstration at MnROAD by Date			
Date	**Time Periods**	**Weather Conditions**	**Demonstrations and Observations**
Mon. Dec. 11th	Day	Uncontrolled Weather; Clear skies; Start Temp.: 24° F Wind: WNW 7 mph Snow present on track	Demonstrations: 1. Operation with no vehicles / bicyclists / pedestrians Observations: 1. Vehicle operated well on track with snow present on roadway. Some emergency stops observed from blowing snow on track 2. Vehicle slowed its speed appropriately when approaching obstacles on track
Mon. Dec. 18th	Day / Night	Clear Weather; Start Temp.: 36° F Wind: S 7 mph	Demonstrations: 1. Operation with other vehicles Observations: 1. Vehicle operated well with other vehicles driving along the track or parked on MnROAD track. 2. Vehicle slowed and stopped at safe distances from parked cars and followed cars at safe distances as well 3. Some emergency stops observed, though none due to operation of other vehicles on track
Tues. Jan. 2nd	Day	Controlled Weather (Ice) and Un-Controlled Weather (Snow); Ice patches placed on road for testing Start Temp.: 12° F (-4° F wind chill) Wind: SW 13 mph	Demonstrations: 1. Operation with other vehicles Observations: 1. Falling snow detected as obstructions by vehicle sensors causing emergency stops. Other stops may have been due to other detections of blowing snow or weeds. 2. Use of vehicle heater reduced battery life over the course of 3 laps.

Table A-1 Observations During Automated Vehicle Demonstration at MnROAD by Date			
Date	**Time Periods**	**Weather Conditions**	**Demonstrations and Observations**
Wed. Jan. 3rd	Day / Night	Uncontrolled Weather; Clear skies Start Temp.: 3^o F (-13^o F wind chill) Wind: WNW 11 mph	Demonstrations: 1. Operation with no vehicles / bicyclists / pedestrians Observations: 1. Blowing snow on road kicked up by tires was being detected as obstructions by vehicle sensors causing emergency stops. 2. Compacted snow on pavement led to slippage of wheels at stops, which in turn created an issue with the bus not understanding its exact location on the track.
Thurs. Jan. 4th	Morning / Day	Clear Weather; Clear skies Start Temp.: -4^o F (-4^o F wind chill) Wind: ENE 3 mph	Demonstrations: 1. Operation with pedestrians and work zone barrels Observations: 1. After plowing roadway to clear snow, there were fewer emergency stops as a result of snow being kicked up by vehicle tires into vehicles' sensors. 2. As vehicle speed increased, instances of vehicle slippage on compact snow / ice also increased, which in turn created an issue with the vehicle not understanding its exact location on the track. 3. Stopping distance of the vehicle from pedestrian increased as the vehicle speed increased, indicating conservative approach to stopping for pedestrians. 4. Increasing the distance of the work zone barrel from the wheel path of the vehicle (from 5 feet to 6 feet) allowed for vehicle to maintain its speed while passing the barrel.

Table A-1 Observations During Automated Vehicle Demonstration at MnROAD by Date			
Date	**Time Periods**	**Weather Conditions**	**Demonstrations and Observations**
Fri. Jan. 5th	Morning	Clear Weather; Clear skies Start Temp.: -13° F (-23° F wind chill) Wind: NNW 4 mph	Demonstrations: 1. Operation with other vehicles Observations: 1. Fewer emergency stops from lack of falling or blowing snow on roadway. 2. Compacted snow on pavement led to slippage of wheels at stops, which in turn created an issue with the vehicle understanding its exact location on the track. 3. Exhaust from vehicle operating parallel to vehicle may have been detected as obstructions by vehicle sensors causing emergency stops.
Mon. Jan. 8th	Morning / Day	Controlled Weather (Snow); Clear skies Start Temp.: 22° F (14° F wind chill) Wind: WSW 5 mph Use of snow machine on track	Demonstrations: 1. Operation with no vehicles / bicyclists / pedestrians Observations: 1. Machine made snow was detected as an obstacle and created more emergency stops from falling / blowing snow on roadway. Fewer stops detected when machines were turned off. 2. Placement of slushy snow on pavement led to slippage of wheels as vehicle speed increased, which in turn created an issue with the vehicle understanding its exact location on the track.
Tues. Jan. 9th	Morning / Day	Controlled Weather (Salt / Snow); Clear skies Start Temp.: 40° F Wind: SE 12 mph Placement of salt at 300 lb. per lane mile	Demonstrations: 1. Operation with other vehicles Observations: 1. Salt spray on front vehicle sensors did not impact interaction of vehicle with other vehicles on track. 2. Instances of vehicle slippage reduced with salt spray placed on track, reducing emergency stops by vehicle. 3. Stopping distances of vehicle from work zone barrel were consistent with previous without salt spray.

Table A-1 Observations During Automated Vehicle Demonstration at MnROAD by Date			
Date	**Time Periods**	**Weather Conditions**	**Demonstrations and Observations**
Wed. Jan. 10th	Day / Night	Clear Weather; Cloudy skies Start Temp.: 37° F Wind: SSE 9 mph Light rain / light fog present near end of testing	Demonstrations: 1. Operation with other bicycles and with work zone barrel Observations: 1. Vehicle kept safe distance from bicycle on roadway performing emergency stops as needed. Behavior was similar to that of other vehicles driving on track. 2. Vehicle was detecting obstructions from unknown source, and was observed in the form of a red dot on the in-vehicle map. Further investigation needed to determine source. 3. Vehicle performed well in light rain and light fog near end of vehicle testing. 4. Vehicle speeds varied with varying distances of the work zone barrel from the wheel path.
Thurs. Jan. 11th	Day / Night	Uncontrolled Weather; Cloudy skies; Start Temp.: 6° F (-12° F wind chills) Wind: NW 16 mph	Demonstrations: 1. Operation with no vehicles / bicyclists / pedestrians Observations: 1. Blowing snow detected as obstructions by vehicle sensors causing emergency stops. Top speed was 12 kph, but only for very brief periods. 2. Battery discharged test found a dramatic drop in battery charge level that inhibited the vehicle from being driven in AV mode. Vehicle was manually driven to garage for overnight charging, EasyMile was provided description of the issue for further analysis.

Table A-1 Observations During Automated Vehicle Demonstration at MnROAD by Date			
Date	**Time Periods**	**Weather Conditions**	**Demonstrations and Observations**
Fri. Jan. 12th	Morning	Controlled Weather (Use of Snow Machine); Clear skies; Start Temp.: -9° F (-24° F wind chills) Wind: N 7 mph	Demonstrations: 1. Operation with no vehicles / bicyclists / pedestrians Observations: 1. Falling snow and blowing snow detected as obstructions by vehicle sensors causing sensor activated stops. Snow on pavement is blown from the vehicle tires to side sensor detection zones on the vehicle which also causes emergency stops. Snow plowing reduced number of stops, though not entirely. 2. Vehicle battery charge was low even from overnight charging. Could be due to a low core battery temperature at start of recharging or a vehicle computer restart that should have been completed the night before.

Figure A-1 represents the total number of sensor activated slowdowns and emergency stops observed per mile of travel on different pavement conditions during the entire testing period of automated shuttle bus. It is evident from the graph that number of sensor activated slowdowns and emergency stops per mile by the automated shuttle bus increased as the pavement condition changed from bare to snowy. Overall, the automated shuttle bus performed well on different conditions. The Figure A-1 graph shows that there were fewer than two sensor activated slowdowns and emergency stops per mile on bare pavement conditions. Even during the road salt pavement condition, there were fewer than three sensor activated slowdowns and emergency stops. When snow covered the pavement, the number of sensor activated slowdowns and emergency stops per mile increased significantly. The automated shuttle bus sensors functioned less efficiently on snow/ice covered pavement and hence the vehicle progressed cautiously. Some of the factors that may have influenced sensor activated slowdowns and emergency stops include blowing snow, falling snow, sensors covered with snow, snow plowed pavement etc.

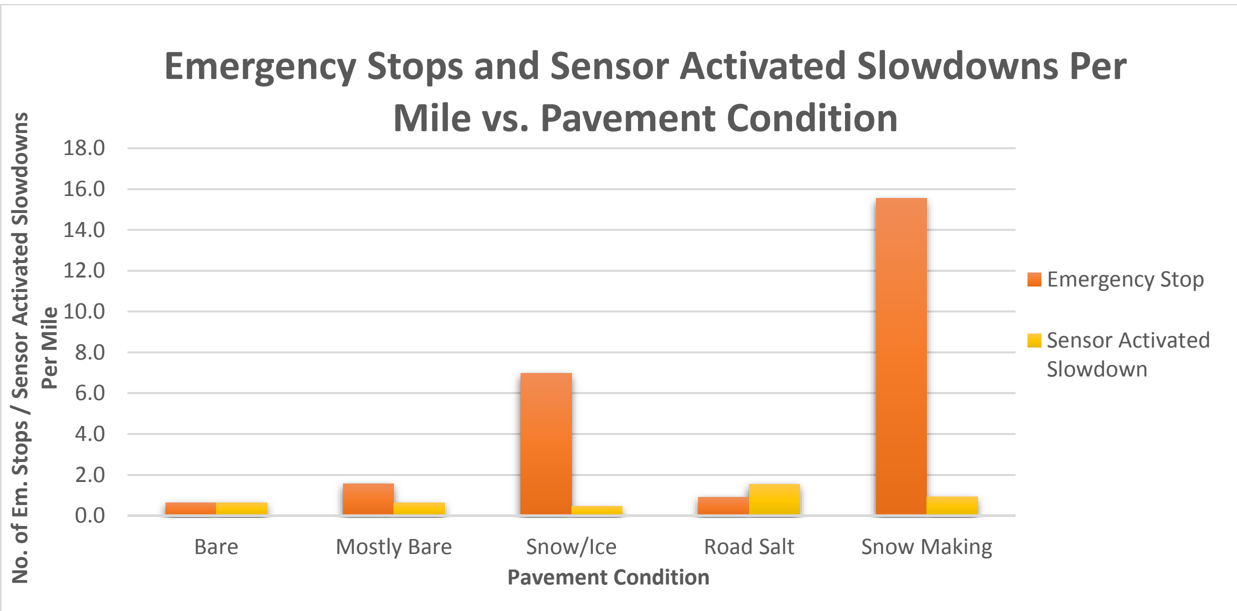


Figure A-1 – Sensor activated Slow Downs and Emergency Stops per Mile vs Pavement Condition

Figures A-2 and A-3 show the total number of sensor activated slowdowns and emergency stops observed per mile of travel during different temperatures for the entire automated shuttle bus testing period . The graph also includes events for the "Feels Like" temperature because during the testing days, even though the measured temperature was above 32^{o} F, the "Feels Like" temperature was close to 0^{o} F.

It is evident from the graph that overall, the automated bus performed well during different temperatures. The number of sensor activated slowdowns and emergency stops per mile by the automated shuttle bus increased as the temperature at the test location decreased to 0^{o} F or lower. It can be seen in the graph that there were more than six sensor activated stops/slowdowns per mile when the temperature went below 32 ^{o} F and got close to 0^{o} F or lower.

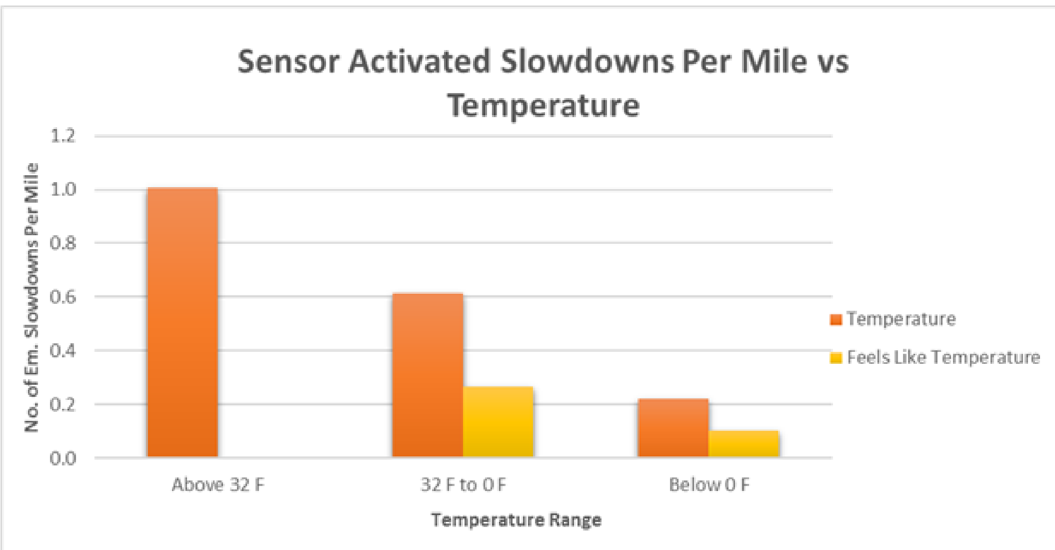


Figure A-2 – Sensor Activated Slowdowns Per Mile vs Temperatures

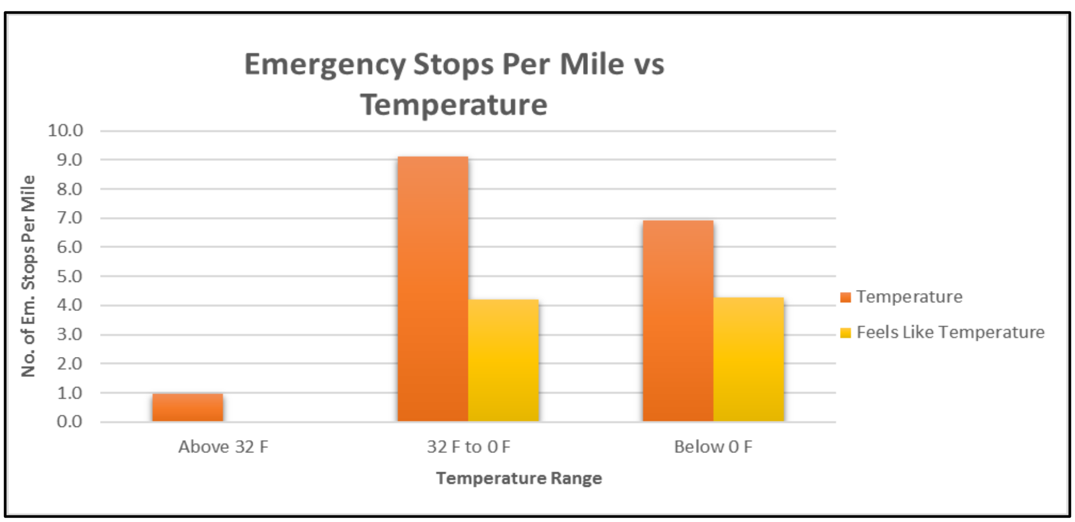


Figure A-3 – Emergency Stops per Mile vs Temperatures

Additional figures are shown below that graph data collected during the testing period.

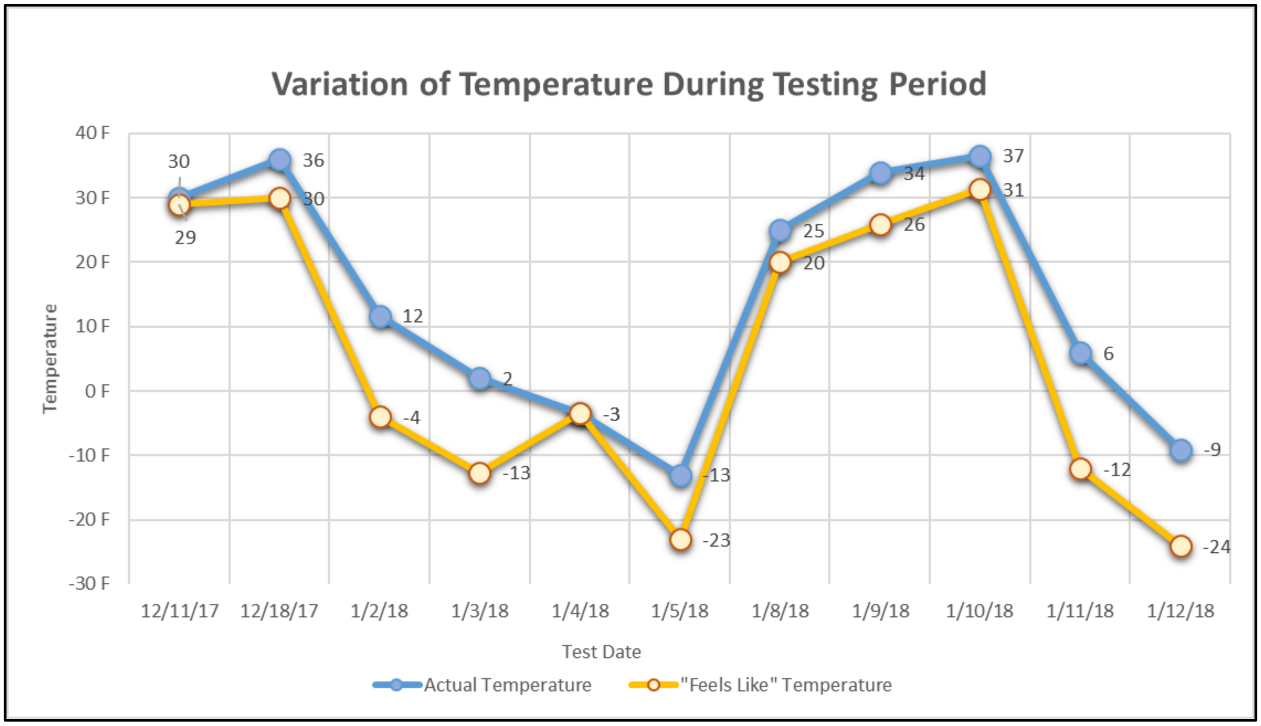


Figure A-4 – Variation of Temperatures During Testing Period

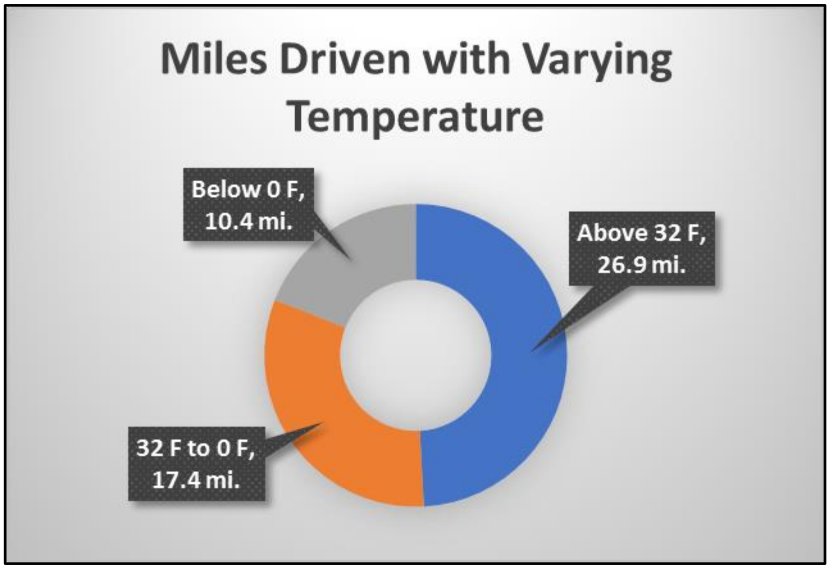


Figure A-5 – Summary of Miles Driven with Varying Temperatures

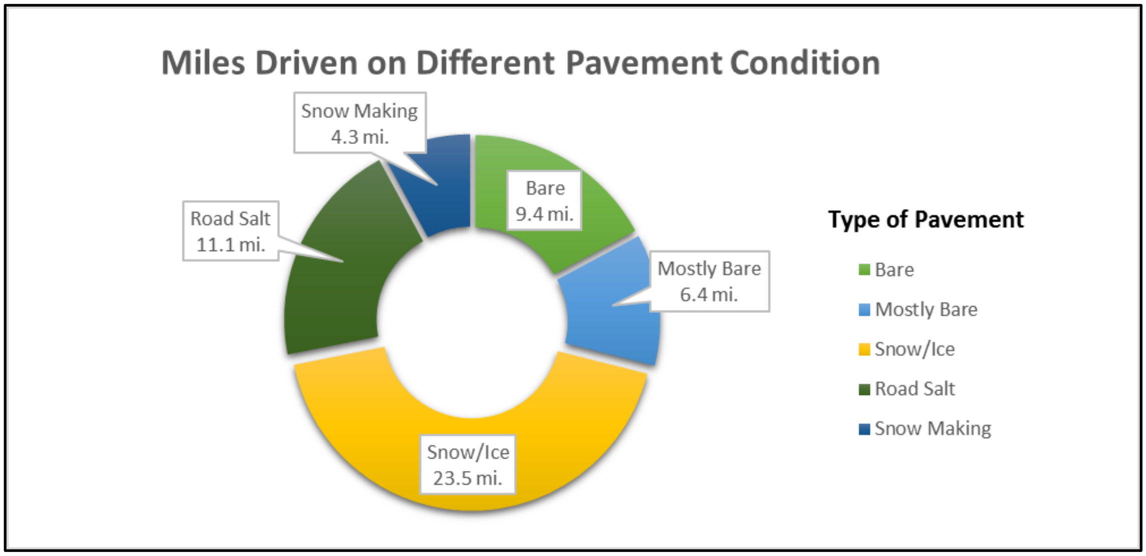


Figure A-6 – Summary of Miles Driven on Different Pavement Conditions

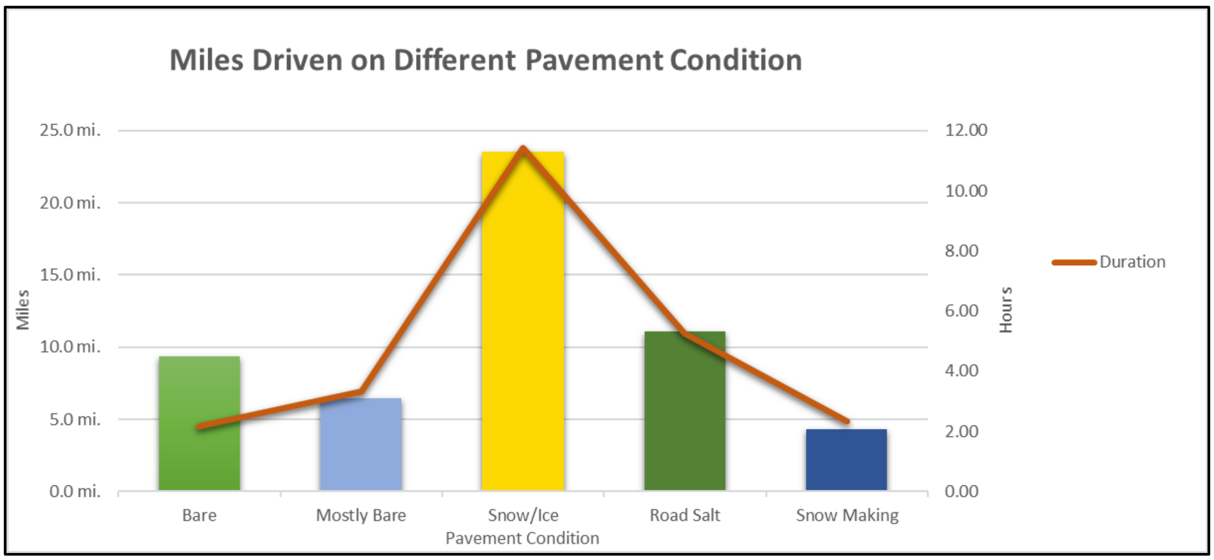


Figure A-7 – Summary of Miles Driven on Different Pavement Conditions with Testing Duration

Figure A-8 represents the average speed of the automated shuttle bus on different pavement conditions during the entire testing period.

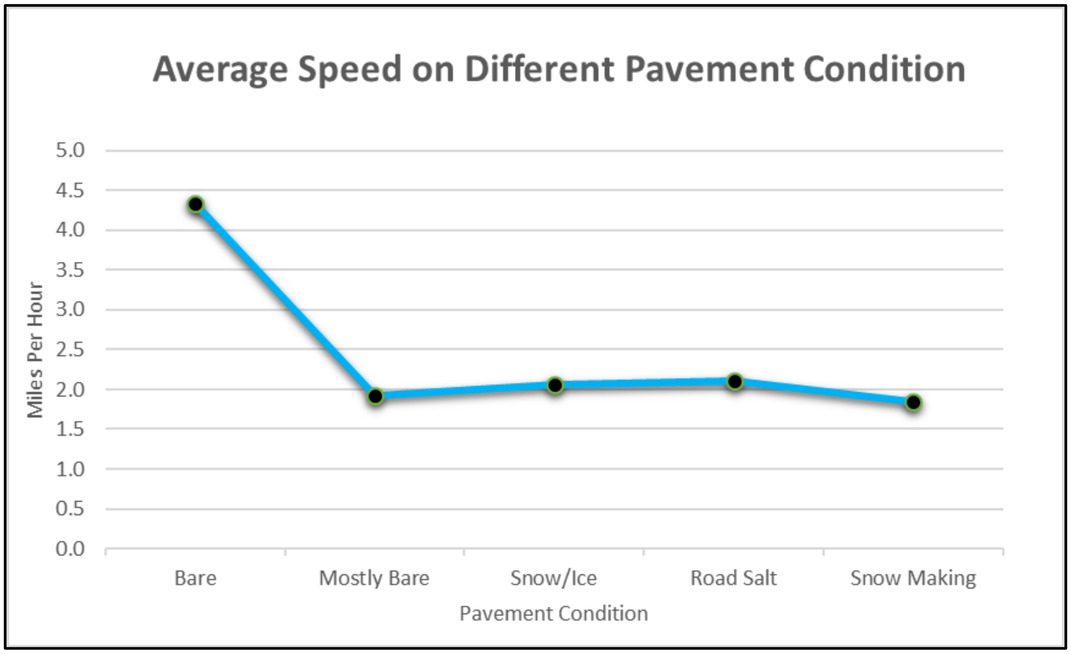


Figure A-8 – Summary of Miles Driven on Different Pavement Conditions

Appendix B

MnDOT Project Sheets

Appendix B-1 – MnROAD Project Sheet

DEPARTMENT OF TRANSPORTATION

Autonomous Shuttle Bus Pilot Project

Autonomous Vehicle technology is rapidly developing around the world. Minnesota offers unique climate challenges compared to other states currently testing these technologies. Deploying an AV pilot project in Minnesota will better position the state to influence national policy and prepare Minnesota transportation owners and stakeholders for the future.

Importance to Minnesota

Each year in Minnesota, more than 300 people are killed, and thousands more injured, in traffic-related crashes. More than 90 percent of traffic crashes involve a human element, such as speeding, distracted driving or impaired driving. Autonomous vehicle technology has significant potential to reduce or eliminate many of these crashes.

As this technology continues to advance, Minnesota must be ready. This includes ensuring the roadways are able to support this technology, understanding how these vehicles affect existing traffic and licensing laws and how they will operate with other modes of transportation, such as pedestrians and bicycles.

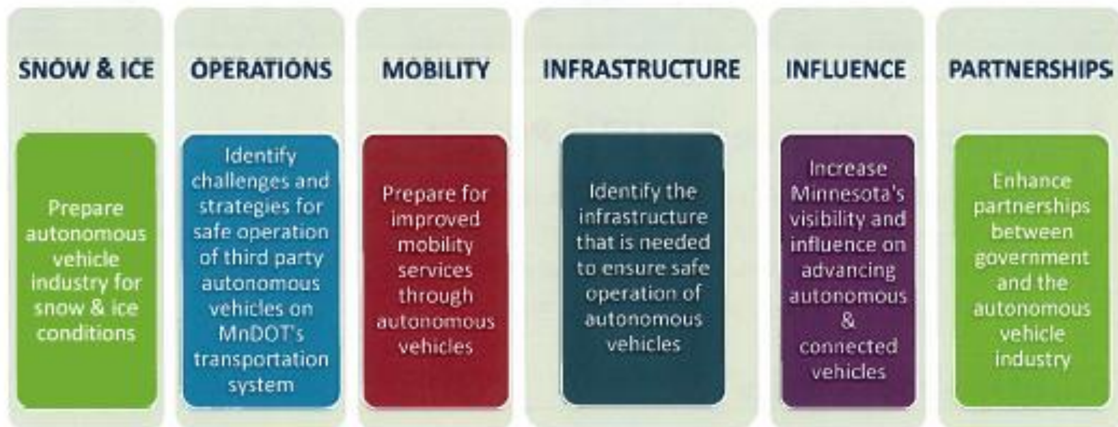
This pilot projects provides Minnesota an opportunity to learn about this technology and how it works in a winter weather environment. This testing also provides an opportunity for the public to ride an autonomous vehicle and experience first-hand the future of transportation.

About the autonomous shuttle bus

The selected autonomous shuttle is a driverless, electric shuttle that can transport up to 12 people (six seated, six standing). It has no steering wheel and operates on pre-mapped routes. The vehicle is manufactured by Easy Mile, and operated by First Transit.

This vehicle has transported more than 160,000 people and logged more than 60,000 miles around the world. This will be the first use of this vehicle in Minnesota and EasyMile's first official test in a harsh winter weather environment.

Project Goals



Shuttle operations

The shuttle is expected to be in Minnesota until at least April 2018. The current schedule for testing and operating the vehicle is:

- **Winter weather testing (December – March).** The vehicle will undergo a series of winter weather conditions at MnDOT's MnROAD facility near Monticello from December 2017 through March 2018. This closed loop facility (not open to other traffic) allows for safely testing the vehicle in snow, ice, cold weather and salt covered road conditions.

- **Public ride opportunities.** With Minneapolis hosting Super Bowl LII, the public will have an opportunity to ride the vehicle at no cost. The vehicle will be tested and operated in downtown Minneapolis on a closed segment of Nicollet Mall from 3rd Street to 4th Street. Operation times will be posted on MnDOT's website http://www.mndot.gov/autonomous/bus and are subject to weather conditions.

- **Other operations.** MnDOT is currently working with local partners to operate and test the vehicle at other locations around the state. These tests and operation would occur after winter weather testing has ended. Updates will be provided on MnDOT's website.

Contact Information

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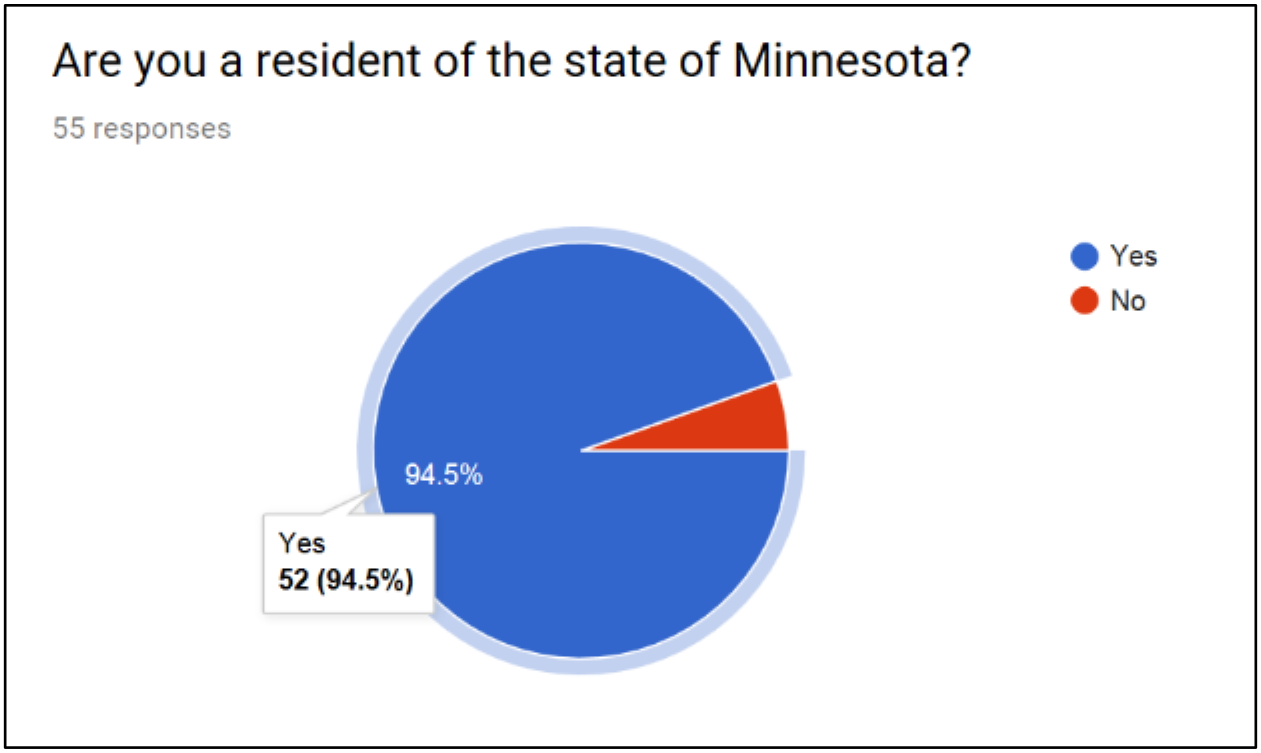
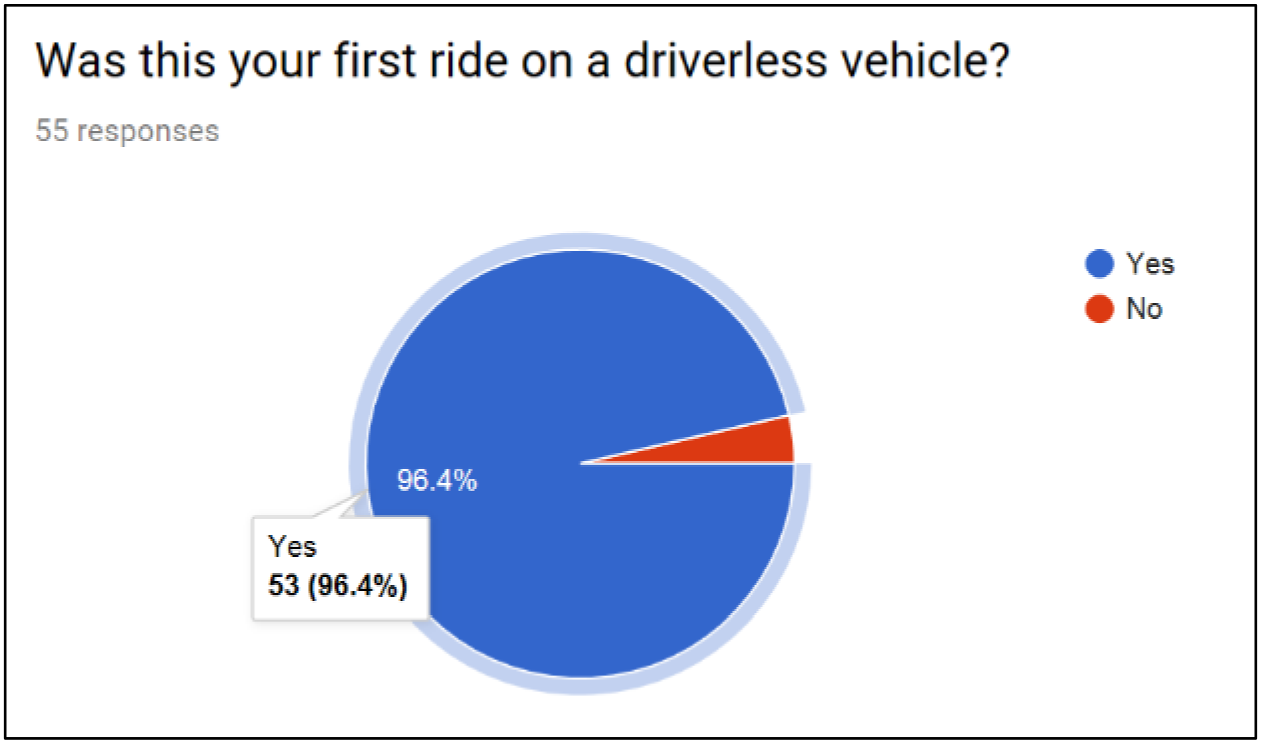
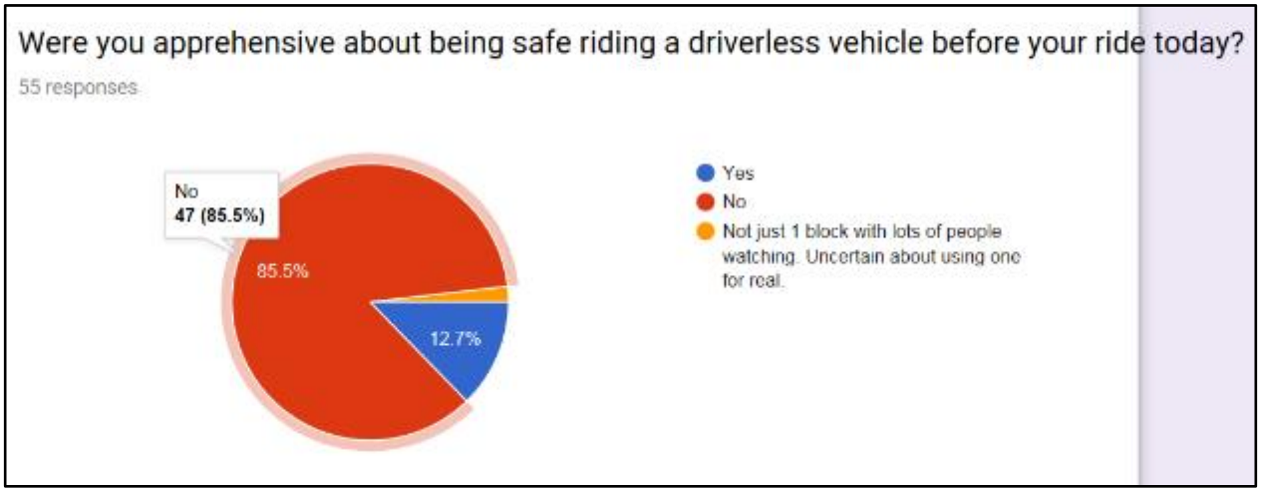
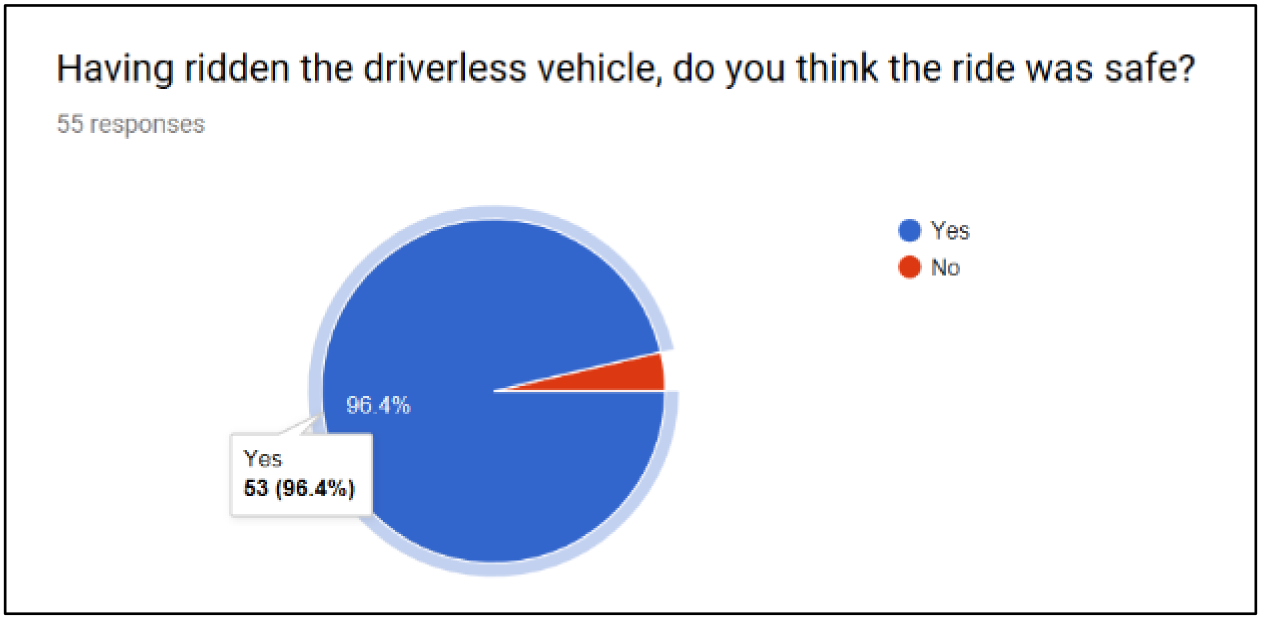
APPENDIX C

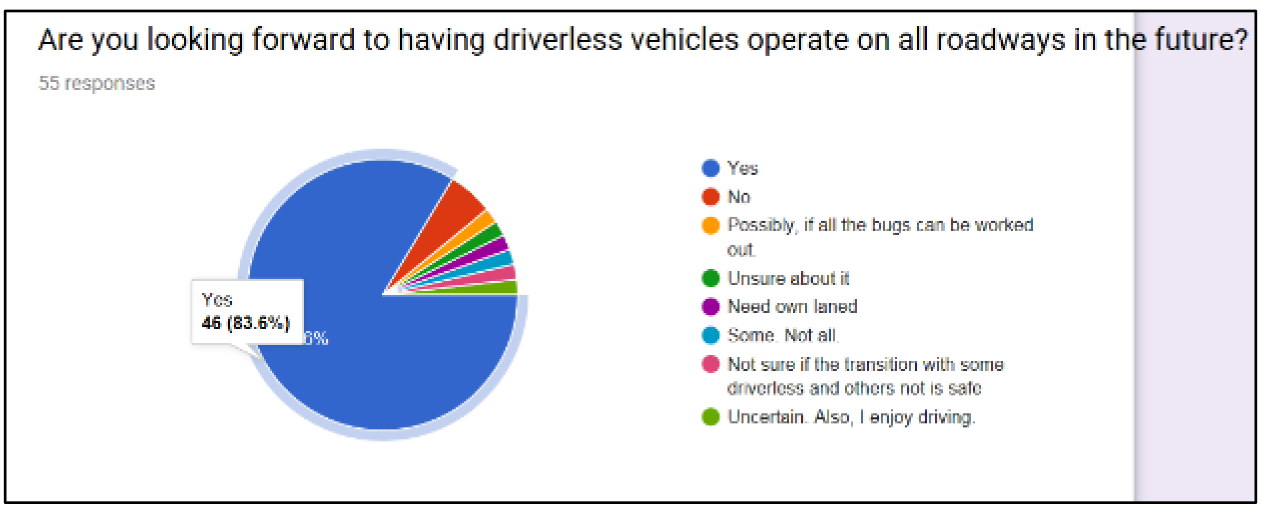
Super Bowl Survey Results






Were you apprehensive about being safe riding a driverless vehicle before your ride today?
55 responses
No
47 (85.5%)
85.5%
12.7%
Yes
No
Not just 1 block with lots of people watching. Uncertain about using one for real.


Having ridden the driverless vehicle, do you think the ride was safe?
55 responses
96.4%
Yes
53 (96.4%)
Yes
No


Are you looking forward to having driverless vehicles operate on all roadways in the future?
55 responses
Yes
46 (83.6%)
Yes
No
Possibly, if all the bugs can be worked out.
Unsure about it
Need own laned
Some. Not all.
Not sure if the transition with some driverless and others not is safe
Uncertain. Also, I enjoy driving.

ADDITIONAL COMMENTS FROM RIDERS

Minnesota should be leaders in the EV autonomous car future! Excellent addition to our city!

Pleasant ride. Nice technology

Thanks for offering this ride to the public for free - it was awesome to experience!

Awesome!!!!

Hurry up and get these things in our city!!! Can’t wait for the future

It was great! I would fully support the use of these in Minneapolis.

Thanks for pursuing a sustainable future!

I am concerned about malicious hacking of driverless vehicles, which would be extremely dangerous for everyone sharing the road with them.

Nice little bus! It goes pretty slow though.

This was really fun and enjoyable. I can’t wait to see more operational in MN!

Very cool.

I am for it if it keeps people safer.

So cool to hear that Minnesota is the first state to test for cold weather conditions in the world!

Great job bringing this to the Twin Cities!

I wish they would replace the buses on Nicollet Mall!

3 thumbs up

Very impressive vehicle and technology. Introducing such technology on controlled roadways will allow the concept to mature in its dependability and public acceptance

thank you city of Minneapolis for setting up events like this to help the public experience future growth projects.

Love it! More please! Thanks for the opportunity and the investment!

It was a good demo and the people explaining it were very good

I think we need to get the ball moving more quickly. This was great, but it seems a long way from being functional (doesn’t operate in traffic; doesn’t operate off of pre-programmed route; didn’t allow for a woman in a wheelchair to ride.) nice start, though.

This was a fun experience and I'm happy that it was available to show residents of MN and guests of the super bowl about driverless vehicles.

Concerned about lack of wheelchair securement areas onboard, as well as passenger safety in the event one is assaulted or harassed

ADDITIONAL COMMENTS (CONT.)

Having seen the effects of having pilot programs of new technology in other states, I am very excited that autonomous vehicles are being tested in MN.

I think right now downtown is a market you could easily start with

Thoroughly enjoyed the ride! Widespread use of these vehicles would be an awesome step toward a future where people request autonomous vehicles instead of Ubers, toward eliminating the need for vehicle ownership and reducing congestion.

Would have liked to travel more than the block of the Nicollet Mall in front of the library.