EVALUATING VEHICLE DATA ANALYTICS FOR ASSESSING ROAD INFRASTRUCTURE FUNCTIONALITY

by

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ABSTRACT

The Indiana Department of Transportation (INDOT) manages and maintains over 3,000 miles of interstates across the state. Assessing lane marking quality is an important part of agency asset tracking and typically occurs annually. The current process requires agency staff to travel the road and collect representative measurements. This is quite challenging for high volume multi-lane facilities. Furthermore, it does not scale well to the additional 5,200 centerline miles of non-interstate routes.

Modern vehicles now have technology on them called “Lane Keep Assist” or LKA, that monitor lane markings and notify the driver if they are deviating from the lane. This thesis evaluates the feasibility of monitoring when the LKA systems can and cannot detect lane markings as an alternative to traditional pavement marking asset management techniques. This information could also provide guidance on what corridors are prepared for level 3 autonomous vehicle travel and which locations need additional attention.

In this study, a 2019 Subaru Legacy with LKA technology was utilized to detect pavement markings in both directions along Interstates I-64, I-65, I-69, I-70, I-74, I-90, I-94 and I-465 in Indiana during the summer of 2020. The data was collected in the right most lane for all interstates except for work zones that required temporary lane changes. The data was collected utilizing two go-pro cameras, one facing the dashboard collecting LKA information and one facing the roadway collecting photos of the user’s experience. Images were taken at 0.5 second frequency and were GPS tagged. Data collection occurred on over 2,500 miles and approximately 280,000 images were analyzed. The data provided outputs of: No Data, Excluded, Both Lanes

Not Detected, Right Lane Not Detected, Left Lane Not Detected, and Both Lanes Detected.

The data was processed and analyzed to create spatial plots signifying locations where markings were detectable and locations where markings were undetected. Overall, across 2,500 miles of travel (right lane only), 77.6% of the pavement markings were classified as both detected. The study found

- 2.6% the lane miles were not detected on both the left and right side
- 5.2% the lane miles were not detected on the left side
- 2.0% the lane miles were not detected on the right side

Lane changes, inclement weather, and congestion caused 12.5% of the right travel lane miles to be excluded. The methodology utilized in this study provides an opportunity to complement the current methods of evaluating pavement marking quality by transportation agencies.

The thesis concludes by recommending large scale harvesting of LKA from a variety of vendors so that complete lane coverage during all weather and light conditions can be collected so agencies have an accurate assessment of how their pavement markings perform with modern LKA technology. Not only will this assist in identifying areas in need of pavement marking maintenance, but it will also provide a framework for agencies and vehicle OEM's to initiate dialog on best practices for marking lines and exchanging information.

1. INTRODUCTION

Assessing lane marking quality is an important part of agency asset tracking. Difficult to detect lane markings can lead to driver confusion and perhaps crashes. Understanding locations where lane markings may be difficult for vehicles to detect, is particularly important for connected and autonomous vehicles. According to a study conducted by the National Cooperative Highway Research Program (NCHRP) approximately 30% of state agencies perform pavement marking evaluations annually and the remaining agencies collect pavement marking condition bi-annually or sporadically (Hawkins and Smadi 2013). The study suggests that the frequency of data collection varies due to cost, collection procedures, and the ability to provide personnel to complete the activities. Better, more frequent data collections can be obtained using LKA technology.

94% of crashes are caused by human error (USDOT 2015) and the use of LKA can aid in reducing the number of crashes. Original Equipment Manufacturers (OEM) have equipped LKA technology in their vehicle's over the course of the last decade. The technology's primary purpose is to provide comfort and enhance safety for customers. In addition, this technology provides OEM's an opportunity to assess algorithms as they begin to enter levels 1-2 of autonomy (SAE International 2018, Beglerovic et al. 2018). Aside from the enhanced safety features of the technology there is a potential to provide agencies and drivers feedback on pavement marking quality. This research explored opportunities to utilize vehicle sensor data to assess pavement marking quality efficiently and economically across the state of Indiana. The primary objective of the study was to determine if LKA data could be used as a measure to determine the quality of pavement markings. The secondary objective was to provide a spatial map on what areas of a roadway contain pavement markings detectable by LKA and areas that are difficult to detect.

1.1 Study Area

The study area includes 8 interstates across the state of Indiana, including I-64, I-65, I-69, I-70, I-74, I-90, I-94 and I-465. The total miles that the study was conducted on is over 2,500 miles and include urban and rural interstates varying from 2-6 lanes. The typical posted speed limit was 70 mph with I-465 and areas on I-94 and I-90 with speed limits posted as 55 mph or less. Exceptions to the posted speed limit include work zones, inclement weather, and accidents. Indiana is divided into 6 districts shown in Figure 1.1. This district organization was used for reporting the results since maintenance activities are typically organized by district. Table 1.1 shows the district, the interstates that lie in that district, the interstate mile markers that start and end within the district, and the total miles that are managed for that specific district.

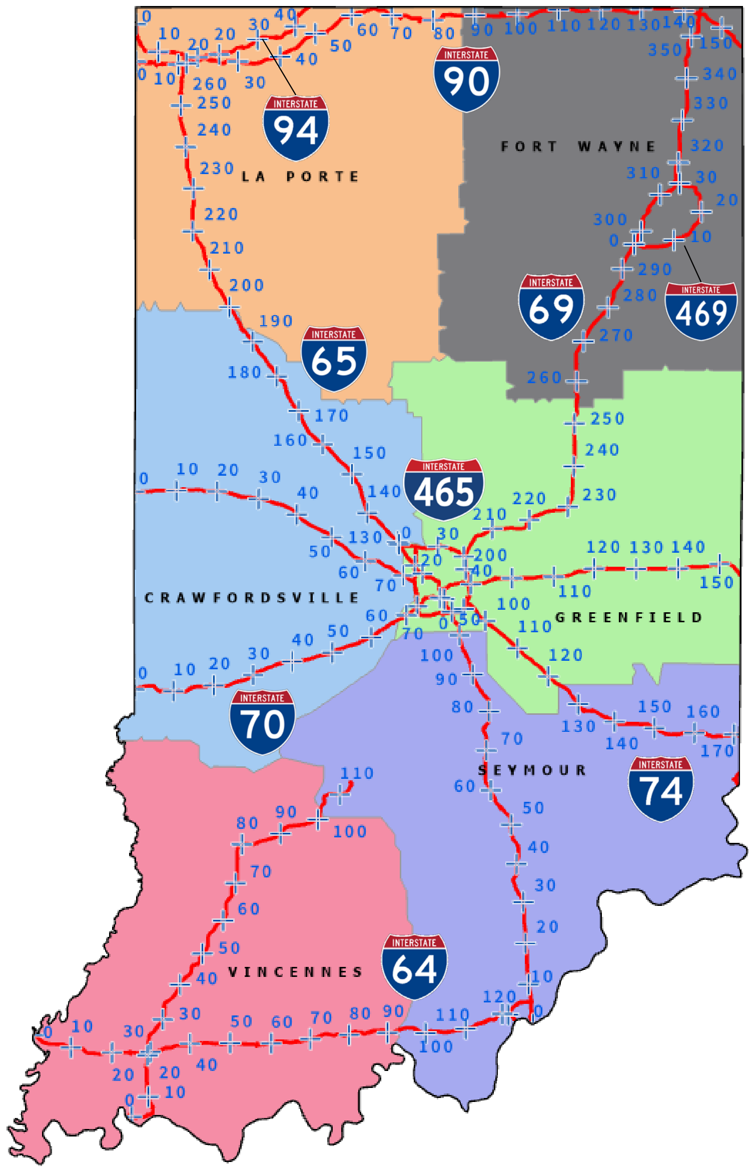


Figure 1.1 Study location: Indiana and the 8 interstates analyzed

Table 1.1 Indiana interstates sorted by district with mile marker (MM)

District	Interstate	Start Mile Marker	End Mile Marker	Total Miles
Crawfordsville	I-65	130	201	71
	I-70	0	69	69
	I-74	0	73	73
Fort Wayne	I-69	255	357	102
	I-90 (toll)	87	156	69
	I-469	0	31	31
Greenfield	I-65	101	130	29
	I-69	200	255	55
	I-70	69	157	88
	I-74	73*	123	50
	I-465	0	53	53
La Porte	I-65	201	262	61
	I-90 (toll)	0	87	87
	I-94	0	46	46
Seymour	I-64	92	124	32
	I-65	0	101	101
	I-69	104	114	10
	I-74	123	171	48
Vincennes	I-64	0	92	92
	I-69	0	104	104

1.2 Study Period

This study was conducted over the course of 3 months from June to August 2020 with a pair of students in the study vehicle. Table 1.2 shows the dates the data was collected for each interstate; including the miles driven, and the time taken to collect the data. The data was obtained at every half a second which is approximately every 50 feet traveling at 70 miles per hour. For initial data processing the data was aggregated into 0.1, 1, 5, and 10-mile bins. After a quick analysis it was determined that due to the size of the data, the amount of infrastructure being assessed, and GPS inaccuracies that aggregating the data into 1-mile bins portrayed the data is the simplest manner.

Table 1.2 Dates of data collection

Date Driven	Interstate	Total Miles	Total Time (Hours)
08/19/2020 08/20/2020	I-64	248	4.0
06/19/2020	I-65	524	13.0
08/11/2020 08/19/2020 08/20/2020	I-69	714	15.3
07/07/2020 07/21/2020	I-70	314	6.7
08/07/2020	I-74	246*	5.1
08/12/2020	I-90	312	5.0
08/12/2020	I-94	92	1.7
08/19/2020	I-465	106	2.3

1.3 Study Scope

INDOT maintains over 3,000 miles of interstates across the state and must maintain pavement quality, pavement markings, and sign retroreflectivity. Retroreflectivity is a term used when evaluating how much light is reflected from an object back to the driver. According to the INDOT website the purpose of pavement markings is to convey which part of the roadway is to be utilized, the upcoming road conditions, and where passing is allowed. Each year INDOT measures pavement marking retroreflectivity and if the value falls below a minimum threshold the pavement marking is repainted ("INDOT: Pavement Markings" n.d.). According to the Manual on Uniform Traffic Control Devices (MUTCD) there are many types of pavement markings that can be used but they can be summarized into four categories: temporary markings, longitudinal, centerlines, and transverse markings ("Chapter 3B - MUTCD 2009 Edition - FHWA" n.d.). The type of line can affect the minimum threshold and the required repainting procedures.

The current methods of evaluating pavement markings include handheld and mobile retroreflectometers. These devices will be discussed in more detail in the next chapter. Mobile retroreflectometers are an effective way to expedite the evaluation of pavement markings, but these units are limited to the capability of the ability to capture one pavement marking at a time. Meaning if an agency has a 4-lane divided highway the mobile retroreflectometer unit must make 6 passes to capture readings on all pavement markings.

Actively managing and assessing pavement retroreflectivity can be very time consuming for agencies but is crucial for user safety. A study on four-lane roads found that there were a decreased number of crashes when retroreflective values were higher for pavement markings at 0.01 and 0.001 level of significance (Bektas et al. 2016). Figure 1.2 shows I-65, which is a rural, 4-lane divided highway. Although the centerline can be seen in the image, callout i shows the lack of a pavement marking that would advise the user where the divide between the travel lane and shoulder lies.

Figure 1.2 Undetected pavement marking on I-65

2. LITERATURE REVIEW

The literature review is intended to provide a background on pavement markings, current methods of pavement marking evaluation, and provide insight on the use of other technology. This information aids in the understanding of the problem and helps determine alternatives to pavement marking evaluation.

2.1 Pavement Marking Background

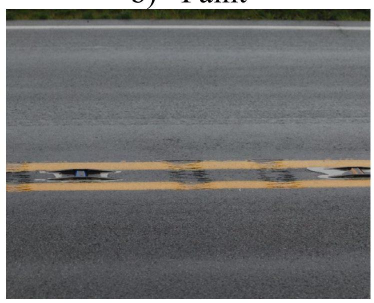
Pavement markings contribute a significant role in driver and user safety. The main purpose of pavement markings is to provide guidance on operating areas to users under various conditions, including exit/entrance ramps, lane changes, and other control purposes (Yu 2004). Although there are many different types of pavement markings that agencies utilize, there are four that are common in Indiana: multi-component, paint, preformed tape, and thermoplastic (Zehr et al. 2019). Figure 2.1 shows the unique type of pavement markings. The use of each type varies by Average Annual Daily Traffic (AADT), the surface life of the pavement, pavement material and other varying pavement characteristics (“INDOT: Pavement Markings” n.d.). There are many types of pavement markings but edge lines provide the greatest safety impact, because they improve lane-keeping performance (Bahar et al. 2006). Edge line markings act as a visual reference for drivers during reduced visibility conditions, helping the driver stay in the driving lane (“Chapter 3B - MUTCD 2009 Edition - FHWA” n.d.).

a) Multi-component

b) Paint

c) Preformed tape[1]

d) Thermoplastic



e) Dry rumble strips

f) Wet rumble strips

Figure 2.1 Different types of lane markings

2.2 Pavement Marking Evaluation

The frequency of evaluation of pavement markings varies by agency due to labor force and cost of collection, but the method of evaluation has to comply with American Society for Testing and Materials (ASTM) Standard D7585 and ASTM Standard E1710 depending on the instrument being used to evaluate the pavement marking ("ASTM D7585 / D7585M - 10" 2015, "ASTM E1710 - 18" 2018). Figure 2.2, from the "Evaluation of Traffic Control Devices: Third-Year Activities", shows the two typical instruments that are used by agencies for evaluating pavement marking retroreflectivity (Hawkins et al. 2007). Figure 2.2a shows a handheld retroreflectometer. Specifications provided by ASTM Standard D7585 must be utilized for the values to be credible. This method provides greater accuracy but is time consuming for agencies. Figure 2.2b is a mobile retroreflectometer, and specifications provided by ASTM Standard E1710 must be followed for the measurement readings to be valid. The mobile unit enables agencies to evaluate more pavement markings efficiently, but the drawback is that the unit only detects retroreflectivity on one pavement marking at a time. If an agency is completing the analysis on a 2-lane undivided highway, the unit must make three passes to evaluate both edge lines and the centerline on the roadway. This inefficiency of pavement marking evaluation provides opportunities for LKA data.

a) Hand-held retroreflectometer b) Mobile retroreflectometer

Figure 2.2 Pavement marking retroreflectivity measuring devices

2.3 Literature on Impact of Lane Markings on Crash Frequency

Improvements in pavement marking visibility has the potential to reduce crashes. Improving existing lane markings has been reported to reduce wet-road crashes (Lyon et al. 2015). This analysis was conducted using a before and after study and concluded that the reduction of crashes was due to the improvement of pavement marking visibility during wet pavement conditions. Another study found that pavement marking retroreflectivity for white edge lines and yellow edge lines were significantly related to crash frequency on four lane roads (Bektas et al. 2016).

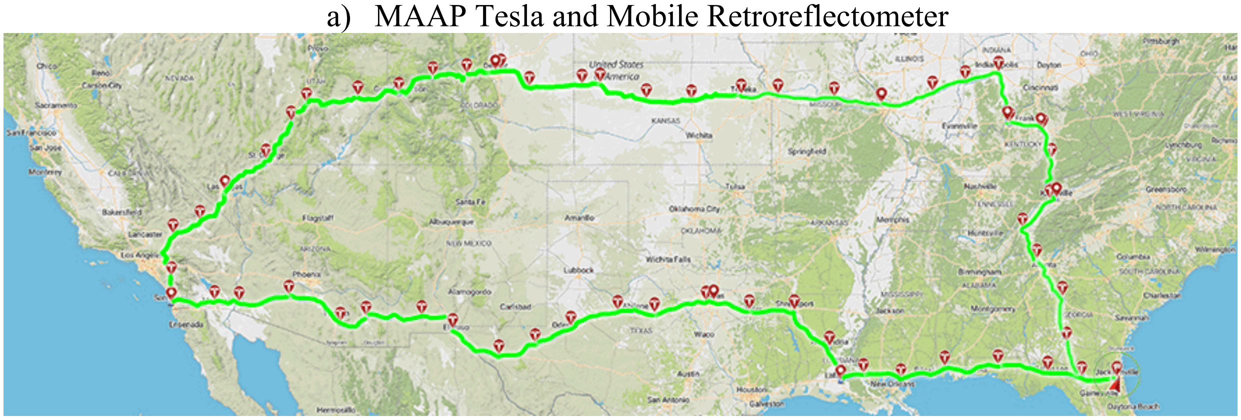
2.4 Opportunities for New Methods for Assessing Lane Markings

It is particularly important to understand locations where line markings may be difficult for vehicles to detect for future connected and autonomous vehicles. Some Advanced Driver Assistance Systems (ADAS) technologies, like LKA and Lane Departure Warning (LDW), have not reached the expected market penetration (Pape and Habtemichael 2018). One of the hypothesized reasons for this lack of penetration is a perceived lack of consistency in systems recognizing lane markings as pavement markings age (Nayak et al. 2020). The farther away a lane can be detected, the longer response time the driver and/or vehicle will have to react to a potential danger or road change (Pike et al. 2019b). To maximize LKA and LDW safety benefits, locations where ADAS technologies have detection issues should be cataloged. This could be used to improve driver experience and provide pro-active feedback to agencies. Depending on the particular scenario, performance can be improved by incorporating high index wet retroreflective beaded optics (Pike et al. 2019b), changing from 4-inch wide to 6-inch wide markings (Pike et al. 2018), or simply by restriping (Pike et al. 2019a). This would also provide a more efficient way to evaluate pavement markings because a vehicle equipped with LKA is capable of detection on both the driver and passenger side, simultaneously. Rather than collecting data on each pavement marking, the vehicle could detect two with a single pass.

2.5 Related Pavement Marking Evaluation

Professional Pavement Products (PPP) Company is currently mapping pavement markings across the United States through their initiative "Measure Across America Project (MAAP)". In that evaluation, PPP has identified several routes to drive using their LLG7-C Mobile Retroreflective Unit which can measure the retroreflectivity of pavement markings at highway speeds seen in Figure 2.3a. Since the beginning of the project in 2018 they have evaluated over 6,500 miles seen in Figure 2.3b and have an additional 1,000 miles planned to assess through the states of Pennsylvania, Ohio, Indiana, and Illinois ("MAAP - PPP, Inc." n.d.). A study limitation is the mobile retroreflectometer can only assess one pavement marking line at a time, meaning if the assessment were to be done on a two-lane road, three passes must be done to collect the data on all of the pavement markings.

a) MAAP Tesla and Mobile Retroreflectometer



b) Coverage of MAAP during the Coast to Coast Project

Figure 2.3 MAAP data collection equipment and data collection area

3. DATA PROCESSING

3.1 Data Collection

Data collection for this study included two Go Pro Hero 8 cameras capturing images at half-second intervals. One camera was focused on the vehicle's dashboard specifically capturing the LKA display. The location of the camera can be seen in Figure 3.1 as callout *i.* The other camera was focused on the roadway pavement markings, seen in Figure 3.1 as callout *ii*. This set up was used to determine under what conditions the vehicle could detect pavement markings. The images also contained timestamps and GPS location in the metadata. When beginning the data collection, the cameras were synchronized using the National Institute of Standards and Technology time synchronization website ("National Institute of Standards and Technology | NIST" n.d.). This allowed the creation of a time-lapse and verification of both location and time when determining highly detectable or undetectable areas.

Figure 3.1 Equipment setup for data collection

3.2 Data Preprocessing

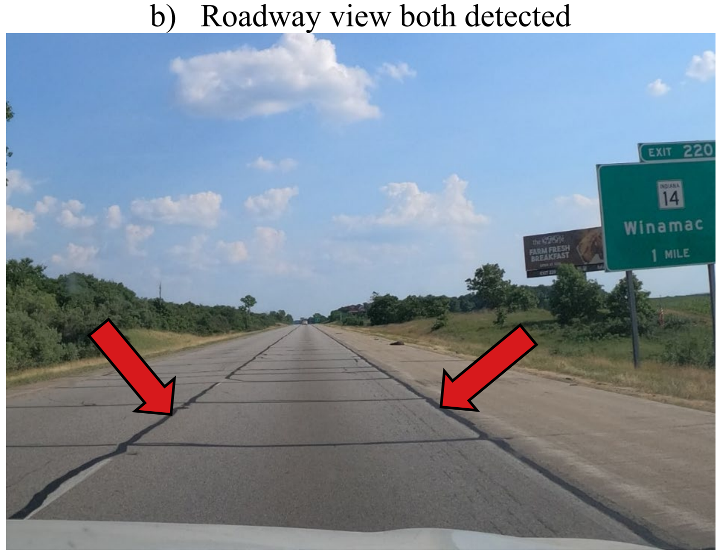
Data collection occurred over 2,500 miles with over 280,000 images collected. The images were compiled and broken into 6 different categories. The first category was when the vehicle detected both pavement markings. Figure 3.2a shows the dashboard image when the vehicle could detect the pavement marking and Figure 3.2b shows the road view image at the same location. The second category was when the vehicle could not detect either pavement marking. Figure 3.2c shows the dashboard image when both pavement markings were undetectable and Figure 3.2d shows the road view image at the same location. Other categories include left not detected Figure 3.3a and Figure 3.3b, and right not detected Figure 3.3c and Figure 3.3d. These were the original categories and during data collection it was noticed that other categories are necessary.

During data collection and preliminary analysis, it was observed that when making a lane change/using a turn signal LKA becomes inactive. To eliminate a misclassification of a detectable pavement marking when a lane change occurred, the data collected during that period was categorized as excluded. An example of an excluded instance can be seen in Figure 3.4a and Figure 3.4b, callout *i* shows the turn signal which makes LKA inactive. It was also found that LKA is inactive when the vehicle is traveling at speeds lower than 35 miles per hour. When the vehicle was traveling at lower speeds, the images were categorized as no data. An example of this can be seen in Figure 3.4c and Figure 3.4d, callout *ii* depicts the low vehicle speed.

a) Dashboard view both detected

b) Roadway view both detected

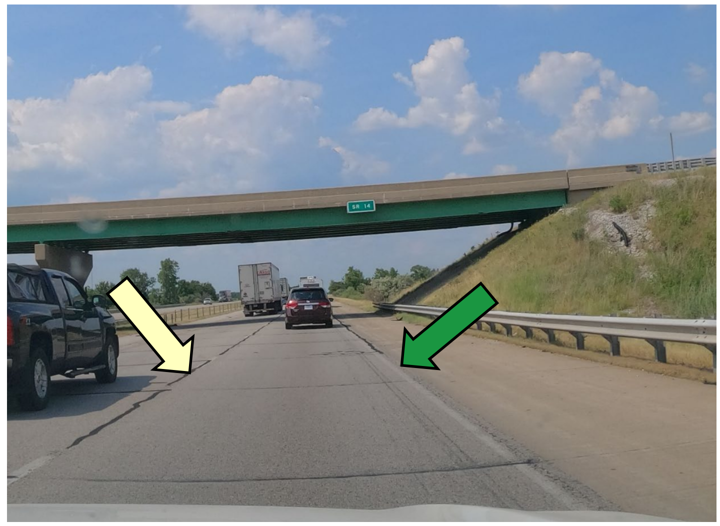
c) Dashboard view both not detected



d) Roadway view both not detected

Figure 3.2 Detectable lane markings and difficult to detect lane markings

a) Dashboard view left not detected



b) Roadway view left not detected

c) Dashboard view right not detected

d) Roadway view both detected

Figure 3.3 Left and right undetectable pavement marking

a) Dashboard view excluded

b) Roadway view left not detected

c) Dashboard view right not detected

d) Roadway view both detected

Figure 3.4 Excluded and no data due to low vehicle speed and lane changes

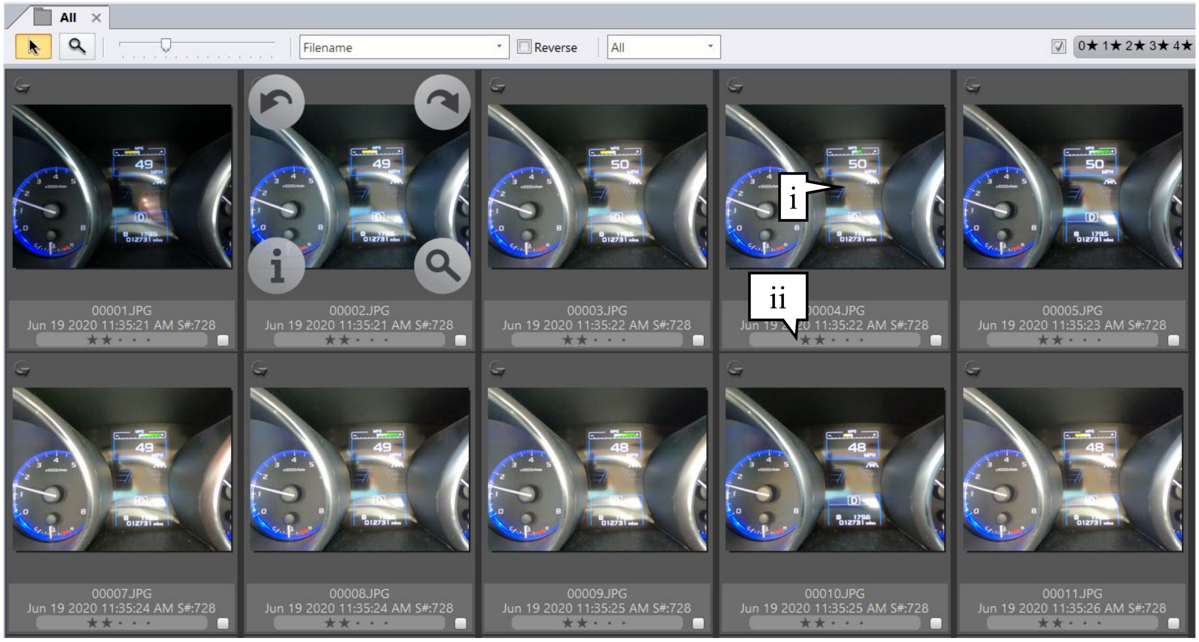
3.3 Processing the Data

Once the six categorizations were developed, all the images must be categorized. The images were categorized using Photo Mechanic (“Photo Mechanic Download” n.d.). The categorizations were printed into the metadata numerically. Table 3.1 shows the numerical classification that is printed into the metadata.

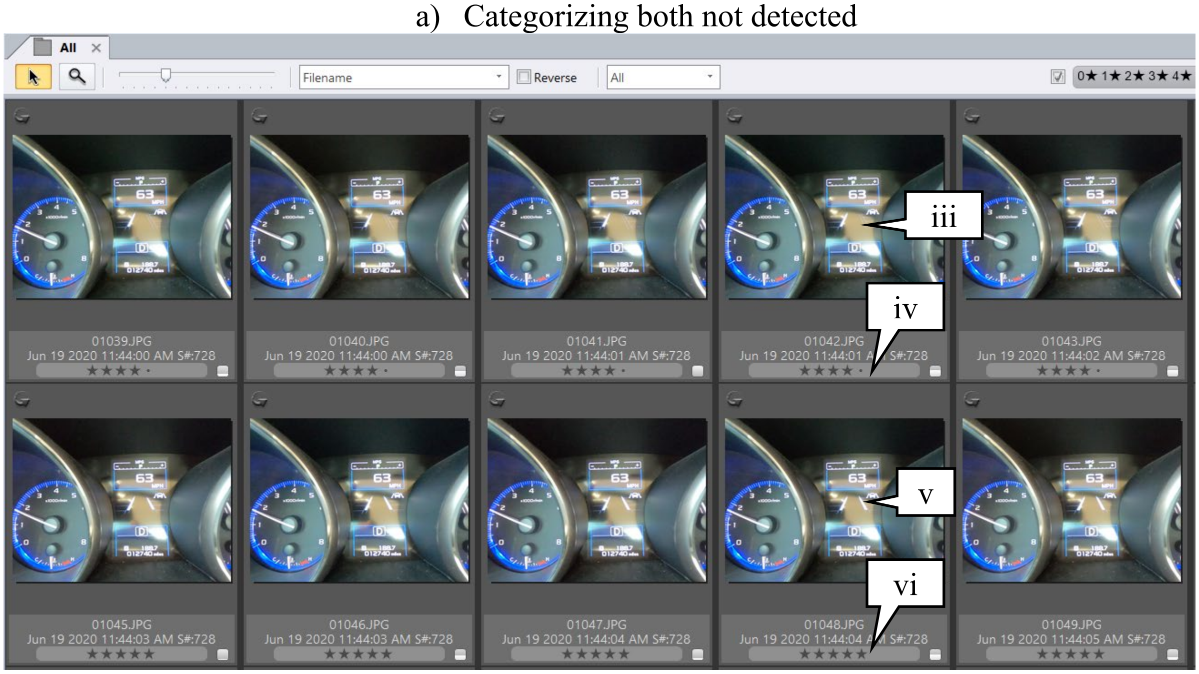
Table 3.1 Numerical Categorizations

Classification	**Category**	**Observation**
0	No Data	Slow Speed Brakes Curve
1	Excluded	Lane Change
2	Both Not Detected	
3	Left Not Detected	
4	Right Not Detected	
5	Both Detected	

Figure 3.5a shows the images being categorized, callout *i* shows when both pavement markings are not detected, and callout *ii* shows the classification being printed into the metadata of the image. Figure 3.5b shows right not detected in callout *iii* and the classification of four being printed into the metadata in callout *iv*. Callouts *v* and *vi* show the classification when the vehicle detected both pavement markings.



a) Categorizing both not detected



b) Categorizing right not detected and both detected

Figure 3.5 Categorizing the data

Figure 3.6 provides the metadata of a sample image, callout *i* shows the classification and callout *ii* shows the latitude and longitude of when the image was taken. To convert the classifications into functional format, the classification, latitude, and longitude were extracted from the metadata using ExifTool ("Installing ExifTool" n.d.). The program is run in the Windows command line and saves the metadata of the images in a comma-separated values (csv) format.

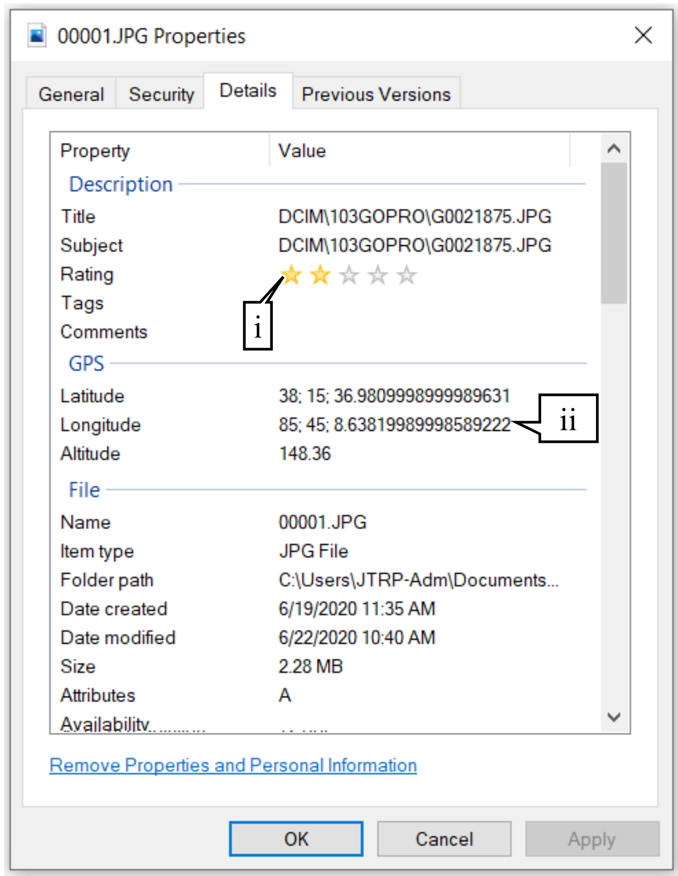


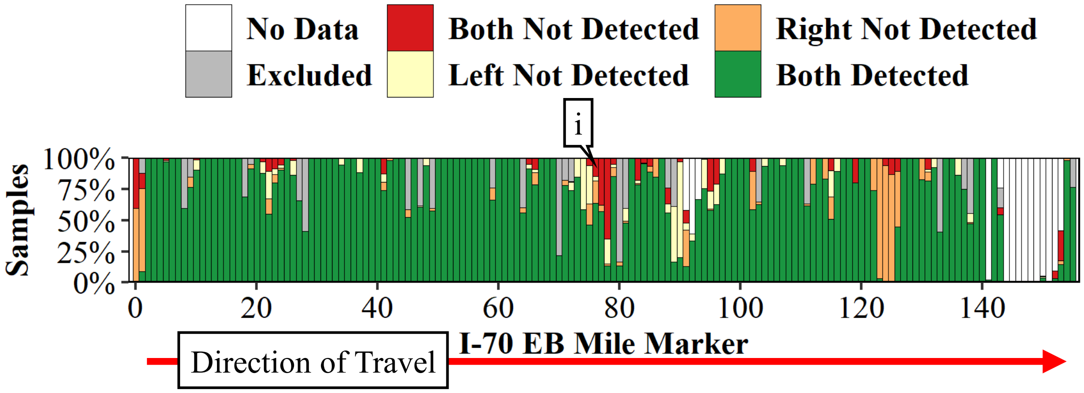
Figure 3.6 Metadata from images

4. ANALYSIS

This chapter presents the results of applying the classification scheme summarized in Table 3.1 to 2,500 miles of Interstates. Section 4.1 describes the visualization developed to represent this data, Section 4.2 presents those graphics for Interstates 64, 65, 69, 70, 74, 90, 94, and 465. The chapter concludes with a table and summary graphic that summarizes the results by interstate, using the classification schemed introduced in Table 3.1.

4.1 Data Visualization

Bar plots were created to aid in visualization of the relationship between detectable and undetectable markings. The plots were arranged spatially, by mile marker on the x-axis and by the percentage of each category on the y-axis. The data were originally aggregated into bins of size equal to a tenth of a mile. Observing over 2,500 miles of data at tenth of a mile aggregation did not provide an easily understandable analysis. The data was then aggregated into one-mile, five-mile, and ten-mile bins. Five- and ten-mile aggregation lost resolution in the data and often hid interesting anomalies. One-mile aggregation provided a good balance of comprehension and accuracy in the representation of the data. Figure 4.1a shows an example bar plot. Callout *i* shows I-70 in the eastbound direction at mile marker 76. At this point, there were some categorizations of both detected, right not detected, left not detected, and both not detected. Although the bar plots provided a great representation of the data, it did not provide a geographical location. Utilizing the bar plot concept, a spatial map with detection categorizations was created. The spatial map aggregated the data into tenth mile bins and portrayed the median value at each point. This provided a better representation at the spatial level; the result can be seen in Figure 4.1b.



a) I-70 eastbound bar plot

b) I-70 eastbound spatial graph

Figure 4.1 I-70 bar plot visualization

An example of how the image data creates a vertical bar can be explained in Figure 4.2. At mile marker 76 there were a total of 140 images: 88 images (63%) were categorized as both detected (Figure 4.2a), 25 images (18%) categorized as right not detected (Figure 4.2b), 5 images (3%) categorized as left not detected (Figure 4.2c), and 22 images (16%) categorized as both not detected (Figure 4.2d).

a) I-70 EB MM 76 Both Detected

b) I-70 EB MM 76 Right Not Detected

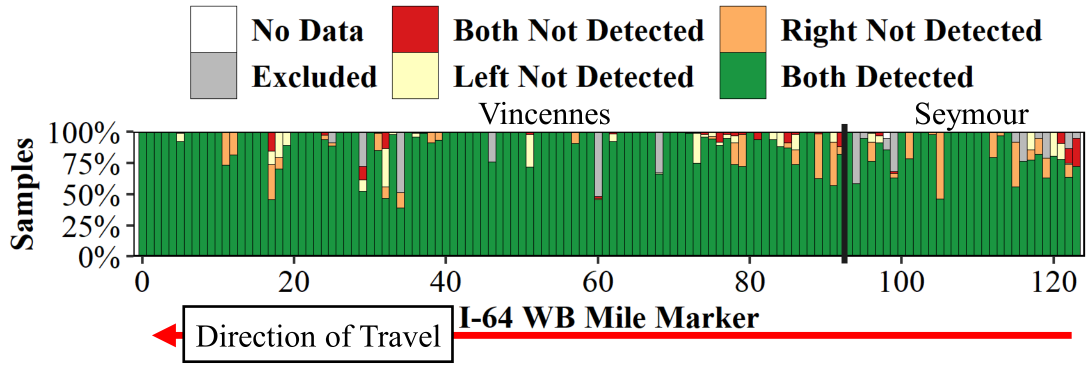
c) I-70 EB MM 76 Left Not Detected

d) I-70 EB MM 76 Both Not Detected

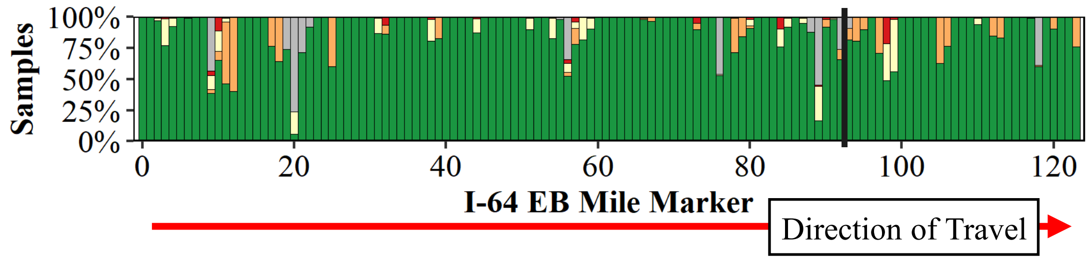
Figure 4.2 Creation of bar plots

4.2 Interstate Analysis

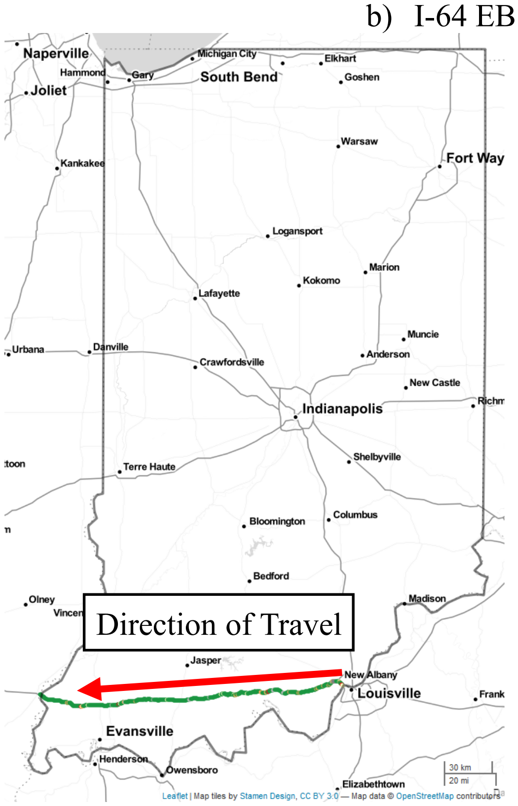
This analysis was applied to all Indiana interstates. Figure 4.3 shows the complete analysis for I-64. The bar plots are included for both directions along the total length of the interstate, 123 miles. As stated earlier, for more convenient asset management and tracking, Indiana is split into 6 districts, each managing their respective infrastructure. An interstate will span over two or more districts due to the length of the interstate except for I-465 lying in only the Greenfield District and I-94 lying only in the La Porte District. The district map can be seen in Figure 1.1. Each district has a separation bar to distinguish the boundary between districts. Figure 4.3a and Figure 4.3b show the two districts I-64 lies in, Vincennes and Seymour, and the border of the two districts. Figure 4.3c and Figure 4.3d show the respective spatial map for I-64.



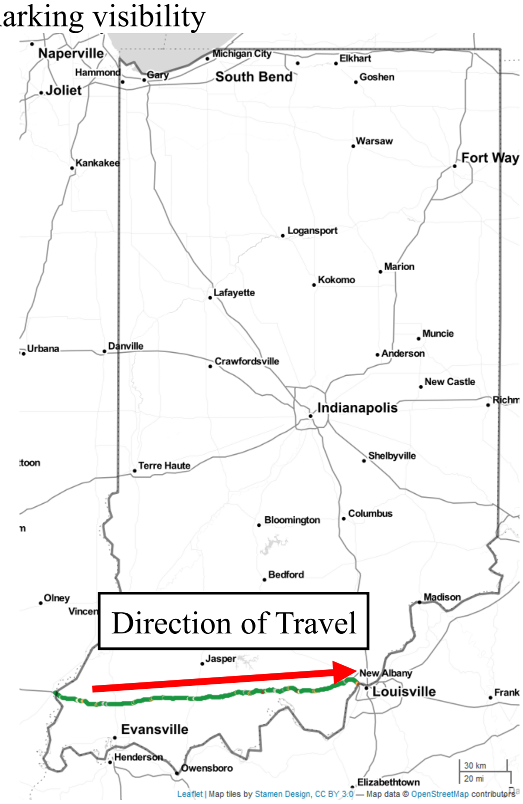
a) I-64 WB lane marking visibility



b) I-64 EB lane marking visibility



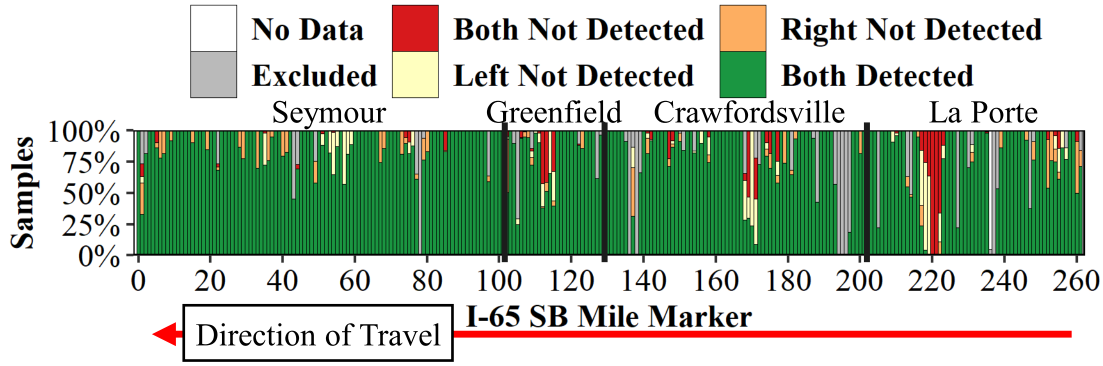
c) I-64 WB spatial lane marking visibility



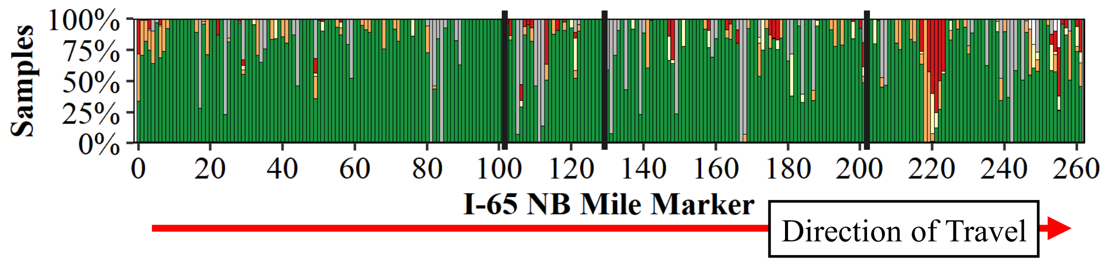
d) I-64 EB spatial lane marking visibility

Figure 4.3 I-64 lane marking visibility

I-65 spans 262 miles and lies in 4 districts, Seymour, Greenfield, Crawfordsville, and La Porte. The borders between each district lie at mile marker 101, 130, and 201, respectively. Figure 4.4a provides the bar plot in the southbound direction, and Figure 4.4b provides the bar plot in the northbound direction. Figure 4.4c and Figure 4.4d are the spatial maps for I-65 in the southbound and northbound direction, respectively.



a) I-65 SB lane marking visibility



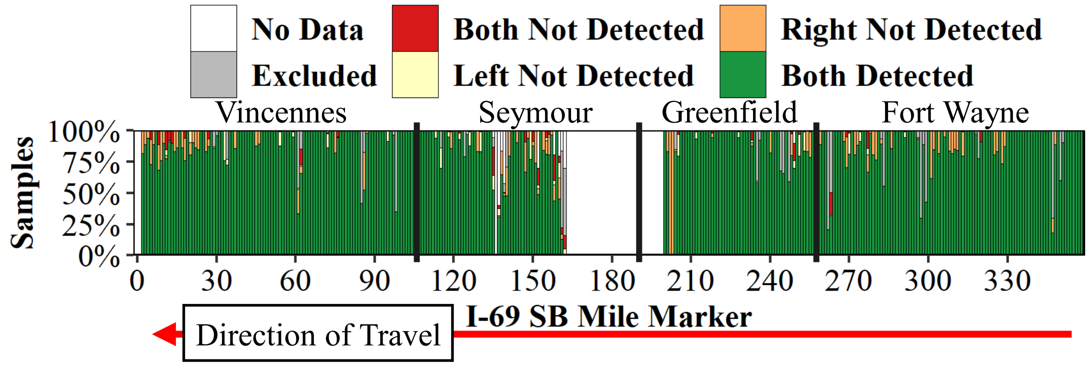
b) I-65 NB lane marking visibility

c) I-65 SB spatial lane marking visibility

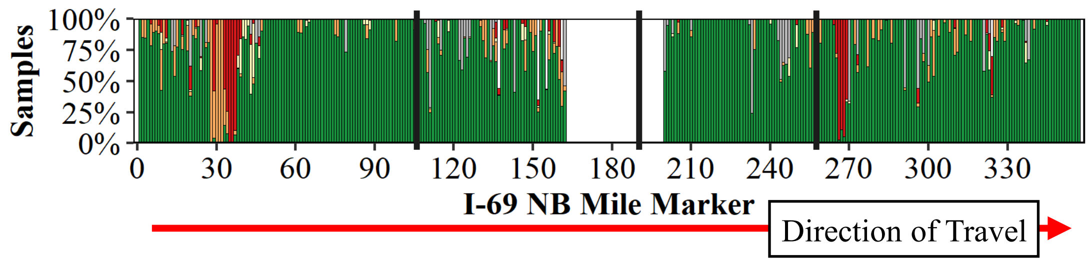
d) I-65 NB spatial lane marking visibility

Figure 4.4 I-65 lane marking visibility

I-69 runs in the north/south direction, spans 357 miles, and lies in 4 districts, Vincennes, Seymour, Greenfield, and Fort Wayne. The borders between each district lie at mile marker 104, 200, and 255, respectively. Figure 4.5a provides the bar plot in the southbound direction and Figure 4.5b provides the bar plot in the northbound direction. Figure 4.5c and Figure 4.5d are the spatial maps for I-69 in the southbound and northbound direction, respectively.



a) I-69 SB lane marking visibility



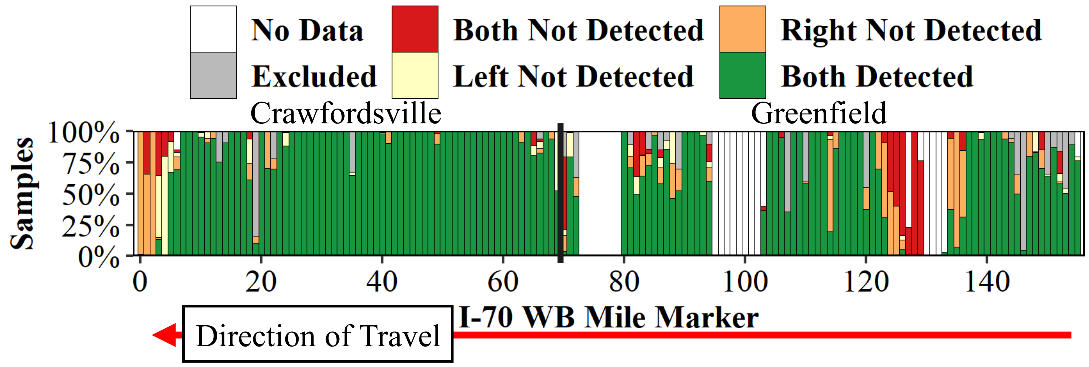
b) I-69 NB lane marking visibility

c) I-69 SB spatial lane marking visibility

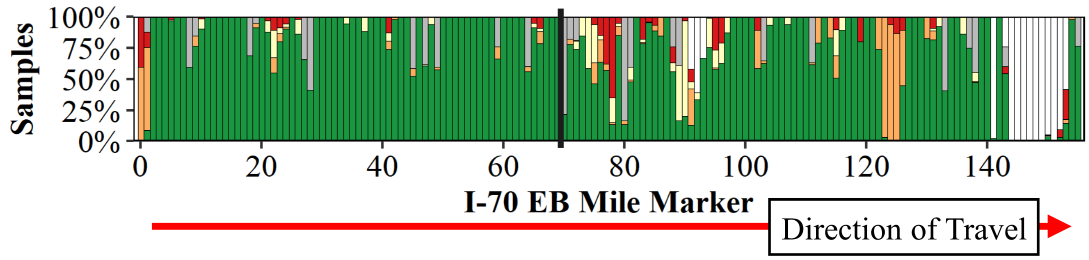
d) I-69 NB spatial lane marking visibility

Figure 4.5 I-69 lane marking visibility

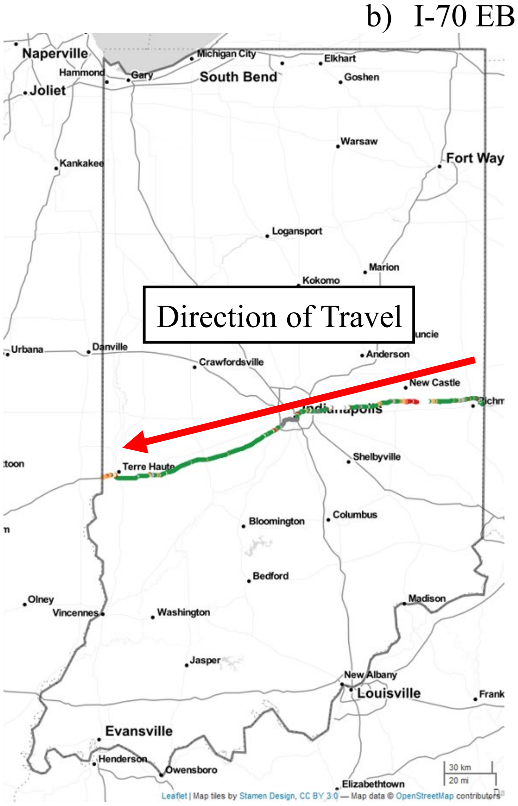
I-70 spans 157 miles and lies in 2 districts, Crawfordsville, and Greenfield. The borders between each district lie at mile marker 69. During data collection there were many construction zones and congestion causing vehicles to travel at lower speeds and preventing collection of data. Figure 4.6a provides the bar plot in the westbound direction and Figure 4.6b provides the bar plot in the eastbound direction. Figure 4.6c and Figure 4.6d are the spatial maps for I-70 in the westbound and eastbound direction, respectively.



a) I-70 WB lane marking visibility



b) I-70 EB lane marking visibility

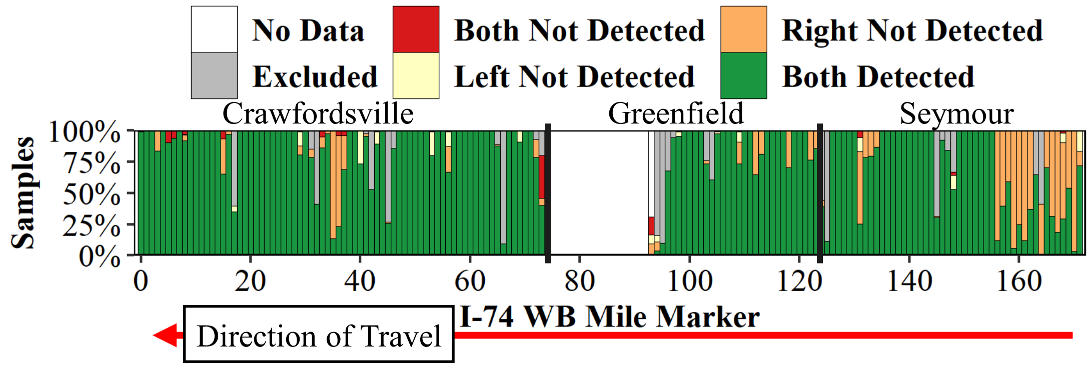


c) I-70 WB spatial lane marking visibility

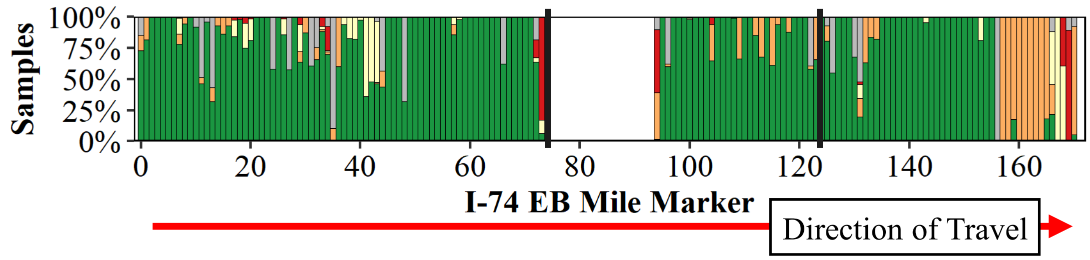
d) I-70 EB spatial lane marking visibility

Figure 4.6 I-70 lane marking visibility

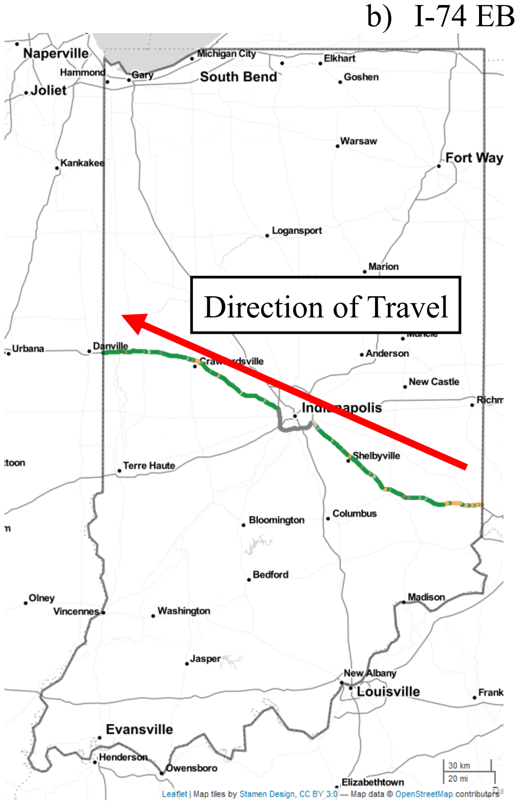
I-74 spans 171 miles and lies in 3 districts, Crawfordsville, Greenfield and Seymour. The borders between each district lie at mile markers 73 and 123. I-74 is discontinuous through Indianapolis for approximately 21 miles. Figure 4.7a provides the bar plot in the westbound direction and Figure 4.7b provides the bar plot in the eastbound direction. The discontinuity begins at mile marker 73 and ends at mile marker 94, which is the no data region in the bar plot. Figure 4.7c and Figure 4.7d are the spatial maps for I-74 in the westbound and eastbound direction, respectively.



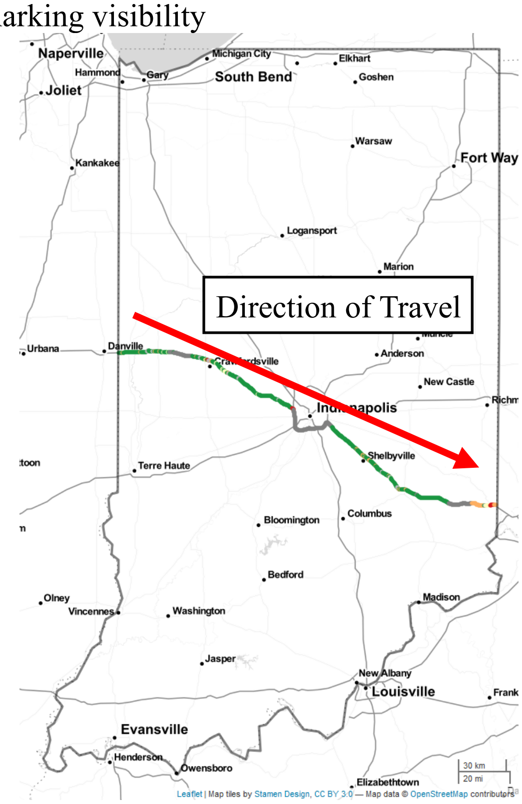
a) I-74 WB lane marking visibility



b) I-74 EB lane marking visibility



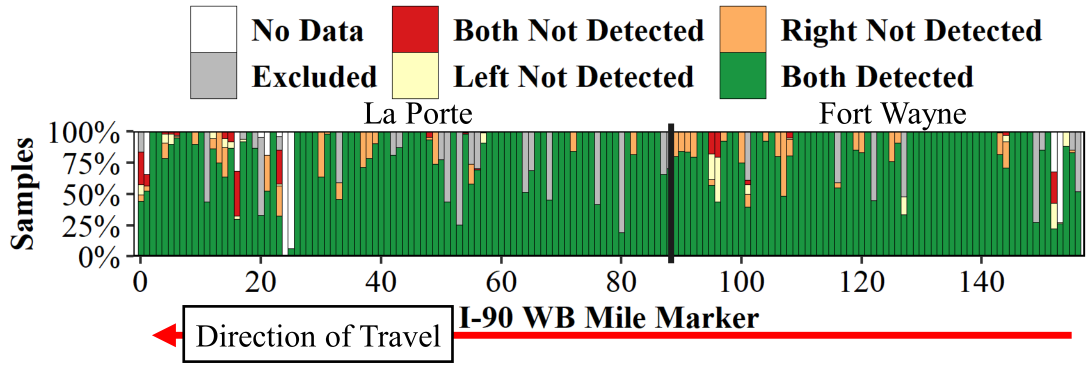
c) I-74 WB spatial lane marking visibility



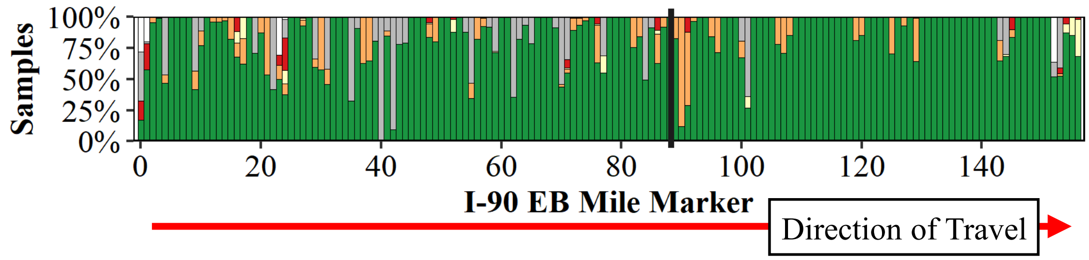
d) I-74 EB spatial lane marking visibility

Figure 4.7 I-74 lane marking visibility

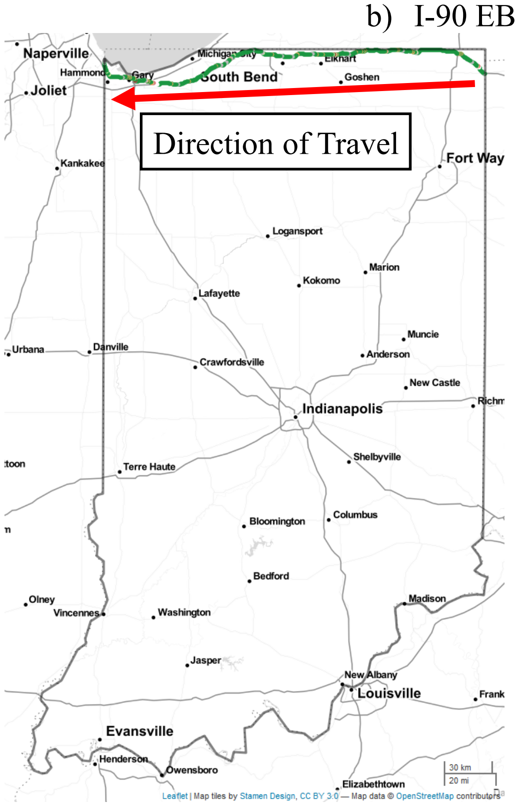
I-90 is a toll road that spans 156 miles and lies in 2 districts, La Porte, and Fort Wayne. The borders between each district lie at mile marker 87. There are four tolls along the route that require a reduction of speed to 5 mph. Figure 4.8a provides the bar plot in the westbound direction and Figure 4.8b provides the bar plot in the eastbound direction. Figure 4.8c and Figure 4.8d are the spatial maps for I-90 in the westbound and eastbound direction, respectively.



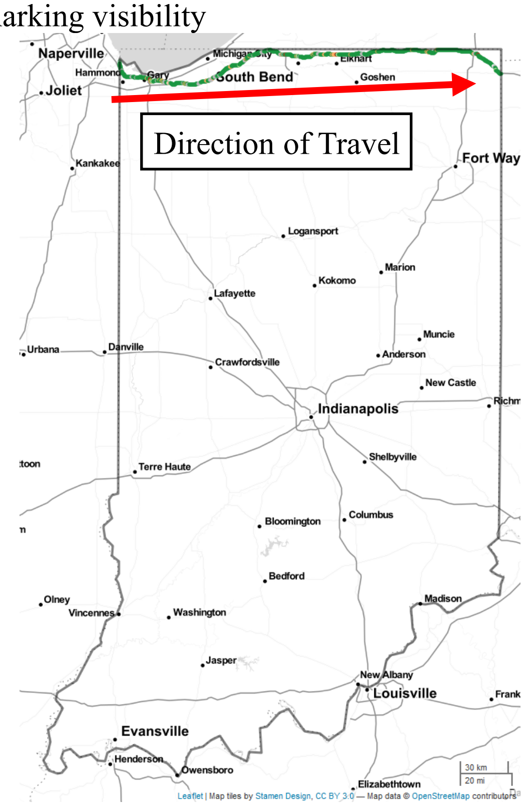
a) I-90 WB lane marking visibility



b) I-90 EB lane marking visibility



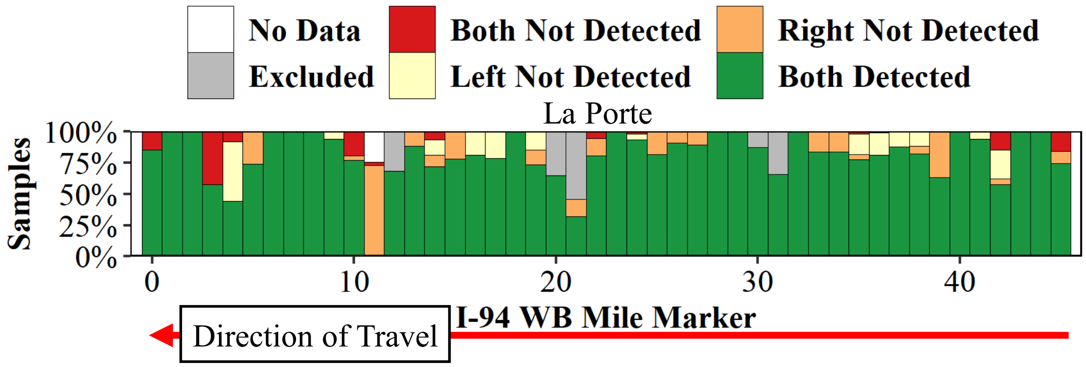
c) I-90 WB spatial lane marking visibility



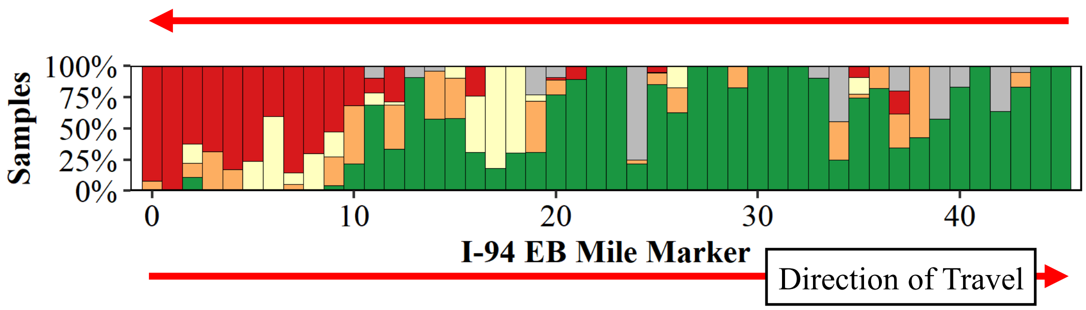
d) I-90 EB spatial lane marking visibility

Figure 4.8 I-90 lane marking visibility

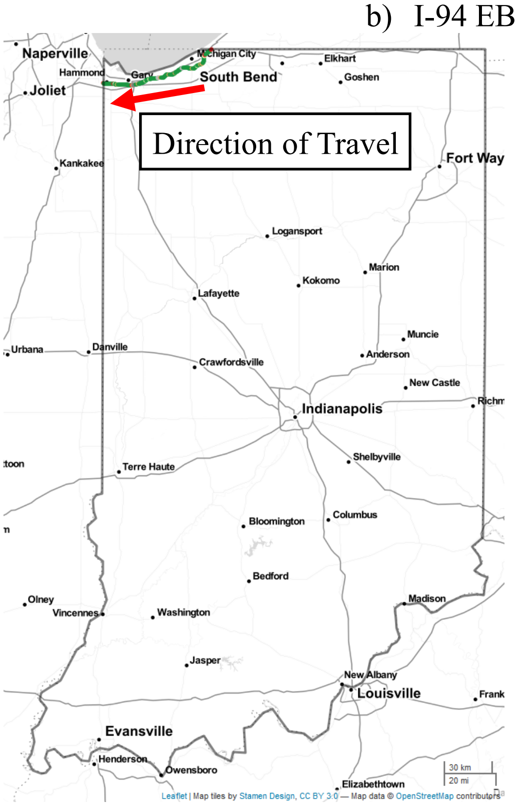
I-94 connects lower Michigan to Illinois, spans 46 miles, and lies in 1 district, La Porte. Figure 4.9a provides the bar plot in the westbound direction and Figure 4.9b provides the bar plot in the eastbound direction. Figure 4.9c and Figure 4.9d are the spatial maps for I-94 in the westbound and eastbound direction, respectively.



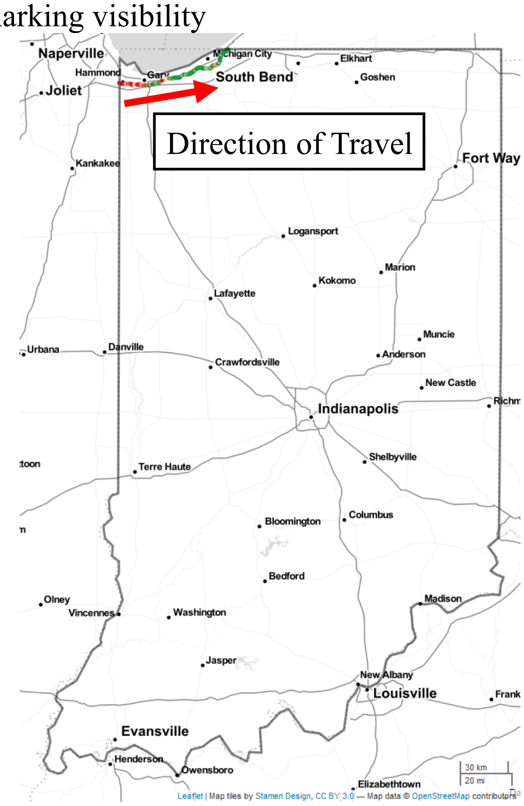
a) I-94 WB lane marking visibility



b) I-94 EB lane marking visibility



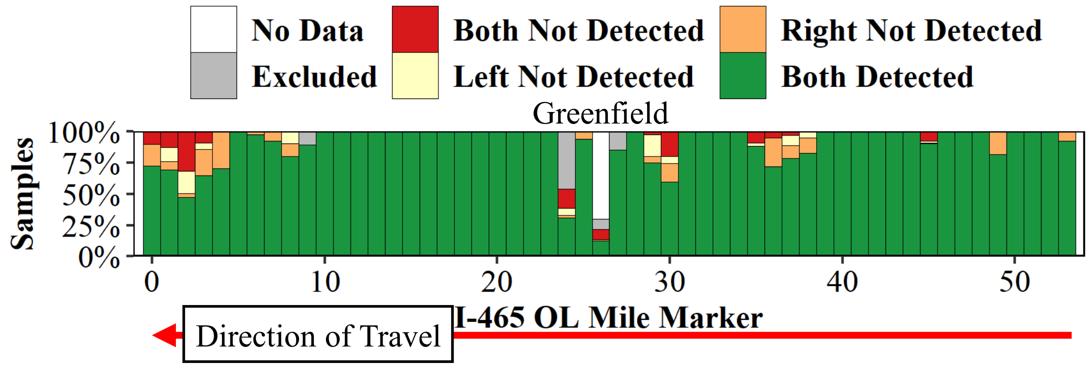
c) I-94 WB spatial lane marking visibility



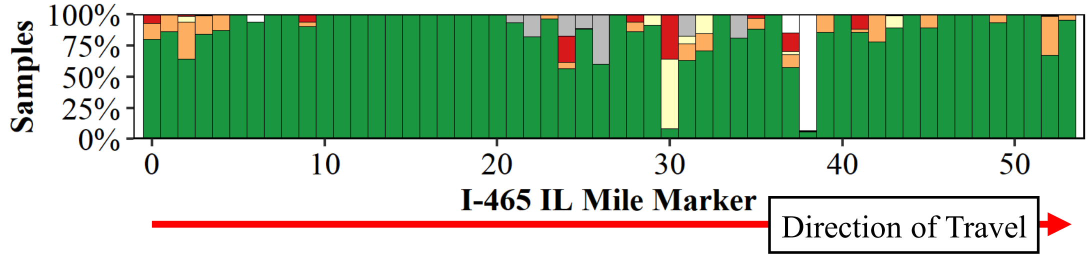
d) I-94 EB spatial lane marking visibility

Figure 4.9 I-94 lane marking visibility

I-465 spans 53 miles and lies in 1 district, Greenfield. I-465 is a loop surrounding the city of Indianapolis. Figure 4.10a provides the bar plot for the outer loop (counterclockwise) direction and Figure 4.10b provides the bar plot for the inner loop (clockwise) direction. Figure 4.10c and Figure 4.10d are the spatial maps for I-465 for the outer loop and inner loop direction, respectively



a) I-465 Outer loop lane marking visibility



b) I-465 Inner loop lane marking visibility

c) I-465 Outer loop spatial lane marking visibility

d) I-465 Inner loop spatial lane marking visibility

Figure 4.10 I-465 lane marking visibility

4.3 Discussion

The results provide agencies with an idea of which interstates need more maintenance and which interstates are performing well. Table 4.1 shows an overall view for each interstate. Most interstates have over 80% detectable pavement markings in both directions. All of I-70, I-74 eastbound, I-90 westbound, and I-94 eastbound provided pavement markings at less than 80% detectable. On the days of data collection for I-70, the vehicle operated at less than 35 mph (LKA operating threshold) for a total of over 21 miles. These slowdowns were due to road construction, inclement weather, and traffic accidents. There was also an 8-mile section of I-70 closed to traffic from mile marker 72 to mile marker 80. I-74 eastbound had road construction on the east end of the interstate just past mile marker 156. This road construction included a new pavement surface and repainting of pavement markings. At the time of data collection, the pavement markings on the passenger side of the vehicle were still being painted, causing the vehicle to be unable to detect the right pavement markings. I-90 is a toll road and contains 4 tolls along the route, at mile marker 22, mile marker 56, mile marker 90, and mile marker 126 ("Travel Information - ITR Concession Co. LLC." n.d.). Each toll collection requires a reduced speed of 5 mph, inhibiting the vehicle from collecting LKA data. I-94 is a major interstate connecting Illinois to Michigan and other essential interstates in Indiana. On the day of data collection, there was heavy traffic with frequent lane changes of vehicles in front of the test vehicle. The vehicle lane changes, and vehicle shadows created a difficult environment for the LKA system to identify pavement markings. This caused many of the pavement markings to be categorized as both not detected. Figure 4.11 depicts this information in a graphical format.

Table 4.1 All Indiana Interstates Lane Marking Visibility

Interstate	Total Miles	Direction	Both Detected	Both Not Detected	Left Not Detected	Right Not Detected	Excluded	No Data
I-64	248	WB	89.7%	1.3%	2.2%	3.7%	3.0%	0.0%
		EB	89.7%	0.7%	2.4%	4.1%	3.0%	0.0%
I-65	524	NB	80.9%	2.9%	1.7%	4.5%	9.7%	0.3%
		SB	80.7%	2.9%	3.0%	3.1%	7.4%	2.9%
I-69	714	NB	83.6%	4.2%	1.2%	5.7%	3.8%	1.5%
		SB	87.7%	1.0%	1.0%	4.4%	3.1%	2.8%
I-70	314	WB	44.7%	3.6%	1.9%	4.6%	2.8%	42.5%
		EB	58.6%	2.8%	2.7%	4.3%	4.2%	27.2%
I-74	246*	WB	81.2%	0.6%	1.0%	10.5%	6.5%	0.2%
		EB	78.5%	2.1%	4.2%	10.0%	5.2%	0.0%
I-90	312	WB	79.0%	1.2%	1.1%	4.0%	6.5%	8.2%
		EB	83.4%	1.1%	0.7%	6.0%	7.6%	1.1%
I-94	92	WB	82.9%	2.9%	4.7%	5.9%	3.4%	0.2%
		EB	52.3%	21.1%	9.4%	11.2%	5.9%	0.0%
I-465	106	IL	81.7%	1.8%	1.8%	4.2%	3.2%	7.4%
		OL	87.1%	2.7%	1.6%	3.6%	1.6%	3.4%
All Interstates	2,556		77.6%	2.6%	2.0%	5.2%	5.1%	7.4%

*I-74 is discontinuous through Indianapolis

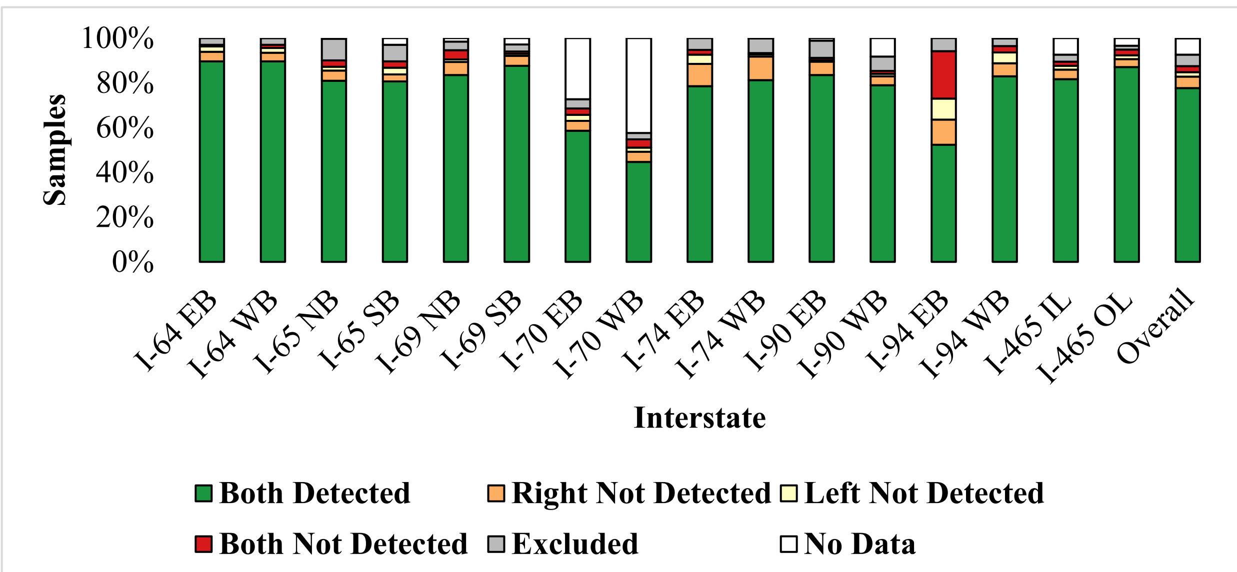


Figure 4.11 Overall Indiana interstate lane marking visibility plot

5. CONCLUSIONS

This thesis evaluated the use of vehicle Lane Keep Assist (LKA) indications to evaluate the quality of highway lane markings. The results suggest that LKA data can provide agencies locations where pavement markings are not detectable and can provide more frequent feedback on pavement marking quality. The analysis was conducted on 8 heavily traveled interstates across Indiana in one travel lane per direction. Table 1.2 summarizes the mileage driven along those results. During this evaluation, approximately 2,500 miles were driven and over 280,000 images were collected. Those images were categorized using the taxonomy illustrated in Figure 3.2, Figure 3.3, and Figure 3.4. Overall, approximately 77% of the lane miles evaluated had lane markings that LKA was able to detect. Table 4.1summarizes the detailed classification of these lane markings by route.

Limitations

Although this technique was demonstrated on over 2,500 centerline miles, it is not practical to use a single vehicle operated by one driver to provide ubiquitous coverage. For example, to cover all lanes on the interstate, one would have to drive approximately 5,500 miles (Figure 5.1). Additionally, this would not provide complete coverage of all the interstate exit ramps (Figure 5.2). Furthermore, if both day and night conditions were to be evaluated, the amount of driving would double. Considering that data will also be lost due to congestion (Figure 5.3), inclement weather, and poor lighting (Figure 5.3), it is clear that the data collection system with a single vehicle and driver will not scale for statewide deployment (Figure 3.1). If one considers INDOT has over 5,200 centerline miles of US and State routes, the challenges of scaling this data collection technique are even more evident.

Scalability

However, with proper coordination with automotive OEM's, the most attractive aspect of this methodology is the ability for automotive OEM's to collect and aggregate autonomous data and provide information to agencies on a regular, characterizing the performance of their pavement markings during all types of weather and lighting conditions (Figure 5.4). Even if there is a significant cost associated with purchasing the data, it would likely be lower than the current amount agencies spend on manual data collection techniques (Figure 2.2). It would also serve to eliminate exposing workers to traffic hazards.

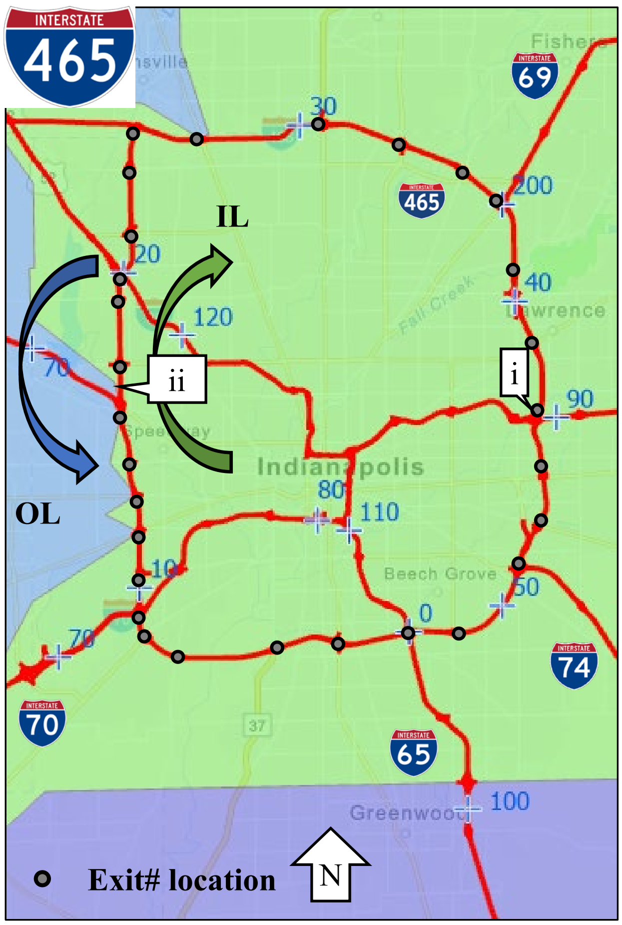
Partnership Opportunities

In the past, automotive OEM's have built cars and transportation agencies have built roads. The standards for pavement markings date back decades and are based upon visibility of the human eye. Although pavement markings currently need to be visible to the human eye, at least in the near future, we are now entering a new frontier where highway agencies and automotive OEM's must forge new relationships to develop pavement markings standards ensuring modern roadways are constructed in a manner that all brands of vehicles using the roadway can effectively identify roadway markings. This is important for both current generation LKA and longer-term autonomous vehicles. Although the methodology from this study could supplement pavement marking evaluations, a partnership between agencies and OEM's and the development of crowd-sourced pavement detection has the potential to augment the current evaluation methods in the near term, and potential replace them in a few years. A vehicle crowd sourced evaluation method could provide more frequent pavement marking evaluations and provide agencies a more responsive asset management data source. This benefits the public in the near term by improving visibility of lane markings and in the longer-term identifying performance measures that are important to autonomous vehicles.

a) Rural I-65 with two travel lanes each direction

b) Urban I-465 with five travel lanes each direction

Figure 5.1 Opportunities for crowd-source data – multiple lanes



a) I-465 Loop with exit ramps marked

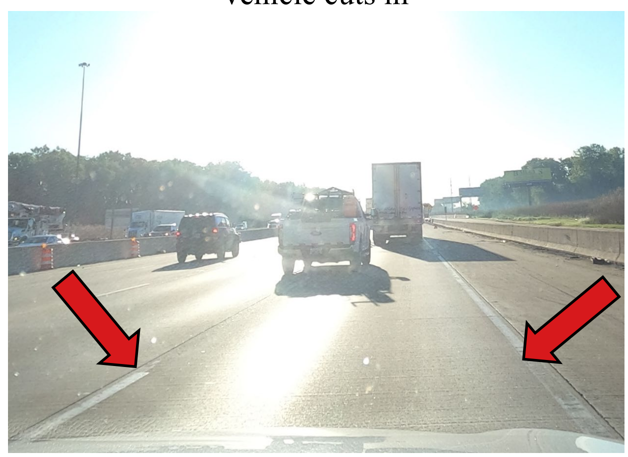
b) I-465 & I-70 interchange

Figure 5.2 I-465 entrance/exit ramps

a) I-94 EB dashboard view both detected before vehicle cuts in

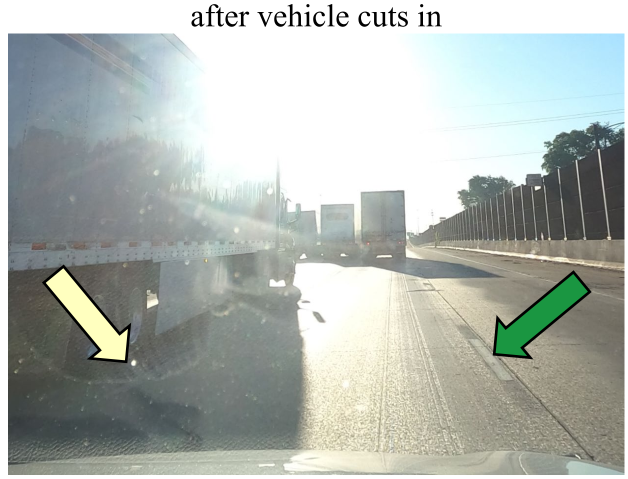
b) I-94 EB roadway view both detected before vehicle cuts in

c) I-94 EB dashboard view both not detected after vehicle cuts in



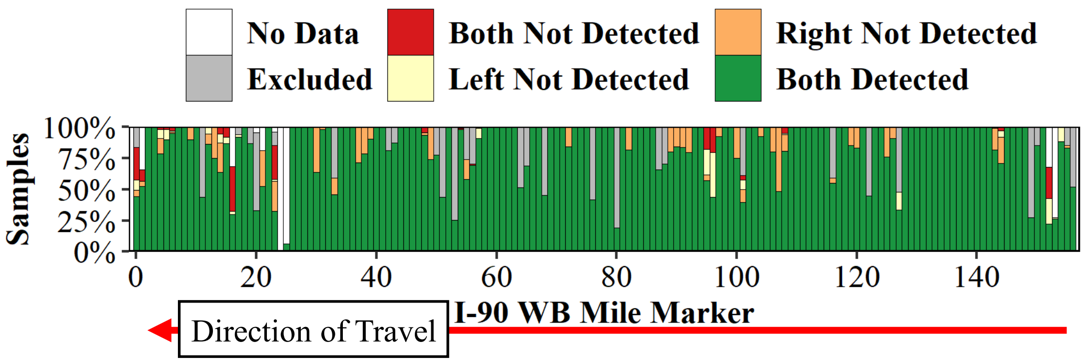
d) I-94 EB roadway view both not detected after vehicle cuts in

e) I-94 EB dashboard view left not detected due to sun glare and vehicle shadow

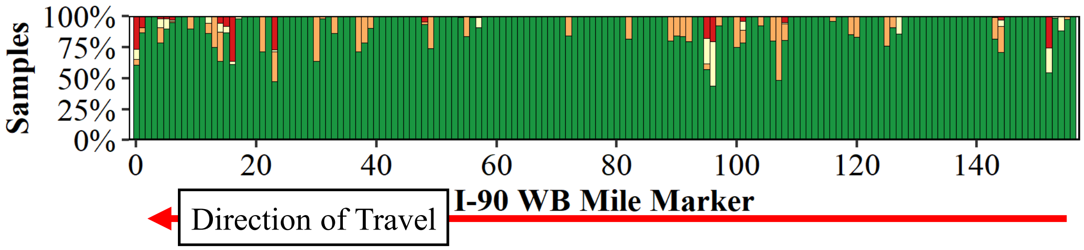


f) I-94 EB dashboard view left not detected due to sun glare and vehicle shadow

Figure 5.3 Opportunities for crowd-source data - vehicle cut-ins and sun glare



a) I-90 WB actual lane marking visibility



b) I-90 WB crowd-source lane marking visibility

Figure 5.4 Opportunities for crowd-source data – lane changes and exclusions

REFERENCES

"ASTM D7585 / D7585M - 10(2015) Standard Practice for Evaluating Retroreflective Pavement Markings Using Portable Hand-Operated Instruments." (2015). <https://www.astm.org/Standards/D7585.htm> (Nov. 8, 2020).

"ASTM E1710 - 18 Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry Using a Portable Retroreflectometer." (2018). <https://www.astm.org/Standards/E1710.htm> (Nov. 8, 2020).

Bahar, G., Masliah, M., Erwin, T., Tan, E., and Hauer, E. (2006). "Pavement Marking Materials and Markers: Real-World Relationship Between Retroreflectivity and Safety Over Time." *NCHRP Web-Only Document*, (92).

Beglerovic, H., Schloemicher, T., Metzner, S., and Horn, M. (2018). "Deep learning applied to scenario classification for lane-keep-assist systems." *Applied Sciences (Switzerland)*, 8(12).

Bektas, B. A., Gkritza, K., and Smadi, O. (2016). "Pavement marking retroreflectivity and crash frequency: Segmentation, line type, and imputation effects." *Journal of Transportation Engineering*, 142(8), 04016030.

"Chapter 3B - MUTCD 2009 Edition - FHWA." (n.d.). <https://mutcd.fhwa.dot.gov/htm/2009/part3/part3b.htm> (Nov. 2, 2020).

Hawkins, H., Sneed, M. A., and Williams, C. L. (2007). "EVALUATION OF TRAFFIC CONTROL DEVICES: THIRD-YEAR ACTIVITIES." *undefined*.

Hawkins, N., and Smadi, O. (2013). *Use of Transportation Asset Management Principles in State Highway Agencies*. *Use of Transportation Asset Management Principles in State Highway Agencies*.

"INDOT: Pavement Markings." (n.d.). <https://www.in.gov/indot/3285.htm> (Nov. 2, 2020).

"Installing ExifTool." (n.d.). <https://exiftool.org/install.html> (Nov. 12, 2020).

Lyon, C., Persaud, B., and Eccles, K. (2015). *Safety Evaluation of Wet - Reflective Pavement Markings*.

"MAAP - PPP, Inc." (n.d.). <https://pppcatalog.com/maap/> (Nov. 18, 2020).

"National Institute of Standards and Technology | NIST." (n.d.). <https://nist.time.gov/> (Nov. 11, 2020).

Nayak, A., Rathinam, S., Pike, A., and Gopalswamy, S. (2020). “Reference Test System for Machine Vision Used for ADAS Functions.” *SAE International*.

Pape, D., and Habtemichael, F. (2018). *Infrastructure Initiatives to Apply Connected- and Automated-Vehicle Technology to Roadway Departures*.

“Photo Mechanic Download.” (n.d.). <https://www.camerabits.com/cgi-bin/download_pm.cgi?plat=win&version=PRO> (Nov. 11, 2020).

Pike, A., Carlson, P., and Barrette, T. (2018). *Evaluation of the Effects of Pavement Marking Width on Detectability By Machine Vision : 4-Inch vs 6-Inch Markings*.

Pike, A., Clear, S., Barrette, T., Hedblom, T., and Whitney, J. (2019a). “Effects of the Wet Retroreflectivity and Luminance of Pavement Markings on Lane Departure Warning in Nighttime Continuous Rain with and without Glare Sources.” *SAE Technical Papers*.

Pike, A. M., Whitney, J., Hedblom, T., and Clear, S. (2019b). “How Might Wet Retroreflective Pavement Markings Enable More Robust Machine Vision?” *Transportation Research Record*, 2673(11), 361–366.

SAE International. (2018). “Surface Vehicle.” *SAE International*, 4970(724), 1–5.

“Travel Information - ITR Concession Co. LLC.” (n.d.). <https://www.indianatollroad.org/travel-information/> (Nov. 15, 2020).

USDOT. (2015). “Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey.” *National Highway Traffic Safety Administration Traffic Safety Facts*.

Yu, C. (2004). *A COMPARATIVE PERFORMANCE ANALYSIS OF PAVEMENT MARKING MATERIALS*. Mississippi State University.

Zehr, S., Hardin, B., Lowther, H., Plattner, D., Wells, T., Habib, A., and Bullock, D. M. (2019). *Rumble Stripes and Pavement Marking Delineation*.