DEPARTMENT OF TRANSPORTATION

Implementation of Inductive Loop Signature Technology for Vehicle Classification Counts

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SRF Consulting Group, Inc.

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Final Report 2024-29

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16. Abstract (Limit: 250 words)

This study evaluates recent technology that uses inductive loop detectors, traditionally used for collecting traffic volume and speed data, to provide vehicle classification data by examining the high-resolution signature produced when a vehicle passes over the sensor. The project aims to verify the accuracy of the new classification system, collect additional heavy vehicle data to help improve system accuracy, and familiarize MnDOT staff with the technology through training and the development of a field deployment manual. Through collaboration with MnDOT and the technology vendor CLR Analytics, Inc., the VSign vehicle classification system has been installed at five sites in Minnesota with preexisting loop detection systems. The final sites are representative of MnDOT facilities, feature a mix of heavy vehicle traffic, and provide accessibility for deployment staff.

Data from the VSign system was compared with manually verified ground-truth data collected from video under both the Federal Highway Administration (FHWA) and Highway Performance Monitoring System (HPMS) classification schemes. The system demonstrated high accuracy for passenger vehicles but varying accuracy for different classes of heavy vehicles, though performance improved under the HPMS classification scheme. The VSign system was also evaluated against the video-based iTHEIA™ system at one site, which VSign outperformed in both classification accuracy and detection rate. The results suggested that the VSign system was more effective at locations where vehicles maintained consistent speeds and were centered in the lane due to the negative effects of variations in speed and lateral position on the consistency of vehicle signatures read by the detector.

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Final Report

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Finally, a special thanks to Dr. Chen-Fu Liao, formerly of the University of Minnesota and now of the Virginia Department of Transportation, for his many years of work researching this technology for MnDOT, which made this latest project possible.

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List of Abbreviations

ATR	Automatic Traffic Recorder
CLR	CLR Analytics, Inc.
CSAH	County State-Aid Highway
FHWA	Federal Highway Administration
HPMS	Highway Performance Monitoring System
IRD	International Road Dynamics
IRIS	Intelligent Roadway Information System
ITS	Intelligent Transportation Systems
LCCA	Life cycle cost analysis
MnDOT	Minnesota Department of Transportation
RTMC	Regional Traffic Management Center
SBIR	Small Business Innovation Research
SRF	SRF Consulting Group, Inc.
TFA	Traffic Forecasting & Analysis
TMG	Traffic Monitoring Guide
UMN	University of Minnesota
USDOT	United States Department of Transportation
WIM	Weigh-In-Motion

Executive Summary

Throughout the United States, roadway sensors are crucial in the decision-making process of transportation management agencies. Inductive loop detectors, automatic traffic recorders (ATR), weigh-in-motion (WIM) sensors, and other systems collect data such as traffic volume, speed, vehicle classification, and weight information. Loop detectors are the most common type of sensor in Minnesota but are traditionally only used for collecting traffic data such as volume and speed. Vehicle classification data is typically collected by a smaller number of permanent ATR or WIM stations or through manual data collection.

Research sponsored by USDOT's Small Business Innovation Research program has facilitated the development and commercialization of technology for collecting vehicle classification data from the high-resolution signature recorded when a vehicle passes over a loop detector. Previous MnDOT-sponsored research has explored the use of this technology in Minnesota.

This study aimed to verify the accuracy of the new classification system, collect additional heavy vehicle data to help improve system accuracy, and create a manual describing the field deployment and installation procedures of the system. To that end, the project team worked with MnDOT personnel to identify five locations along MnDOT roads with existing loop detection systems to serve as study sites. An initial list of 31 sites was developed based on ease of access, estimated daily truck volumes, proximity to MnDOT district offices, and whether each site would be operational in summer 2023. The project team then used Google Maps and Google Street View to evaluate the opportunities for accessing the ATR controller cabinets. The final sites were selected to meet these criteria and be representative of MnDOT facilities, resulting in five study sites – four in the Twin Cities metro area and one near Manhattan Beach in northern Minnesota.

The project team worked with MnDOT and the technology vendor CLR Analytics, Inc. to install CLR's VSign vehicle classification system hardware in the cabinets at each of the study sites. Following the installation of hardware, the project team collected several hours of timestamped video of vehicles passing over the loops at each of the sites.

Using the video data collected, individual vehicle records were manually verified and validated with video ground-truth data using the 13-bin vehicle classification scheme from the Federal Highway Administration (FHWA) and the 7-bin Highway Performance Monitoring System (HPMS) classification categories described in the FHWA *Traffic Monitoring Guide* (TMG). In both classification schemes (which use the same classes for passenger vehicles), the VSign system was quite accurate at classifying passenger vehicles with accuracy rates of 99% and 91% for Class 2 (passenger cars) and Class 3 (light duty trucks), respectively, with classes 2 and 3 being the only two passenger vehicle classes with more than 100 observations. VSign had some difficulty accurately sorting trucks into the FHWA classification scheme's 9 classes for trucks with accuracies of 63%, 70%, and 87% for FHWA Classes 5, 6, and 9 (the only three heavy vehicle classes with more than 100 observations), respectively. The VSign system performed far better at classifying trucks when using the HPMS scheme, which splits trucks into just 3

classes – with accuracy rates of 81% and 97% for the single unit trucks and single trailer classes, respectively (the multi-unit trailer class only had 14 observations).

At one location, the results of the inductive loop-based classification system were then compared to those of the video-based iTHEIA™ counting and classification system developed by International Road Dynamics (IRD), the VSign system outperformed the IRD system both in terms of accuracy in classifying vehicles by HPMS class (92% vs 86%) but also in terms of detection rate (100% vs 77%).

The evaluation of the VSign system's performance at the five study sites suggests that it performs better at locations where vehicles are traveling at consistent speeds and are centered in the lane due to the negative effects of variations in vehicle speed/acceleration and lateral position on the consistency of vehicle signatures read by the sensors.

Based on a preliminary life-cycle cost analysis of the system, the ongoing software subscription and hardware maintenance costs are fairly high, but there are some situations in which the benefits of the technology still make it cost effective. Further research is recommended to better understand these considerations and how they should be evaluated during the planning and programming process.

Chapter 1: Introduction

State transportation agencies monitor and evaluate their existing traffic systems using devices like loop detectors, automatic traffic recorders (ATR), and weigh-in-motion (WIM) sensors. Agencies use these sensors to collect traffic volume, speed, vehicle classification, and weight information and then use these data for safety evaluation, pavement design, decision making, traffic forecasting, modeling, and much more. In Minnesota, vehicle classification information is typically collected from WIM sensors, ATR stations, or manually on low-volume roadways. With a limited number of ATR and WIM stations permanently installed throughout the state highway network, temporary double road tubes are often deployed to get axle-based vehicle classification counts on roadways with less traffic. These methods require a significant amount of time and effort to collect vehicle classification data annually [1].

Research over the last few decades has investigated the feasibility of using inductive loop detectors to collect vehicle classification data with existing infrastructure by examining the high-resolution signature produced as a vehicle passes over the sensor. Beginning in 2012, the United States Department of Transportation (USDOT) sponsored research to build on this work and help commercialize this technology through its Small Business Innovation Research (SBIR) program [2]. Through this and subsequent efforts, CLR Analytics, Inc. developed an inductive loop signature classification system with high accuracy that could be easily deployed to new or existing inductive loop sensor stations [3, 4].

In recent years, this technology has been deployed in several states across the country, including California, Alaska, Alabama, Washington, Colorado, Delaware, and New Hampshire. Previous studies sponsored by the Minnesota Department of Transportation (MnDOT) and conducted by researchers at the University of Minnesota (UMN) investigated applications of this technology to Minnesota roads [5, 6]. This current study sought to continue this work, performing additional demonstration deployments of the technology, evaluating the performance of the system compared to video ground truth data, and preparing documentation to support future deployments by MnDOT staff.

1.1 Potential Benefits

Inductive loop signature technology could allow MnDOT to collect vehicle classification data anywhere there is a loop detector – not just at ATR and WIM sites – thus dramatically expanding the number of locations at which MnDOT could collect vehicle counts broken down by vehicle type. The loop signature technology would also replace the road tubes or piezoelectric sensors that have historically been used to get vehicle class counts. This would save time and money and reduce the frequency needed for staff to enter the roadway to lay temporary tubes or replace piezoelectric sensors when they fail.

1.2 Study Objectives

The objectives of this study were to develop field deployment and installation procedures and validate the classification libraries for heavy trucks by deploying the loop signature technology to five additional locations. SRF worked with MnDOT to review and prioritize current traffic count locations that already had inductive loops installed, taking advantage of any GIS information available. SRF then collaborated with members of the project's Technical Advisory Panel (TAP) to select the five sites. Following selection of the sites, SRF and MnDOT installed the hardware necessary to collect vehicle classification data and report it back to a central server.

Drawing in large part on the lessons learned during the deployment and data collection tasks, SRF developed a guide for installing loop signature classification systems for use in future expansion of the technology. SRF also collected video ground truth data from the test sites to assess the accuracy of the technology, providing the results of this analysis to the technology vendor for future enhancements of the classification libraries. The study results and findings were documented in this report.

Chapter 2: Research Sites

The project team installed new detector cards, processing hardware, and cellular modems at five sites around Minnesota that already have inductive loops in place. These sites were selected to be representative of a variety of different deployment scenarios and infrastructure types.

To select the five study sites, the project team worked with representatives of the MnDOT Traffic Forecasting and Analysis (TFA) office to create a list of 31 potential study locations around the state with inductive loops. The group then performed a rough prioritization based on ease of access, estimated daily truck volumes, proximity to MnDOT district offices, and whether each site would be operational by the summer of 2023. This second pass eliminated five sites that were found to have one or more non-functional loops and identified eight sites to be investigated in further detail. The project team then used Google Streetview to evaluate the accessibility of ATR controller cabinets and used MnDOT's Advanced Traffic Management System (ATMS) IRIS to determine whether any nearby MnDOT cameras could be used to collect video for a subsequent video ground truth validation. After completing this review, the five sites detailed in the following section were selected for inclusion in the study.

2.1 Site 1: I-694 south of CSAH 35 (50th St N) in Oakdale

Site 1 was located at ATR station 341 on I-694 approximately 800 feet south of 50th St N in Oakdale (Figure 2.1), covering four lanes of interstate traffic. Situated on the primary bypass route for I-94 in the Twin Cities, traffic at this site was expected to provide a large sample containing a high percentage of heavy freight vehicles. The inductive loops in the pavement at this site were also installed shortly before equipment was installed, reducing the likelihood of any technical issues with the loops themselves. These factors put this site among the most optimal deployment scenarios, making it good for inclusion in the study.

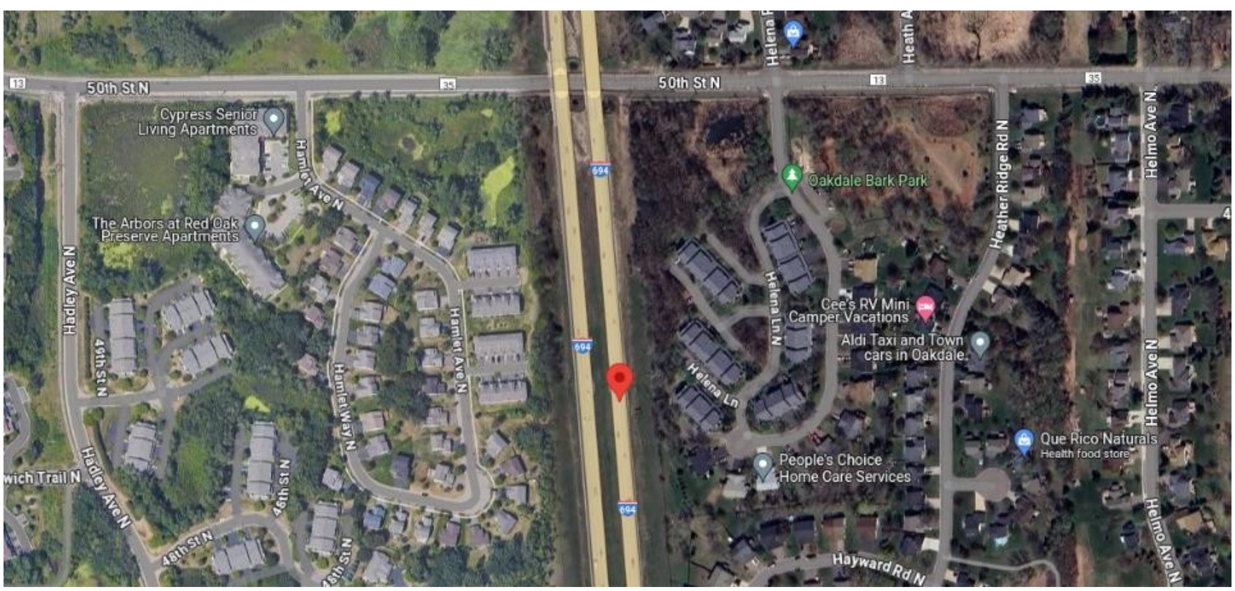

Figure 2.1. Aerial view of Site 1 in Oakdale.

2.2 Site 2: CSAH 15 (Shoreline Dr) northeast of Spates Ave in Orono

Site 2 was located at ATR site 407 on CSAH 15 (Shoreline Dr) approximately 400 feet northeast of Spates Ave in Orono (Figure 2.2). CSAH 15/Shoreline Drive is a two-lane undivided road that serves vehicles traveling from US-12 to a number of residential communities situated on the shores of Lake Minnetonka. Traffic largely consists of passenger vehicles and smaller (e.g., class 5-7) trucks, along with more recreational traffic like light trucks towing watercraft. In addition to having an interesting traffic makeup, the existing cellular modem at this site was not operational, so this study provided an opportunity to bring the site back online.

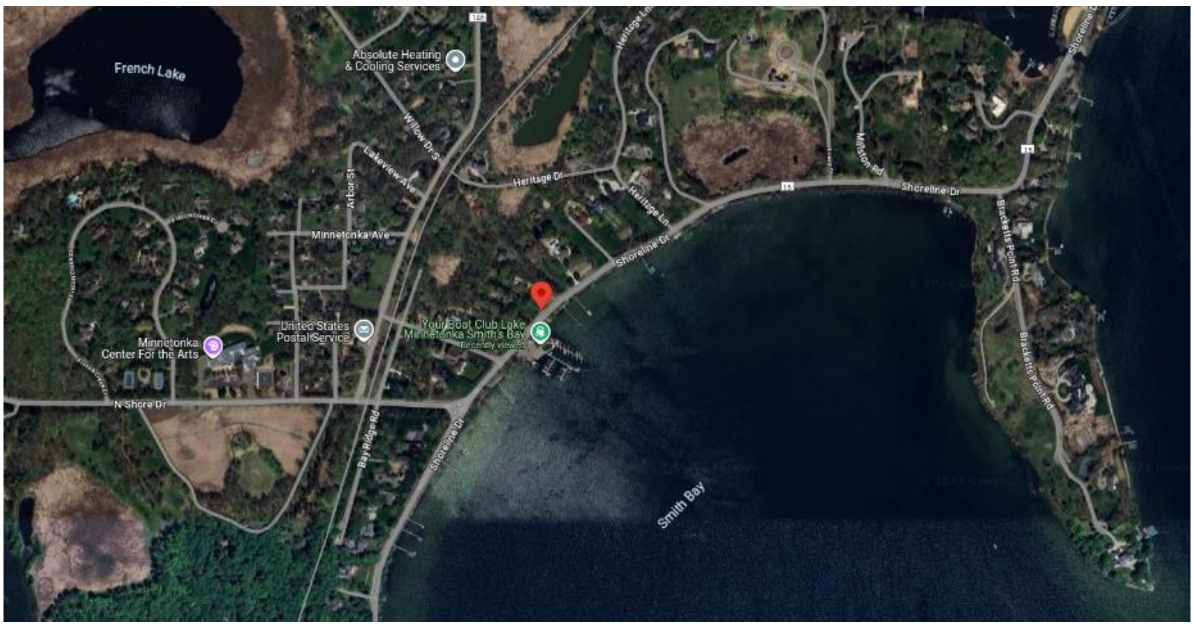

Figure 2.2. Aerial view of Site 2 in Orono.

2.3 Site 3: CSAH 1 at CR 134 (Spring Brook Rd) near Manhattan Beach

Site 3 was located at WIM site 44 on CSAH 1 (Paul Bunyan Scenic Byway) at CR 134 (Spring Brook Rd) approximately two miles west of Manhattan Beach (Figure 2.3). CSAH 1 at this location has three lanes of traffic, with two through lanes and one southbound right turn lane. Situated in a relatively remote area of Northern Minnesota, this site allowed testing of the technology in a rural setting. As this site was located far from SRF's main office in Minneapolis, MnDOT offered to have TFA staff deploy the equipment to this site without SRF, providing MnDOT staff with additional experience working with the technology and helping the development of the field installation guide produced as part of the project. MnDOT also collected ground truth video data from this site using a commercial video-based vehicle classification system, allowing for a comparison of the inductive loop signature technology to competing technologies.

Figure 2.3. Aerial view of Site 3 near Manhattan Beach.

2.4 Site 4: US-169 north of Cedar Lake Road in St. Louis Park

Site 4 was located at ATR site 405 on US-169 approximately 2,500 feet north of Cedar Lake Rd in St. Louis Park (Figure 2.4). US-169 at this location is a four-lane expressway that primarily serves commuter traffic, with some heavy vehicles in the mix. This site is operated by MnDOT's Regional Traffic Management Center (RTMC) and uses slightly different technology in the cabinet to collect data, allowing testing the inductive loop signature technology in another deployment scenario that is common for MnDOT.

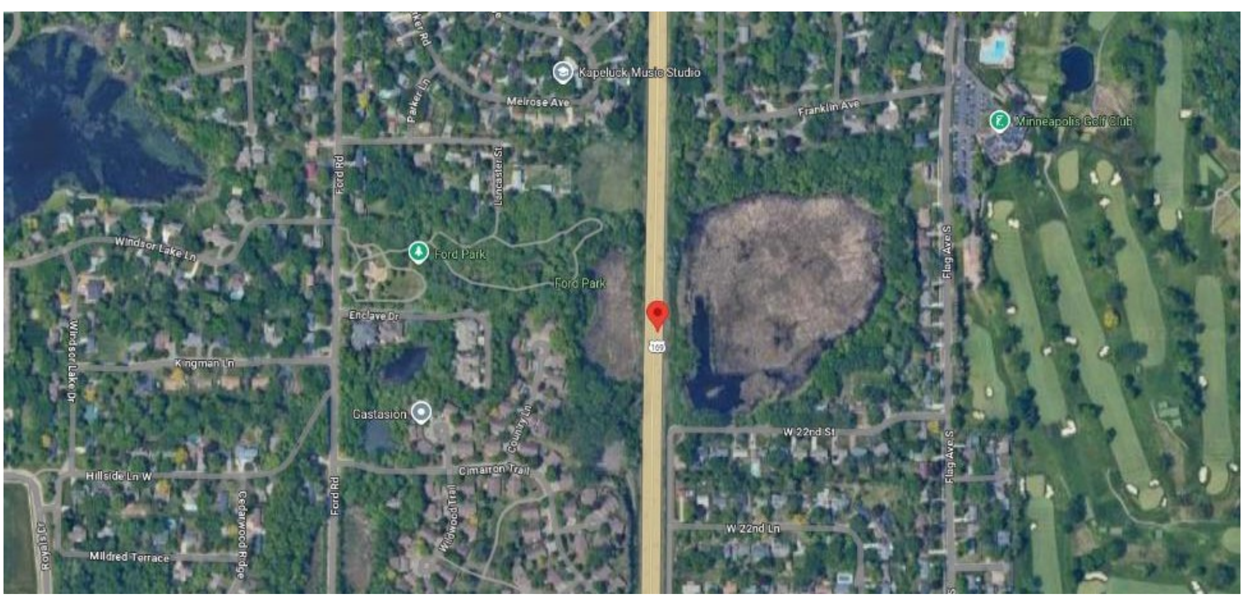

Figure 2.4. Aerial view of Site 4 in St. Louis Park.

2.5 Site 5: MN-55 at Glenwood Ave in Golden Valley

Site 5 was located at the intersection of MN-55 and Glenwood Ave in Golden Valley (Figure 2.5). MN-55 at this location is a signalized arterial, which allowed testing the system in another common MnDOT scenario. As a traffic signal, this site is operated by MnDOT Signal Operations, but also features additional loop detectors that were formerly used for the SMART Signal system which was deployed in this corridor as part of unrelated previous research [7]. As the SMART Signal system ceased operation several years ago, this allowed deploying loop signature technology to a traffic signal site with minimal impact on signal operations. There were also additional options for loop sensor selection at this site; loops located downstream of the intersection were used to provide vehicle signatures to avoid errors associated with vehicles stopping over a sensor.

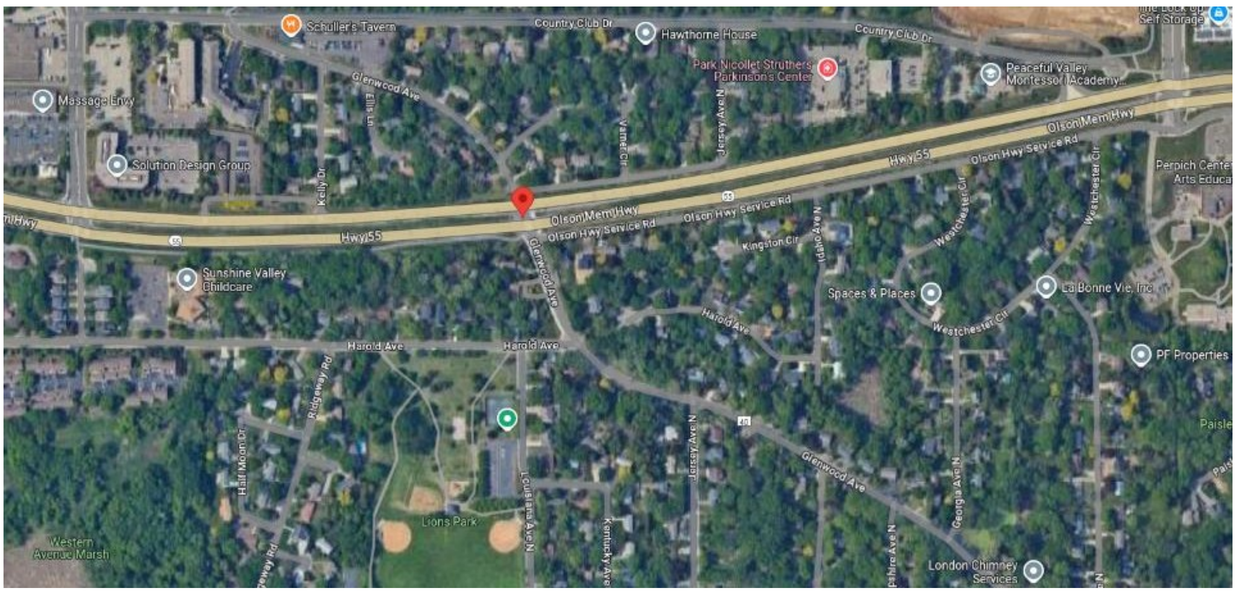

Figure 2.5. Aerial view of Site 5 in Golden Valley.

Chapter 3: Installation and Testing

With the five study sites selected as described in the previous chapter, installation of the inductive loop signature technology and preliminary testing could begin. The installation for the four metro locations was performed on Monday, September 25th and Tuesday, September 26th, 2023. A representative from the system vendor (CLR Analytics), Dr. Lianyu Chu, traveled to the Twin Cities to assist with this process. In addition to Dr. Chu, three SRF engineers and two MnDOT staff members were present over the course of the two-day period.

For the final site, located in Manhattan Beach in Northern Minnesota, equipment was installed on November 1st, 2023, by MnDOT staff without in-person assistance from SRF or CLR. This was done both as a cost-saving measure and to help MnDOT gain more familiarity with the system and installation process.

The locations of the five sites, the office that manages them, and the date of installation of the inductive loop signature hardware are listed in Table 3.1. An asterisk in the table indicates that additional work was conducted after the initial installation to make the site fully operational.

Table 3.1. Site locations and installation dates.

Site	Location	City	MnDOT Office	Install Date
1	I-694 south of CSAH 35 (50th St N)	Oakdale	TFA	9/25/2023
2	CSAH 15 (Shoreline Dr) NE of Spates Ave	Orono	TFA	9/25/2023
3	CSAH 1 at CR 134 (Spring Brook Rd)	Manhattan Beach	TFA	11/1/2023
4	US-169 north of Cedar Lake Rd	St. Louis Park	RTMC	9/25/2023*
5	MN-55 at Glenwood Ave	Golden Valley	Signal Operations	9/26/2023*

Two versions of the inductive loop signature technology that use different hardware for interfacing with the inductive loops at the cabinet were used for this project, though in each case the remainder of the equipment is the same. The equipment purchased for this project consisted of four systems that use the Phoenix Counter/Classifier to interface with the inductive loops at the site. MnDOT also already owned a set of equipment from previous phases of this research that used the I-Loop Duo detector card to interface with the loops, for which a site transfer service was purchased. In addition to this hardware, during the installation planning process, it was discovered that MnDOT Signal Operations owned several I-Loop Duo cards from an unrelated deployment of the SMART Signal system that was no longer operational. Due to the different cabinet configurations in place at each site, different combinations of this equipment were ultimately deployed at each site.

3.1 Metro-Area Sites

Installation at the four metro-area sites started with the St. Louis Park site on US-169, followed by the Orono site on CSAH 15, and the Oakdale site on I-694. A brief site visit was also conducted at the MN-55 site in Golden Valley to inspect the wiring of loops to the cabinet, however the installation at this site was performed on the following day (9/26). These installations are discussed in further detail below in chronological order.

3.1.1 US-169 in St. Louis Park

The first site visited on September 25th was the US 169 site in St. Louis Park, managed by the RTMC. Most RTMC data collection sites, including this one, use the “ITS Cabinet” standard, which has a very small form-factor to maximize space efficiency. Because of the space constraint, this site was outfitted with a set of I-Loop Duo cards that could be swapped in for the existing detector cards in the cabinet. A cellular modem (and antenna mounted to the roof of the cabinet), web power switch, and VSign hub were also installed at the site. Figure 3.1 shows photos of the cabinet following the installation, with new equipment outlined in red.

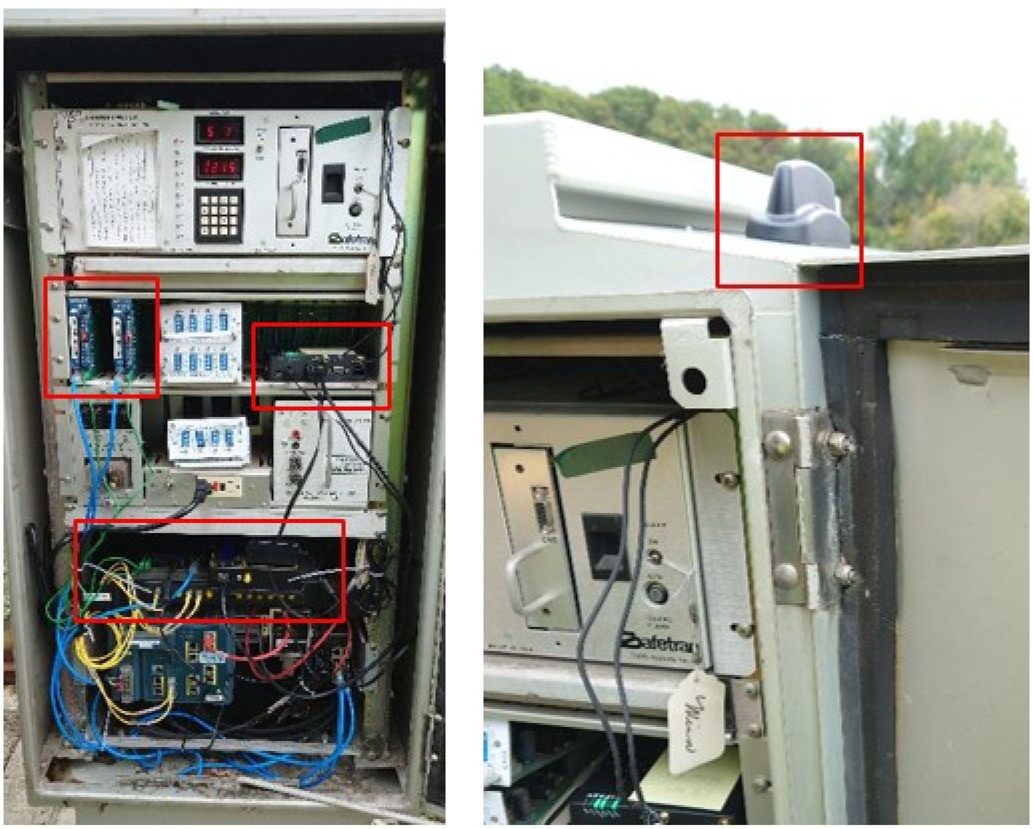

Figure 3.1. (Left) Inside of the cabinet at the US-169/St. Louis Park Site. (Right) Antenna mounted to the top of the cabinet.

Following the initial installation on September 25th, a brief follow-up visit was conducted on the 26th to upgrade the firmware of the I-Loop Duo detector cards, concluding the installation activities at this site.

3.1.2 CSAH 15 (Shoreline Dr) in Orono

The second site visited on September 25th was the CSAH 15 site in Orono, managed by TFA. This site, like other TFA sites, uses the larger NEMA TS2 standard cabinet to house the equipment, which provides ample room for additional equipment and allowed for the use of the Phoenix counter system to interface with the loops at the site, which is currently the vendor's preferred setup for the system. Like the other sites, this site was also outfitted with a cellular modem, web power switch, and VSign hub. This site already had an antenna that was previously used by a TFA modem, so the existing antenna was used rather than installing a new one. Figure 3.2 shows photos of the cabinet following the installation, with new equipment outlined in red.

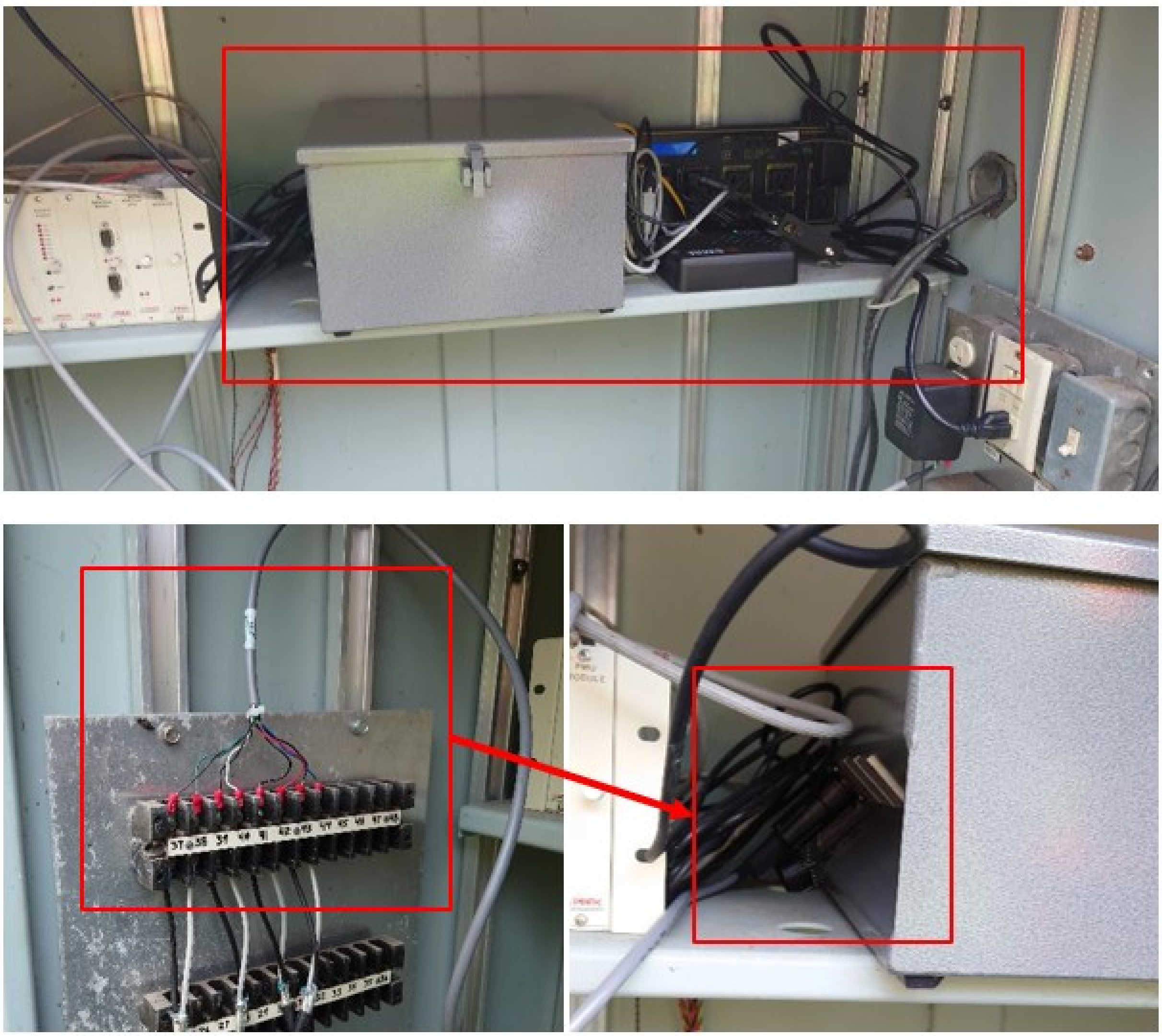

Figure 3.2. (Top) Phoenix counter, web power switch, VSign hub, and cellular modem installed in the CSAH 15 site in Orono. (Bottom left) Cabinet wiring bus. (Bottom right) Phoenix counter cable connected to wiring bus.

3.1.3 I-694 in Oakdale

The final site installed on September 25th was the I-694 site in Oakdale, also managed by TFA. The cabinet at this site was similar to the cabinet at the Orono site, so the equipment deployed was almost identical. This site required a new antenna for the cellular modem, however due to inclement weather, the team opted to not drill a hole to mount it to the cabinet and instead left it inside the cabinet. This was found to provide adequate signal strength for the modem to communicate properly and TFA staff could mount the antenna externally in the future if this becomes an issue.

3.1.4 MN-55 in Golden Valley

The final Metro area site, on MN-55 in Golden Valley, was visited on September 26th. This site is managed by MnDOT Signal Operations which runs the traffic signal at the intersection of MN-55 and Glenwood Ave. Because of the cabinet configuration and existing equipment present, the Phoenix counter could not be used for interfacing with the loops. Instead, the I-Loop Duo cards from the retired SMART Signal system, shown in Figure 3.3, were used.

Figure 3.3. I-Loop Duo cards from the retired SMART Signal system at MN-55 site in Golden Valley.

Installing the system at this site required additional coordination with MnDOT Signal Operations to properly wire the correct loops to the system. The loops used for the system were also previously used by the SMART Signal system, selected partly due to their location on the downstream side of the intersection, and to minimize any potential impact to the operation of the signal. However, following the replacement of this cabinet a few years ago, not all of the loops were wired into the cabinet. Through some testing, the team established which wires corresponded to which loops and communicated this to Signal Operations, who submitted a work order to have a technician complete the wiring that was completed in October 2023.

Following another visit by a Signal technician, however, it was discovered that many of the loops were labelled incorrectly, and the cabinet was rewired to correct the issue. This required a reconfiguration of the system which was performed remotely on November 15th, after which the site installation and configuration was complete.

3.1.5 CSAH 1 in Manhattan Beach

The final site where the system was installed was the CSAH 1 site in Manhattan Beach, located in Northern Minnesota. Due to the distance required to travel to this site, MnDOT staff performed the installation without in-person assistance from SRF or CLR, though CLR provided remote assistance to help configure the system. This installation was performed on Wednesday, November 1st, 2023. As another TFA-managed site, the cabinet at this location was large enough to accommodate the Phoenix counter, resulting in a similar installation to the sites in Orono and Oakdale.

3.2 Equipment Summary

Table 3.2 lists the major equipment that was installed at each site (excluding minor items like power supplies and cables). The final row notes the spare equipment that was not installed at any sites but was instead provided to TFA staff for any future needs.

Table 3.2. List of equipment installed at each site.

Site	City	MnDOT Office	Equipment List
1	Oakdale	TFA	1x Phoenix Counter (3/4-lane) 1x VSign Hub 1x Sierra Wireless LX60 cellular gateway & antenna 1x Web Power Switch
2	Orono	TFA	1x Phoenix Counter (2-lane) 1x VSign Hub 1x Sierra Wireless LX60 cellular gateway 1x Web Power Switch
3	Manhattan Beach	TFA	1x Phoenix Counter (3/4-lane) 1x VSign Hub 1x Sierra Wireless LX60 cellular gateway & antenna 1x Web Power Switch
4	St. Louis Park	RTMC	2x I-Loop Duo detector cards 1x VSign Hub 1x Sierra Wireless LX60 cellular gateway & antenna 1x Web Power Switch
5	Golden Valley	Signal Operations	2x I-Loop Duo detector cards 1x VSign Hub 1x Sierra Wireless LX60 cellular gateway & antenna 1x Web Power Switch
NA	Spare	TFA	1x Phoenix Counter (3/4-lane) 1x Sierra Wireless antenna

3.3 Preliminary Testing

Following the installation at each site, the vendor configured the system and ensured that it was operational, at times requiring some fine tuning of parameters used for reading data from inductive loops. Further details on this process are provided in the field deployment and installation procedure, as shown in Chapter 4. Preliminary testing was also conducted at this point by performing spot checks to ensure that the data collected was reasonable given the traffic patterns. This generally consisted of monitoring the live data feed from the system as vehicles were driving over the loops and visually inspecting the resulting signature. The variation in the signatures produced by different types of vehicles, like passenger cars, trucks, and buses, was used to help verify that the system was working and producing reasonable data.

Figure 3.4 shows screenshots from the VSign portal used to view and configure the system, including the map interface containing an overview of all the sites, the page for viewing and configuring loop board parameters, and live vehicle signatures shown in real-time.

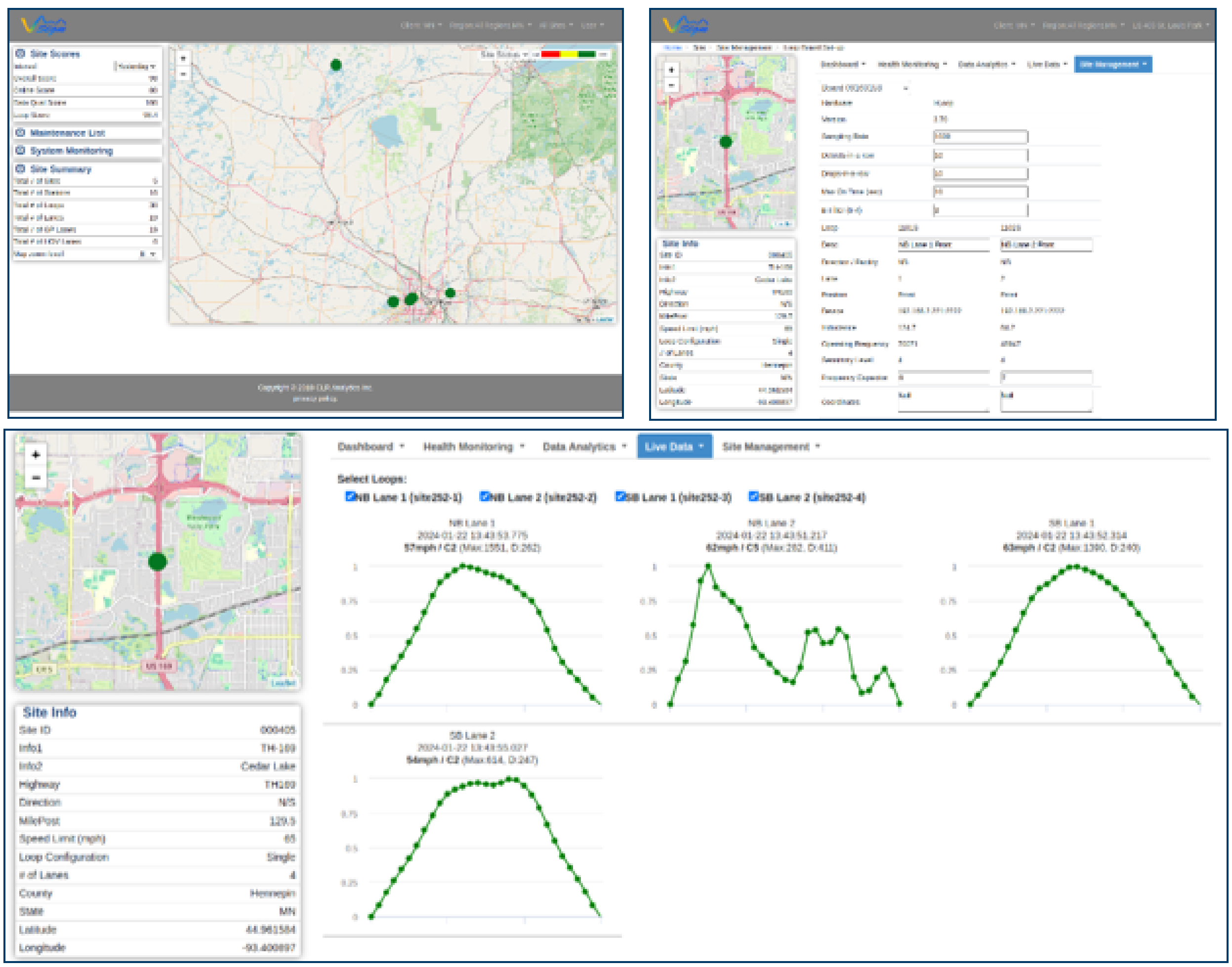

Figure 3.4. VSign portal screenshots. (Top left) Main map interface and site overview. (Top right) Loop board parameters page. (Bottom) Live vehicle profiles like those used to perform preliminary testing.

Chapter 4: Development of a Field Deployment and Installation Procedure

To facilitate easier integration of loop signature classification technology into MnDOT's data collection systems, researchers developed a field deployment and installation procedure to guide the setup and configuration of the system. Building on researchers' knowledge of the system and information from the technology vendor, the document describes the most important details required for engineers to procure equipment, install, and configure hardware in the field, and ensure the system is working properly. As part of this, the document briefly covers the following:

- Fundamentals of the technology and the general architecture of this implementation.
- Considerations for installing the system in counting/classification stations, or in systems used for traffic signals, ramp metering, or other Intelligent Transportation System (ITS) applications, including the different hardware typically involved in each case.
- Available options for communication and backend processing required by the system.
- Pre-deployment preparations, including information required by the vendor, configuration tasks that can be performed in-office, hardware and software components required in the field, and tools/supplies needed to perform the installation.
- The procedure for installing each piece of equipment, new or existing equipment each component must be connected to, and configuration that should be performed in the field, noting tasks that require the vendor's involvement.
- Additional information that may be helpful when configuring or troubleshooting the system.
- Basic instructions on accessing the web portal for monitoring and administering the system.
- The vendor's contact information for obtaining additional support.

The document is formatted to be easily referenced in the field, while still containing sufficient context for technicians to understand the tasks that must be performed and options for dealing with unforeseen challenges. To aid this, the document contains many figures, tables, and checklists to help staff prepare for an efficient deployment of the technology.

The field deployment manual was developed as a standalone document separate from this report. To obtain a copy of this document, please contact staff at MnDOT's Office of Transportation System Management.

Chapter 5: Collecting Data to Verify and Improve Truck Classification

To gain insight into the effectiveness of this automatic classification system and to help improve it, SRF manually collected vehicle classification data and compared it to the VSign data. Emphasis was placed on collecting data related to heavy vehicles, as identifying these vehicle types poses the greatest challenge for the system.

FHWA Classifications are based primarily on the use case for different vehicles. Buses, motorcycles, and passenger vehicles each have their own classifications. Trucks are further distinguished by the number of axles in contact with the roadway, number of wheels, and body/trailer configuration. An overview of the different classifications is provided in Figure 5.1 [8].

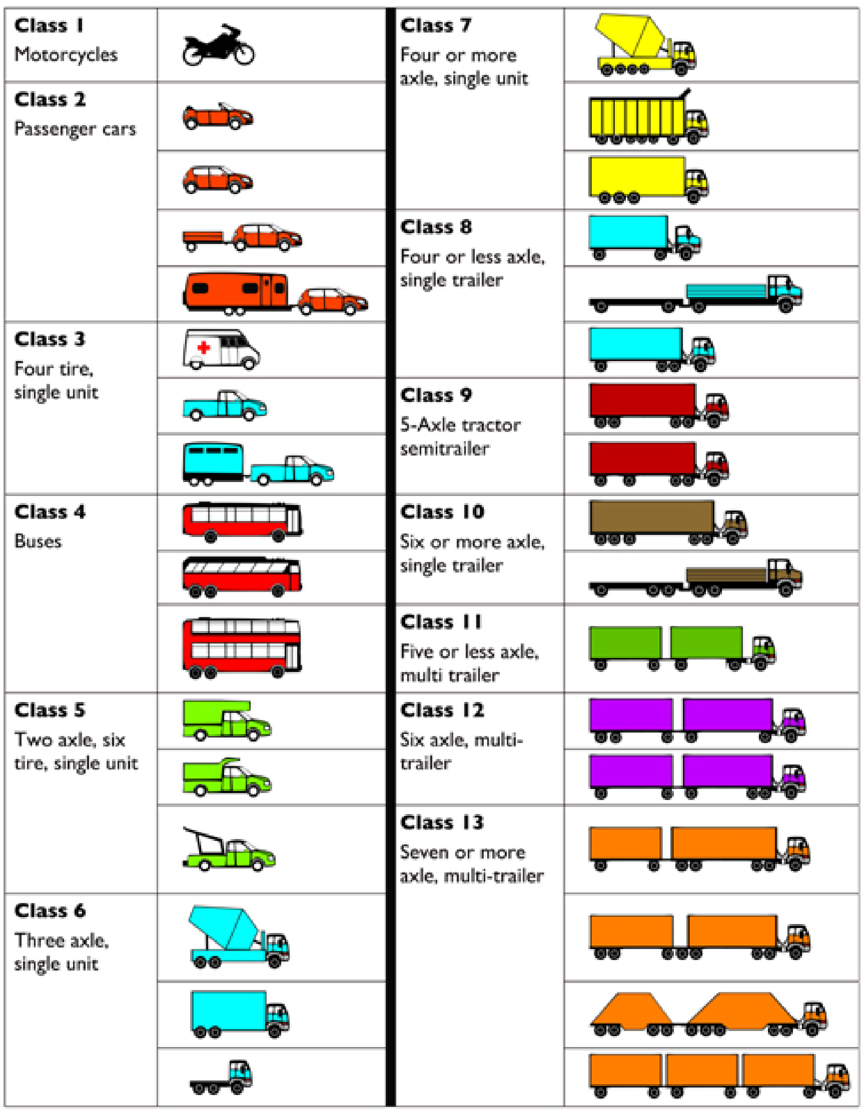

Figure 5.1. FHWA vehicle classification chart.

5.1 Manual Vehicle Classification

Video cameras were used to collect video ground truth data concurrently with loop signature data. In most locations, video was collected using a small, battery-powered camera attached to a luminaire or other object near the road. This was supplemented with video recorded from an RTMC camera which provided a good view of one site, as well as video recorded by MnDOT staff for the site in northern Minnesota.

From the videos, SRF manually recorded the time a vehicle drove over a loop in the roadway, which loop was driven over, and what the FHWA classification. Occasionally, if any one of these parameters was unclear, the manually collected data related to that vehicle was discarded from further analysis.

The time was recorded to the nearest second, matching the precision of the video timestamps. At times, two vehicles of the same class passed over a loop detector within the same second. This resulted in data entries that were indistinguishable, requiring some records to be excluded from further analysis. Future data entry processes should be adjusted to increase time precision where necessary to avoid this problem. Sample data entry is shown in Figure 5.2, where discarded data is shown highlighted in red.

Time (HH:MM:SS)	Loop Number (1-4)	Vehicle Class (1-13)	Vehicle Class (name)	Comments
10:50:13	2	3	Four tire, single unit	
10:50:15	2	2	Passenger Cars	
10:50:21	1	9	5-Axle tractor or semitrailer	
10:50:22	2	9	5-Axle tractor or semitrailer	
10:50:24	2	2	Passenger Cars	
10:50:25	2	2	Passenger Cars	
10:50:27	0	2	Passenger Cars	Between Lanes
10:50:29	1	2	Passenger Cars	
10:57:26	2	2	Passenger Cars	
10:57:31	1	3	Four tire, single unit	
10:57:32	2	3	Four tire, single unit	
10:57:32	2	3	Four tire, single unit	

Figure 5.2. Sample of vehicle classification spreadsheet with discarded data highlighted in red.

Over all five sites, data from 11,926 vehicles were manually collected and used for analysis. Data collection was dispersed over all five locations and for both directions of the roadways. To optimize the resources available, data collection prioritized observations of vehicles of FHWA class 5 or higher, though many observations of lower-class vehicles were still noted.

5.2 Data Processing

VSign classification data were exported and provided by CLR. For each manually classified vehicle record, a corresponding vehicle was searched for within the VSign dataset based on the timestamp. At each location, a constant time offset was applied to all manual entries to obtain the best overlap between both manual and VSign datasets. Records that most closely matched were assumed to be records of the same vehicle. Any vehicle in the manual classification dataset without a corresponding record in the VSign dataset within one second was recorded as missing, with some follow up investigation conducted on missing vehicles that further reduced these cases. Once the two datasets were matched to the greatest extent possible, an analysis of the VSign system was performed.

5.3 Ground Truth Analysis

For vehicle records with matching entries, the VSign vehicle classification matched the manual classification in 95% of cases. Within individual vehicle classes, however, accuracy varied significantly, and sample sizes were often very small. While 99% of Class 2 passenger vehicles were classified correctly by VSign, representing around 70% of all vehicles in the dataset, larger classes showed higher error rates. For example, only 6 vehicles of Class 11 were observed in the dataset, of which only 2 (33%) were classified correctly (the remainder of which were placed in Classes 9 or 10). An overview of these results can be seen in Figure 5.3, where matches indicate when manual classification agreed with VSign classification.

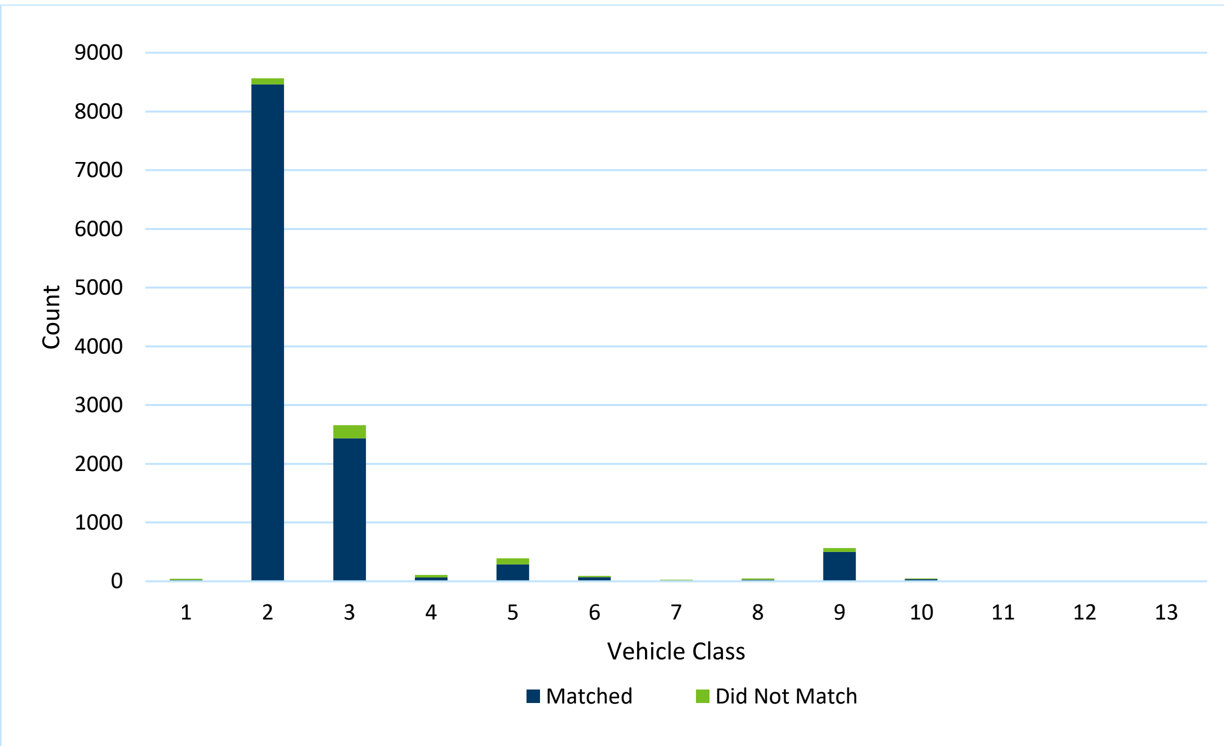

Figure 5.3. VSign algorithm accuracy of vehicle classification.

The most common misclassifications tended to place vehicles in adjacent classes with similar overall configurations but subtle differences in axle or trailer counts, such as mistaking Class 7 (four or more axle, single unit) with Class 6 (three axle, single unit), or Class 8 (four or less axle, single trailer) with Class 9 (5-axle semitrailer. A complete breakdown of results by FHWA class can be seen in Table 5.1.

Table 5.1. Comparison of VSign inductive loop signature classification results to manually classified ground-truth using the 13-bin FHWA vehicle classification scheme.

		VSign Classification (FHWA)														
		1	2	3	4	5	6	7	8	9	10	11	12	13	Total	Accuracy
FHWA Class (Manual)	1	4	19	0	0	0	0	0	0	0	0	0	0	0	23	17.4%
	2	0	8686	106	2	12	2	0	0	1	0	0	0	0	8809	98.6%
	3	0	144	2255	0	63	4	1	16	5	0	0	0	0	2488	90.6%
	4	0	0	5	18	25	14	0	0	0	3	1	0	0	66	27.3%
	5	0	3	41	9	184	32	3	13	5	2	0	0	0	292	63.0%
	6	0	0	0	0	14	51	7	0	1	0	0	0	0	73	69.9%
	7	0	0	0	0	3	9	2	0	0	0	0	0	0	14	14.3%
	8	0	0	3	0	0	2	0	4	14	1	2	0	0	26	15.4%
	9	0	1	6	0	1	1	0	22	436	34	0	1	0	502	86.9%
	10	0	0	0	0	0	0	0	2	13	20	0	0	0	35	57.1%
	11	0	0	0	0	0	0	0	0	3	1	2	0	0	6	33.3%
	12	0	0	0	0	0	0	0	0	0	0	2	5	0	7	71.4%
	13	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0.0%
	Tot.	4	8853	2416	29	302	115	13	57	478	62	7	6	0	12342	94.5%

VSign system performance was also evaluated under the 7-bin Highway Performance Monitoring System (HPMS) classification scheme. This system places vehicles in FHWA classes 1-4 in the same HPMS classes: motorcycles (MC), passenger cars (PC), light duty trucks (LT), and buses (BS), respectively. Vehicles in larger classes are grouped together: FHWA class 5, 6, and 7 are grouped together as single unit trucks (SU); 8, 9, and 10 are grouped into trucks with single trailer (ST); and 11, 12, and 13 are grouped into trucks with multi-unit trailers (MT). Using this classification scheme, the VSign system performed much better at classifying larger vehicles, with 81%, 97%, and 64% accuracy for SU, ST, and MT types, respectively. Full results by HPMS class can be seen in Table 5.2.

Table 5.2. Comparison of VSign inductive loop signature classification results to manually classified ground-truth using the 7-bin HPMS vehicle classification scheme.

Vehicle Class		VSign Classification (HPMS)							Total	Accuracy
HPMS	FHWA	1	2	3	4	5	6	7		
MC (1)	1	4	19	0	0	0	0	0	23	17.4%
PC (2)	2	0	8686	106	2	14	1	0	8809	98.6%
LT (3)	3	0	144	2255	0	68	21	0	2488	90.6%
BS (4)	4	0	0	5	18	39	3	1	66	27.3%
SU (5)	5, 6, 7	0	3	41	9	305	21	0	379	80.5%
ST (6)	8, 9, 10	0	1	9	0	4	546	3	563	97.0%
MT (7)	11, 12, 13	0	0	0	0	0	5	9	14	64.3%
Total		4	8853	2416	29	430	597	13	12342	95.8%

Comparing these results to the corresponding results from the previous phase of the project, shown in Table 5.3 and Table 5.4 shows similar overall performance (Liao, 2021, p. 27). Comparing results, classes with at least 100 samples showed results within 1% of the previous research in all but one case under both the 13-bin FHWA classification scheme and the 7-bin HPMS classification system, with the largest difference observed with classes with the smallest sample size. The observed variation is likely due to localized differences like site configuration or traffic conditions between the locations analyzed in each study, in addition to normal statistical variation in the smaller sample size cases.

Table 5.3. Tabulation of FHWA 13-bin vehicle classification results from previous report [6].

Vehicle Class		Classification from Loop Signature													Total	Vehicle Class		Classification Accuracy %
		1	2	3	4	5	6	7	8	9	10	11	12	13				
FHWA Class	1	56	1	1											58	FHWA Class	1	96.6%
	2	10	8968	119		17	8		2	1					9125		2	98.3%
	3		57	2199	5	38	23	1	109	18					2450		3	89.8%
	4			2	13	2	1								18		4	72.2%
	5		5	15	8	333	26	2	20	3					412		5	80.8%
	6			3	2	47	90	3	7	4	2				158		6	57.0%
	7				1	16	45	10		1					73		7	13.7%
	8			2			2	1	0	20					25		8	0.0%
	9		2	1	3	20	3	2	66	1168	61	3	2		1331		9	87.8%
	10			5	1		1	2	8	48	15				80		10	18.8%
	11											2			2		11	100.0%
	12												7		7		12	100.0%
	13													0	0		13	NA
Total		66	9033	2347	33	473	199	21	212	1263	78	5	9	0	**13739**	Overall		**93.6%**

Table 5.4. Tabulation of HPMS 7-bin vehicle classification results from previous report [6].

Vehicle Class		Classification from Loop Signature HPMS Class							Total (N)	Vehicle Class		Classification Accuracy %
HPMS	FHWA	1	2	3	4	5	6	7		HPMS	FHWA	
MC (Bin 1)	1	56	1	1					58	MC (Bin 1)	1	96.6%
PC (Bin 2)	2	10	8968	119		25	3		9125	PC (Bin 2)	2	98.3%
LT (Bin 3)	3		57	2199	5	62	127		2450	LT (Bin 3)	3	89.8%
BS (Bin 4)	4			2	13	3	0		18	BS (Bin 4)	4	72.2%
SU (Bin 5)	5, 6, 7		5	18	11	572	37		643	SU (Bin 5)	5, 6, 7	89.0%
ST (Bin 6)	8, 9 10		2	8	4	31	1386	5	1436	ST (Bin 6)	8, 9 10	96.5%
MT (Bin 7)	11, 12, 13						0	9	9	MT (Bin 7)	11, 12, 13	100.0%
Total		66	9033	2347	33	693	1553	14	**13739**	**Total**		**96.1%**

5.3.1 Site Considerations

Examining results for the specific sites, seen in Table 5.5, shows similar performance of the system overall, though with some variation.

Table 5.5. Classification accuracy by site.

Site	Sample Size	FHWA Class		HPMS Class	
		Correct Matches	Accuracy	Correct Matches	Accuracy
Manhattan Beach	528	486	92.0%	500	94.7%
Oakdale	4451	4243	95.3%	4323	97.1%
US-169	662	616	93.1%	623	94.1%
Orono	6285	5942	94.5%	5994	95.4%
MN-55	416	380	91.3%	383	92.1%
Total	**12342**	**11667**	**94.5%**	**11823**	**95.8%**

Sites with larger sample sizes show higher accuracy, with additional variation between sites due to location-specific factors. Researchers noted the following details that likely led to the increased error rate observed at some sites:

- A high proportion of vehicles at the CSAH 15 site in Orono were observed driving off-center, which can increase classification errors. The loops at this site have also shown clear degradation in recent months, early symptoms of which may have impacted the classification results during the data collection period.
- The use of loops at the entrance of a segment, like at the MN-55 site in Golden Valley, can reduce system performance due to the variation in vehicle speed/acceleration and lateral position when driving over sensors; the use of mid-segment loops, such as those used for advanced detection at intersections, is preferred when possible.
- Site geometrics at the US-169 site in St. Louis Park and CSAH 1 site in Manhattan Beach often limited researchers' ability to properly see vehicle axle configurations when processing video data, which may have affected ground truth data.

Despite these issues, the overall classification accuracy exceeded 90% at all sites, with most sites closer to 95% accuracy. These site-specific considerations can also help inform future decisions on where to install this technology for maximum benefit.

5.4 Comparison to IRD System

In addition to the video ground truth analysis, the VSign classification results at one site (CSAH 1 in Manhattan Beach) were compared to those from the video-based iTHEIA™ counting and classification system developed by International Road Dynamics (IRD) [9]. Comparing the VSign system to another commercial vehicle classification system helps provide context around how well a classification system can be expected to perform. These results can be seen in Table 5.6 and Table 5.7 (classes with no ground truth observations are omitted to save space).

Table 5.6. Comparison of VSign and IRD Vehicle Classification systems to ground truth using the 13-bin FHWA classification scheme.

Dataset	FHWA Class (Blanks Omitted)								Matches	Total Observations
	2	3	4	5	6	7	9	10		
Ground Truth	229	220	3	40	6	2	15	13		528
VSign	226	205	2	29	4	1	11	8	486	528
VSign Accuracy	99%	93%	67%	73%	67%	50%	73%	62%	92%	100%
IRD	154	154	1	24	3	2	10	3	351	408
IRD Accuracy	67%	70%	33%	60%	50%	100%	67%	23%	86%	77%

Table 5.7. Comparison of VSign and IRD Vehicle Classification systems to ground truth using the 7-bin HPMS classification scheme.

Dataset	HPMS Class (Blanks Omitted)					Matches	Total Observations
	PC (2)	LT (3)	BS (4)	SU (5)	ST (6)		
Ground Truth	229	220	3	48	28		528
VSign	226	205	2	34	19	486	528
VSign Accuracy	99%	93%	67%	71%	68%	92%	100%
IRD	154	154	1	29	13	351	408
IRD Accuracy	67%	70%	33%	60%	46%	86%	77%

Though limited in sample size, in these results the VSign system outperforms the IRD system by a notable margin. Errors are still observed in both systems, but at reduced rates for the VSign system. The IRD system also demonstrated a high rate of missing vehicles entirely, as seen in the reduced number of total observations. Further comparison of inductive loop signature classification technology to alternate systems, including both modern and legacy technologies, should be performed to better understand the tradeoffs of each technology.

5.5 Improvement of Classification Library

Following this analysis, researchers worked with the VSign technology vendor, CLR Analytics, to assess the need for changes to the system's classification library. Based on a detailed assessment of individual vehicle records, a subset of vehicles displaying a specific signature curve are under consideration for reassignment into a different classification. Further modifications to the library, which could potentially result in the misclassification of other vehicle types, are unlikely though also under consideration.

Chapter 6: Life Cycle Cost Analysis

While the VSign system performs well relative to other classification data collection systems, there is nonetheless a cost associated with installing and operating this system, including an annual software subscription and hardware maintenance fee. Given this, users of this technology will want to consider the performance and other benefits of the technology in the context of the overall cost to deploy and maintain it.

To help with planning and decision making for future consideration of inductive loop signature technology, a basic life cycle cost analysis (LCCA) was conducted to compare the overall cost of the system to the conventional piezoelectric brass linguine vehicle classification systems that are typically installed by MnDOT. This was performed using a standardized LCCA calculator spreadsheet provided by MnDOT for use in various engineering planning scenarios. The analysis performed for this project was relatively simple, comparing the cost of a 2-lane site under the different scenarios, and assuming a 7-year lifespan for piezoelectric sensors, 10-year lifespan for controllers and other electronic components, and 15-year lifespan for preformed loops used by the inductive loop system. These costs were simulated over a 35-year period based on a 4.5% interest rate and annualized for comparison. The results of this analysis are presented in Table 6.1 and Table 6.2 (with some lines consolidated for conciseness).

Table 6.1. Life cycle cost analysis of conventional piezoelectric ATR station with brass linguine sensors.

Year(s)	Cost Description	Future Value	Present Value	Annualized
0	Conventional ATR	$5,800	$5,800	$332
1-6		$0	$0	$0
7	Furnish and install BL sensors	$21,000	$15,431	$884
8-9		$0	$0	$0
10	Replace Controller and other electronic components	$5,800	$3,735	$214
11-13		$0	$0	$0
14	Furnish and install BL sensors	$21,000	$11,339	$649
15-19		$0	$0	$0
20	Replace Controller and other electronic components	$5,800	$2,405	$138
21	Furnish and install BL sensors	$21,000	$8,333	$477
22-27		$0	$0	$0
28	Furnish and install BL sensors	$21,000	$6,123	$351
29		$0	$0	$0
30	Replace Controller and other electronic components	$5,800	$1,549	$89
31-34		$0	$0	$0
35	Furnish and install BL sensors	$21,000	$4,499	$258
Totals		$128,200	$59,214	$3,391

Table 6.2. Life cycle cost analysis of inductive loop signature system with preformed loops.

Year(s)	Cost Description	Future Value	Present Value	Annualized
0	Inductive Loop Signature System	$24,275	$24,275	$1,390
1-2	Software subscription & hardware maintenance (Year 2-3)	$2,300	$2,201	$126
3-9	Software subscription & hardware maintenance (Year 4+)	$2,400	$2,103	$120
10	Replace Controller and other electronic components	$6,275	$4,041	$231
11-12	Software subscription & hardware maintenance (Year 2-3)	$2,300	$1,417	$81
13-14	Software subscription & hardware maintenance (Year 4+)	$2,400	$1,354	$78
15	Furnish and install preformed loop + software & hardware maintenance	$20,400	$10,541	$604
16-19	Software subscription & hardware maintenance (Year 4+)	$2,400	$1,187	$68
20	Replace Controller and other electronic components	$6,275	$2,602	$149
21-22	Software subscription & hardware maintenance (Year 2-3)	$2,300	$913	$52
23-29	Software subscription & hardware maintenance (Year 4+)	$2,400	$872	$50
30	Replace Controller and other electronic components + F&I preformed loop	$24,275	$6,481	$371
31-32	Software subscription & hardware maintenance (Year 2-3)	$2,300	$588	$34
33-35	Software subscription & hardware maintenance (Year 4+)	$2,400	$562	$32
Totals		$155,100	$84,989	$4,867

Based on these results, the inductive loop signature system has an estimated annualized cost of $4,867 compared to $3,391 for the conventional system, a 44% increase. However, this does not account for many of the other considerations related to these technologies, including the variation in lifespan of hardware, sensitivity to physical degradation, the cost of other recurring maintenance activities, or the benefits provided by improved classification accuracy. For the comparison of these two technologies in particular, the sensitivity of piezoelectric systems to pavement degradation is noteworthy, as the development and growth of pavement cracks will typically lead to accelerated failure of components embedded in the pavement, particularly in cold climates. By comparison, inductive loop sensors will generally continue working despite pavement damage as long as continuity is maintained for the loop coil and wiring to a cabinet. Further investigation is suggested to better understand the sensitivity of a cost analysis to these and other considerations.

The cost comparison between conventional ATR and inductive loop signature systems was also extended to demonstrate the value of the system in situations where loop sensors are already in place for other purposes, as shown in Table 6.3. When the analysis is performed with the cost of preformed loops removed, assuming a scenario where installation and maintenance of in-pavement loops is covered by an existing program, the cost of the system is significantly reduced to an annualized cost of $3,029 (an 11% decrease over conventional ATR). This may better reflect the intended use of the technology as a way to retrofit existing volume data collection sites to provide vehicle classification data.

Table 6.3. Life cycle cost analysis of inductive loop signature system with the cost preformed loops removed.

Year(s)	Cost Description	Future Value	Present Value	Annualized
0	Inductive Loop Signature System	$6,275	$6,275	$359
1-2	Software subscription & hardware maintenance (Year 2-3)	$2,300	$2,201	$126
3-9	Software subscription & hardware maintenance (Year 4+)	$2,400	$2,103	$120
10	Replace Controller and other electronic components	$6,275	$4,041	$231
11-12	Software subscription & hardware maintenance (Year 2-3)	$2,300	$1,417	$81
13-19	Software subscription & hardware maintenance (Year 4+)	$2,400	$1,354	$78
20	Replace Controller and other electronic components	$6,275	$2,602	$149
21-22	Software subscription & hardware maintenance (Year 2-3)	$2,300	$913	$52
23-29	Software subscription & hardware maintenance (Year 4+)	$2,400	$872	$50
30	Replace Controller and other electronic components	$6,275	$1,675	$96
31-32	Software subscription & hardware maintenance (Year 2-3)	$2,300	$588	$34
33-35	Software subscription & hardware maintenance (Year 4+)	$2,400	$562	$32
Totals		$101,100	$52,883	$3,029

While this cost analysis is very simple, it helps illustrate some of the ongoing costs of inductive loop signature technology, as well as some of the scenarios in which it makes sense to deploy. Further research to better assess the costs of sensor failures, system downtime, increase maintenance activities, and the sharing of equipment, and to better quantify the benefits of the respective technologies, should be performed. Such research could inform a more thorough cost-benefit analysis of various vehicle classification or travel monitoring technologies, providing a valuable decision-making tool for those evaluating these systems for use in their operations.

Chapter 7: Conclusions

When classifying vehicles into the FHWA's 13 vehicle classes, the VSign classification system had an average accuracy of 95%. The accuracy was somewhat lower for trucks (Classes 5-13) than for passenger vehicles (Classes 1-4). Of the vehicle classes with at least 100 observations, the accuracies for passenger vehicles were 99% for Class 2 and 91% for Class 3, whereas the accuracies for trucks were 63% for Class 5, 70% for Class 6, and 87% for Class 9. This trend matched the results of previous evaluations, which showed higher classification accuracy for passenger vehicles and lower accuracy for heavy vehicles and other classes with fewer observations.

When examining the truck classes and their relatively low accuracy rates, it became apparent that many of the errors in classifying trucks came from the algorithm having difficulty distinguishing between similar classes of trucks. For example, there were a combined total of 563 Class 8, 9, and 10 trucks, 460 of which were accurately classified by VSign (82% accuracy). Of the 103 misclassifications, 83% of them were misclassified within the group of three Classes (e.g., a Class 8 misclassified as a Class 9 or a Class 10 misclassified as a Class 8). The HPMS somewhat alleviates this issue with its simplified classes including the single trailer class that combined FHWA Classes 8, 9, and 10. When using the HPMS classes, VSign had a 97% accuracy rate when classifying vehicles in the single trailer class (FHWA Class 8-10). In fact, VSign had an accuracy above 80% for all four HPMS classes with at least 100 observations.

At the Manhattan Beach site, which was outfitted with both the VSign inductive loop-based classification system and the video-based iTHEIA™ counting and classification system developed by IRD, the VSign system not only outperformed the IRD system both in terms of accuracy in classifying vehicles by HPMS class (92% vs 86%) but also in terms of detection rate (100% vs 77%).

The evaluation of the VSign system's performance at the five study sites suggests that it performs better at locations where vehicles are traveling at consistent speeds and are centered in the lane – not near intersections, on curves, or on freeway segments with frequent recurring congestion – due to the negative effects of variations in vehicle speed/acceleration and lateral position when driving over sensors. Given this, the use of mid-segment loops is preferred when possible.

To help improve the classification algorithm's ability to accurately classify vehicles, the loop signatures of each of the manually classified vehicles will be annotated by CLR, so that they can be added to the data set used to train the VSign algorithm. The quality of the dataset will be improved both by increased quantity of loop signatures and the increased diversity of settings/circumstances in which the new loop signatures were collected.

A preliminary life-cycle cost analysis of the system suggests that, while the ongoing software subscription and hardware maintenance costs are fairly high, there are some situations where the benefits of the technology still make it cost effective. Further research is recommended to better understand these considerations and how they should be evaluated during the planning and programming process.

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