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Common Advanced Driver Assistance Systems (ADAS) present on Minnesota roadways have significant reliance on the existing infrastructure – mostly notably the lane markings. Areas within the existing roadway network exist that are not conducive to automated driving or the use of certain ADAS features. This project utilized technology-equipped research vehicles to drive a pre-planned and diverse route across over 1000 miles of Minnesota to discover these areas and learn about them. Of the issues noted on the drive, the team grouped them into eight categories that, depending on the specific infrastructure, setting, and context could cause the technology to disengage and are as follows: Freeway Ramps and Turn Lanes, Poor Lane Line Condition and Visibility, Construction and Maintenance Activities, Poor Contrast, Tight Curvature, Environmental Issues, and Dynamic Lanes.

These different categories may have specific ties to existing policies and guidance commonly used by practitioners charged with maintaining and designing these roadway facilities. This study does not specify exact changes to these policies that should be enacted but rather provides the findings for existing committees and agency professionals to use to make improvements that in most cases will benefit both automated driving systems as well as human drivers.

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# Drive MN

*Final report*



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# EXECUTIVE SUMMARY

Various components of automated driving are present on Minnesota roadways and continue to be more common with technology being added to new vehicle models each year. Some of these systems rely on the roadway infrastructure to function as intended. This project used technology-equipped research vehicles to drive a subset of roadways across the state to understand potential infrastructure situations that could be problematic for these automated driving technologies. Findings from this study are intended to be used by transportation professionals and agencies to make improvements to the transportation system in an effort to make Minnesota roadways more suitable for automated driving and Advanced Driver Assistance Systems (ADAS).

The team developed a route that was comprised of over 1000 miles of roadways across the State of Minnesota. The route was meant to be diverse and included a mixture of pavement types, number of lanes, functional classifications, traffic control devices, presence of work zones, and likelihood of potential environmental situations such as sun glare. While the route provided an opportunity to collect data, the geographic spread of the route allowed the team to also host live events in each MnDOT District where information was shared about Connected and Automated Vehicles in Minnesota, the state of the industry and vehicle technology, and observations from the drive.

Data was gathered during the drive for use in analysis. The vehicle computers and sensors were operating in “shadow mode” during the drive to collect data while a human driver was in complete control of the vehicle at all times. This data was post-processed using lane detection algorithms to identify areas along the driven route where vehicles using certain ADAS features like Lane Keep Assist or Lane Centering may encounter issues. The project team manually reviewed the post-processed data and called out areas where different roadway conditions would likely cause problems or areas that appeared to be conducive to proper ADAS behavior. The various items identified were grouped into eight categories that, depending on the specific infrastructure, setting, and context could cause the technology to disengage and are as follows:

- **Freeway Ramps and Turn Lanes** – Specifically situations where the opening is not delineated from the major roadway travel lane.
- **Poor Lane Line Condition and Visibility** – Existing markings that have worn off substantially or been partially covered during maintenance activities.
- **Construction and Maintenance Activities** – Existing markings covered or removed more conspicuously than how temporary markings are placed.
- **Poor Contrast** – Light markings on light colored pavement.
- **Tight Curvature** – Situations with horizontal curvature tighter than what is normally experienced affecting lane recognition.
- **Environmental Issues** – Fog and extreme shadowing as well as other issues such as sun glare and precipitation.
- **Dynamic Lanes** – Areas with unique pavement markings or pavement markings intended to illustrate two different outcomes.

These different categories may have specific ties to existing policies and guidance commonly used by practitioners charged with maintaining and designing these roadway facilities. This study does not specify changes to these policies that should be enacted but rather provides the findings for existing committees and agency professionals to use to make improvements that in most cases will benefit both automated driving systems as well as human drivers.

# 1. INTRODUCTION

How ready are Minnesota Roads for Connected and Automated Vehicles (CAV)? Drive MN was an effort undertaken to begin answering this question based on driving a sample of Minnesota roadways of various settings (pavement type, functional classification, intersection control, time of day/daylight conditions, and roadway widths). Technology-equipped research vehicles were utilized on the drive to gather radar, LiDAR, and video data on over 1,000 miles of roadway. This discovery mission was meant to provide findings and information from the drive to key individuals and committees both within MnDOT as well as the Minnesota transportation industry as a whole for use in future decision making.

## 1.1 PROJECT PURPOSE

The purpose of Drive MN was to understand CAV infrastructure readiness, executed by sharing vehicle/infrastructure interaction with transportation professionals and elected officials. Drive MN consisted of three primary activities:

- *Drive:* Equipped vehicles gathered data along a sampling of road types while driving to designated event locations around Minnesota.
- *Events:* Short, demonstration events at each location showcased vehicle automation and its interaction with road infrastructure.
- *Post-Processing and Report:* Data was post-processed to identify areas of interest. This report summarizes key findings about this data and participant interactions during events.

### 1.1.1 Goal: Understand AV readiness with respect to infrastructure and policy

There are many guiding documents and policies related to infrastructure decisions. From a pure design perspective, the MnDOT Facility Design Guide, MnDOT Traffic Engineering Manual, and Minnesota Manual of Uniform Traffic Control Devices are examples of guiding documents that shape decisions impacting infrastructure on a daily basis. How decisions are made through implementing infrastructure projects may have different levels of compatibility with CAV technologies. The same can be said of maintenance practices and how those efforts leave a segment of roadway after completion. Understanding how these elements factor into infrastructure readiness for vehicle automation was a critical goal of this work.

### 1.1.2 Goal: Engage with local policy makers and transportation professionals

Given the nature of the drive itself and the project, the team had the opportunity to build a route in a way that engaged with a variety of local elected officials and transportation professionals along the way. While the primary purpose of Drive MN was data collection, the team saw the opportunity to build off the 2018-19 CAV scenario planning workshops[1] in which city, county, and regional transportation

[1] http://www.dot.state.mn.us/automated/scenario-planning-workshops.html

organizations were engaged to identify challenges, opportunities, and potential responses to CAV in Minnesota. The focus of the engagement was to educate participants about CAV work in Minnesota, provide tours of vehicle technology used during the drive, and share highlights about observations made during the drive.

# 2. PROJECT APPROACH

The project team worked with MnDOT to thoughtfully plan both the route and event locations to best serve the purpose and goals of this project. Both elements were critical to procuring good, relevant data as well as engaging with the intended groups of people along the way. The drive took place August 15th-18th, 2022. Each day consisted of two legs of driving and two events. **Section 4.1** describes the process used to collect data during the drive, as well as post-processing methodology.

## 2.1 ROUTING

The route for DriveMN was curated to collect both a depth and breadth of roadway and intersection types across the state of Minnesota. Through all eight MnDOT districts, the overall route included the following characteristics as shown in **Figure 1**.

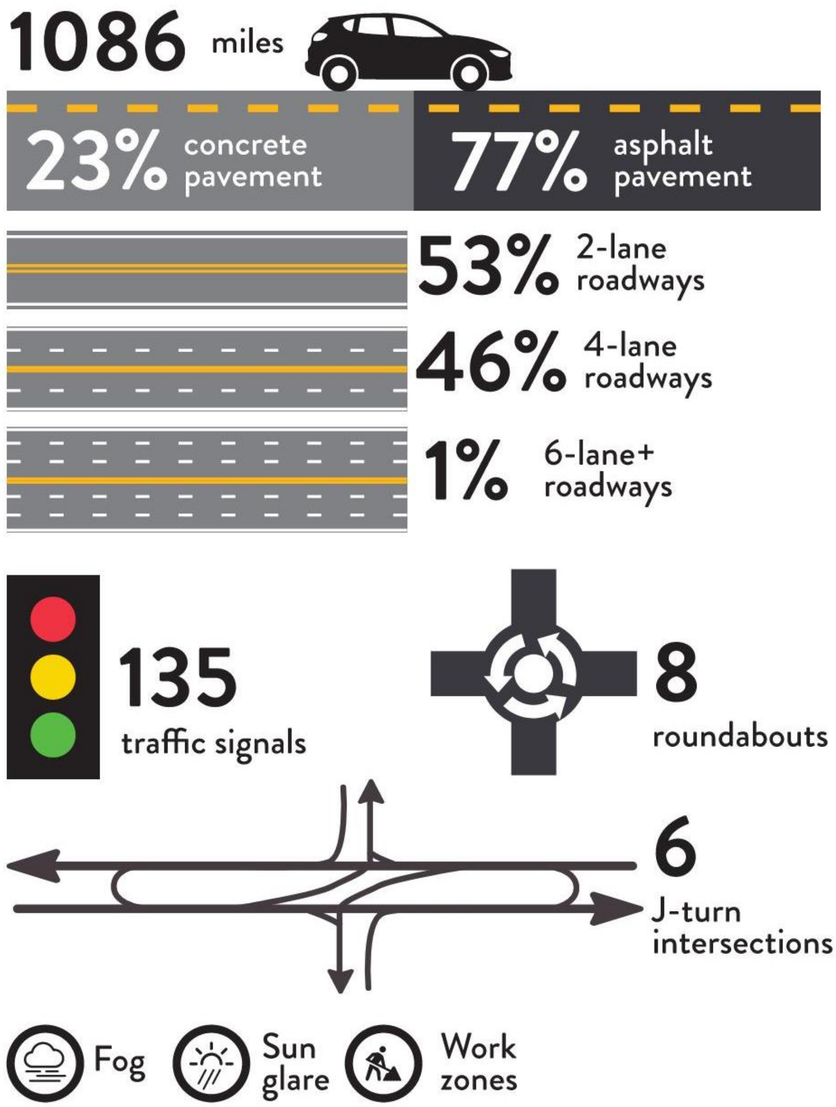


**Figure 1 - Route Summary Statistics**

The variety in pavement material, roadway configuration, and intersection control paired with environmental factors such as sun glare and potential weather events made this a very diverse route. See **Figure 2** for a map of the route.

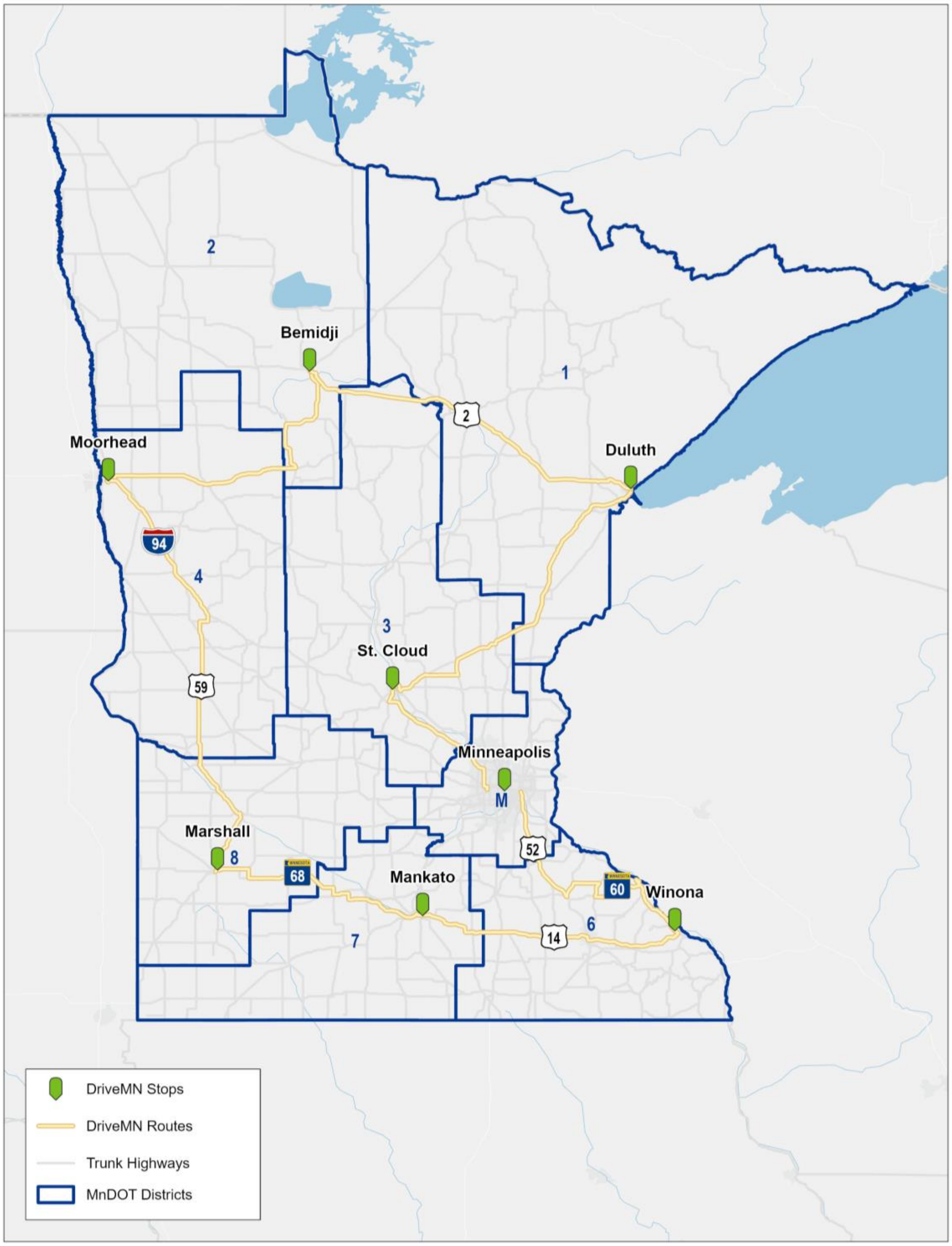


Figure 2 - Route Overview

### 2.1.1 Event Destinations and Route Legs

Drive MN began and ended in the Twin Cities Metro and included stops at seven other locations. The locations were selected from those used in the 2018-19 CAV scenario planning workshops. The stops at each location necessitated the following route breakdown into eight legs as follows:

- Leg 1: St. Louis Park to St. Cloud
- Leg 2: St. Cloud to Duluth
- Leg 3: Duluth to Bemidji
- Leg 4: Bemidji to Moorhead
- Leg 5: Moorhead to Marshall
- Leg 6: Marshall to Mankato
- Leg 7: Mankato to Winona
- Leg 8: Winona to U of M Campus

### 2.1.2 Guiding Principles

The route and leg splits were developed and selected based on the following guiding principles:

1. The duration and distance of each leg fit into the overall schedule needs.
2. 10-20% of total route (max) to be non-Trunk Highway. The intent of the study was to analyze Trunk Highway performance with Advanced Driver Assistant Systems (ADAS) equipment, which can be used as surrogate data in discussing performance on the local system as well.
3. Encounter a reasonable cross section of the following characteristics:
    a. Pavement type (bituminous vs. concrete)
    b. Functional classification
    c. Traffic control (signals, stop signs, roundabouts, RCIs)
    d. Number of lanes
    e. Sun glare vs. normal driving conditions
    f. Construction vs. normal roadway conditions

### 2.1.3 Route Data

In total, the overall route allowed the team to analyze 1,086 miles of roadways across the State of Minnesota. The legs of the route were developed with the Guiding Principles in mind and are shown in the route figures in **APPENDIX A: Route Maps**. The mapping displays characteristics about each leg as well as where particular traffic control devices, potential sun glare, and construction were encountered. The route characteristics are also summarized in **Figure 3** through **Figure 7** by leg and for the overall drive. The horizontal dotted lines in **Figure 3** through **Figure 6** represent the statewide split for each metric to provide context as to how the route compares to statewide statistics.[2]

2 Statewide statistics were developed based on available GIS data that was not independently verified by the project team.

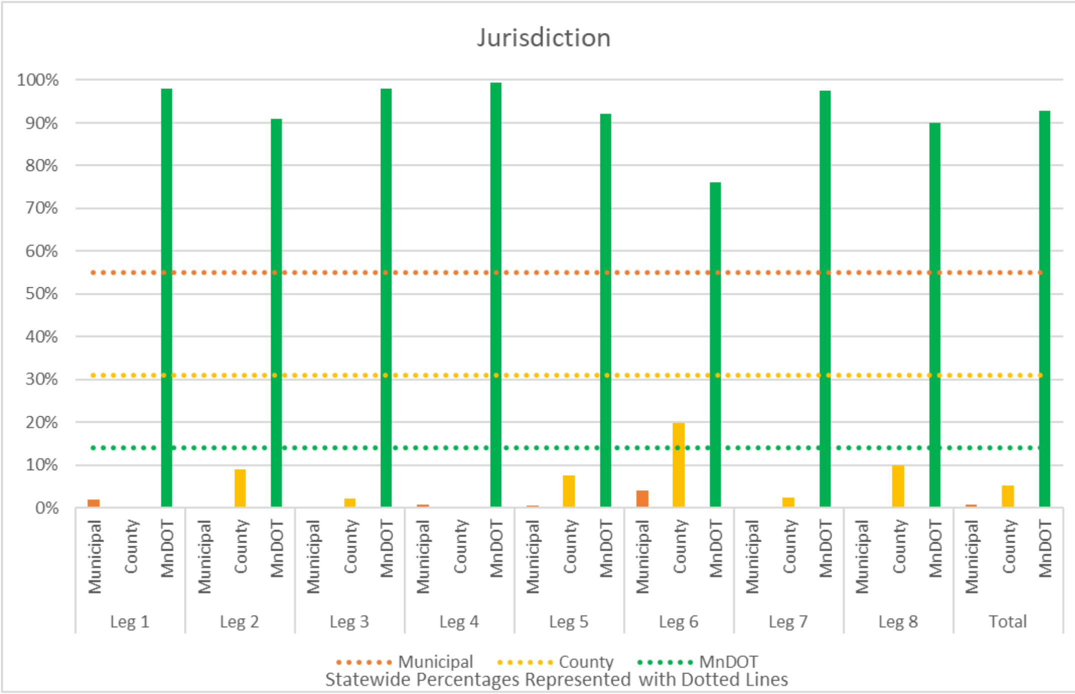


**Figure 3 - Route Jurisdiction Breakdown**[3]

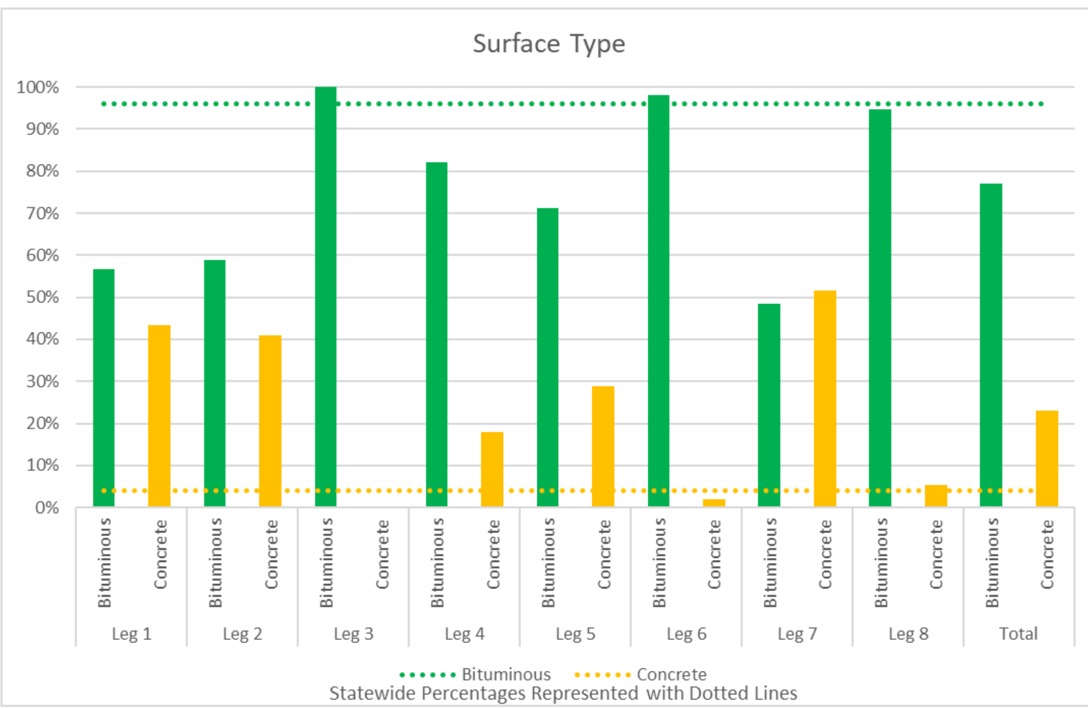


**Figure 4 - Route Surface Type Breakdown**

[3] Share of local routes is significantly higher on Leg 6 due to construction and subsequent detour along TH 14 west of Mankato.

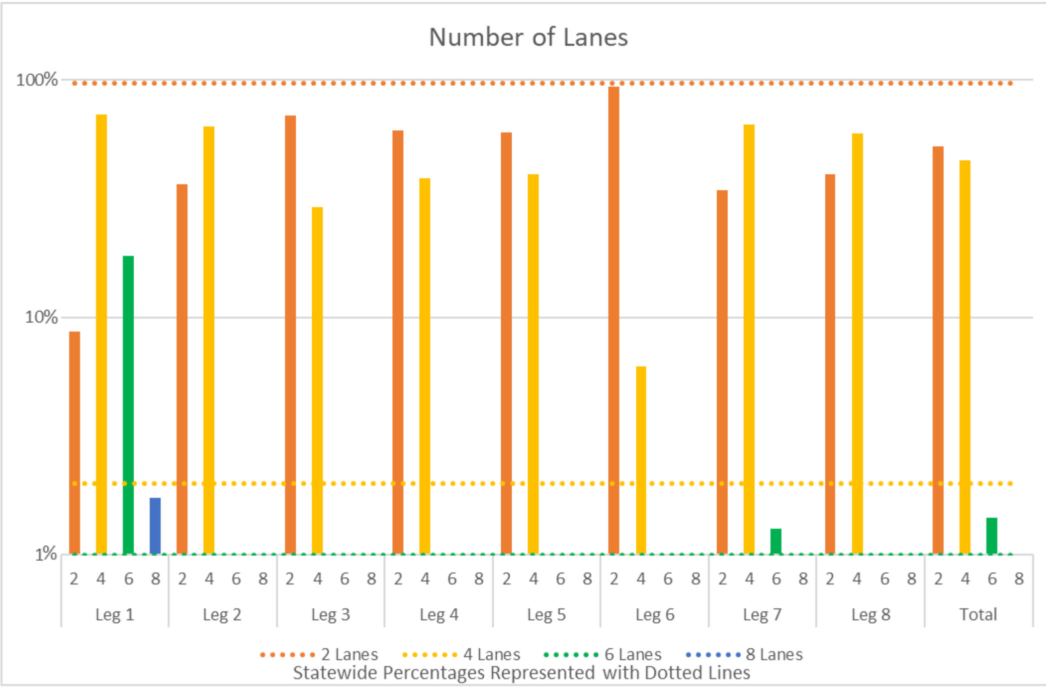


**Figure 5 - Route Number of Lanes Breakdown[4]**

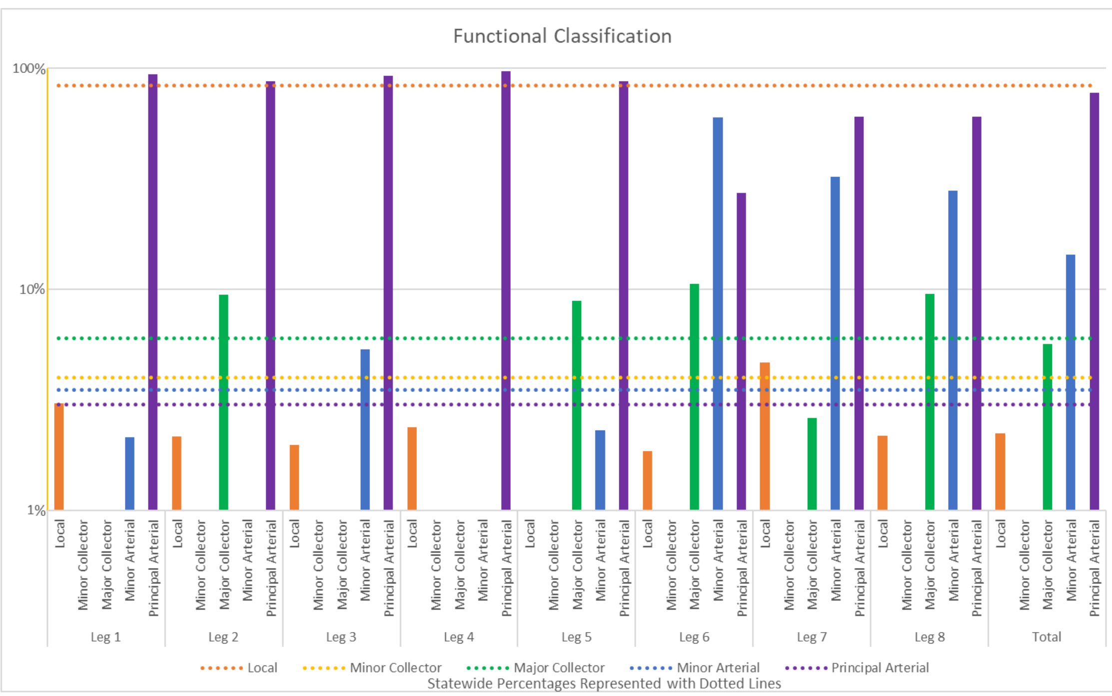


**Figure 6 - Route Functional Classification Breakdown[5]**

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[4] Due to log scale, any values under 1% are not shown.

[5] Due to log scale, any values under 1% are not shown.

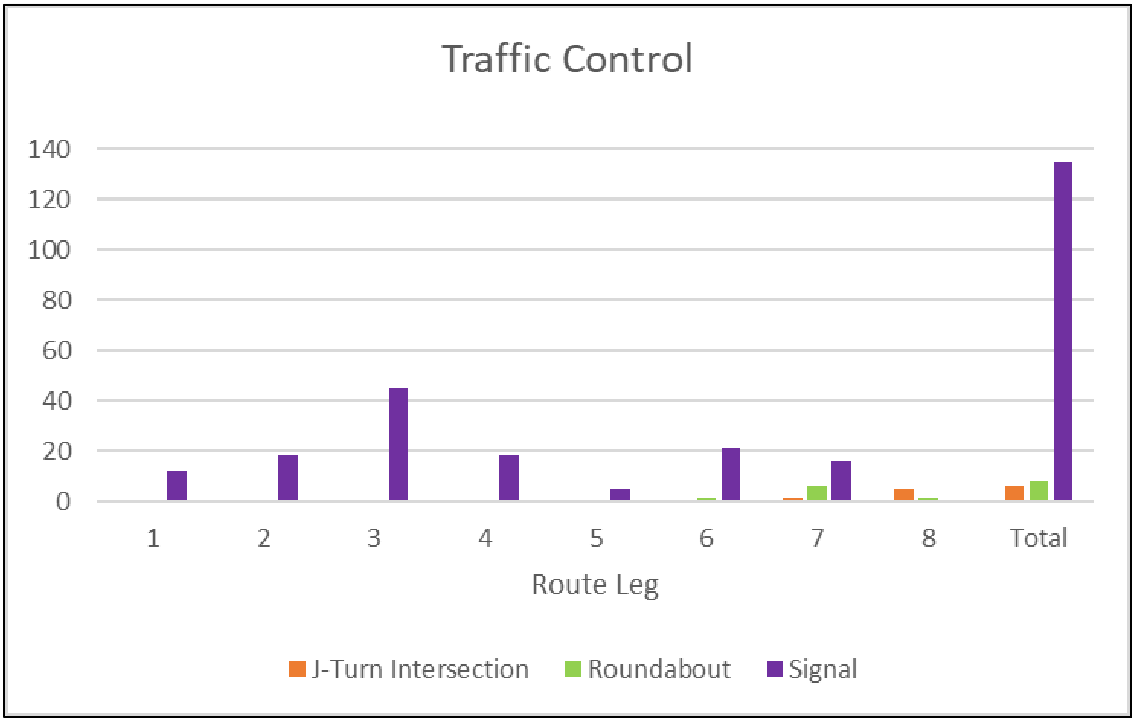


**Figure 7 - Route Traffic Control Type Breakdown**

## 2.2 EVENTS

Each of the events included a presentation about the state of CAV initiatives in Minnesota, information about vehicle technology, and preliminary observations from the drive.

The presentation was followed by an opportunity for question-and-answer, tours of the vehicles, and breakout conversations. This allowed the team to glean insight from local roadway and political jurisdictions, as well as share thoughts, concerns, experiences, and observations unique to the area. **Figure 8** exemplifies an event format and turnout. Ultimately, these events and conversations allowed the team to better connect with statewide and local planners to learn and prepare for future CAV use in Minnesota.

Figure 8 - Event Held in Bemidji

### 2.2.1 Event Summaries

High-level summary information can be found in **Table 1** to provide a sense of both event scale and attendance. A frequently asked questions list was also developed summarizing the events which can be found in **APPENDIX B: Frequently Asked Questions from Events**.

Table 1: Event Locations and Attendees

| Location | Registered Attendance | Authorities and Personnel Present |
|---|---|---|
| Saint Cloud | 12 Attendees | State Patrol, Saint Cloud APO, Sherburne County, Congress members, Benton County |
| Duluth | 21 Attendees | Douglas County, Metro Interstate Council (MIC), Duluth Transit Authority (DTA), MnDOT, St. Louis County, UW-Superior, Duluth City Council, Duluth Seaway Port Authority (DSPA), Various Other Industry Professionals |
| Bemidji | 7 Attendees | MnDOT- D2, State Patrol, City of Bemidji, Various Other Industry Professionals |
| Moorhead | 14 Attendees | Grand Forks/East Grand Forks MPO, AAA, North Dakota State University, Fargo/Moorhead Metro Council of Governments, MnDOT-D4, Minnesota State University- Moorhead, City of Moorhead, City of Barnesville |
| Marshall | 6 Attendees | MnDOT- D8 Traffic, State Patrol, Lincoln City Highway Department |
| Mankato | 17 Attendees | MnDOT, City of St. Peter, Nicollet County, Various Other Industry Professionals |
| Winona | 9 Attendees | MnDOT, Plum Catalyst, Winona County, Various Other Industry Professionals |
| Twin Cities | 50+ Attendees | NiceRide MN, University of Minnesota, FHWA, MN Senate and House of Representatives, MnDOT, Minnesota Information Technology (MNIT), Various Other Industry Professionals |

### 2.2.2 After Survey Results

Following the Drive MN events, the team sent out a thank you email to attendees that included a survey to gauge general acceptance of CAV in Minnesota. Of the approximately 101 total Drive MN event attendees, fourteen responded to the follow-up survey and results were compared to previous CAV surveys at both the national level and within Minnesota.

**Figure 9** below is a side-by-side comparison of the 2018 AAA (American Automobile Association) survey, the 2018 Minnesota State Fair survey, 2020 live CAV demonstrations conducted with the Minneapolis/St Paul Metropolitan region, and the 2022 Drive MN survey. The surveys are not an apples-to-apples comparison[6] or necessarily all statistically significant; however, acceptance of CAV appears to be trending up with a positive correlation between the level of demonstration exposure and acceptance to an automated vehicle.

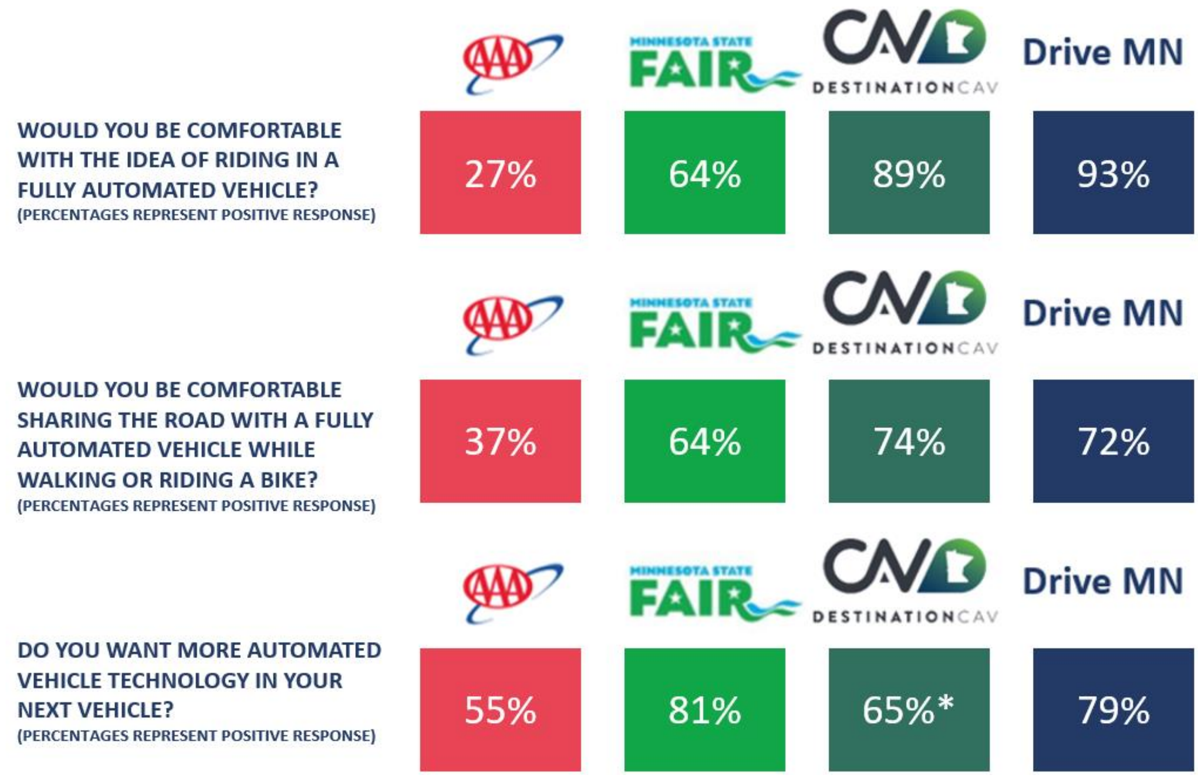


**Figure 9 - Survey Result Comparison[7]**

*After the live demo experience, 65% of attendees stated they wanted more automated vehicle technology in their next vehicle which shows a decrease from the previous Minnesota State Fair static demo. This response was accompanied with questions and concerns about the cost of the technology and responsibility and ethical considerations for owning that technology. This led the demonstration team to believe the experience made the technology more real to attendees. It should also be noted that the research vehicle used is more technical in appearance and doesn't resemble what a personal vehicle would look like.

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[6] Each of these surveys was not based on the same style of event. For example, some included live demonstration and some did not. The data presented at each was also not the exact same either.

[7] A summary of each survey is as follows:

- 2017 AAA Survey: An online nationwide survey in which respondents did not have any exposure to a connected and automated vehicle.
- 2018 Minnesota State Fair Survey: A survey administered (in person) to respondents who participated in a static demonstration meaning they did not ride in an automated vehicle but were able to see an automated vehicle and talk to an attendant about the technology.
- 2020 Live CAV Minnesota Survey: A survey administered (in person) to participants after they took a ride in a level 2 automated research vehicle.
- 2022 Drive MN Survey: An online survey administered to a group who had recently attended a static demonstration at a Drive MN event location.

# 3. THE VEHICLES AND AUTOMATION TECHNOLOGIES

While fully automated vehicles are still being developed and tested, components of automation are very common on our roadways today. The varying levels of automation available in new cars today drove the need and raised the importance of this project and its findings. The Society of Automotive Engineers lists six levels of automation in vehicles, the first three leave the driver responsible for monitoring the road conditions, traffic, weather, and other surroundings. The six levels are as follows:

1. **No automation (Level 0):** Driver handles steering, throttle, and braking with no assistance.
2. **Driver Assistance (Level 1):** Car can handle some elements of steering, throttle, and braking. Requires constant driver attention. Able to operate in a limited Operational Design Domain (ODD)
3. **Partial Automation (Level 2):** Car can handle all facets of steering, throttle, and braking. Requires constant driver attention. Able to operate in a limited ODD.
4. **Conditional Automation (Level 3):** Car monitors surroundings and handles all steering, throttle, and brake in certain environments. Driver must be ready to intervene if car requests it. Able to operate in a limited ODD.
5. **High automation (Level 4):** Car monitors surroundings and handles all steering, throttle, and brake in a wider range of environments, but not all (such as severe weather). Driver is not required once automation is turned on. Able to operate in a limited ODD.
6. **Full automation (Level 5):** The car can handle all elements of driving in an unlimited ODD. Driver is not required once automation is turned on.

## 3.1 ADAS TECHNOLOGIES

Over 90% (AAA, 2019) of new vehicles sold come equipped with at least one Advanced Driver Assistance System (ADAS). Approximately 50% of these vehicles come equipped with Lane Keep Assist (Consumer Reports, 2021), a system designed to assist the driver in preventing the vehicle from departing the lane when active. The Insurance Institute for Highway Safety and Highway Loss Data Institute studied the effects of such features in passenger vehicles and estimate significant positive impacts on roadway safety[8]. Common ADAS features found in new vehicles are typically Level 0 or Level 1 systems by themselves, but when paired with other active systems may be considered Level 2 in total[9].

[8] https://www.iihs.org/media/259e5bbd-f859-42a7-bd54-3888f7a2d3ef/e9boUQ/Topics/ADVANCED%20DRIVER%20ASSISTANCE/IIHS-real-world-CA-benefits.pdf

[9] For example, the combination of certain Level 1 systems (Lane Centering and Adaptive Cruise Control) would be considered a Level 2 system

The following is a list of common ADAS technologies available on new production vehicles today. Some of these technologies rely on the surrounding infrastructure to function properly, namely Lane Keeping Assist, which was analyzed with this work.

- Adaptive Cruise Control
- Automatic Emergency Braking
- Blind Spot Warning
- Forward Collision Warning
- Lane Keeping Assist

While this drive did not directly analyze a fully autonomous scenario, the tools analyzed are foundational to understanding the capabilities and responses of the technology over various roadway conditions. The analysis is a step in further improving technologies, roadways, and enhancing driver/rider experience. Horizontal/lateral control (i.e. Lane Keep Assist) is a major element required for full autonomy, which is essentially the combination of full lateral and longitudinal control. With these technologies ever more present on new vehicles today, slowly increasing fleet penetration, understanding the interaction with infrastructure is critical.

## 3.2 THE VEHICLES

Two research vehicles were driven for this project: a Ford Fusion (Vehicle 1) and a Chrysler Pacifica (Vehicle 2). Each vehicle was outfitted with a drive-by-wire kit, numerous sensors, and significant computing power to handle the collection and storage of data throughout the drive. See vehicle equipment lists below for an inventory of sensors installed. Equipment designated with a (*) was directly used in collecting and storing data eventually analyzed with this project. Camera technology is considered the best sensor type for lane marking detection, therefore those were the sensors utilized for analysis purposes.

**Vehicle 1 (Figure 10)**

- (1) 64-channel Outser Lidar
- (1) Aeye LR Ouster
- (1) Lucid HDR Camera*
- (1) Blackfly Camera*
- (1) Flir Thermal Camera
- (1) Aptiv ESR MR/LR Radar
- (1) Trimble RTX positioning*
- (1) Crystal Rugged Liquid cooled computer*

**Vehicle 2 (Figure 11)**

- (1) 64-channel Outser LiDAR
- (2) 16-channel Ouster LiDARs
- (4) Blackfly video cameras
- (1) FLIR ADK thermal camera
- (2) Conti Radar
- (1) Novatel GNSS receiver
- (1) Neousys Nuvo computer

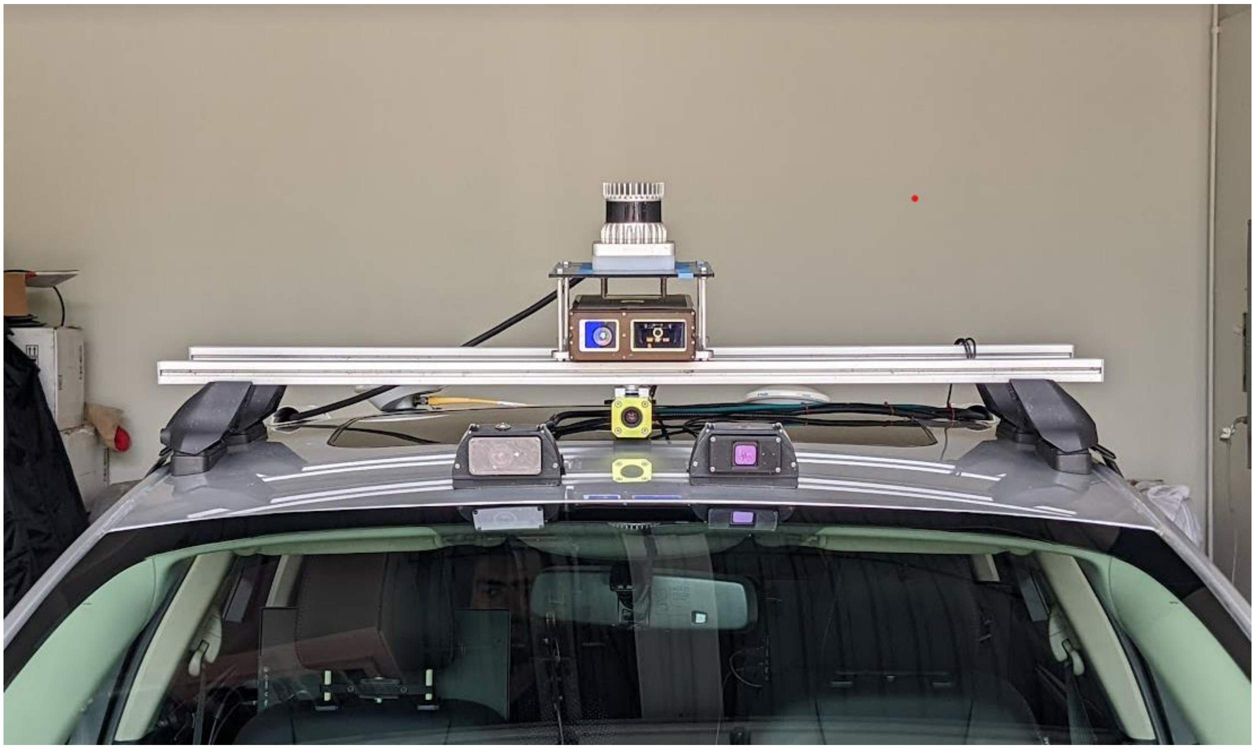

**Figure 10 - Image of Vehicle 1 Top Rack**

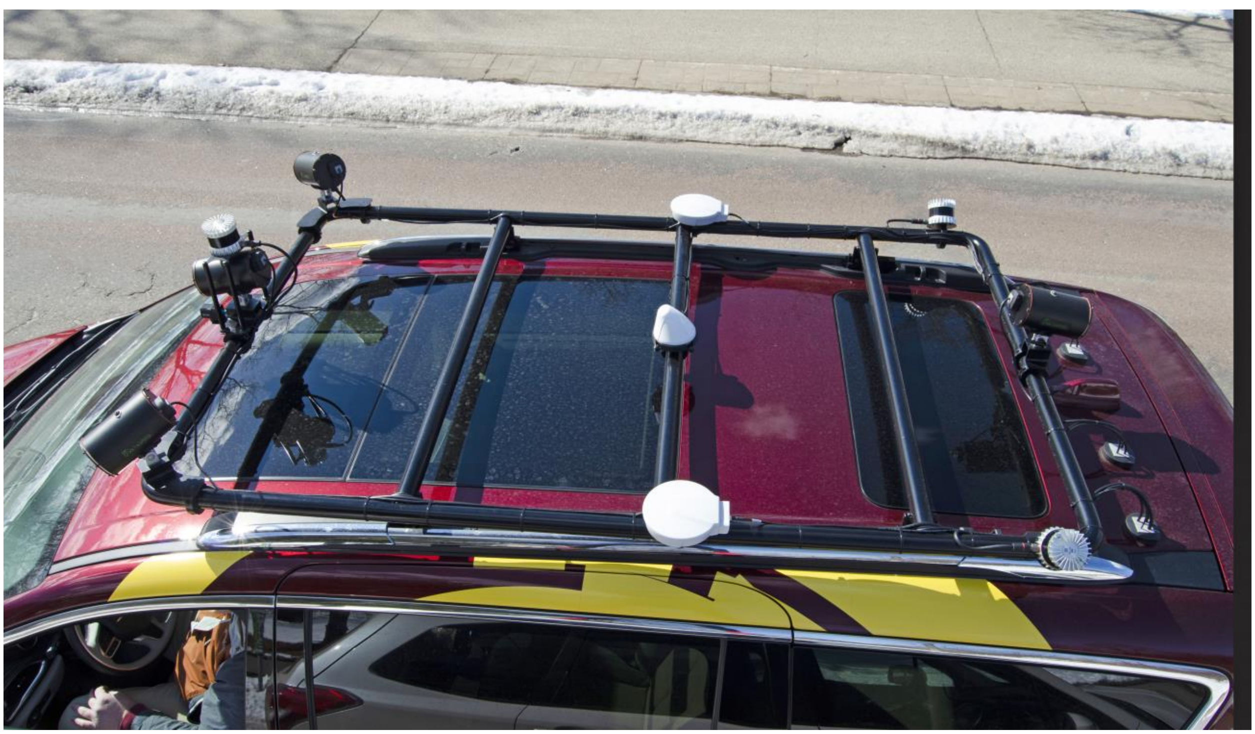

**Figure 11 - Image of Vehicle 2 Top Rack**

# 4. ANALYSIS METHODOLOGY AND FINDINGS

## 4.1 METHODOLOGY

The overall methodology implemented is outlined in **Figure 12** and consisted of three steps: data collection, post processing, and manual annotation/QAQC.

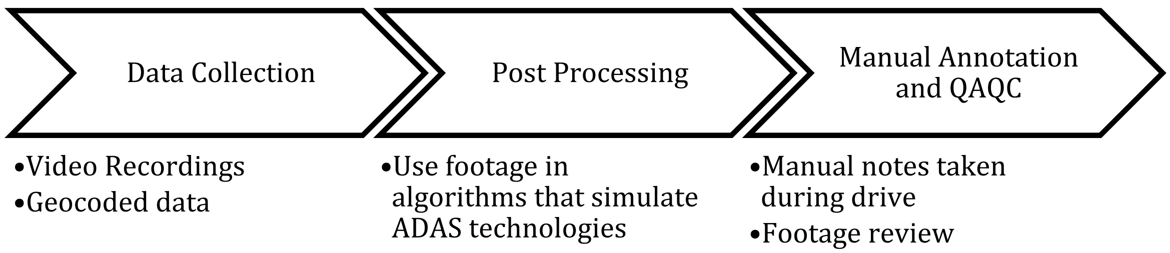


Figure 12 - Analysis Methodology

### 4.1.1 Data Collection

Each vehicle included three team members: the driver, a traffic engineer, and a systems engineer. While the vehicles driven are capable of full automation in certain settings, available onboard computing power is not sufficient to both run active automation and collect data simultaneously. Given the main goal of data collection, each vehicle was 100% driven by a human during this project with no ADAS functions active. This meant that driving best practices were implemented whenever possible, such as driving in the rightmost lane, only overtaking when required, and driving the posted speed limit. The traffic engineer rode in the front passenger seat and was actively engaged in discussions with the driver and systems engineer about the status of the vehicle, as well as monitoring the infrastructure and environment for potential annotations. The annotation process is further described in 4.1.3 The systems engineer rode in a rear seat and monitored the vehicle computer and sensor suite to keep all systems active, functioning, and collecting data during the drive.

Between the two vehicles, at least 4.2 terabytes of data were collected during the drive and stored for post processing. Note that both Vehicle 1 and Vehicle 2 collected data, however only the data from Vehicle 1 was used in post processing. Data collected from Vehicle 2 was considered backup data in the event data from Vehicle 1 was compromised.

### 4.1.2 Post Processing

The main benefit of collecting data during the drive and using post processing is that the experience captured during the driven route can be played back as many times as desired using different algorithms simulating various ADAS technologies – namely lane keep assist. A secondary benefit is that flagged areas where the system fails can be reviewed in detail to better understand the reasons for failure. The other option would have been to drive the route with ADAS technologies active and annotate issues on the fly, which was not preferred by the project team given the added possibilities of missing key items.

For this project, data from two cameras was processed through two unique algorithms[10], generating four computing instances to validate conditions and findings. The first step in the processing involves the algorithm placing raw detections (tiny dots) in places where there is enough contrast. During the second step, the algorithm attempts to join those dots into best fit lines. The line fitment is controlled by parameters that determine what is possible or not. For example, the algorithm would not draw a line in a horizontal manner, in a zigzag pattern, or if lines crossed. Ultimately, if the computer has enough confidence in what it sees it produces a virtual line that should overlay the marked line on the pavement.

### 4.1.3 Manual Annotation and QAQC

Annotation occurred two separate times during the process. First, geocoded annotations were entered during the drive to flag certain elements of interest. These included areas of concern related to infrastructure condition, encounters with vulnerable road users, sun glare and other environmental influences, as well as areas where both the driver and engineer believed the roadway facilities were very suitable for ADAS use. The first round of annotation was done based only on the suspicion of issues or high suitability. Second, manual annotations were completed in the form of written or typed notes based on the raw output from the postprocessing exercise to perform quality checks on the results. These were utilized to confirm or better define why the software process flagged certain areas along the route. For example, if the vehicle was traveling along a roadway with notable traits (marking deficiency, roadway curvature, weather event), a note might include information about what was observed at the location of the occurrence. This was a critical step to better understand why a certain area was flagged. Over 300 items were annotated as part of this process, and the frequency of each item's occurrence is shown below in **Figure 13.** The frequency of the study's callouts is not necessarily indicative of the total frequency on the roadways, nor do they imply or assign severity. These were items that caused misdetections or were good examples of proper detection that could spur further discussion and analysis on potential CAV behavior when encountering that specific situation.

10 Algorithms used in this project ("Lanenet" and "Apollo") are open source and not specific to any given OEM.

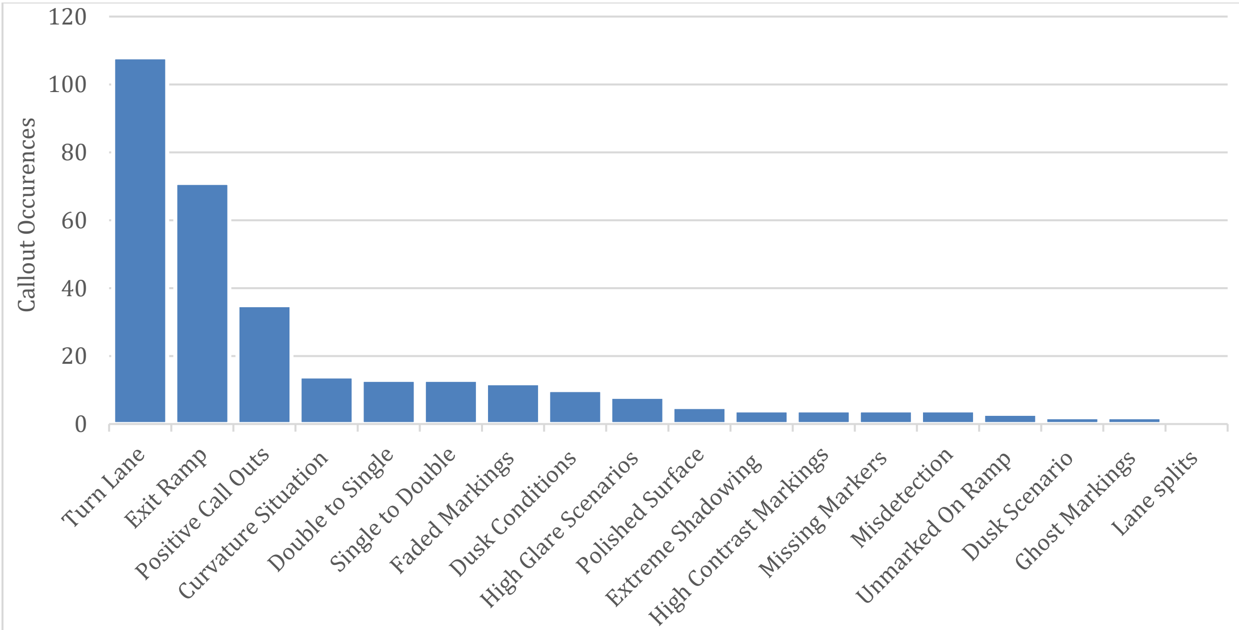


**Figure 13 - Breakdown of Annotated Callouts**

## 4.2 FINDINGS

As mentioned, the route for Drive MN was chosen to consume the widest variety of roadways in Minnesota. The 300-plus items noted during the drive were tagged according to the different categories shown previously in **Figure 13**, with some instances having up to three different tags. The team developed eight categories from the list of items to best highlight the overall findings. The following findings are purely observational and are intended to be used as indications of how vehicle automation may respond to similar situations found on Minnesota roadways.

The following descriptions contain photos from the drive either from the BlackFly or Lucid cameras on board Vehicle 1. In each image, lanes are delineated by colored lines placed during post processing depicting the machine vision view derived from the sensor data. The team drew conclusions from the data based on how well the digitized lines aligned with the markings on the road. Note that the color of the lines placed on the images through postprocessing are purely for contrast purposes and do not have specific meanings other than that each is a detected line.

### 4.2.1 Freeway Ramps and Turn Lanes

When driving in the right-most lane, a vehicle is adjacent to an exit ramp, entrance ramp, or turn lane. These features include a mixing area where vehicles are entering or exiting the major roadway that can either have a delineation marking the major roadway edge or no marking. When vehicle automation relies on striping to the left and right of the travel path, this lack of striping may cause a misdetection, potentially causing the vehicle to follow an incorrect path despite driver and route intentions. **Figure 14** and **Figure 15** show desirable and undesirable vehicle paths on entrance and exit ramp configurations to illustrate this issue.

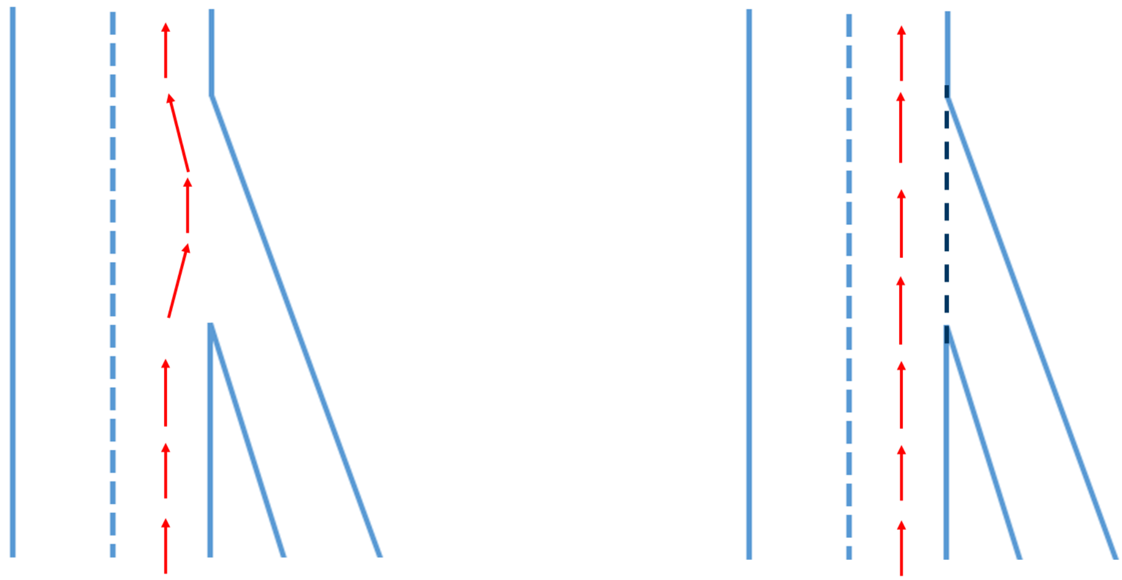

Figure 14 - Entrance Ramp Diagram (Undesirable Vehicle Path on Left, Desired Vehicle Path on Right)

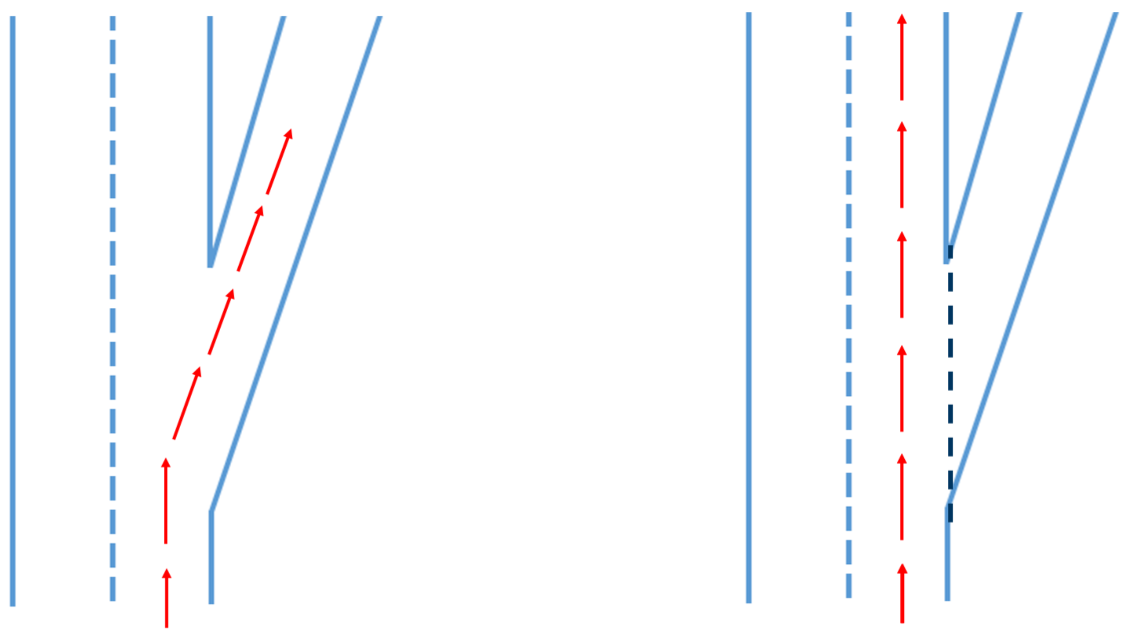

Figure 15 - Exit Ramp Diagram (Undesirable Vehicle Path on Left, Desired Vehicle Path on Right)

Figure 16 - Misdetection of Lane Due to Unstriped Diverge Area

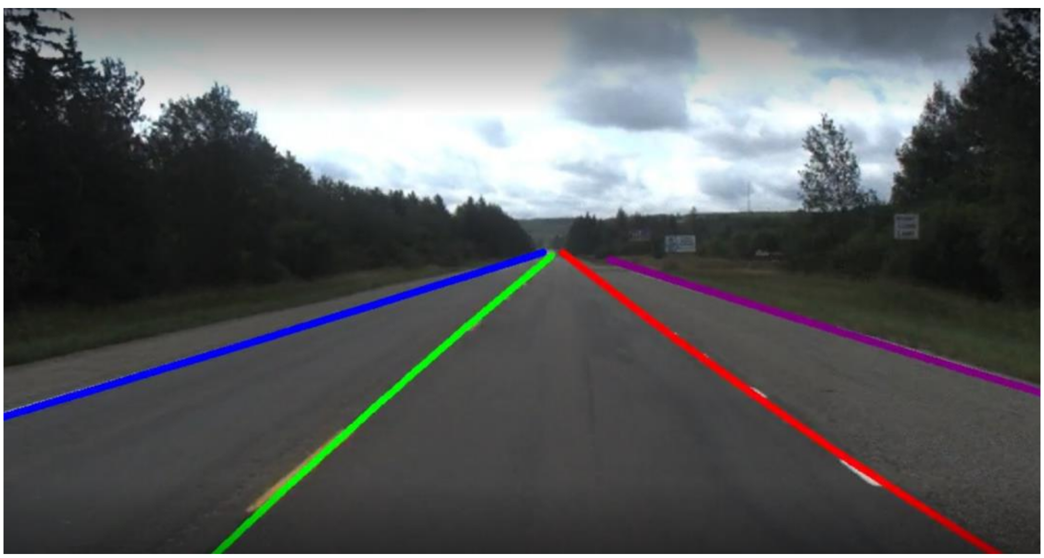

Figure 17 - Proper Detection of Lane Due to Dotted Line Placement

As seen in **Figure 16,** the unmarked area between the right driving lane and the turn lane causes the sensor to assume the driving lane continues into what is actually the turn lane (the red line). **Figure 17** shows how the continuous marking leads to the proper delineation of a turn lane which allows the sensor to distinguish the edge of the current driving lane (red) and the edge of the turn lane (purple).

### 4.2.2 Poor Lane Line Condition and Visibility

Similar to a lack of right edge striping in the driving lane for an exit ramp or turn lane, improper or insufficient centerline markings may cause a misdetection that could lead to incorrect automated vehicle horizontal control.

Figure 18 - Example of Poor Lane Line Visibility

Various conditions may contribute to poor centerline visibility on the roadway. Deteriorating pavement, chipped or faded markings, or pavement repairs can make it difficult for the vehicle's equipment to properly place the edge line, as seen in **Figure 18**. Therefore, the system believes the outside edge of the driving lane is the edge of the opposite direction's lane (green). This could cause the vehicle to veer into the oncoming driving lane while centering itself in its intended driving lane.

Figure 19 - Fresh Markings Increases Centerline Visibility

As illustrated in **Figure 19**, the contrast and quality of pavement materials and markings make it easier for the system to determine both the centerline and edge lines to keep the vehicle in the proper center of lane.

### 4.2.3 Construction and Maintenance Activities

Pavement scarring, pavement cracks and joints, or rumble strips may cause misdetection. These instances were more prominent when there were lane reductions or shifts on a roadway due to past or current construction.

**Figure 20** and **Figure 21** show construction zones on multilane highways. In both cases, there are misdetections due to existing markings on the roadways from prior maintenance, masked existing markings, or tire marks.

Figure 20 - Misdetection Due to Crack Seal


Figure 21 - Pavement Scarring/Tire Mark Causes Misdetection

**Figure 22** shows a proper identification of lane markings in a construction zone even though the previous lane marking scar is distinguishable to a human eye. Because the pavement was removed completely and the new marking is more contrasted to the pavement, the system can correctly identify the proper lane marking.

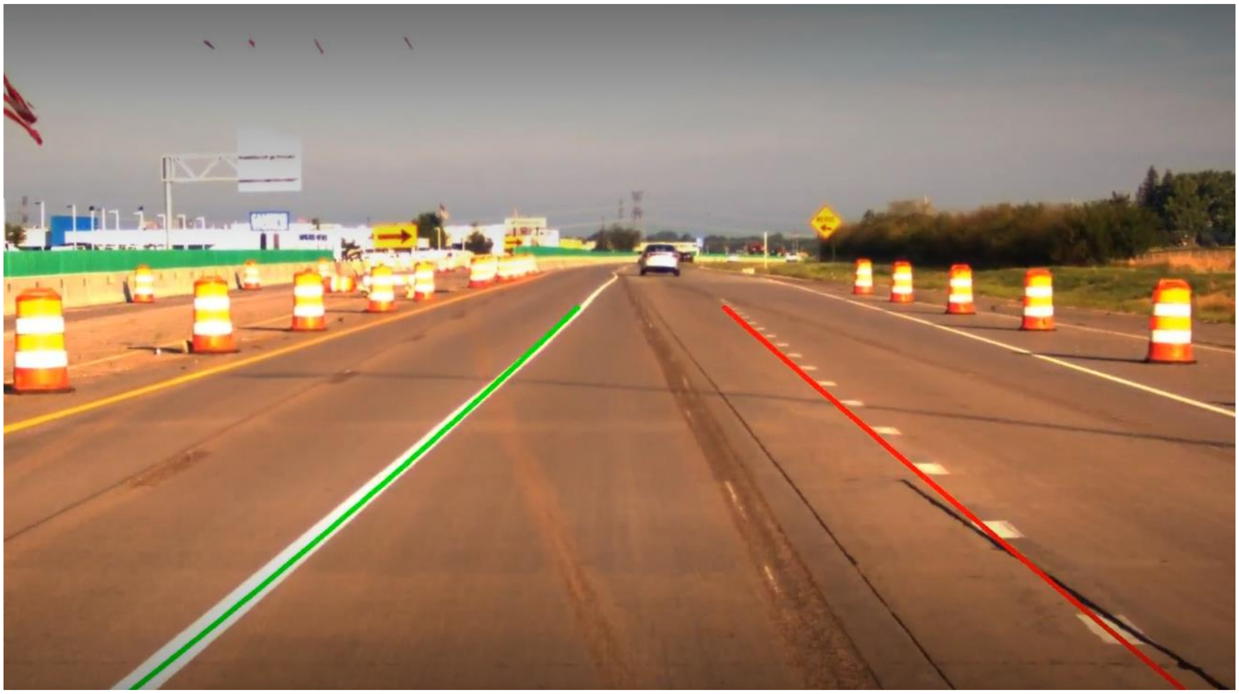

Figure 22 - Proper Identification of Lane Marker in Construction Zone

The sample size for construction work zones was small compared to the route in total, and the examples shown illustrate the potential variability of response in these types of scenarios due to the many factors that could be at play. Certain factors such as pavement type and condition as well as marking color and width appear to affect how a system may identify lanes when there are competing lines like scars or crack seals. It is possible that the system could not identify the left lane marking in **Figure 21** due to the yellow color, versus properly identifying a wider white temporary marking shown in **Figure 22** with higher contrast.

### 4.2.4 Poor Contrast

Poor contrast generally occurs on roadways with light colored pavement in comparison to light colored pavement markings. **Figure 23** shows an instance of poor contrast where the left edge line is not being identified. While the centerline is identified, it may be largely due to the presence of a crack seal versus the actual pavement marking that by human eye does not stand out. **Figure 24** shows an example of high contrast markings that can positively impact the vehicle's ability to properly identify markings even on light colored pavement. The white striping is clearly visible to the system.

Figure 23 - Poor Contrast between Pavement and Striping Contributes to Difficulty Identifying Lane

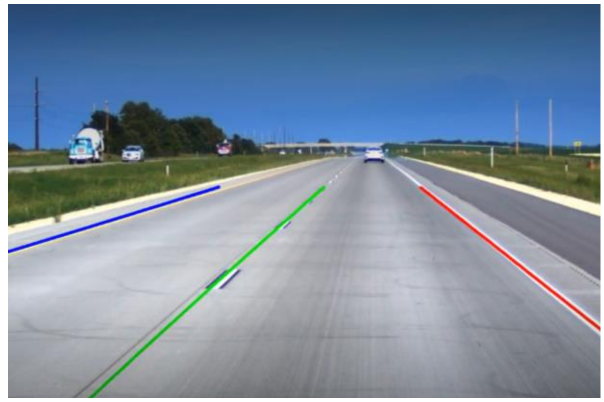

Figure 24 - Higher Contrast Increases Visibility

### 4.2.5 Tight Curvature

In some cases, the horizontal curvature of the roadway was too tight for the system to properly fit lane lines, potentially causing misdetections or poor performance. **Figure 25** shows an example of this. These situations may be unavoidable from a design perspective given the context of many roadways, meaning either more sophisticated/fine-tuned algorithms are needed or high-definition mapping would be required for smooth performance. Most automated driving functions on the market today do not work well in tight curvature situations for the following reasons:

- Camera may not have a wide field of view
- The algorithms are optimized for highway lane keep assist or autopilot applications

Figure 25 - Example of Tight Curvature Causing Poor Performance

### 4.2.6 Environmental Issues

#### 4.2.6.1 Extreme Shadowing

**Figure 26** shows how the blocks of sun and shadows create inconsistent lane marking contrast for the system to utilize. The image shows that the lane line is identifiable for approximately 10-20 feet but once it reaches the block of extreme shadow, it cannot identify the center lane line anymore. **Figure 27** shows how bright sun coming out of a shaded area washes out the image and leads to an inability to detect the center lane marking. Jagged and flickering dark shadows appear to have the most negative impact on system performance. Similar to human eyes, the vision systems are able to perform well in shaded conditions that are more consistent or have smoother transitions from light to dark.

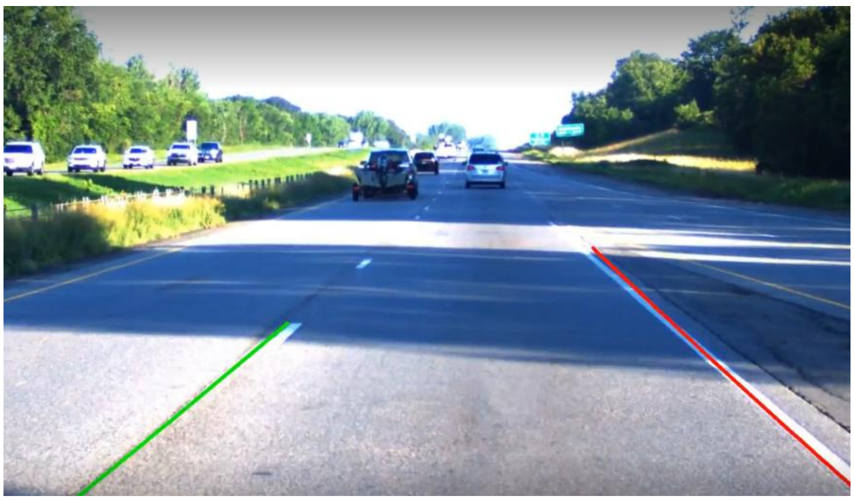

**Figure 26 - Blocks of Sun and Shadows Cause Misdetection of Lane Markers**

**Figure 27 - Especially Sunny Area Makes Marking Indistinguishable**

#### 4.2.6.2 Fog

One instance of fog was experienced during the drive. As shown in **Figure 28**, it was dense enough to cause detection issues on an exit ramp. The frame of video used shows only right edge line partial detection, although on the majority of other frames neither edge line was detected.

**Figure 28 - Poor Sensor Performance in Fog**

### 4.2.7 Dynamic Lanes

A unique feature in Minnesota is the MnDOT MnROAD facility on I-94 between Albertville and Monticello. There are lane markings leading to both roadways, though only one is ever open at a time. Human drivers can distinguish between the path they need to take by using the overhead signals as well as road barriers. However, an automated vehicle may not have the capability to distinguish or choose. The vehicle responded and connected with the lanes as shown in **Figure 29**, which may incorrectly cause the vehicle to attempt to take the rightmost lane. This situation could also arise on other highway splits/merges or in other areas with dynamic lanes and shoulder uses. The behavior demonstrated in **Figure 29** may cause an unintended exit or crash depending on other traffic in the area.

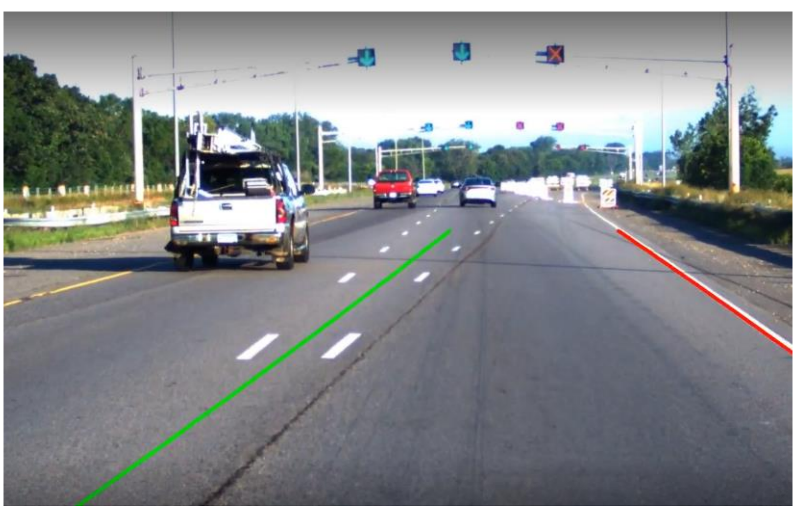

**Figure 29 - MnROAD Lane Closures May Cause Misdetection**

# 5. TIES TO EXISTING TRAFFIC ENGINEERING STANDARDS

The *Minnesota Traffic Engineering Manual (TEM)* and the *Minnesota Manual on Uniform Traffic Control Devices (MnMUTCD)* have specific guidelines and procedures for pavement markings. These are frequently used documents by practitioners that influence how Minnesota roadways look and feel. Guidance and standards exist for many facets of traffic engineering, including several areas that specifically correlate to the findings from this drive. These manuals will likely be updated after the planned release of the Federal MUTCD expected in 2023. The Notice of Proposed Amendments (NPA) for the 11$^{th}$ Edition of the MUTCD contains *Part 5: Automated Vehicles* which provides guidance for different traffic control devices that may impact automated driving safety and performance. In addition to the sources listed in the following sections, *MnDOT's Technical Memorandum 22-01-T-01* includes statewide guidance on marking life expectancy, wet reflectivity, skid resistance, and alternative practices and installations.[11]

## 5.1 HIGH CONTRAST MARKINGS

The MnMUTCD allows the use of black marking when used in conjunction with white markings where "light colored pavement does not provide sufficient contrast with the markings" (MnMUTCD 3A.5). There is no specific measure provided for when contrast markings should be used and therefore is left to engineering judgment. In practice, this is generally interpreted to be referencing white markings on concrete pavements. There are ongoing studies that aim to provide conclusions and guidance on markings: *Assessing Pavement Markings for Automated Vehicle Readiness*[12] and *Human Factors - Pavement Marking Cycle Lengths and Widths*[13]

## 5.2 RETRO REFLECTIVITY AND WET REFLECTIVE MARKINGS

The MnMUTCD includes the following language regarding retro reflectivity. "Markings that must be visible at night shall be retroreflective unless ambient illumination assures that the markings are adequately visible. All markings on Interstate highways shall be retroreflective." Given recent FHWA rulemaking regarding minimum standards (87 FR 47921), the MnMUTCD will likely be updated to provide additional information.

The Minnesota TEM states that pavement markings that have reached a minimum performance level for retro reflectivity must be scheduled for replacement (Mn TEM 7-4.01.02). The TEM also provides a recommendation that any pavement markings installed on pavement expected to last more than three years should be wet reflective (Mn TEM 7-4.01.03).

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[11] https://edocs-public.dot.state.mn.us/edocs_public/DMResultSet/download?docId=15654703

[12] https://researchprojects.dot.state.mn.us/projectpages/pages/projectDetails.jsf?id=23861&type=CONTRACT&jftfdi=&jffi=projectDetails%3Fid%3D23861%26type%3DCONTRACT

[13] https://researchprojects.dot.state.mn.us/projectpages/pages/projectDetails.jsf?id=22013&type=CONTRACT&jftfdi=&jffi=projectDetails%3Fid%3D22013%26type%3DCONTRACT

## 5.3 TEMPORARY MARKINGS AND REMOVAL OF MARKINGS

Section 7-4.05 of the TEM states that markings that are no longer applicable or that may cause confusion shall be removed or obliterated to be unidentifiable as soon as practical. Additionally, removal techniques that may leave pavement scars may confuse drivers. This applies to certain items seen on the road in construction zones and discussed in **Section 4.2.3** .

## 5.4 DOTTED LINE MARKINGS

Line width and pattern guidance for markings within a turn lane or ramp taper can be found in the TEM Section 3A.6 as well as the MnMUTCD Section 3B.4. These dotted lines are shorter and closer together than broken lines. While section 3B-20 generally suggests that dotted lines are optional, MnDOT generally has adopted a practice of using dotted lines as a default option. They are distinguishable from regular lane delineation. See **Figure 30** for an example.

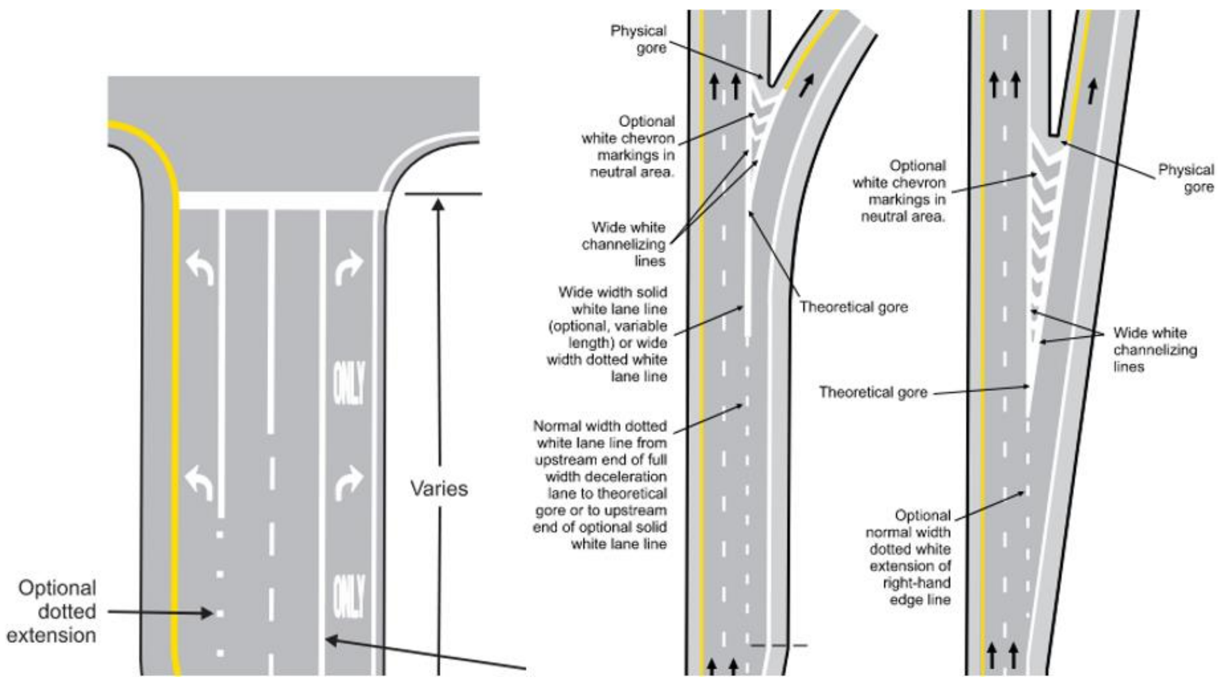



**Figure 30 – Examples of MnMUTCD Guidance on Dotted Extension for Ramps and Turn Lanes, MUTCD Figure 3B-11 (left) and Figure 3B-8 (right)**

# 6. CONCLUSION

While many different situations were identified based on the data processed from the drive, the following key categories were more prevalent than others:

- **Freeway Ramps and Turn Lanes** – Misdetections caused by lack of continuous edge line guidance
- **Poor Lane Line Condition and Visibility** – Misdetections caused by lack of lane lines or poor condition of lane lines
- **Construction Zones or Maintenance Activities** – Misdetections caused in approaches to work zones or along areas of roadway with scarring, ghost markings, or solid lines from crack sealer.
- **Poor Contrast** – Misdetections typically caused by lighter colored pavement with faded/white pavement markings.

The items discussed in this report are meant to outline potentially common occurrences on Minnesota roadways based on the sample that was driven for this project. There are many next steps that could occur following this project to continue learning and make meaningful changes to both the infrastructure and standards/policies influencing the readiness of Minnesota roadways for vehicle automation, some of which are outlined below.

1. Share findings of this project with key decision makers at the state, county, and city levels of government. Key groups may include MnDOT Traffic Engineering Organization (TEO), City Engineers Associate of Minnesota (CEAM), and Minnesota County Engineers Associate (MCEA) among others.
2. Use the forthcoming Federal MUTCD update, particularly the proposed Part 5 – Automated Vehicles, to further conversations in Minnesota about what should be incorporated into the MnMUTCD.
3. Consider detailed evaluation of key corridors or groupings of roadways in advance of programmed projects to ensure roadway suitability for vehicle automation. While findings from this work may capture a significant portion of potential issues on other roadways in the state, specific site conditions (horizontal and vertical curvature, roadside elements such as trees, pavement condition, pavement marking condition, day vs. night performance, etc.) all play a factor in how suitable a certain segment of roadway may be.

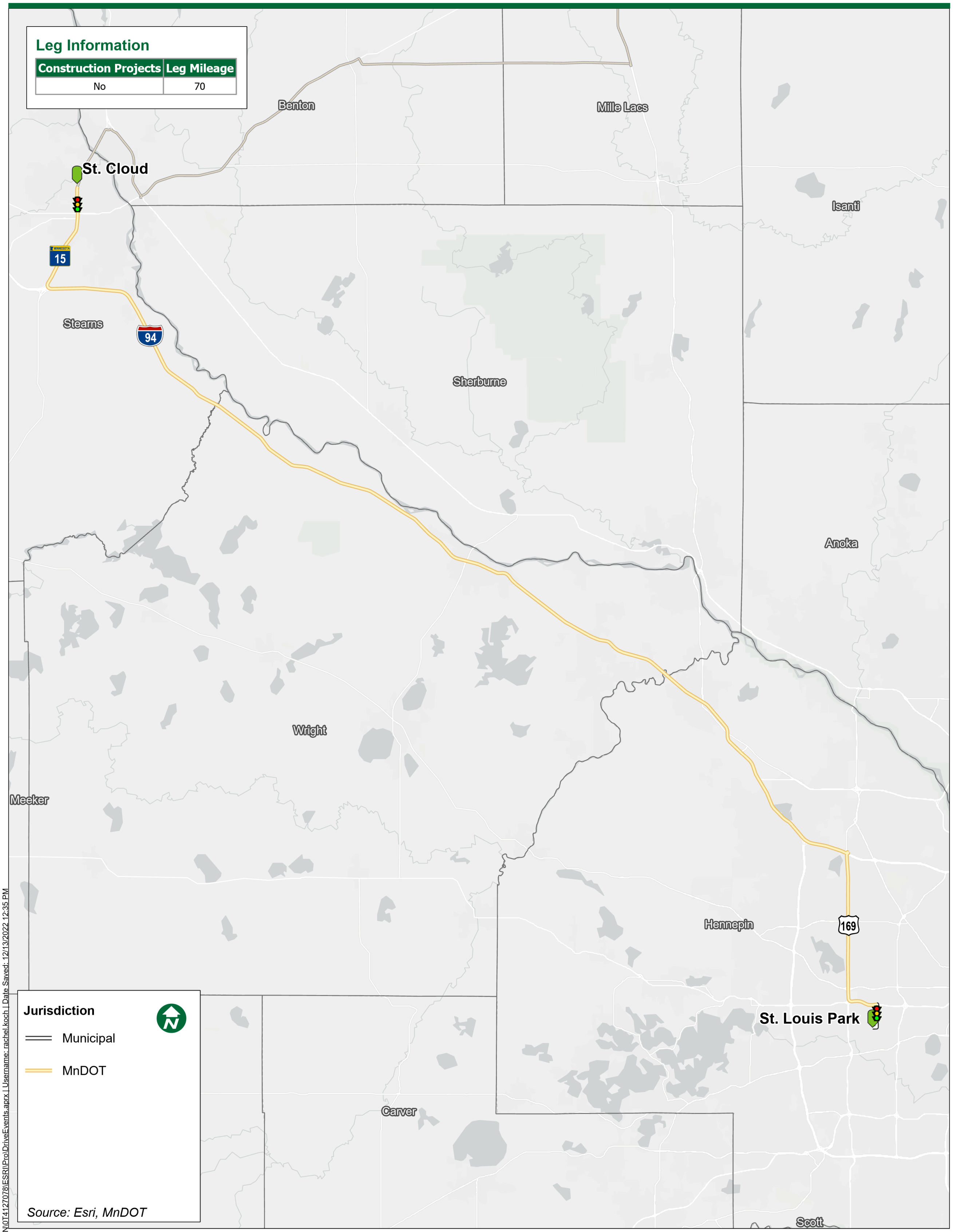
The findings from this study, combined with the anticipated additional guidance in the Federal MUTCD on automated vehicles and the multitude of CAV testing events in the state are contributing to a greater understanding of how ready Minnesota roadways are for vehicle automation.

# REFERENCES

AAA. (2019). *Advanced Driver Assistance Technology Names.*

Consumer Reports. (2021). *Understanding the Current State of Vehicle Automation.*

# APPENDIX A: ROUTE MAPS




| Jurisdiction | Percent of Leg's Total Miles |
|---|---|
| MnDOT | 97.99% |
| Municipal | 2.01% |
| County | - |

| Pavement Type | Percent of Leg's Total Miles |
|---|---|
| Bituminous | 57.05% |
| Concrete | 43.75% |

| Functional Class | Percent of Leg's Total Miles |
|---|---|
| Principal Arterial | 97.66% |
| Local | 3.16% |
| Minor Arterial | 2.21% |
| Major Collector | 0.59% |
| Minor Collector | - |

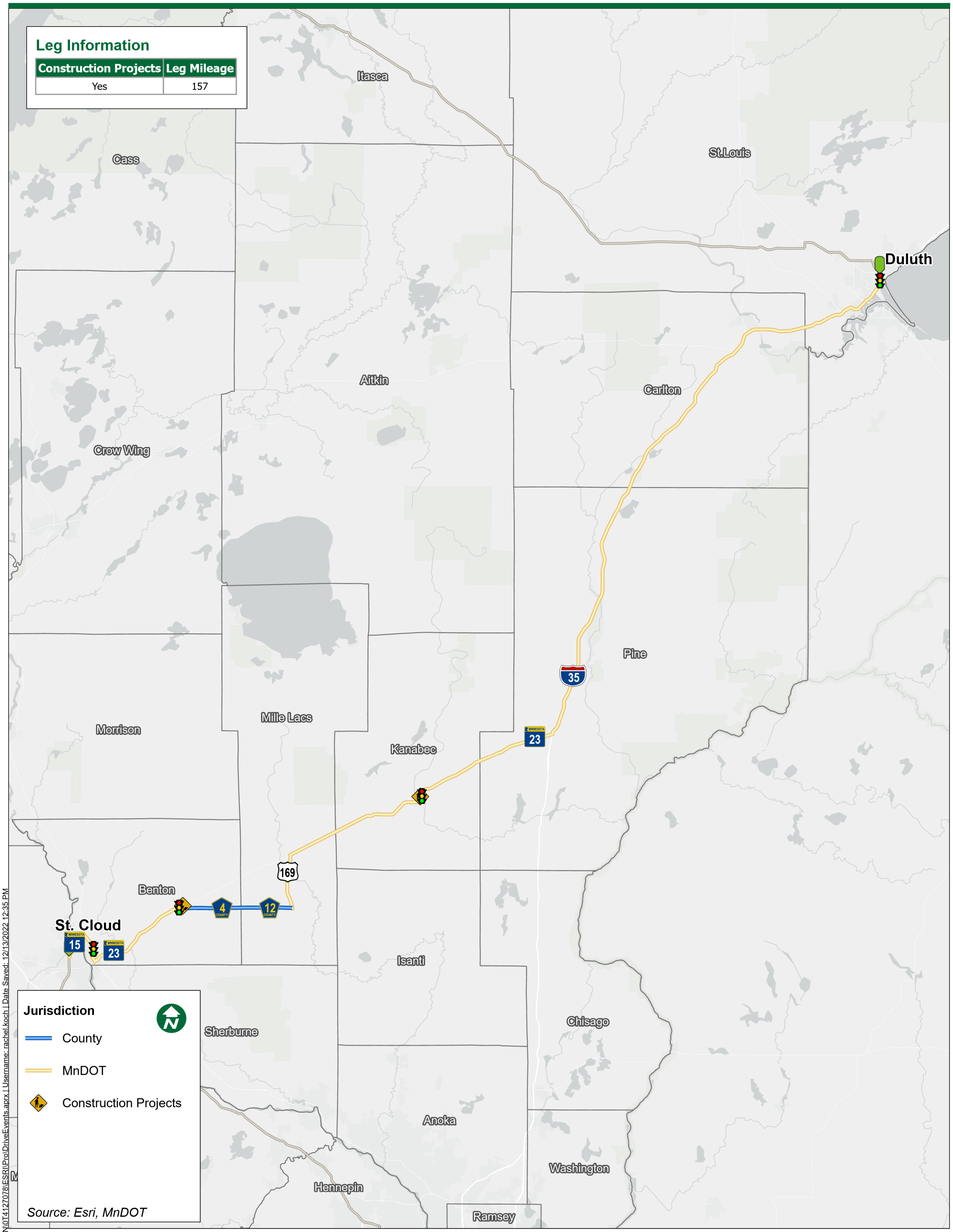
| Thru Lanes | Percent of Leg's Total Miles |
|---|---|
| 4 | 75.63% |
| 6 | 19.20% |
| 2 | 9.20% |
| 8 | 1.83% |

| Traffic Control Device | Count |
|---|---|
| Reduced Conflict Intersection | 0 |
| Roundabout | 0 |
| Signal | 12 |

Map Document: \\arcserver1\GIS\UOFM_ED_MN\0T4127078\ESRI\Pro\DriveEvents.aprx | Username: rachel.koch | Date Saved: 12/13/2022 12:35 PM

## Leg Information

| Construction Projects | Leg Mileage |
|---|---|
| Yes | 157 |






| Jurisdiction | Percent of Leg's Total Miles |
|---|---|
| MnDOT | 91.02% |
| County | 8.98% |
| Municipal | - |

| Pavement Type | Percent of Leg's Total Miles |
|---|---|
| Bituminous | 58.70% |
| Concrete | 40.83% |

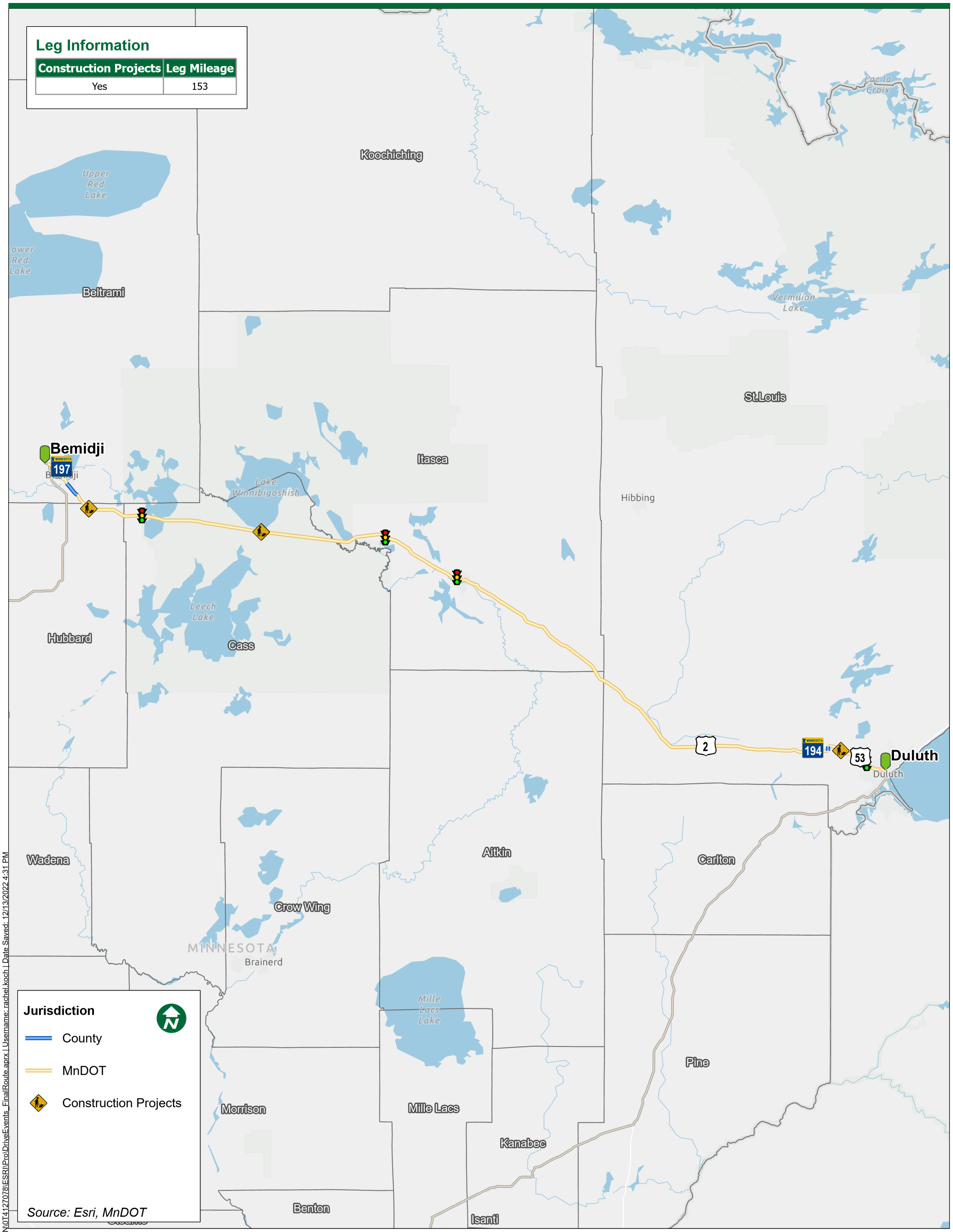
| Functional Class | Percent of Leg's Total Miles |
|---|---|
| Principal Arterial | 89.69% |
| Major Collector | 9.68% |
| Local | 2.21% |
| Minor Arterial | 0.67% |
| Minor Collector | 0.25% |

| Thru Lanes | Percent of Leg's Total Miles |
|---|---|
| 4 | 64.43% |
| 2 | 36.56% |
| 6 | - |
| 8 | - |

| Traffic Control Device | Count |
|---|---|
| Reduced Conflict Intersection | 0 |
| Roundabout | 0 |
| Signal | 18 |

## Leg Information

| Construction Projects | Leg Mileage |
|---|---|
| Yes | 153 |




| Jurisdiction | Percent of Leg's Total Miles |
|---|---|
| MnDOT | 97.89% |
| County | 2.11% |
| Municipal | - |

| Pavement Type | Percent of Leg's Total Miles |
|---|---|
| Bituminous | 99.98% |
| Concrete | 0.02% |

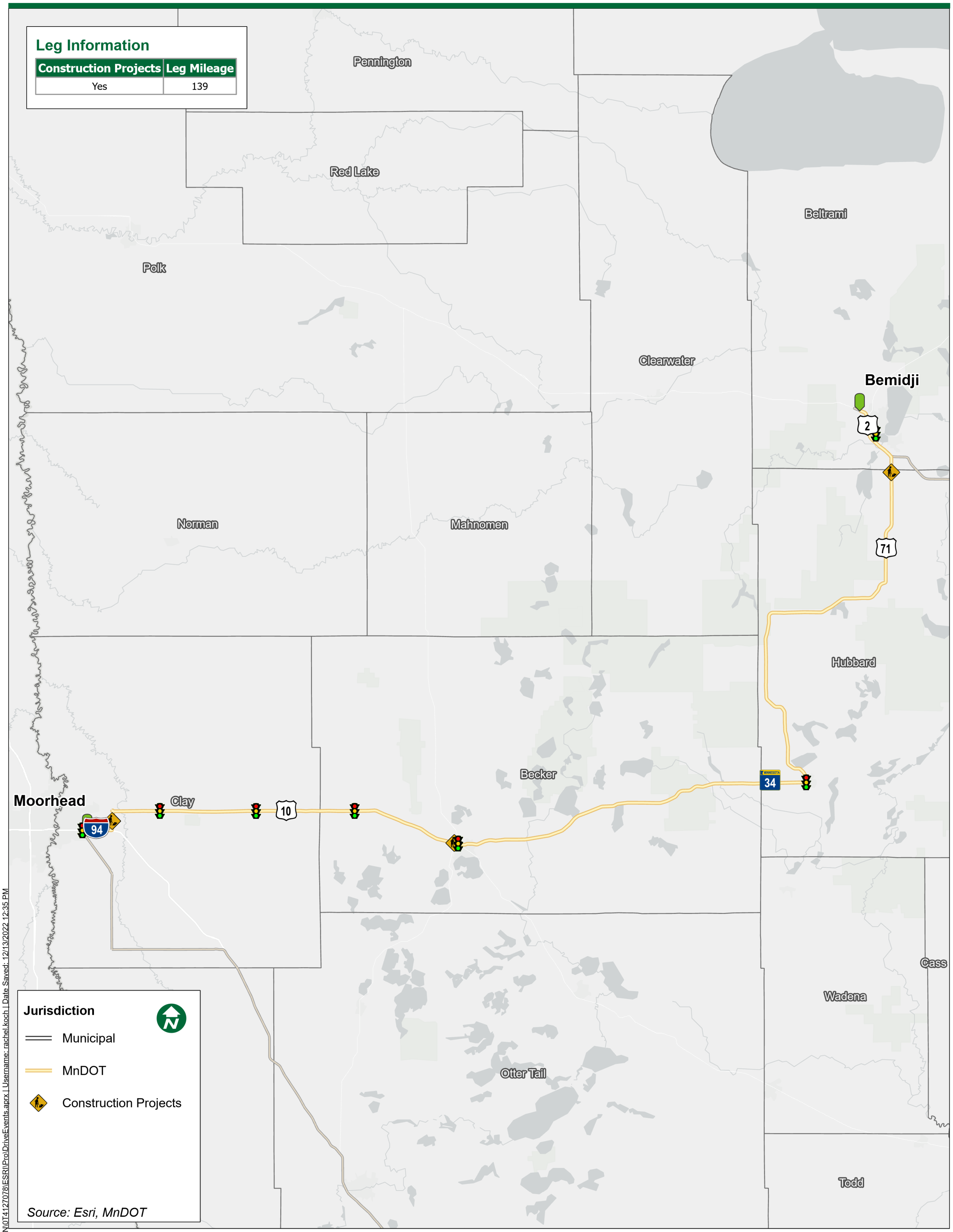
| Functional Class | Percent of Leg's Total Miles |
|---|---|
| Principal Arterial | 92.34% |
| Minor Arterial | 5.34% |
| Local | 1.98% |
| Major Collector | 0.21% |
| Minor Collector | 0.13% |

| Thru Lanes | Percent of Leg's Total Miles |
|---|---|
| 2 | 71.00% |
| 4 | 29.00 |
| 6 | - |
| 8 | - |

| Traffic Control Device | Count |
|---|---|
| Reduced Conflict Intersection | 0 |
| Roundabout | 0 |
| Signal | 45 |

### Leg Information

| Construction Projects | Leg Mileage |
|---|---|
| Yes | 139 |




Jurisdiction
- Municipal
- MnDOT
- Construction Projects

Source: Esri, MnDOT

| Jurisdiction | Percent of Leg's Total Miles |
|---|---|
| MnDOT | 99.36% |
| Municipal | 0.64% |
| County | - |

| Pavement Type | Percent of Leg's Total Miles |
|---|---|
| Bituminous | 81.96% |
| Concrete | 17.89% |

| Functional Class | Percent of Leg's Total Miles |
|---|---|
| Principal Arterial | 98.73% |
| Local | 2.41% |
| Minor Arterial | 0.33% |
| Major Collector | 0.19% |
| Minor Collector | - |

| Thru Lanes | Percent of Leg's Total Miles |
|---|---|
| 2 | 61.88% |
| 4 | 38.93% |
| 6 | - |
| 8 | - |

| Traffic Control Device | Count |
|---|---|
| Reduced Conflict Intersection | 0 |
| Roundabout | 0 |
| Signal | 18 |

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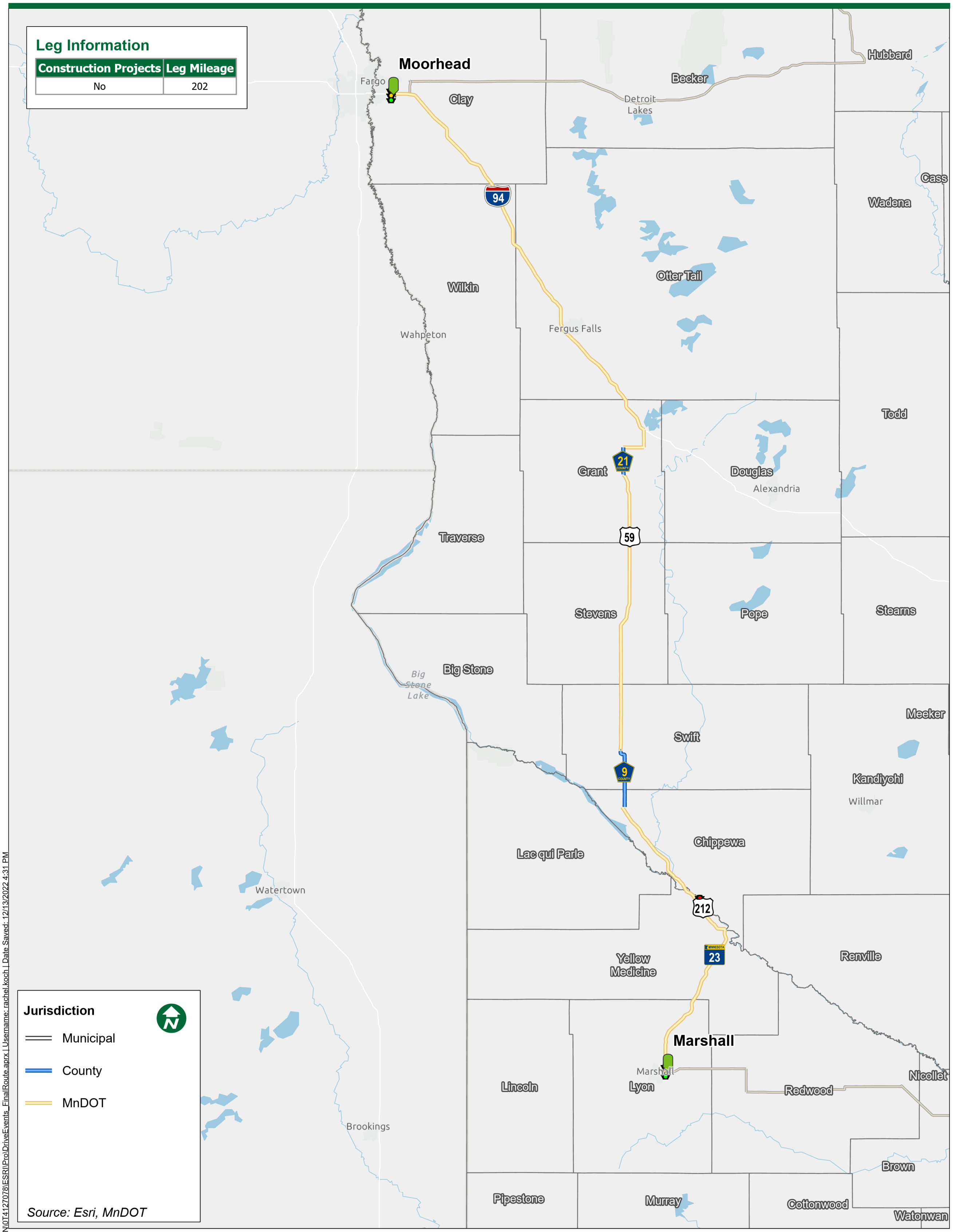



| Jurisdiction | Percent of Leg's Total Miles |
|---|---|
| MnDOT | 92.04% |
| County | 7.49% |
| Municipal | 0.47% |

| Pavement Type | Percent of Leg's Total Miles |
|---|---|
| Bituminous | 71.20% |
| Concrete | 28.80% |

| Functional Class | Percent of Leg's Total Miles |
|---|---|
| Principal Arterial | 87.79% |
| Major Collector | 8.88% |
| Local | 0.91% |
| Minor Arterial | 2.3% |
| Minor Collector | 0.12% |

| Thru Lanes | Percent of Leg's Total Miles |
|---|---|
| 2 | 60.11% |
| 4 | 39.89% |
| 6 | - |
| 8 | - |

| Traffic Control Device | Count |
|---|---|
| Reduced Conflict Intersection | 0 |
| Roundabout | 0 |
| Signal | 5 |

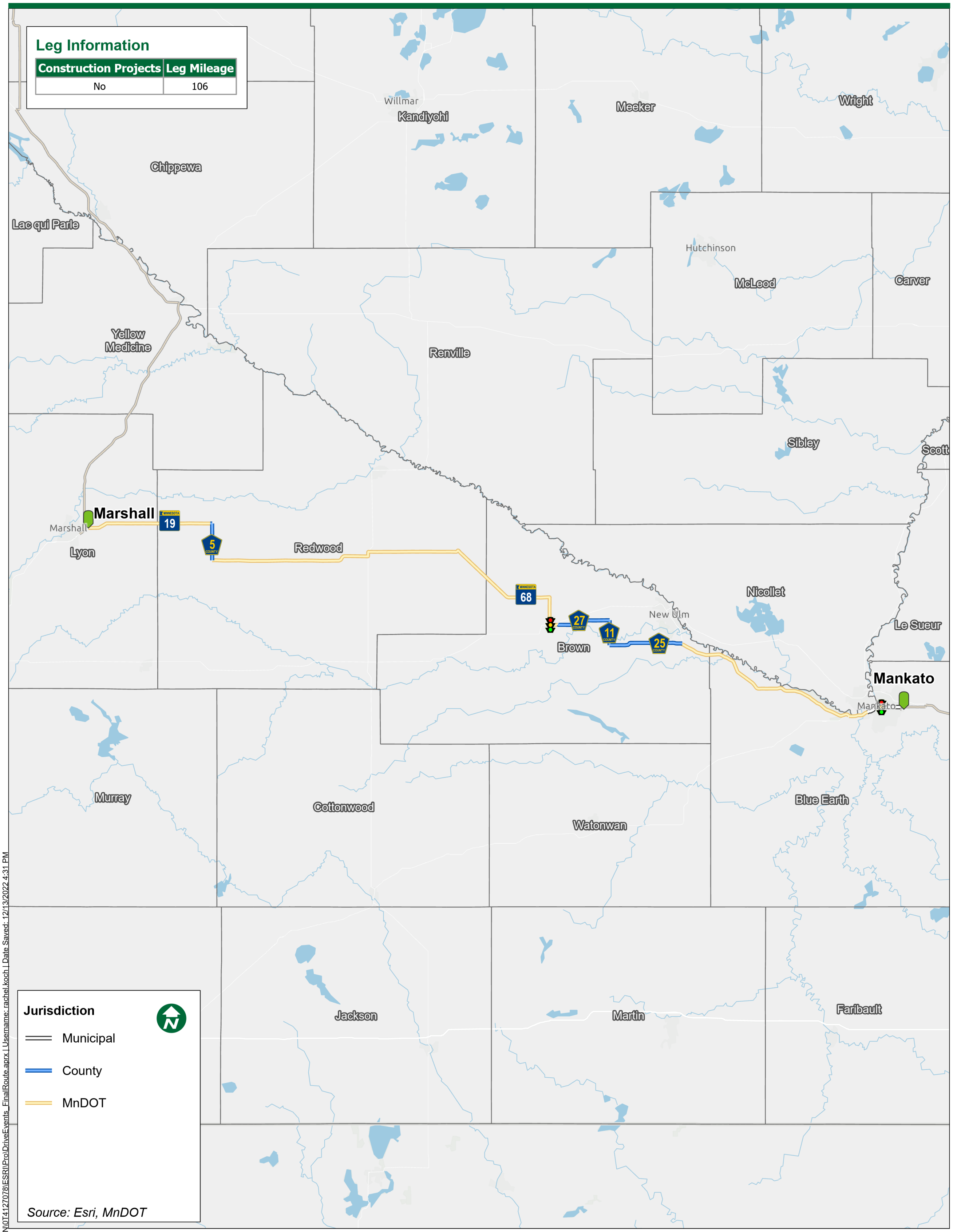
Map Document: \\arcserver1\GIS\UOFM_ED_MN\0T4127078\ESRI\Pro\DriveEvents_FinalRoute.aprx | Username: rachel.koch | Date Saved: 12/13/2022 4:31 PM

DriveMN
University of Minnesota

Routes, Leg 6 of 8
December 2022

## Leg Information

| Construction Projects | Leg Mileage |
| --- | --- |
| No | 106 |



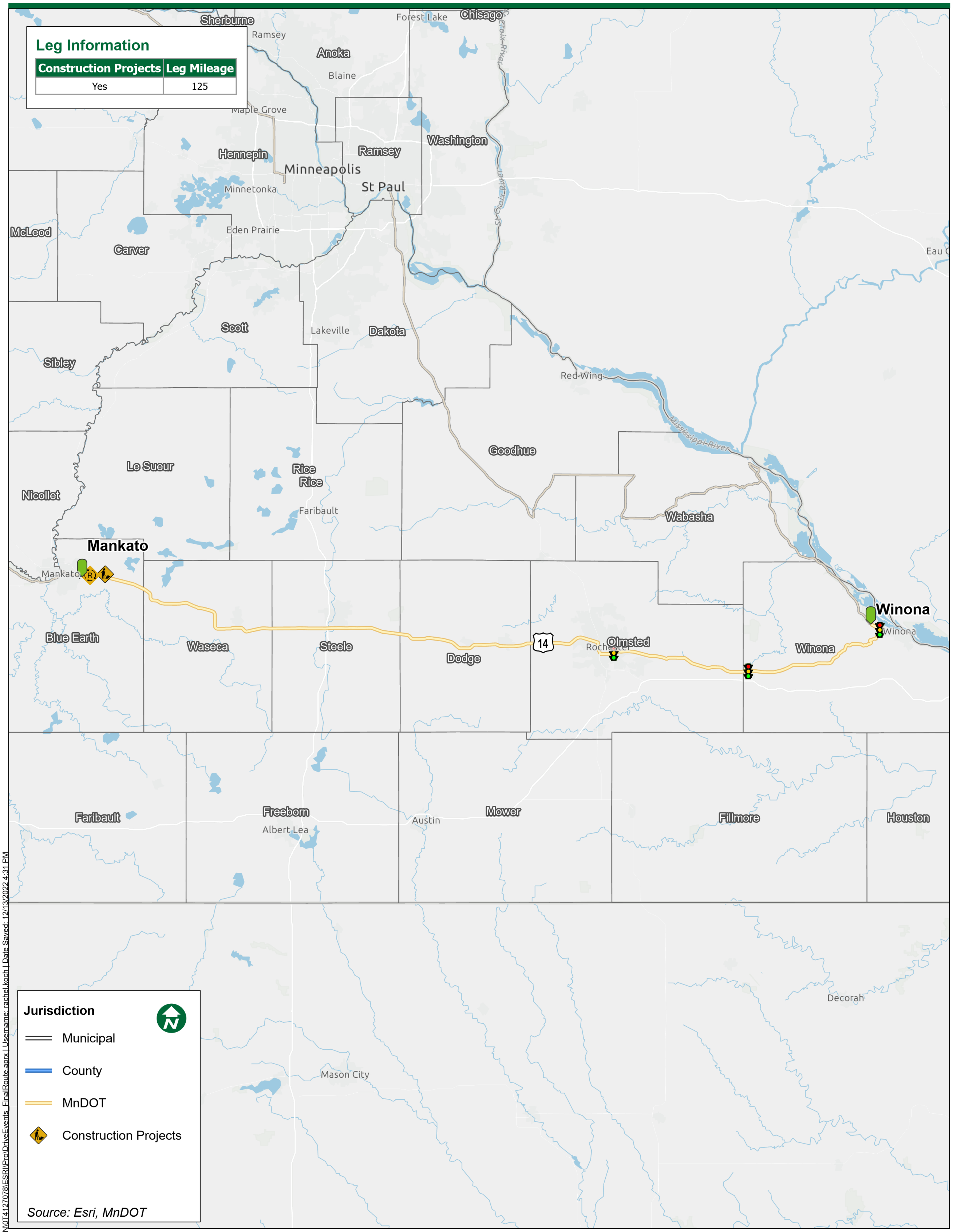

| Jurisdiction | Percent of Leg's Total Miles |
| --- | --- |
| MnDOT | 76.06% |
| County | 19.84% |
| Municipal | 4.10% |

| Pavement Type | Percent of Leg's Total Miles |
| --- | --- |
| Bituminous | 98.08% |
| Concrete | 1.92% |

| Functional Class | Percent of Leg's Total Miles |
| --- | --- |
| Minor Arterial | 59.54% |
| Principal Arterial | 20.18% |
| Major Collector | 15.04% |
| Local | 0.40% |
| Minor Collector | 4.83% |

| Thru Lanes | Percent of Leg's Total Miles |
| --- | --- |
| 2 | 93.82% |
| 4 | 6.18% |
| 6 | - |
| 8 | - |

| Traffic Control Device | Count |
| --- | --- |
| Reduced Conflict Intersection | 0 |
| Roundabout | 1 |
| Signal | 21 |

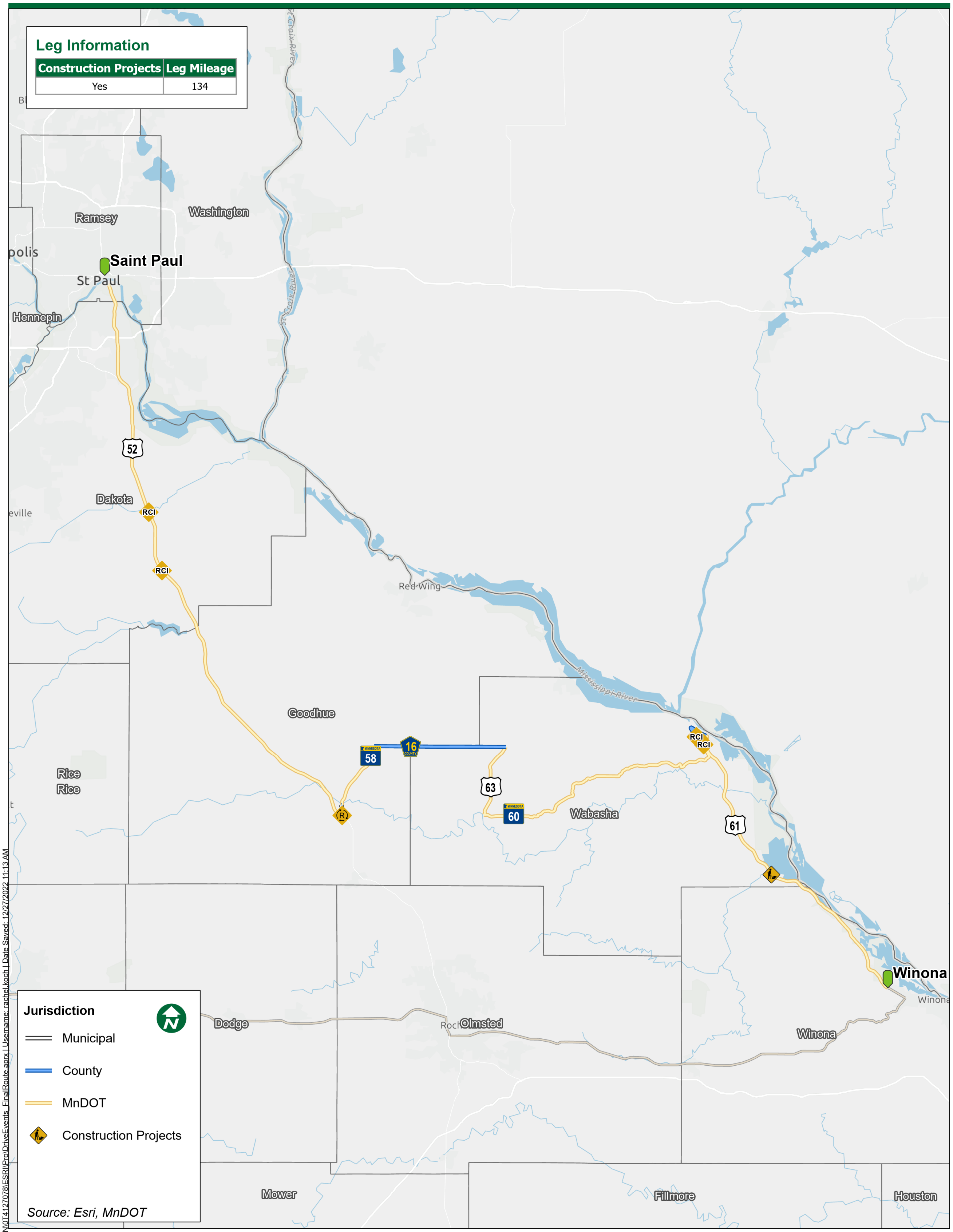



| Jurisdiction | Percent of Leg's Total Miles |
|---|---|
| MnDOT | 97.51% |
| County | 2.40% |
| Municipal | 0.09% |
| **Pavement Type** | **Percent of Leg's Total Miles** |
| Concrete | 51.62% |
| Bituminous | 48.38% |

| Functional Class | Percent of Leg's Total Miles |
|---|---|
| Principal Arterial | 60.31% |
| Minor Arterial | 32.38% |
| Local | 4.64% |
| Major Collector | 2.62% |
| Minor Collector | 0.05% |

| Thru Lanes | Percent of Leg's Total Miles |
|---|---|
| 4 | 64.59% |
| 2 | 34.13% |
| 6 | 1.28% |
| 8 | - |

| Traffic Control Device | Count |
|---|---|
| Reduced Conflict Intersection | 1 |
| Roundabout | 6 |
| Signal | 16 |




| Jurisdiction | Percent of Leg's Total Miles |
|---|---|
| MnDOT | 89.93% |
| Municipal | 0.17 |
| County | 9.89% |

| Pavement Type | Percent of Leg's Total Miles |
|---|---|
| Bituminous | 94.57% |
| Concrete | 5.43% |

| Functional Class | Percent of Leg's Total Miles |
|---|---|
| Principal Arterial | 60.25% |
| Minor Arterial | 27.99% |
| Local | 2.18% |
| Major Collector | 9.52% |
| Minor Collector | 0.07% |

| Thru Lanes | Percent of Leg's Total Miles |
|---|---|
| 4 | 59.36% |
| 2 | 39.88% |
| 8 | 0.00 |
| 6 | 0.76% |

| Traffic Control Device | Count |
|---|---|
| Reduced Conflict Intersection | 5 |
| Roundabout | 1 |
| Signal | 0 |

Map Document: \\arcserver1\GIS\UOFM_ED_MN\0T412707\ESRI\Pro\DriveEvents_FinalRoute.aprx | Username: rachel.koch | Date Saved: 12/27/2022 11:13 AM

# APPENDIX B: FREQUENTLY ASKED QUESTIONS FROM EVENTS

## Q: HOW DID THE VEHICLE HANDLE "X" SITUATION ON THE ROADWAY?

A: The vehicle is solely for data collection purposes driven solely by humans and does not react or respond in an automated manner.

## Q: HOW CAN LOCAL JURISDICTIONS BE MORE AWARE OF CAV STANDARDS AND READINESS PRACTICES IN MINNESOTA?

A: Focus on projects that provide transportation value both today and in the future. One example is maintaining standardized pavement markings. For more ideas, LRRB's CAV interactive FAQ resource website was developed targeted for locals and has information.

## Q: WHY ARE WE DOING DRIVE MN NOW?

A: We want to discover and learn- both from the roads and local authorities. Vehicle automation is on our roads today with capabilities like lane keep assist and adaptive cruise control. National traffic engineering standards are in the process of being updated as well, with elements specifically noted with respect CAV for pavement markings, signing, traffic signals, and construction work zones.

## Q: WHEN WILL CONNECTED AND AUTOMATED VEHICLES BE AVAILABLE?

A: Now. Basic levels of connected and automated vehicle technology are on Minnesota roadways today. However, vehicles that are fully automated, in all settings, are still many years away.

## Q: WHAT IS THE CAV CHALLENGE AND HOW MUCH MONEY IS AVAILABLE FOR CAV TESTING?

A: It's an open-call funding program focused on spurring innovation and creativity from proposers to advance planning and preparing for CAV in Minnesota. Around $2 million is available annually.