Developing a System to Identify Passing and No Passing Zone Boundaries on Rural Two-Lane Highways

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Developing a System to Identify Passing and No Passing Zone Boundaries on Rural Two-Lane Highways

FINAL REPORT

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MRIGlobal developed an automated system to measure and display the distance between two instrumented vehicles traveling along a road. The system uses GPS modules and radio modems to send location information between the vehicles five times per second. A field software was developed to calculate the distance between the vehicles based on this GPS data in real time and report it to the following driver. The field software is designed to allow the two vehicles to identify locations along a two-lane road where minimum passing sight distance is available. A post-processing software was also developed to produce a recommended striping plan, for both directions of travel along the route, based on the data recorded by the field data collection software. This system can be operated at near-highway speeds.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

(Revised September 1993)

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Section 1. Introduction

1.1 Background

Passing and no-passing zones are marked on the centerline of two-lane undivided highways, and on three-lane undivided highways where passing is permitted in the opposing direction to a passing lane, to identify areas where the available passing sight distance (PSD) is above or below the minimum values presented in MoDOT's *Engineering Policy Guide* (EPG) Table 620.2.2.1, which is identical to Table 3B-1 in the FHWA *Manual on Uniform Traffic Control Devices* (MUTCD). These minimum PSD values range from 450 ft on 25-mph roads to 1,200 ft on 70 mph roads. The speed level selected for a given road may be based on the 85th-percentile speed of traffic (if available), the posted speed limit, or the speed limit applicable by statute (if no speed limit is posted).

PSD is measured from a viewpoint 3.5 ft above the pavement surface (equivalent to the typical height of a driver's eye) to an object or target height of 3.5 ft. This makes PSD reciprocal—if the driver of one vehicle can see a second vehicle, then the driver of the second vehicle can see the first vehicle. In determining PSD, both vertical and horizontal sight distance must be considered. At crest vertical curves, PSD is limited by roadway geometry alone. At horizontal curves, both roadway geometry and the location of roadside sight obstructions on the inside of the curve must be considered.

The PSD criteria used in design used to be substantially larger than those used in marking passing and no-passing zones. However, these were changed in the 2011 AASHTO *Green Book*, based on research by MRIGlobal in NCHRP Report 605, *Passing Sight Distance Criteria* (Harwood et al., 2008). Harwood et al. demonstrated that it made little sense to have independent PSD criteria for design of PSD and marking of passing and no-passing zones, so the *Green Book* and MUTCD criteria are now identical.

The MUTCD states that where the distance between successive no-passing zones is less than 400 ft, no-passing markings should connect the two zones; this effectively sets a minimum passing zone length of 400 ft. Harwood et al. (2008) demonstrated that passing zones with lengths between 400 and 800 ft contribute very little traffic operational benefit to two-lane highways.

Methods that have been used for locating the boundaries of passing and no-passing zones in the field include: the walking method, the two-vehicle method, the one-vehicle method, the eyeball method, the videolog method, and the laser or optical rangefinder method (Brown and Hummer, 2000). MoDOT has been using the two-vehicle method, but since the equipment for applying this method is now obsolete, MoDOT would like to implement a replacement method based on GPS data that could be collected at highway or near-highway speeds.

1.2 Objective

The objective of the proposed research is to (1) recommend the best method for MoDOT to locate the boundaries of passing and no-passing zones using GPS data and/or other related data collected from a moving vehicle; (2) provide MoDOT with a set of hardware and software to apply the recommended method; and (3) document the recommend method, including the use of the hardware and software, so that the method can be applied by MoDOT. The recommended method will involve automated analysis of data collected from a vehicle moving at highway or near-highway speeds. Methods that involve field staff leaving their vehicle (e.g., the walking method) or that involve slow-moving vehicles were not considered. The hardware will be portable so that it can be easily removed from one vehicle and installed in another. The recommended method will be selected such that the cost to MoDOT to obtain additional sets of the hardware and software needed to apply the method will not exceed $10,000 per unit (i.e., per hardware/software set).

The results expected from the research include (1) a recommended and validated method to locate the boundaries of passing and no-passing zones from GPS data concerning the roadway alignment and related information about roadside sight obstructions; (2) a user's manual explaining how to apply the recommended method to identify the boundaries of passing and no-passing zones, how to utilize the associated hardware and software, and how to manage and store the necessary data for both current use and future application; and (3) delivery to MoDOT of all hardware and software acquired by MRIGlobal during the study and needed by MoDOT to implement the recommended method.

1.3 Organization of this Report

Chapter 2 describes the two primary approaches to determining no-passing zone boundaries that were considered early in the research, as well as the benefits and drawbacks of each approach. It then describes the approach that was selected and the considerations that went into that selection from both MoDOT's and the research team's perspective.

Chapter 3 describes the hardware components used in the system and their functionality. Chapter 4 discusses the development of the field data collection software, including the set-up procedure, the algorithm for measuring and reporting the distance between vehicles, the various messages provided to the driver during data collection, and the process for collecting and recording data in the field.

Chapter 5 describes the post-processing software that reports the recommended passing and no-passing zone striping along the length of the roadway in both directions of travel. It provides a description of each data element shown on the output report.

Chapter 6 discusses the field testing that was conducted to validate the hardware and software components of the system and presents the degree to which the system's recommended passing and no-passing zone boundaries align with MoDOT's existing striping.

Chapter 7 presents a discussion of the testing results, describes the current limitations of the system, and suggests areas for further testing and future improvements to the system.

Appendix A provides the post-processing system reports for the segments of five routes in Cooper County that were used to test and validate the system.

Section 2.
Research Approach

Prior to the start of the project, the research team identified reports in the literature from two university research efforts to develop systems that identified the boundaries between passing and no-passing zones on two-lane roads (Azimi and Hawkins, 2012; Namala and Rys, 2006). The research team believed that the algorithm and/or code from one or both of these systems could be made available for further testing and modification for application to MoDOT's needs. In both research projects, a single vehicle was instrumented with a GPS unit collecting not only latitude and longitude, but also altitude, to allow mathematical computation of available passing sight distance based on roadway geometry and assumptions about available clear zones on the inside of horizontal curves. Assuming that these systems could be made available to the research team, the initial research approach was to 1) evaluate the benefits and disadvantages of each system, assess how compatible they were likely to be with various off-the-shelf hardware components, and determine how easily they could be tested and modified to meet MoDOT's needs; 2) obtain the preferred system, conduct local testing, and modify as needed; 3) test the modified system on MoDOT routes to determine how well the results matched existing striping determined by MoDOT to be "correct"; and 4) report results and develop a user manual for the modified system.

However, early in the research, it became apparent that, for various reasons, neither system identified in the literature would be available for us to test and modify. At that point, the focus of the research shifted from evaluating and modifying an existing system to developing a new system to meet MoDOT's desired functionality. While this shift required additional time and resources, it allowed for MoDOT and the research team to consider a wider range of approaches, including a two-vehicle system that more closely resembles the system they were accustomed to using.

The research approach was organized into four primary tasks as follows:

- Task 1—Identify and Evaluate Alternative Approaches
- Task 2—Choose Approach and Develop Hardware and Software System
- Task 3—Test System on Missouri Roadways in the Field
- Task 4—Prepare User Manual and Final Report

This section describes the alternatives considered by the research team and presented to MoDOT, as well as a discussion of why the chosen alternative was selected. It then describes the conceptual design of the selected alternative and gives an overview of the testing plan for the new system. A detailed discussion of the hardware components, field data collection software, post-processing software, and testing and results are provided in Sections 3, 4, 5 and 6 respectively.

2.1 Alternatives Considered

The research team considered two basic alternatives for determining passing sight distance availability along a roadway:

- Alternative 1—Single-vehicle system instrumented with a GPS unit that would provide highly accurate latitude, longitude and elevation measurements to record the roadway vertical and horizontal profile as the vehicle traveled along the roadway. Geometric calculations could then be used to determine positions along the roadway where available sight distance is less than the required passing sight distance due to vertical curves (hill crests). To determine sight distance limitations due to sight obstructions on the inside of horizontal curves, two approaches were considered:
  - Alternative 1A—A clear-zone width could be assumed and included in the calculations. Shoulder width might be a surrogate for clear zone width, assuming shoulders are generally clear of objects and vegetation that might cause a sight obstruction. Clear-zone width could also be set based on an in-field assessment, or on agency policy. In any case, a default number would be used for the length of the roadway being evaluated.
  - Alternative 1B—The second approach to determining the impact of sight obstructions inside a horizontal curve would be to measure the distance to sight obstructions in the field during data collection, or to use aerial images of the roadway in the office to identify potential sight obstructions. In this case, sight distance calculations along horizontal curves would be based on actual conditions along the roadside for each horizontal curve rather than an assumed clear zone.

  Both variations of this single-vehicle approach rely on geometric calculations, rather than visual confirmation, to determine where passing sight distance is available along the road.
- Alternative 2— Two-vehicle system that relies on the driver of the following vehicle reporting the visibility of the lead vehicle along the route to determine where passing sight distance is available. This system would use GPS units, radios, a laptop, and a secondary monitor to calculate and report the distance between the two vehicles in real time, and provide the driver feedback as to whether the system was collecting data. This system essentially replicates MoDOT's previous system for identifying passing and no-passing zone boundaries, but modernizes the method for measuring and reporting the distance between the two vehicles.

2.2 Selection of Alternative

The research team and MoDOT staff considered the advantages and disadvantages of the system alternatives, summarized next:

Alternative 1—Single-Vehicle System

Advantages	*Disadvantages*
• Minimum equipment required: GPS unit and data logger • Minimum staff required: only one driver needed • Data collection needed in only one direction of travel to acquire roadway alignment	• Complicated mathematical algorithm required for determining available sight distance based on three-dimensional roadway alignment • Requires a more expensive GPS unit that provides highly accurate elevation/altitude data

- No real-time computations required; all data processing occurs after data collection is complete
- No visual confirmation of available sight distance; must trust results of mathematical computations (after testing algorithm)
- Secondary approach required to address sight obstructions inside of horizontal curves

Alternative 1A—Horizontal Clear Zone Assumed

Advantages

- Requires little to no field data collection

Disadvantages

- May give overly conservative results and eliminate passing zones where more than minimum default clear zone is available

Alternative 1B—Distance to Horizontal Sight Obstructions Measured

Advantages

- Provides flexibility in using the available clear zone width for each horizontal curve

Disadvantages

- Requires additional field or aerial image measurements, may complicate geometric calculations of available sight distance along the roadway

Alternative 2—Two-Vehicle System

Advantages

- Operation similar to system MoDOT has previously used
- Can use fairly inexpensive GPS units because altitude/elevation data is not needed
- Provides visual confirmation of available sight distance
- Incorporates all elements of roadway and environment (horizontal and vertical alignment, roadside sight obstructions, overhead structures, roadside vegetation)
- No advanced mathematical algorithms required for computation of sight distance

Disadvantages

- Accuracy is dependent on driving speed and driver reaction time
- More equipment and staff needed (two vehicles, two drivers, two GPS units, communication devices, distance reporting devices)
- Requires real-time computation of distance between vehicles
- Quality of data based on both vehicles receiving good data and communicating it in real time

After discussing the alternatives with several MoDOT staff members, we learned that MoDOT places a high value on the visual confirmation of available sight distance. They believe that a system in which a human indicates whether the vehicle ahead is visible or not at the required passing sight distance based on actual field conditions is most defensible. They also value a system that operates similarly to the system they were accustomed to using. For these reasons, Alternative 2 was chosen for development.

2.3 Conceptual Design

At its most basic level, the concept of the two-vehicle system is to provide a mechanism by which the two vehicles can travel along the roadway at a consistent distance from each other (that distance being the required passing sight distance), that allows the following driver a means to indicate his or her location along the road when the lead vehicle goes in and out of view, and that develops a report of recommended centerline striping based on those indications from the following driver.

MoDOT specified that the system should be relatively low-cost, be easily transferred between vehicles, keep staff from having to leave the vehicle during data collection, require minimal training for operation, and allow for data collection at near highway speeds. MoDOT also desired that the components would be off-the-shelf (to allow them to purchase and assemble additional units of the system), and that any software used or developed will be available to MoDOT without a license.

The specific concept for the mapping of passing and no-passing zone boundaries on two-lane roads developed in this research includes the following functionalities:

- Identify the position of lead and following vehicles along the road in real time
- Establish communication between the lead and following vehicle so GPS data can be sent from lead vehicle to following vehicle in real time
- Compute the distance between the vehicles in real time
- Display the distance between the vehicles to the following driver in real time
- Provide feedback to following driver on:
    - Availability of satellites for both vehicles
    - Status of communication between vehicles
    - Whether following vehicle is within acceptable range of required passing sight distance from lead vehicle
- Allow following driver to indicate the locations where a target 3.5 ft off of the surface of the roadway on the rear of the lead vehicle transitions from visible to not visible, and vice versa, using a switch or button, and tie the time and/or location of these indications to the incoming GPS data
- Provide field data collection software that allows system user to input site characteristics, define file path for data storage, and allows data collection to be started and stopped in the field

- Provide post-processing software that:
  - Reports the latitude and longitude of locations where striping should change in either direction of travel (creates a GPS-based striping log for the roadway segment)
  - Looks for passing zones shorter than 400 ft and eliminates them from the striping log
  - Indicates locations where a striping change is indicated by the field data, but where either no GPS data were available or the vehicles were not within acceptable range of the required passing sight distance.

2.3.1 Hardware Integration

The system hardware requires the integration of two GPS receivers, one in the leading vehicle and one in the following vehicle, two radios (one in each vehicle), a laptop used as a data logger, a secondary monitor used to display distance between the vehicles to the following driver in real time, and a switch that allows the driver of the following vehicle to indicate when the target on the lead vehicle goes into and out of view. Both the GPS devices and the radios use external antennas that attach to the roof of the vehicle via magnetic bases. The components are powered through adapters plugged into the cigarette lighters in the vehicles. The hardware system integration is illustrated in Figure 1.

2.3.2 Field Data Collection Software

The laptop in the following vehicle uses custom software to log the GPS data from both vehicles, the time associated with each reading, and input from a switch that indicates when the leading vehicle is visible to the driver of the following vehicle. The GPS data from the leading vehicle are transmitted in real time to the following vehicle via a radio link. The software calculates and displays the distance between the vehicles on a secondary monitor located on the dashboard to assist the following driver in maintaining the desired distance (approximately equal to the passing sight distance) behind the lead vehicle.

Graphical User Interface

The graphical user interface (GUI) for the field data collection software was designed to allow the operator to:

- Input detailed data describing the beginning and end of the data collection route, including route name, direction of travel, beginning and ending county, and text description of beginning and end points
- Specify the speed limit for the route, which automatically identifies the applicable MUTCD passing sight distance (users can overwrite this value if desired)
- Specify the acceptable range of distance beyond the minimum passing sight distance for the following vehicle to maintain. That is, if the passing sight distance is 900 ft, the following driver will be considered within range if they maintained a distance between 900 and 950 ft (if 50 ft was identified as the acceptable range) from the following vehicle. A distance below 900 ft or above 950 ft would be flagged as out of range

- Document the location of the GPS antenna relative to the position of the driver in the following vehicle and relative to the back of the lead vehicle to adjust the measured distance between the GPS receivers in the two vehicles to the distance between the eye of the following driver and the rear of the leading vehicle
- Accept the default file path for saving the data, or adjust the file path as needed
- Monitor the number of satellites tracked by the GPS units in both vehicles
- Monitor the data being read by the satellites
- Ensure the correct hardware devices are being read by the correct communication ports on the laptop
- Start and stop the recording of data

The GUI is shown and described in more detail in Section 5.

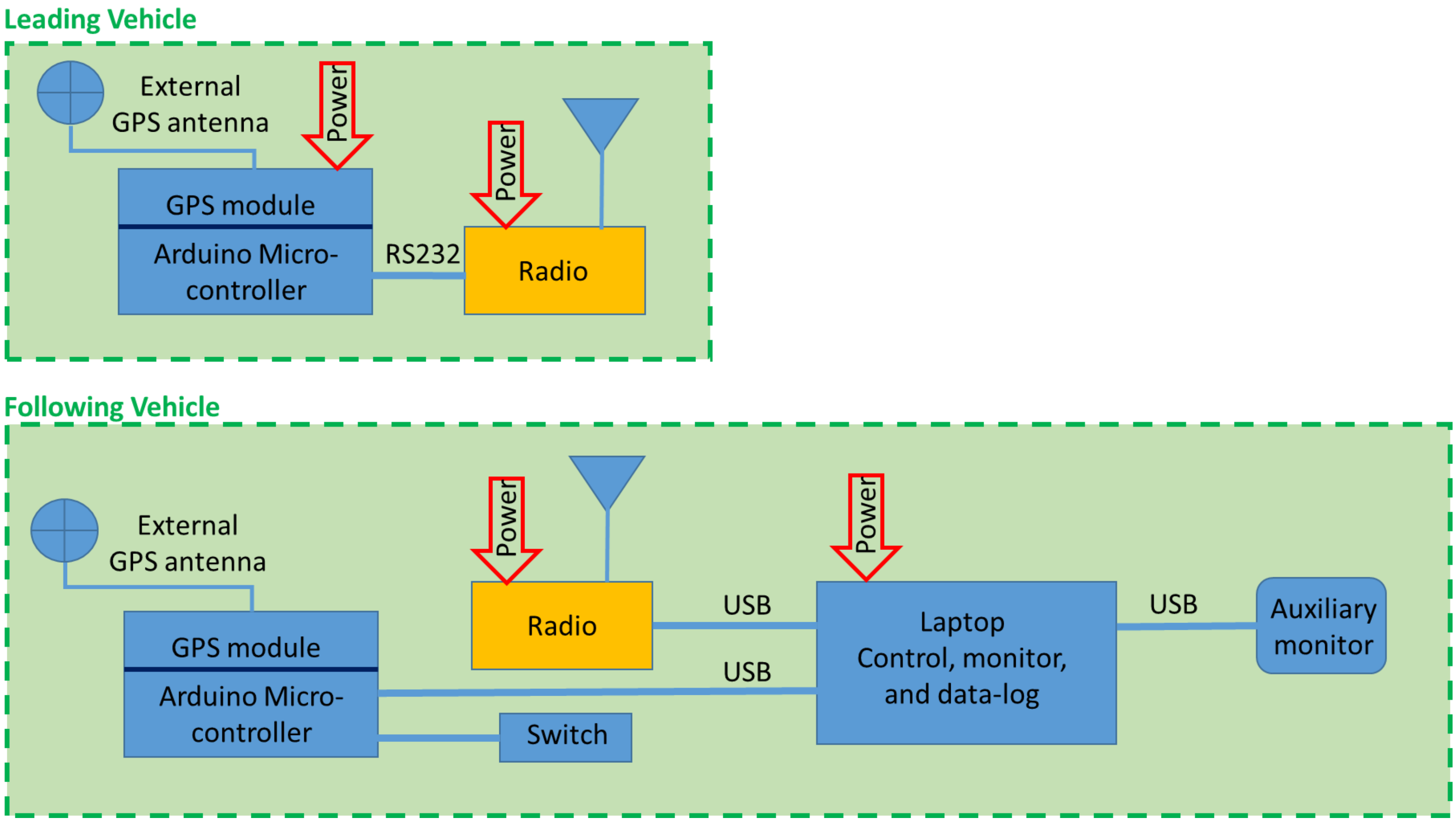

Figure 1. Schematic of hardware configuration.

Real time calculations

The field data collection software collects and logs the GPS data from the two vehicles in real time. In addition, it converts the GPS data from degrees, minutes, and seconds to decimal degrees. These values are used to calculate the distance between vehicles and display the information in real time. Several algorithms were used and tested in order to provide acceptable accuracy and speed.

The first version of the field software calculated distance between vehicles as a straight line between GPS location points of the two vehicles. This straight-line approach, while mimicking the old “drag a rope” system of measuring passing sight distance, had two significant limitations. First, along horizontal curves, the actual distance between vehicles would be greater than what the system reported. Table 1 shows the possible error in distance measurement for various passing sight distances and curve radii. Note that for longer passing sight distances (on higher speed routes) and shaper curves, this distance can be quite substantial. This discrepancy results in conservative passing zones near horizontal curves because vehicles would need to maintain visibility over a longer distance than necessary to satisfy passing sight requirements in order for the following driver to indicate a passing zone was permitted. Second, this discrepancy in the distance reported was confusing to the following driver and made it difficult for the following driver to maintain a relatively constant distance between the vehicles. As the lead vehicle entered a horizontal curve, the reported distance between vehicles decreased and the following driver slowed to increase the distance. But as the following vehicle exited the same curve and both vehicles were on a tangent again, the displayed distance between vehicles would increase quickly as the straight line distance became equivalent to the distance along the road between the vehicles. Because maintaining a constant speed resulted in a rapidly fluctuating displayed distance between vehicles near horizontal curves, the following driver was constantly trying to adjust speed, which resulted in further deviations from the desired distance. In addition, these erroneous distances between the vehicles near horizontal curves were reported in the data files used by the post-processing software to determine where no-passing zones should be marked. Because many of the boundary locations (between passing and no-passing zones) were at locations near horizontal curves, the reported distance between vehicles at these locations was often outside of the desirable range. This made it difficult to determine whether the vehicles were a sufficient distance from each other when a passing zone was recommended, or whether the shorter reported distance was simply the result of the error between the straight line distance and the distance along the road between the vehicles.

Table 1. Potential distance error by passing sight distance and curve radii.

Difference between passing sight distance and chord length (error)									
	Curve Radius (ft)								
PSD	400	600	800	1000	1200	1400	1600	1800	2000
400	16	7	4	3	2	1	1	1	1
500	32	14	8	5	4	3	2	2	1
600	**55**	25	14	9	6	5	4	3	2
700	**86**	39	22	14	10	7	6	4	4
800	**127**	**58**	33	21	15	11	8	7	5
900	**178**	**82**	47	30	21	15	12	9	8
1000	**241**	**112**	**64**	41	29	21	16	13	10

MoDOT requested that the research team explore the possibility of calculating distance along the roadway between the vehicles rather than a straight-line distance between the vehicles. Given that both vehicles receive location data five times per second and assuming uninterrupted data, the distance each vehicle has traveled along the roadway can be computed as the sum of all the straight-line distances between individual data points traversed by the lead vehicle, approximating the alignment of the roadway.

The research team developed and incorporated into the field software an algorithm to measure the distance along the roadway (rather than a straight line distance) between the two vehicles and to allow the user to reset this distance measurement after periods of data dropouts. This algorithm is discussed in more detail in Section 5.

Post-Processing Software

The post-processing software uses the data collected by the following vehicle, including the time-stamped GPS data, and the time stamp and location at which the following driver flipped the switch to indicate a change in visibility of the target on the lead vehicle (representing the potential beginning and ends of no-passing zones) to develop striping recommendations for the roadway segment being measured. The software evaluates the GPS data files for both directions of travel to find a common beginning and ending point and to match the nearest point in the secondary direction of travel to each point in the primary direction of travel between the common beginning and ending points. This allows the software to create a single striping log for the roadway that indicates points along the road where the striping in either direction should change from solid to dashed or from dashed to solid. The software also checks for short passing zones and eliminates any that are shorter than 400 ft to meet MUTCD requirement. For each point where a striping change is recommended in either direction of travel, the striping report shows the latitude and longitude of that point, whether distance between the two vehicles was within the specified allowable range, and whether GPS and distance data was being collected and recorded at that point. The post-processing software creates an Excel spreadsheet with this location data and basic descriptive information about the route and the data collection run.

2.4 Field Testing

As the scope of the research shifted from the testing and evaluation of existing single-vehicle algorithms or software to one of designing a new two-vehicle system from scratch, the testing plan changed accordingly. Rather than simply collecting data and comparing the algorithm outputs (striping recommendations or no-passing zone log) to MoDOT's no-passing zone log for several routes, the testing plan shifted to ensuring the functionality of various hardware components and connections, the successful operation of field and post-processing software, the ability to calculate distances in real-time and the accuracy of those calculations, and the ability of the system operator to use the system successfully. After verification and testing of all of these system elements, the results of the post-processing software could be compared to MoDOT's striping logs.

System testing was ongoing and incremental in nature. That is, as system components were purchased, modified, and integrated, and as software functionalities were added, continual testing was conducted to ensure they were performing as expected. Periodically, system components were taken into the field to ensure data was being collected as expected. The following functionalities were tested during system development:

- GPS units
  - Ensure they can read data five times per second
  - Ensure location readings are accurate (within a few meters)
  - Ensure GPS units can receive satellite data even during cloudy conditions and through overhead foliage
- Radios
  - Ensure they can send GPS messages between themselves at the speed that the messages are received
  - Ensure they can transmit data across the full range required (up to 1,200 ft), through foliage and other obstructions
- Laptop/data logger
  - Ensure executable field software program will run on laptop
  - Ensure data is stored properly and can be retrieved from laptop
  - Ensure laptop can provide sufficient power to various hardware components
- Secondary monitor
  - Ensure monitor provides critical data to driver in easy-to-read format
- Switch
  - Ensure driver can easily and quickly flip switch when lead vehicle goes in and out of view
  - Ensure switch data is tied to a time stamp so that even if location data is bad at the time of switch activation, the time record of that switch is accurate
- Field software
  - Ensure data is logged 5 times a second for both lead and following vehicle, even when satellite data is not available or radios are not transmitting
  - Provide user opportunity to clearly identify the testing location and distinguish among multiple runs
  - Ensure comm ports (USB ports) on the laptop are properly matched to hardware components
  - Ensure real-time feedback to driver is functioning properly (error messages appear as expected when expected)
- Data accuracy
  - Ensure logged GPS data represents the true location of the vehicles
  - Ensure the calculated distance between vehicles truly represented the difference in distance traveled along the road between the two vehicles

Functionality of the post-processing software was tested using data from local, short system test trials.

After all components and software components were finalized and integrated, full system field testing was conducted on several routes selected by MoDOT. A no-passing zone log was provided for the test routes. MoDOT identified specific testing routes for which they believed the striping log to be highly accurate. The full field testing evaluated the following system features:

- Frequency and conditions of "data dropouts" (when GPS units failed to receive satellite data or radios failed to transmit)
- Ability of drivers to maintain desired distance between vehicles and conditions where maintaining a specific distance became difficult
- Ability of following driver to monitor distance and indicate visibility of lead vehicle with the switch while driving safely

After the field testing on each MoDOT route was complete, the post-processing software was applied to create a recommended striping log for that route, and this recommended striping log was compared to MoDOT's existing striping log to evaluate the quality of data collected by the new system. The results of this comparison are presented in Section 6.

Section 3.
System Hardware

The research team identified the hardware components for use in this system based on desired specifications, price, and availability. While off-the-shelf components were used for the system, some modifications were necessary to obtain the desired data, ensure compatibility among devices, and provide stable connections between components. These modifications included:

- The GPS modules were capable of reading GPS location information at a rate of 10 times per second. The modules were programmed to gather the data at five times per second (every 0.2 seconds) to balance the desired precision of the vehicles' positions along the roadway during the run with the need to complete real-time calculations with those position data for every position reading.
- The switch used by the following driver to indicate when the lead vehicle goes in and out of view was hard-wired into the GPS unit of the following vehicles so that the switch indication could be tied to a specific location and time point recorded in the data file of the following vehicle.
- The connections between the GPS units and radios were modified to ensure reliable data transfer.
- The components of the GPS modules were housed together in a plastic case, with connections for the cables mounted on the outside of the case (allowing for disconnection of cables without disrupting the hardware inside the case).
- The radios were programmed so that the lead vehicle radio would only transmit data and the following vehicle radio would only receive data.

Each device requires power during data collection runs. In the lead vehicle, the radio and GPS units are powered through a 12V DC power adapter, split to accommodate two devices. In the following vehicle, the secondary monitor, GPS unit, switch, and radio are powered through USB connection to the laptop. The laptop is powered by an AC power inverter plugged into a 12V DC outlet in the following vehicle. The laptop battery alone is not sufficient to provide sufficient power to all components.

In the two-vehicle system, location information is needed in real-time for both the lead and following vehicles to calculate the distance between vehicles. Therefore, the system includes a set of hardware components for each of the vehicles. These components and the structure of their connections, power sources, and communication paths are described below. Refer to Figure 1 in Section 2 for a schematic of the hardware components for both the lead and following vehicles.

3.1 Lead Vehicle Components

The hardware components installed in the lead vehicle include a GPS module (Figure 2), radio modem (Figure 3), GPS external antenna (Figure 4), radio antenna (Figure 5), serial cable (Figure 6), two power adapters, and DC power splitter (Figure 7).

Figure 2. GPS logger (inside plastic housing case), front and back.

The GPS module (Figure 2) is comprised of a microcontroller board (Arduino Uno R3) and an add-on GPS logger shield housed together inside a hard plastic case. The GPS logger shield gathers location data from an external antenna that retrieves global positioning information from satellites. The GPS logger shield specifications indicate that it is accurate to within 10 ft. The Arduino is used to parse that location message into the elements needed for the system and to send that location message to the radio. An RS232 cable connects the GPS module to the radio.

The approximate cost of GPS module components is as follows:

Arduino microcontroller:	$26.00
GPS logger shield:	$50.00
RS232 cable:	$4.00
Plastic case:	$12.00
Total per GPS module:	$92.00

Additional information about the Arduino microcontroller can be found here: https://www.adafruit.com/product/50

Additional information about the GPS logger shield can be found here: https://www.adafruit.com/products/1272

The radio used to transmit the GPS location data from the lead vehicle to the following vehicle is a 900- MHz radio modem manufactured by Digi (Figure 3). Digi claims the radio can transmit over 3,000 ft indoors and over 40 miles outdoors when a clear line of sight is available. The radio is connected directly to the GPS module via an RS232 cable.

The radio cost is approximately $300. More information can be found at: http://www.digi.com/products/xbee-rf-solutions/modems/xtend-900mhz-rf-modems

Figure 3. Digi XTend-PKG 900 MHz Radio Modem, front and back.

An external antenna (Figure 4) is needed to improve reception of the satellite signals. This antenna plugs into the GPS module case and has a magnetic base for attaching to the roof of the lead vehicle. The GPS antenna costs approximately $13. Similarly, the radio uses an external antenna to better transmit the GPS message to the following vehicle. The radio antenna (Figure 5) has a strong magnetic base, allowing it to attach to the roof of the lead vehicle. The radio antenna costs approximately $20.

Figure 4. External GPS antenna.

Figure 5. Radio Antenna.

A serial cable (Figure 6) is used to link the GPS module to the radio. Both the radio and GPS module are powered through a DC power adapter that plugs into the 12V DC outlet of the lead vehicle (Figure 7).

Figure 6. Serial Cable to link radio and GPS module.

Figure 7. DC power adapter (2) and DC power splitter.

3.2 Following Vehicle Components

The following vehicle contains a GPS module with a passing sight distance rocker switch (Figure 8), a radio modem (Figure 9), external GPS and radio antennae (Figure 4 and Figure 5 above, respectively), USB cables for GPS module and radio (Figure 10 and Figure 11, respectively), a secondary dashboard monitor (Figure 12), a laptop computer (Figure 13), and a DC to AC inverter (Figure 14) to power the laptop.

The following vehicle includes the same GPS module and radio as the lead vehicle. However, in the following vehicle, these devices do not connect directly to each other, but instead each connects to the laptop through USB ports, which provides the power these devices require during field operation. The rocker switch, which is used to indicate the locations where the target on the lead vehicle transitions from visible to not visible and vice versa, is hard-wired to the GPS module so that the switch position can be indicated directly in the following vehicle GPS data file. The cord connecting the switch to the module is sufficiently long to allow the driver to hold the switch comfortably in his or her hand during the data collection run. Both the GPS unit and the radio in the following vehicle have external antennae with magnetic bases identical to those on the lead vehicle.

Figure 8. GPS module with rocker switch.

Figure 9. Radio for following vehicle.

Figure 10. USB cable for GPS module.

Figure 11. USB cable for radio.

A secondary dashboard monitor mounted on the dash, using a high-grip rubber mat, to display the current distance between the lead and following vehicles in a clear, easy-to-read format is shown in (Figure 12). The driver uses this display to maintain the appropriate distance (the required passing sight distance) between vehicles during the data collection run. This monitor is a Lilliput 7-inch USB LCD video monitor, and the display is generated by the field data collection software. The monitor costs approximately $100, and the rubber mat for keeping the monitor in place on the dash costs approximately $10.

Figure 12. Dashboard Monitor.

A basic laptop computer is used to run the field data collection software, store the data files as they are collected in the field, and power the dashboard monitor, GPS module, switch, and radio.

The laptop is an HP 15.6-in, with anti-glare screen, running an AMD Quad-Core A8-6410 processor. It has 4GB of memory and a 500GB hard drive. It runs the Windows 7 Professional operating system. The laptop costs approximately $400.

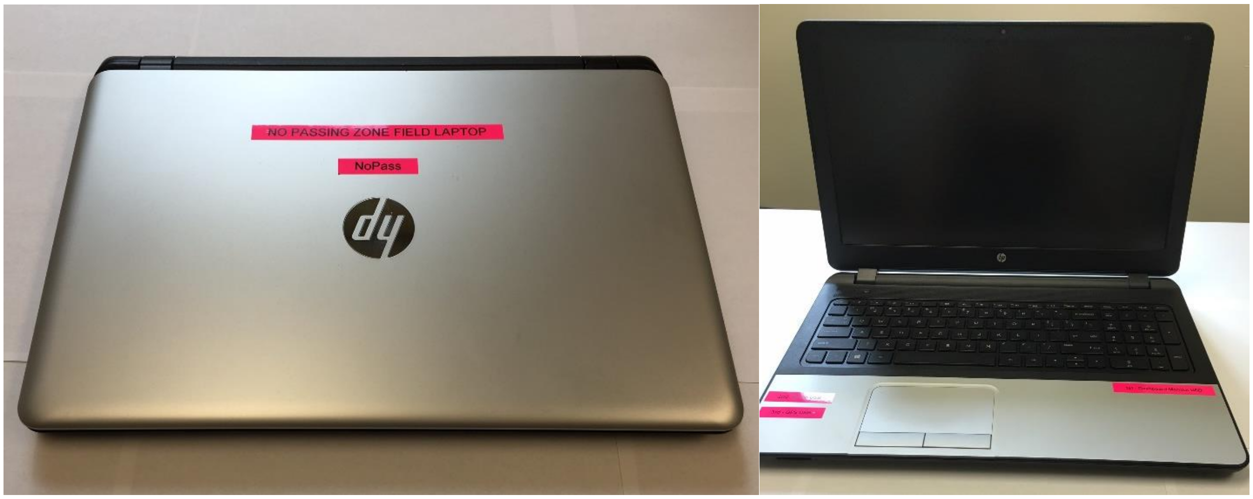

Figure 13. Field laptop.

The laptop battery does not provide sufficient power for the dashboard monitor, GPS module, switch and radio without itself being externally powered. An AC power inverter is used to plug the laptop into the following vehicle's 12V DC outlet.

Figure 14. AC power inverter.

The approximate off-the-shelf cost of all system components for both vehicles, including cables and power converters, is $1,400.

Section 4.
Field Software

The field software was developed in LabVIEW to be run on the laptop computer in the following vehicle. It allows users to specify the characteristics of their data collection run in the field, collect GPS data from both the lead and following vehicles, compute the distance along the road between the vehicles in real time, report this distance to the following driver, and save all relevant data to files for use in the post-processing software. While LabVIEW requires a license for use (which MRIGlobal had prior to this research project), the field software runs on the laptop as an executable file, which only requires a free software driver and not a license for the LabVIEW software itself.

4.1 Graphical User Interface (GUI)

The graphical user interface (GUI) for the field software includes four tabs (Trial setup, Monitor, GPS & Radio, and System Settings). The operator primarily uses the first tab, which records all the inputs that define the data collection run (shown in Figure 15). These inputs include the route name, the county in which the run begins and ends, the direction of travel, the posted speed limit, the distance beyond the passing sight distance the operator considers to be an acceptable range for maintaining between the lead and following vehicle, the locations of the GPS antenna relative to the back of the lead vehicle and the driver in the following vehicle, and the file path for recorded data.

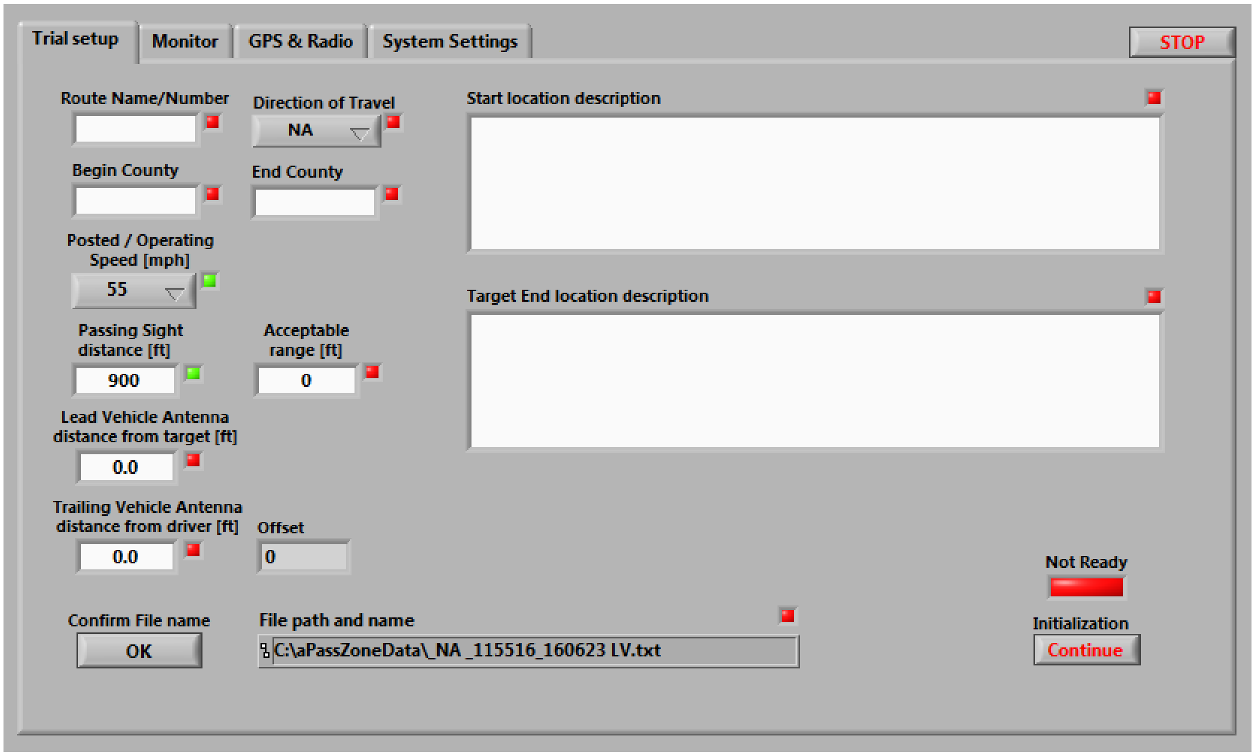

Figure 15. Field software GUI for inputs at start-up.

The value for passing sight distance is automatically populated based on MUTCD and AASHTO *Green Book* policy for the input value of the posted speed limit. Alternatively, as specified in the MUTCD, the user can also elect to use the statutory speed limit (if a speed limit is not posted) or the 85th percentile speed (if available). These distances are shown in Table 2. However, the user can manually overwrite this distance if a different passing sight distance is considered appropriate.

Table 2. Passing Sight Distance by Speed

Speed (mph)	Passing Sight Distance (ft)
20	400
25	450
30	500
35	550
40	600
45	700
50	800
55	900
60	1000
65	1100
70	1200

Once this input data is initialized, the user is given a screen with a button for starting and stopping the recording of field data.

A secondary display is sent from the laptop to the secondary monitor, placed on the dashboard in plain sight of the driver of the following vehicle, to clearly display the distance between the lead and following vehicles, both numerically and on a slider bar, showing when the vehicle drifts out of the acceptable distance. An indicator on the display lights green when the switch is flipped to indicate that the lead vehicle is visible. A sample display from the secondary monitor is shown in Figure 16.

A more detailed explanation of how the user operates the field software is provided in the System User Manual available at http://library.modot.mo.gov/RDT/reports/TR201514/.

Figure 16. Display of distance between vehicles shown on secondary monitor.

4.2 Distance Calculation

The primary function of the software is to identify the position of each of the vehicles several times a second, calculate the distance between them along the roadway, and report this distance to the driver of the following vehicle in real time. Because the system does not know the roadway alignment prior to the route being driven, this calculation must begin on a tangent, where the straight-line distance between the vehicles (which can be calculated from only the known GPS points of the two vehicles) is equal to the distance along the roadway. Therefore, each data collection run should begin and end on a tangent section of roadway. After the initial distance is determined by the field software, the system can then calculate the distance between the vehicles along the road by adding the distance traveled by the lead vehicle since the initial position, and subtracting the distance traveled by the following vehicle since the initial position. When satellite data or communication between the radios is lost, this calculation can no longer be performed (because there is no longer a previous distance to add to or subtract from), and so the distance calculation must be reset by recalculating a new straight-line distance. These distance calculations in various scenarios are described in more detail below.

Prior to the development of the software, the research team conducted a small study looking at different methods of calculating distances between two points on Earth. Three methods were considered: calculate distance assuming Earth as an ellipsoid; calculate distance assuming Earth as a sphere; and calculate distance assuming a flat Earth. These three methods ranged from very complex to very simple, respectively. The research team identified several sets of GPS points using Google Earth and calculated the distance between them using all three methods to determine any discrepancies.

Given that the distance between the vehicles will generally be 1,200 ft or less during data collection, the research team found that there was very little difference in results among the three approaches. Additionally, since the field software must calculate this distance five times per second, and a more complicated approach takes additional processing time and computing power, simpler methods are preferred. The research team determined assuming the Earth as a sphere was most appropriate for the system. The Haversine Formula was used for this computation. Note that latitude and longitude must be converted from decimal degrees to radians to perform the following equations.

$$\Delta long = long_{lead\ veh} - long_{following\ veh}$$

$$\Delta lat = lat_{lead\ veh} - lat_{following\ veh}$$

$$a = \left[\sin\left(\frac{\Delta lat}{2}\right)\right]^2 + \cos\left(lat_{following\ veh}\right)\cos\left(lat_{lead\ veh}\right)\left[\sin\left(\frac{\Delta long}{2}\right)\right]^2$$

$$c = 2\sin^{-1}\left[\min\left(1, \sqrt{a}\right)\right]$$

$$distance = Radius_{Earth}\ c$$

4.2.1 Distance Calculation at Initiation of a Data Collection Run

At the very beginning of data collection, the software calculates the distance between vehicles as a straight-line distance. The vehicles must begin the run on a tangent segment of roadway to obtain an accurate value of the starting distance between vehicles, even if this initial distance is substantially less than the passing sight distance.

After this initial distance is calculated from the very first GPS location recorded for each vehicle, subsequent distances are calculated tracking the incremental distance traveled by both the lead and following vehicles separately between each location observation (every 0.2 seconds). The software adds the difference between these values to the previous calculated distance to obtain the distance along the roadway between the vehicles.

As long as location data are being continuously read by the GPS module and communicated between the radios, the dashboard display will show a yellow background around the reported distance between vehicles, indicating the distance calculating is being computed as expected.

4.2.2 Distance Calculation During and After Data Dropouts

If either GPS module loses satellite connection or the radio transmission between vehicles is interrupted, the background of the distance display on the dashboard monitor will turn red, and the distance shown will be “99999”. This error display is shown in Figure 17. For short disruptions, i.e., less than 2 seconds, the calculated distance will correct itself and return to a normal display on a yellow background. If the disruption is longer, the distance display will show the red background with the “99999” error message until satellite and/or radio communication is restored. At that point, the display background will return to yellow, but the distance display will show “11111”. This indicates that the distance along the road between the vehicles can no longer be calculated because the alignment of the roadway during the data dropout could not be detected. When the display shows “11111”, the following vehicle operator must click the Reset Distance button at the next point where the two vehicles are on a tangent section in order to re-establish the straight-line distance between vehicles. After this straight-line distance has been reset, the calculation of the distance along the road can be computed from that point forward.

Figure 17. Data dropout error message.

4.3 Recording Potential Boundary Locations of Passing and No-Passing Zones

The following vehicle driver uses a rocker switch to tell the software that the lead vehicle is visible or not visible. The following vehicle operator determines the visibility of the lead vehicle by evaluating whether or not a target on the rear of the lead vehicle 3.5 ft above the roadway surface is visible. The locations where the switch position is changed are the locations of the boundaries between segments where sufficient passing sight distance is available and segments where sufficient passing sight distance is not available.

The rocker switch is wired into the GPS module in the following vehicle. The field software logs the position of the switch (on or off) in the recorded GPS data file for the following vehicle. The following vehicle data file includes a row of data for every 0.2 seconds, even when GPS data is not being communicated. This allows the time of the change in switch position to be recorded even when location and distance data are not being received and calculated. A visual indication on the dashboard monitor shows the position of the switch. This light is green when the target on the lead vehicle is visible and grey when the lead vehicle is not. (See the upper right-hand corner of Figure 17.) If the switch is flipped during a period of data dropout, the indication on the dashboard display will flash, indicating that the distance between the vehicles is not known for the location where the switch was flipped.

4.4 Operation of No-Passing Zone System in the Field

The No-Passing Zone System User's Manual provides detailed guidance for operating the system in the field. The responsibilities of the drivers of each vehicle are summarized as follows.

Lead Vehicle Driver's Responsibilities:

- Install lead vehicle hardware components; ensure components are properly powered.
- When following driver indicates the field software inputs are complete, begin run. Gradually increase speed to pre-determined running speed for the route.
- After reaching the pre-determined running speed, maintain a constant speed throughout the run to the extent possible.
- If running speed must slow to navigate a sharp curve, maintain the reduced speed until the following vehicle has also exited the curve, then slowly accelerate to pre-determined running speed.

Following Vehicle Driver's Responsibilities:

- Install following vehicle hardware components; ensure components are properly powered.
- While stopped in a safe place prior to the start of the run, open the field data collection software on the laptop and input all necessary data.
- Indicate to the lead driver when the run can begin.
- Begin the run slowly; accelerate to the pre-determined running speed gradually, allowing the lead vehicle to achieve the proper spacing between vehicles.
- Near the desired start point of the data collection run, click the "begin writing" button on the GUI on the laptop to begin recording GPS data to the file.
- Watch the display of the distance between vehicles on the dashboard monitor and adjust speed as necessary to maintain the desired distance behind the lead vehicle.
- Watch the target on the lead vehicle. Flip the rocker switch when the target goes out of view or comes into view.

- As the lead vehicle approaches a sharp curve that will require a speed reduction, try to anticipate that speed reduction and reduce speed accordingly.
- If data dropouts occur, wait until GPS data communication is available (distance display will go from "99999" or a red background to "11111" on a yellow background). At the next point at which both vehicles are on the same tangent section of roadway, click the reset button on the GUI.
- At the completion of the run, click the "stop writing" button on the GUI and pull off the road at an appropriate location.
- Determine if another run in that direction of travel is desired.

The workload for the following driver can be somewhat high at times, especially on rolling or curvy terrain, where frequent changes between passing and no-passing zones are expected. To make this workload more manageable, MoDOT may consider assigning a passenger to the following vehicle to share the workload. The passenger could be responsible for any required interaction with the field software during the run (such as starting and stopping writing to the file and using the "reset" button). The passenger may also be responsible for operating the switch, although, because passing sight distance is measured from the perspective of the driver, the driver would need to provide verbal indication of when the switch should be flipped. The passenger can also help monitor the distance shown on the dash monitor and tell the driver to speed up or slow down to maintain the desired distance.

Section 5.
Post-Processing Software

The software is embedded in a macro-enabled Microsoft Excel workbook (.xlsm file). If Microsoft Office is not installed on the field data collection laptop, then data files recorded in the field must be saved on a portable device and opened on a computer in the office on which Microsoft Excel has been installed. Section 5.2 explains the mechanics of the software tool and Section 5.3 discusses the operation of this tool in detail.

5.1 Functionality

The post-processing software uses the data files (.txt files) that were assembled in the field by the following vehicle and parses out all necessary information in order to determine the location of centerline striping changes in both directions of travel. The following vehicle data files contain a record of latitude/longitude coordinates, position of rocker switch, distance between vehicles, and total distance traveled every 0.2 seconds. If the GPS receiver loses connection with satellites, the data file shows this by indicating a distance between vehicles of “99999” for data rows where no position data was received or transmitted between vehicles.

The post-processing software first matches the events of opposing directions of travel into one common line. The software scans through the reverse direction log file and finds points where the rocker switch changes as well as occurrences of bad data. For each one of these points, the software searches for the latitude/longitude coordinate in the forward direction log file that is closest to the event point in the reverse direction log file. The closest point in the forward direction log file is tagged with the reverse direction event data. It is important to match the events of both directions to a common line so that the centerline striping can be determined for any point on the roadway segment (e.g. double solid line, solid-dash combination)

Once these events are linked, the post-processing software tool determines points of change in the centerline striping as well as eliminates passing zones less than 400 ft in length. The results of this analysis are reported in a separate worksheet (tab) in the same workbook.

5.2 Operation

Microsoft Excel is required to run the post-processing software tool. The user must enable macros for the software tool to run. Raw data files (.txt files) are transferred from the field computer to the computer running the post processing tool using a USB flash memory stick. When the post processing tool starts, the user must direct the tool to where these raw data files are stored on the computer. Then the user selects the raw data files from the desired data collection run for each direction of travel. A macro then runs in the background, retrieving all necessary data from the raw data files and assembles a report on a separate worksheet containing information about the run and latitude/longitude coordinates where centerline striping changes.

5.3 Report

The results appear in a new worksheet automatically when the macro is finished running. Figure 18 shows the output results from Route J in Cooper County, MO. The report includes information about the roadway segment, time and date of both directions' runs, and number of passing zones removed due to being less than 400 ft in length. The report also shows the coordinates for each point where the centerline striping changes. The report indicates what the striping should change to, and whether or not the following vehicle was within acceptable range of the lead vehicle at the striping point of change. If the satellites are out of range of the GPS receivers during a point where the rocker switch is flipped, the report will highlight that striping change in red.

5.4 Interpretation of Results

As explained in the previous section, the report shows more than just latitude and longitude coordinates for changes in centerline striping. Ideally, satellites are always within range of the GPS receivers, but sometimes a data dropout occurs. The only time this is an issue is when the rocker switch is flipped, because the following vehicle does not have confirmation that they are within an acceptable distance of the lead vehicle. When this occurs, the cell in the report will turn red at the location where the data dropout occurred. If this happens, it may be necessary to redo the data collection for that road segment.

The results also indicate whether the following vehicle is within acceptable range of the lead vehicle. If the following vehicle is closer to the lead vehicle than what is acceptable at the point of centerline striping change, the report will show a negative value in the "distance from acceptability" column and this cell will be highlighted in red. Otherwise, if the vehicle is further from the lead vehicle than what is acceptable at the point of centerline striping change, the report will show a positive value in the "distance from acceptability" column and this cell will not be highlighted in any color. The user may interpret a greater distance as being more conservative and acceptable if the distance from acceptability is not too great. However, the user may decide to recollect the data if the distance from acceptability is negative.

Route	J
Forward Run Direction	E
Reverse Run Direction	W
County Start	Cooper
County End	Cooper
Forward Run Start Time	6/7/2016 11:08
Forward Run Start	B
Forward Run End	O
Reverse Run Start Time	6/7/2016 11:29
Reverse Run Start	O
Reverse Run End	B
Number of Passing Zones Removed	6

Striping Changes in the Forward Direction					
Latitude	**Longitude**	**Reverse Stripe**	**Forward Stripe**	**Range Status**	**Difference from Acceptability**
38.79584	-92.855855	Solid	Solid		
38.788175	-92.783548	Solid	Dash	Vehicles Within Acceptable Range	
38.788173	-92.781658	Solid	Solid	Vehicles Within Acceptable Range	
38.788172	-92.780273	Dash	Solid	Vehicles Within Acceptable Range	
38.78817	-92.779417	Dash	Dash	Vehicles Within Acceptable Range	
38.788173	-92.778708	Solid	Dash	Vehicles Within Acceptable Range	
38.78818	-92.776852	Solid	Solid	Following Vehicle Out of Range	-34
38.788183	-92.776242	Dash	Solid	Following Vehicle Out of Range	-18
38.788197	-92.774598	Dash	Dash	Vehicles Within Acceptable Range	
38.788195	-92.773963	Solid	Dash	Vehicles Within Acceptable Range	
38.788183	-92.772517	Solid	Solid	Vehicles Within Acceptable Range	
38.788175	-92.771383	Dash	Solid	Vehicles Within Acceptable Range	
38.788165	-92.769737	Dash	Dash	Vehicles Within Acceptable Range	
38.788167	-92.769298	Solid	Dash	Vehicles Within Acceptable Range	
38.788177	-92.767458	Dash	Dash	Vehicles Within Acceptable Range	
38.788223	-92.759523	Dash	Solid	Vehicles Within Acceptable Range	
38.78825	-92.756958	Dash	Dash	Vehicles Within Acceptable Range	
38.788258	-92.756375	Solid	Dash	Vehicles Within Acceptable Range	
38.788285	-92.753765	Dash	Dash	Vehicles Within Acceptable Range	
38.788312	-92.751423	Dash	Solid	Vehicles Within Acceptable Range	
38.788333	-92.74907	Dash	Dash	Vehicles Within Acceptable Range	
38.788338	-92.748595	Solid	Dash	Vehicles Within Acceptable Range	
38.78836	-92.746072	Dash	Dash	Vehicles Within Acceptable Range	
38.788377	-92.74427	Dash	Solid	Vehicles Within Acceptable Range	
38.788398	-92.74167	Dash	Dash	Vehicles Within Acceptable Range	
38.788403	-92.74126	Solid	Dash	Following Vehicle Out of Range	-8
38.788442	-92.738438	Dash	Dash	Following Vehicle Out of Range	-5
38.788482	-92.7356	Dash	Solid	Vehicles Within Acceptable Range	

Figure 18. Results from post-processing software tool.

Section 6.
Field Testing and Performance Measures

6.1 Early Testing of Hardware and Software Components

At each step of system development, various hardware components and software functionalities were tested.

First, the research team completed test runs in the field with a single GPS unit sending data to the field software. This testing was conducted to ensure that the GPS unit was collecting data at the desired frequency (5 times per second) and that sufficient satellites could be detected even in cloudy weather and in areas with thick foliage.

The data collected during this trial included GPS points along a roadway segment in both directions of travel. These data were used for preliminary development of the location matching algorithm that was used in the post-processing software.

Next, the two-vehicle system and basic distance calculations and display were tested. At this stage, several programming bugs were identified and corrected. These included an error in the distance calculation formula, and issues with the laptop assigning the correct communication ports to the GPS unit and radio connected with USB cables. In addition, the display to the driver on the secondary monitor, and the graphical user interface on the computer were tested and improved for user-friendliness and completeness.

Finally, the entire system, including the switch to record locations where the lead vehicle came into and went out of sight, was tested on local routes. These tests were to verify functionality and to determine the ability of the drivers to maintain a constant distance under real driving conditions. At this stage, changes were made to the display presented to the following driver to indicate undesirable conditions that could affect results, including:

- Times when satellites were not available or the radios were not communicating between the vehicles
- Times when the switch was switched from passing to no passing (or vice versa) when no satellite data was being recorded
- Times when satellites were back on line, but the distance calculation needed to be reset

6.2 Field Testing of Completed System on Routes Identified by MoDOT

MoDOT identified segments of five routes in Cooper County, just south of Boonville, Missouri, for testing. Each site, listed below, was between approximately 4 and 8 mi long and included several vertical and horizontal curves.

1. MO 5 from Boonville maintenance building South to Rt F Junction. (7.32 mi)
2. Rt B from Moniteau county line to Rt J Junction (7.97 mi)
3. Rt J from Junction of Rt B to Junction of Rt O (6.97 mi)
4. Rt T from Junction of Rt B to state maintenance ends (4.93 mi)
5. Rt EE from Junction of MO 87 to state maintenance ends (6.13 mi)

MoDOT chose these sites for comparison because they believed the striping to be accurate and good for a baseline comparison to the striping recommendations generated by the new system designed in this research.

Two research team members completed a full day of testing on Tuesday, June 7, 2016. The weather was clear and traffic was light during the trial runs. At each site, except site 4, a trial was conducted twice in both directions of travel. Only one run in each direction of travel was conducted at site 4 due to time constraints. The results from the better of the two trial runs were used for comparison to the existing MoDOT striping. The better run for inclusion in the comparison of results was chosen based on the frequency of data dropouts and the amount of time the vehicles were able to travel within the designated distance of each other.

6.3 Comparison of Results to Existing Striping

MoDOT staff provided the research team with the no-passing striping log for each of the five test sites, with start and end points identified as log mile points along the route. The research team had to first convert our passing and no-passing zone boundary location information from latitude and longitude coordinates to log miles. This was done by plotting the points on Google Earth and manually measuring the distance along the road between boundary locations. For routes that began prior to the test segment or ended after the end of the test segment (specifically sites 1 and 3), MoDOT's log point for the start of the test segment did not begin at 0.0. In addition, MoDOT defined the 0.0 point based on the direction of travel, so the same point along the road had a different log mile for each direction of travel. This required further manipulation of the data to ensure we were comparing the same points along the road during the analysis.

Tables 3 through 7 compare the number of passing zones and no-passing zones, the total length of the road on which passing is prohibited and permitted, and the percent of the route on which passing is prohibited. They also show the total length and percent of the route, in each direction, on which the striping recommended by the system developed in this research differs from the existing striping on the route.

The portion of each route for which MoDOT's striping and the new recommended striping were inconsistent ranged from 9.8 percent (eastbound direction on Route EE) to 22.3 percent (southbound direction of MO 5). Figure 19 through Figure 23 graphically illustrate portions of each route where the two striping plans do not match. The figures show both the striping plan recommended by the system developed in this research and the existing striping on each test route stacked on top of each other. Directions of travel are separated vertically. Areas of discrepancy (where the difference in location of the boundary of a passing or no-passing zone is greater than 0.02 mi, or approximately 100 ft) are highlighted in blue for the forward direction of travel and red for the reverse direction of travel. (Forward and reverse directions of travel are defined by the operator in the field.)

The test site along MO 5 (shown in Table 3 and Figure 19) shows the largest discrepancy between MoDOT striping and recommended striping of any of the test sites, although the number of passing and no-passing zones was nearly identical between the two striping plans. In the southbound direction of travel, most of the discrepancy (highlighted in blue) appears to be in areas where MoDOT's no-passing zones extend beyond the limits of the recommended no-passing zones. That is, there are locations on the edges of MoDOT's no-passing zones where the research team found that sufficient passing sight distance was available. In the northbound direction of travel, MoDOT also appears to have more conservative (longer) no-passing zones than those found by the research team, but additionally, the no-passing zones seem to be offset from each other slightly. The discrepancies in the northbound direction are highlighted in red.

The test site along Route B (shown in Table 4 and Figure 20) shows discrepancy over a slightly smaller portion of the route than the site along MO 5 (15.9 percent in the northbound direction and 18.4 percent in the southbound direction); however, the number of passing and no-passing zones are substantially different between MoDOT's striping plan and the recommended striping plan. In the northbound direction of travel, MoDOT has 12 no-passing zones and 11 passing zones, while the research team found 20 no-passing zones and 19 passing zones. Every discrepancy, in both directions of travel, is at a location where the research team found sufficient passing sight distance but MoDOT has a no-passing zone striped. Many of the passing zones identified by the research team are relatively short passing zones located within a MoDOT long no-passing zone.

Along the test site on Route J, the research team found one additional potential passing zone in the eastbound direction and three additional potential passing zones in the westbound direction, compared to MoDOT's existing striping. Striping plans matched along 89 percent of the route in the eastbound direction and along 83 percent of the route in the westbound direction. In most cases of discrepancy in both directions, the research team identified sufficient passing sight distance in locations where MoDOT striped a no-passing zone.

Along the test site on Route T, the research team found three additional potential passing zones in the northbound direction (eight compared to MoDOT's five) and five additional potential passing zones in the southbound direction (eight compared to MoDOT's three). However, striping plans matched along 87 percent of the route in the northbound direction and along 88 percent of the route in the southbound direction. Most of the areas of discrepancy were located in the first two miles of the route (when traveling from the north end to the south end), where the research team identified several potential short passing zones that were striped as no-passing zones by MoDOT. Passing sight distance was not available over much of the remainder of the route.

Of all the test sites, the site along Route EE had the best match between the recommended striping plan and MoDOT's existing striping. The research team found one additional potential passing zone in each direction of travel compared to the existing striping, and the striping matched over 90 percent of the route in the eastbound direction and over 86 percent in the other direction. Most of the areas of discrepancy were short, and generally occurred on the edge of MoDOT's no-passing zones, where the research team found that sufficient sight distance was available.

Table 3. Comparison of MRIGlobal results to existing MoDOT striping for Site 1 (MO 5)

Statistic	MRIGlobal NB	MoDOT NB	MRIGlobal SB	MoDOT SB
Number no-passing zones	13	13	13	13
Number passing zones	14	13	13	12
Length no passing (mi)	2.86	3.79	2.90	4.04
Length passing (mi)	4.57	3.64	4.53	3.39
Percent route no passing	38.5	51.0	39.0	54.4
Total length of discrepancy (mi)	1.51		1.66	
Percentage of route discrepancy	20.3		22.3	

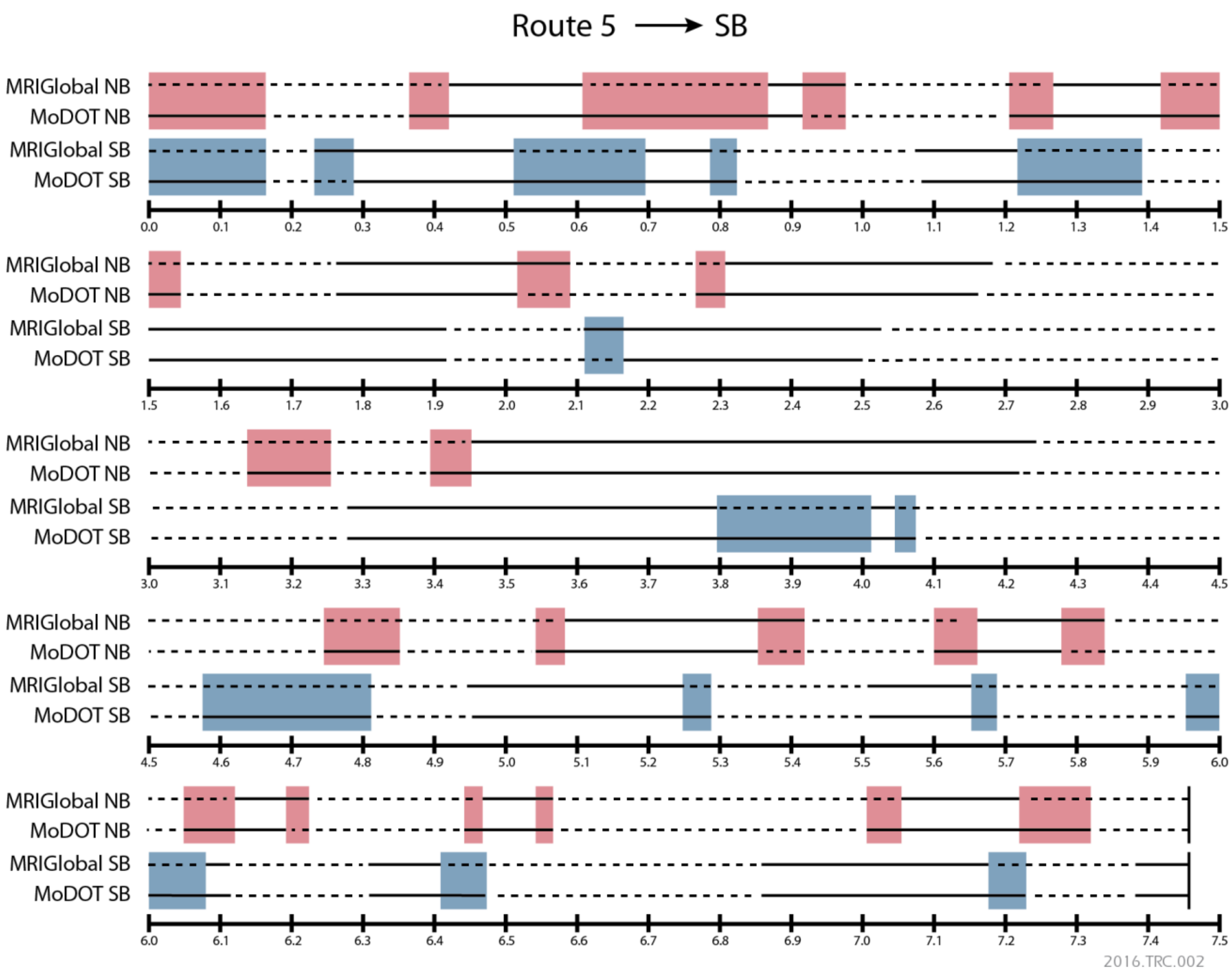

Figure 19. Comparison of existing MoDOT striping and striping recommended by post-processing software for the forward (SB) and reverse (NB) direction of travel on MO 5.

Table 4. Comparison of MRIGlobal results to existing MoDOT striping for Site 2 (Rt B)

Statistic	MRIGlobal NB	MoDOT NB	MRIGlobal SB	MoDOT SB
Number no-passing zones	20	12	18	11
Number passing zones	19	11	18	10
Length no passing (mi)	4.25	5.36	4.42	5.85
Length passing (mi)	3.68	2.57	3.51	2.08
Percent route no passing	53.6	67.6	55.7	73.8
Total length of discrepancy (mi)	1.27		1.47	
Percentage of route discrepancy	15.9		18.4	

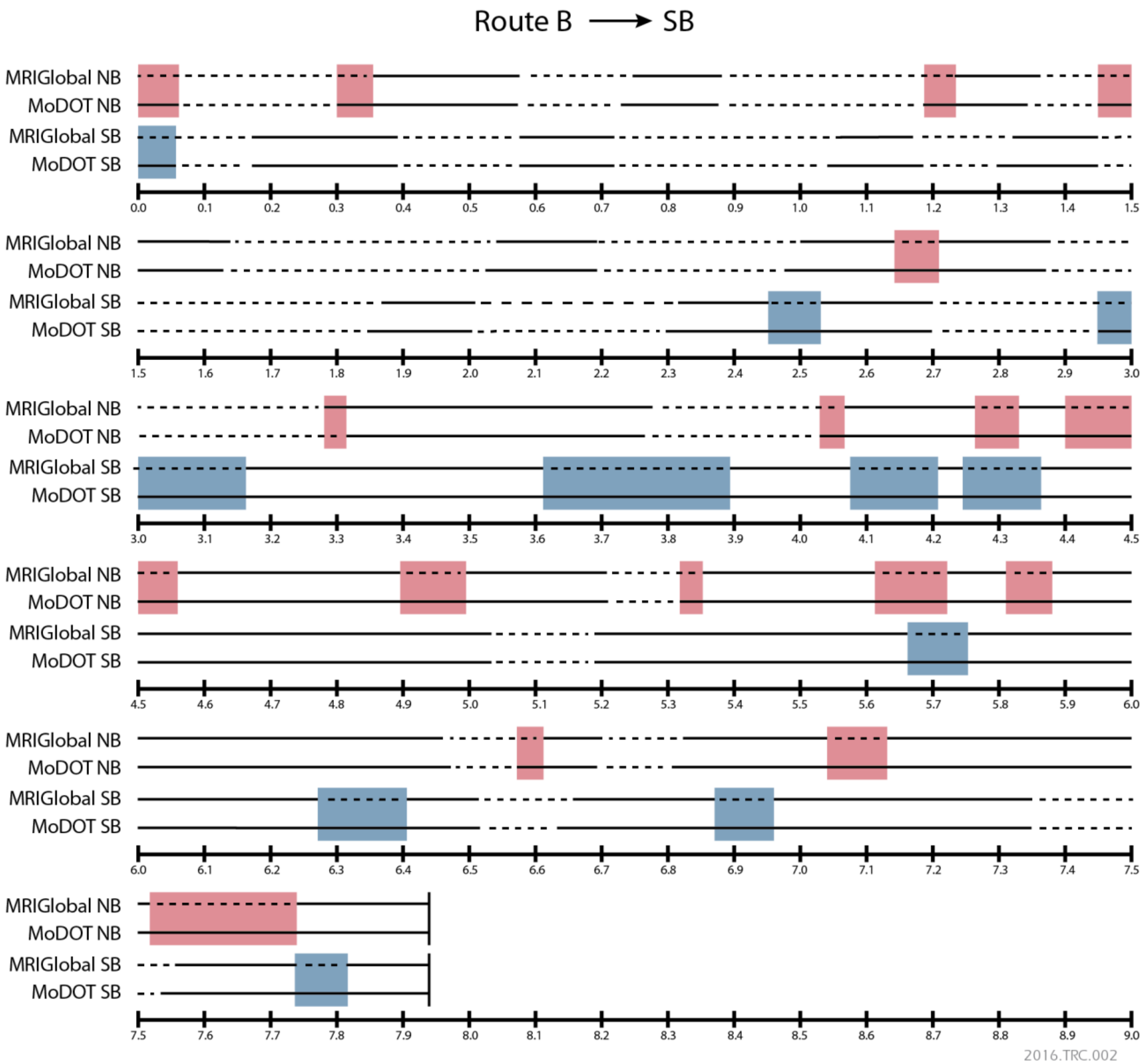

Figure 20. Comparison of existing MoDOT striping and striping recommended by post-processing software for the forward (SB) and reverse (NB) direction of travel on Rt. B.

Statistic	MRIGlobal EB	MoDOT EB	MRIGlobal WB	MoDOT WB
Number no-passing zones	14	13	17	14
Number passing zones	13	12	16	13
Length no passing (mi)	2.55	3.67	2.65	3.57
Length passing (mi)	4.42	3.30	4.32	3.40
Percent route no passing	36.6	52.7	38.0	51.2
Total length of discrepancy (mi)	0.77		1.18	
Percentage of route discrepancy	11.0		16.9	

Table 5. Comparison of MRIGlobal results to existing MoDOT striping for Site 3 (Rt J)

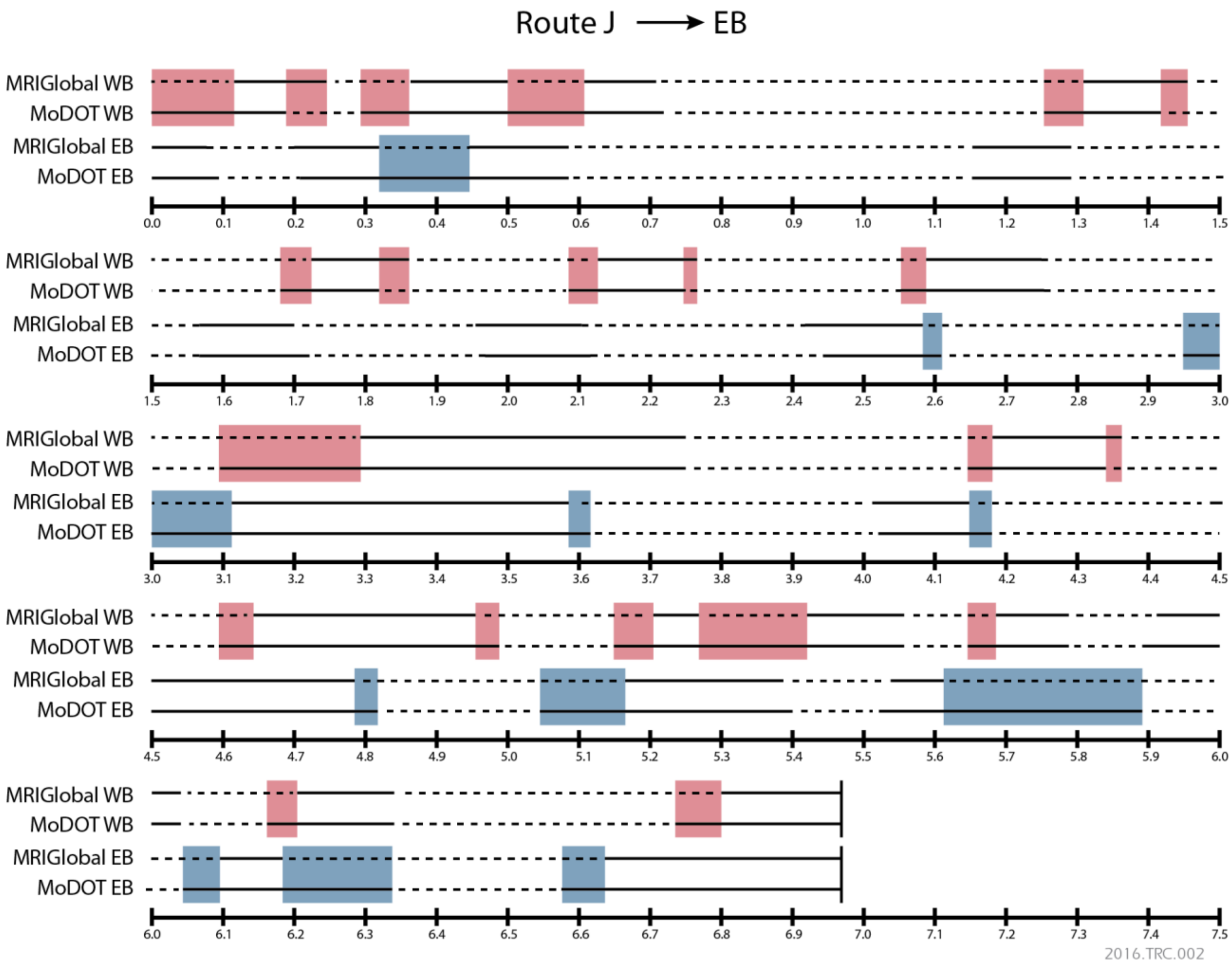

Figure 21. Comparison of existing MoDOT striping and striping recommended by post-processing software for the forward (EB) and reverse (WB) direction of travel on Rt. J.

Table 6. Comparison of MRIGlobal results to existing MoDOT striping for Site 4 (Rt T)

Statistic	MRIGlobal NB	MoDOT NB	MRIGlobal SB	MoDOT SB
Number no-passing zones	8	5	9	4
Number passing zones	7	4	8	3
Length no passing (mi)	3.56	4.1	3.65	3.97
Length passing (mi)	1.36	0.84	1.27	0.97
Percent route no passing	72.4	83.0	74.2	80.4
Total length of discrepancy (mi)	0.62		0.58	
Percentage of route discrepancy	12.6		11.8	

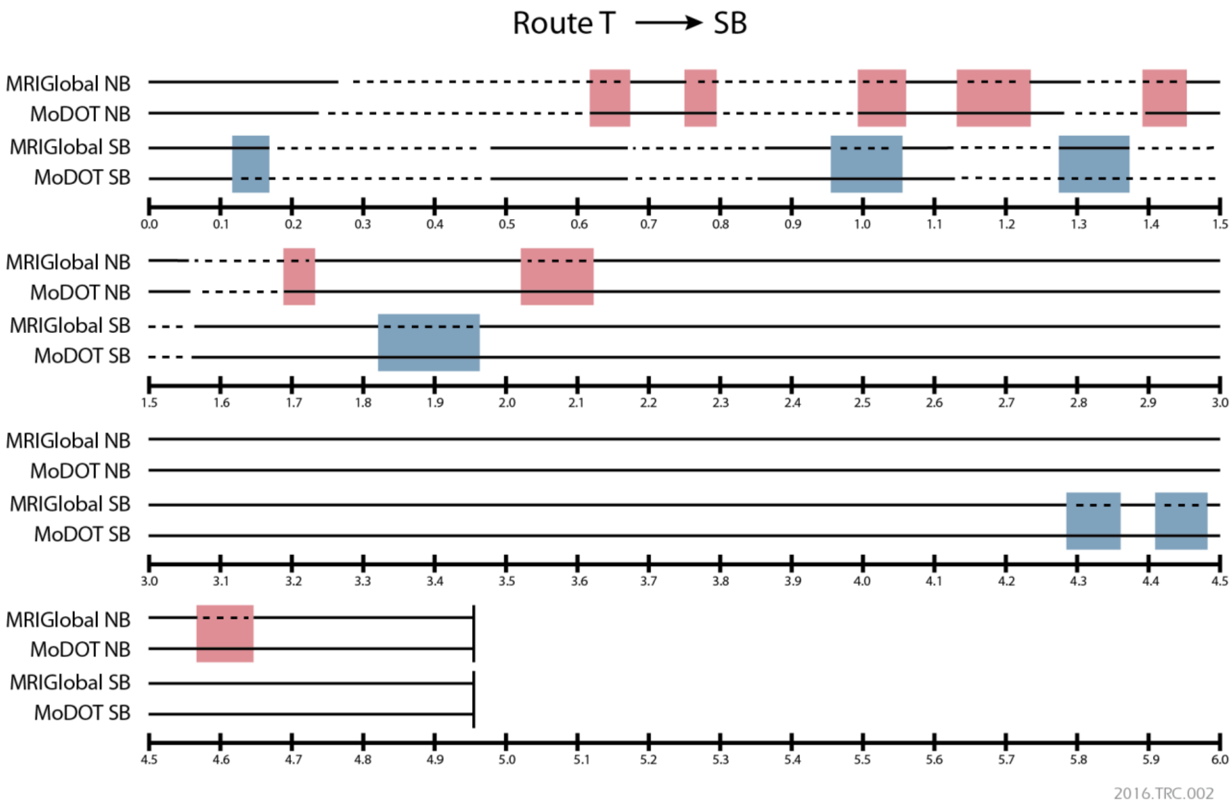

Figure 22. Comparison of existing MoDOT striping and striping recommended by post-processing software for the forward (SB) and reverse (NB) direction of travel on Rt. T.

Table 7. Comparison of MRIGlobal results to existing MoDOT striping for Site 5 (Rt EE)

Statistic	MRIGlobal EB	MoDOT EB	MRIGlobal WB	MoDOT WB
Number no-passing zones	9	9	10	10
Number passing zones	9	8	10	9
Length no passing (mi)	3.71	4.17	3.42	4.14
Length passing (mi)	2.17	1.85	2.46	1.88
Percent route no passing	63.1	69.3	58.2	68.8
Total length of discrepancy (mi)	0.6		0.84	
Percentage of route discrepancy	9.8		13.7	

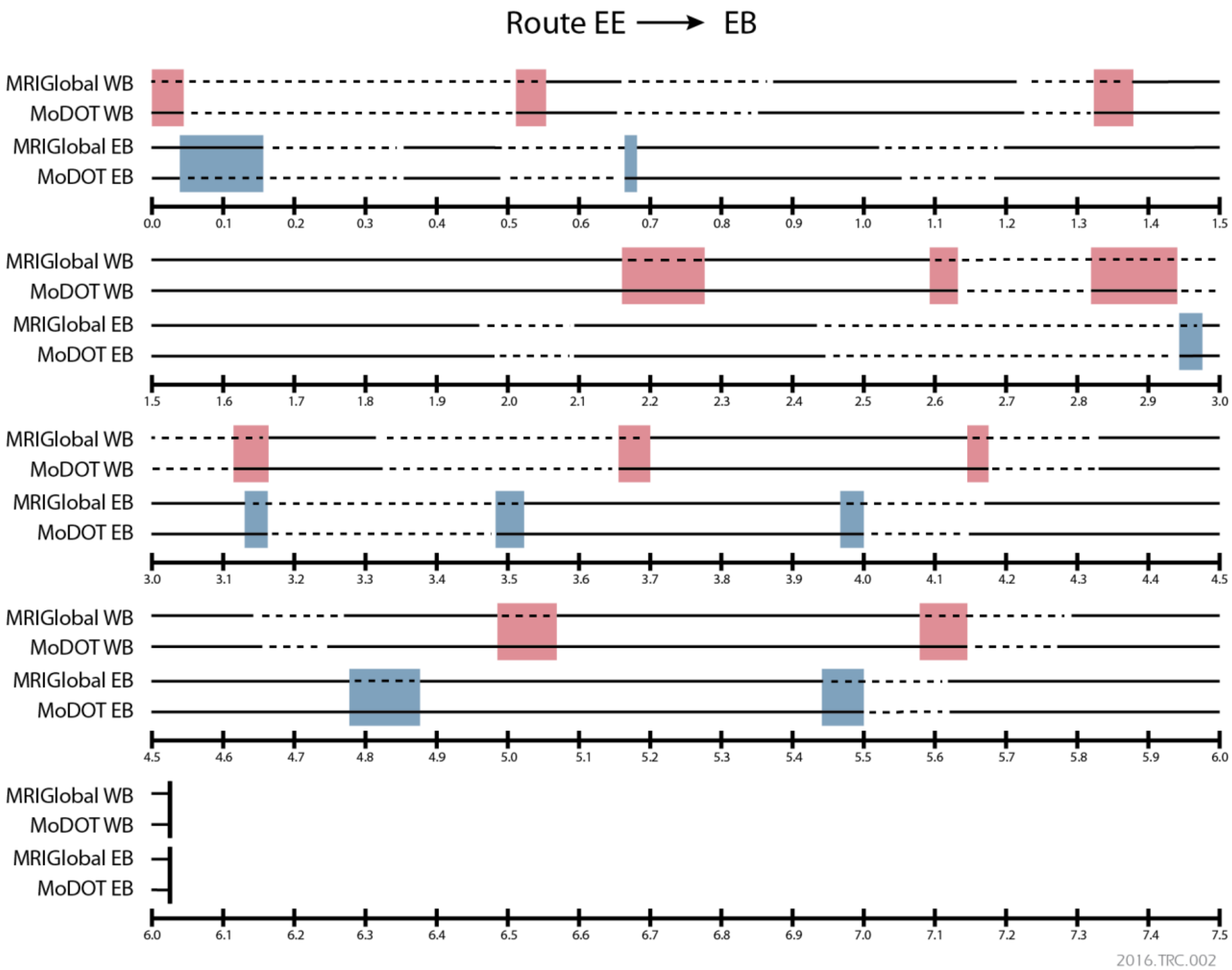

Figure 23. Comparison of existing MoDOT striping and striping recommended by post-processing software for the forward (EB) and reverse (WB) direction of travel on Rt. EE.

Section 7.
Conclusions and Recommendations

7.1 Discussion of Results

The field trials of the no-passing zone system showed that it is functional and able to provide an accurate calculation of the distance between vehicles in real time. Because the system is based on human observations, the accuracy of the data depends on observer reaction time, vehicle speed during the data collection run, and foliage conditions (which can vary throughout the year), as well as the system operator's ability to maintain the desired distance between vehicles.

The system accurately records, to the nearest 0.2 seconds, the time and location where the driver indicates a potential no-passing zone boundary, so the overall accuracy of the recorded no-passing zone boundaries depends on the following driver's ability to maintain the proper distance between vehicles during the data collection run and his or her reaction time in identifying locations where the lead vehicle goes into and out of view.

During the test runs, the drivers focused on minimizing the time the distance between the vehicles fell below the required passing sight distance, since that could result in an indication of passing zones where the full sight distance is not available. Maintaining a slightly longer distance between vehicles than the required passing sight distance results in a more conservative striping plan, in which passing zones may be slightly shorter than necessary. When the distance between vehicles is substantially longer than the required passing sight distance, potential passing zone areas may be shortened unnecessarily, or eliminated completely, which can negatively impact operations on the roadway. The field testing showed that drivers unfamiliar with the route, and with minimal practice using the system, were generally able to stay within 50 ft beyond the passing sight distance.

Test drivers on the research team found that as familiarity with the route improved, the ability to maintain the desired distance between vehicles improved. In addition, with increased practice using the system, it became easier to maintain a constant distance between vehicles. Setting both vehicles' cruise control at a pre-determined speed after the desired spacing was initially achieved helped maintain the desired distance between vehicles during the data collection run. However, even using cruise control, vehicles tend to slow on upgrades and speed up on downgrades. In addition, many horizontal curves must be driven at a much slower speed than the route's posted speed limit. The research team test drivers found that in most cases, the appropriate travel speed for the data collection run was a speed between the posted speed limit and the advisory speed on the sharpest curve along the route. Driving the route at 55 mph was appropriate on routes with only minor vertical and horizontal curves, but in locations where sharp curves substantially changed driving speed over sections of the roadway, it became too difficult for the following driver to anticipate the lead driver's change in speed at these locations and break and accelerate accordingly. At the same time, driving at the lowest advisory speed marked along the route made the tangent sections unnecessarily slow and increased the likelihood that other vehicles on the road would tailgate or pass the following driver at inappropriate locations. While it is impossible to avoid the potential for other vehicles to drive between the two test vehicles, it is helpful to try to minimize the likehood of this situation as much as possible, since vehicles between the lead and following vehicle can interrupt sight lines and make it difficult to determine if the lead vehicle would be visible to the following driver at certain locations along the road. The research team test drivers found that data collection speeds between 40 and 50 mph were appropriate for most routes. In addition, it was helpful to take a "practice" data collection run along the route to identify the places where vehicle speeds would need to be reduced to safely negotiate certain curves. This allows the drivers to be prepared for these speed changes on the second pass through along the roadway.

The comparison of the system's recommended striping plan to MoDOT's current striping log shows that MoDOT's striping is generally more conservative. In general, boundaries between longer passing and no-passing zones correlated very well between the two striping logs. However, in many cases, the research team identified additional locations where passing could be permitted. Many of these additional passing zones were fairly short, although all exceeded the 400-ft minimum identified in the MUTCD. Passing zones as short as 400 ft contribute little to improving traffic operations on a two-lane highway, so MoDOT might consider continuing the no-passing zone marking through such short potential passing zones. Table 3-5 in the AASHTO *Green Book* suggests minimum passing zone lengths to be effective enough for inclusion in traffic operational analyses. Thus, passing zones shorter than the lengths shown in that table can be omitted without any substantial loss in traffic operational efficiency.

MoDOT may also choose not to provide passing zones in other situations, such as near higher volume intersections. The system designed by the research team suggests potential passing zones at every location along the route where minimum passing sight distance is available for more than 400 continuous feet. However, MoDOT has the option to evaluate the recommended striping plan and eliminate suggested passing zones that appear inappropriate if so desired.

7.2 System Limitations

The primary constraint on the accuracy of the passing and no-passing zone boundaries recommended by the post-processing software is the following vehicle driver's ability to maintain a constant distance behind the lead vehicle and to quickly indicate through the switch when the lead vehicle goes out of and comes back into view. These constraints on accuracy are the same as those of the system MoDOT was previously using. However, the new system is able to accurately report the distance between vehicles in real time, allowing the following driver to quickly adjust his or her speed and return to the proper following distance. The two drivers do not need to have any communication during a data collection run, and in fact, the research team test drivers did not use any means of communication during test runs. However, radios or cell phones may be helpful for communication between drivers in situations when the data collection is not going well and either driver feels that it would be better to abort the current data collection run and start it again.

There are a few additional minor limitations of the new system. One is that on very tall crest vertical curves, radio communication between the vehicles may drop out for a short period of time when the vehicles are on either side of the hillcrest. If the GPS data cannot be communicated between vehicles for more than a second or two, the calculation of the distance along the road between the vehicles becomes unreliable and that distance calculation must be reset when communication is restored and when the vehicles are on a tangent section (because on a tangent section, the straight line distance between the vehicles is equivalent to the distance along the roadway between the vehicles).

Areas where radio communication is lost, or where satellite data is lost, create segments along the route where accurate distance between the vehicles is unknown. If passing and no-passing zone boundaries are indicated in a section where the distance between the vehicles was not known (due to radio communication drop-out or satellite data loss in the lead vehicle), but the following vehicle was still recording good GPS data, the location of those boundaries is available in the recorded data, but it is possible that the vehicles were not at the minimum passing sight distance at the time the boundary was indicated. Therefore, the system user would need to evaluate the length of that radio communication drop-out and the distance between the vehicles prior to that loss of data and after that data was regained to make a judgement about whether the boundary locations can be used or whether the data collection should be conducted for that route again.

In areas where GPS data in the following vehicle is lost, the time stamp associated with the passing and no-passing zone boundary is still provided in the data, but the location is not available. This was an extremely rare occurrence during testing runs. Even on cloudy days and in dense foliage, the GPS units were generally able to lock onto enough satellites to provide good location data. The condition that appeared to contribute to GPS data loss was when power to the unit was interrupted. This generally did not happen in the following vehicle, because the unit was powered through the laptop. However, the 12V adapter used to power the GPS and radio through the 12V outlet in the lead vehicle, occasionally dropped power. The connection seemed less stable than desirable, especially over routes with bumpier surface conditions. This limitation could be eliminated by providing an external battery or other power source for the lead vehicle GPS and radio. Power cords with different adapters would need to be wired to these devices.

The system provides an error message to drivers both when GPS data or radio connection is lost and the distance between vehicles cannot be computed (“99999”) and when communication has been reestablished by the distance between vehicles needs to be reset (“11111”). Resetting this distance during the data collection run requires the driver of the following vehicle to push a button on the GUI for the field data collection software during the data collection run. This can be a difficult task for the driver who is still trying to maintain a constant speed and indicate locations where the lead vehicle goes into and out of view. To minimize this additional driver workload, the system could potentially be modified to automatically reset this distance for the driver when communication is re-established. However, if the distance is reset while the vehicles are on a horizontal curve, the software will have no means of correcting for the difference between the straight line distance and the distance along the road between the vehicles. This could introduce a measurement error throughout the remainder of the run. Additional work would be needed to explore options for addressing this and testing them in the field.

7.3 Recommendations for Future Research and System Improvements

The scope of this research was limited by the project timeframe and available resources for developing and testing the system. While the research team has been able to provide MoDOT with a functional system, we believe additional testing would be desirable to confirm system accuracy in a wider range of field situations and could lead to the identification of potential system improvements. Based on the testing conducted as part of this project, recommendations for future potential improvements to the system include the following:

- Modify power cord adaptors in the lead vehicle to connect to a portable battery source, and assess all connections between hardware components for potential improvement. Improving the reliability of the connection of the GPS and radio units to a power source will minimize data dropouts during the data collection runs.
- Improve the features of the switch used by the following driver to identify locations where the lead vehicle goes into and out of view. Consider mounting the switch in an easily accessible location using a touch-screen button on the dash monitor, or incorporating voice-activated commands into the field software.
- Identify hardware and software modifications to minimize the workload for the following driver to the extent possible.
- Explore field data collection software features that could fill in data gaps using previously recorded data and assumptions about vehicle speed and travel path, allowing the following driver to have an approximation of the distance between the two vehicles even when data is unavailable.
- Explore post-processing software features that could approximate the distance between vehicles when no data was available, using information collected before and after the data dropout and route path information available from the lead vehicle GPS data file (if available).
- Add features to the post-processing software to report length of passing and no-passing zones, and provide boundary locations in a log-mile system as well as in latitude and longitude coordinates.
- Add features to the post-processing software to allow users to easily plot boundary locations of passing and no-passing zones onto electronic maps (such as in Google Earth or Google Maps).
- Add feature to the post-processing software to allow the user to set the desired minimum length of passing zones.
- Develop a sleek and efficient system for setting up, breaking down, and storing the system components. This may include shortening excessively long power and connection cords, including devices for winding long cords around retractable spools, identifying light weight cases (one for each vehicles) with dedicated pockets or cutouts for each hardware component.

Section 8.
References

American Association of State Highway Transportation Officials, *A Policy on Geometric Design of Highways and Streets*. 2011.

Azimi, M., and H.G. Hawkins, *Automating the Process for Locating No-Passing Zones Using Georeferencing Data*, Report No. SWUTC/12/161102-1, Texas A&M University System, August 2012.

Brown, R.L., and J.E. Hummer, "Determining the Best Method for Measuring No-Passing Zones," *Transportation Research Record 1701*, Transportation Research Board, 2000.

Harwood, D.W., D.K. Gilmore, K.R. Richard, J.M. Dunn, and C. Sun, *Passing Sight Distance Criteria*, NCHRP Report 605, Transportation Research Board, 2008.

Namala, S.R., and M.J. Rys, *Automated Calculation of Passing Sight Distance Using Global Positioning System Data*, Report No. K-TRAN: KSU-03-2, Kansas State University, July 2006.

Appendix A.
Post-Processing Software Reports for MoDOT Routes on which Testing was Conducted

Table A-1. MO 5

Route	5
Forward Run Direction	S
Reverse Run Direction	N
County Start	Cooper
County End	Cooper
Forward Run Start Time	6/7/2016 10:48
Forward Run Start	Shed
Forward Run End	F
Reverse Run Start Time	6/7/2016 13:52
Reverse Run Start	F
Reverse Run End	Shed
Number of Passing Zones Removed	13

Striping Changes in the Forward Direction					
Latitude	Longitude	Reverse Stripe	Forward Stripe	Range Status	Difference from Acceptability
38.932852	-92.778717	Solid	Solid		
38.929728	-92.779305	Dash	Solid	Following Vehicle Out of Range	-3
38.926718	-92.77953	Solid	Solid	Vehicles Within Acceptable Range	
38.925455	-92.779535	Solid	Dash	Following Vehicle Out of Range	97
38.924262	-92.779588	Dash	Dash	Following Vehicle Out of Range	-9
38.923145	-92.779978	Dash	Solid	Vehicles Within Acceptable Range	
38.921772	-92.781085	Dash	Dash	Following Vehicle Out of Range	-18
38.921102	-92.781735	Solid	Dash	Vehicles Within Acceptable Range	
38.919727	-92.78306	Dash	Dash	Following Vehicle Out of Range	-8
38.918468	-92.78428	Dash	Solid	Following Vehicle Out of Range	-15
38.916882	-92.785807	Dash	Dash	Vehicles Within Acceptable Range	
38.91637	-92.786292	Solid	Dash	Following Vehicle Out of Range	84
38.914692	-92.787917	Dash	Dash	Following Vehicle Out of Range	75
38.913557	-92.789038	Dash	Solid	Vehicles Within Acceptable Range	
38.913427	-92.789132	Solid	Solid	Vehicles Within Acceptable Range	
38.913133	-92.789412	Dash	Solid	Vehicles Within Acceptable Range	
38.910753	-92.792177	Solid	Solid	Following Vehicle Out of Range	-36
38.909232	-92.794285	Solid	Dash	Vehicles Within Acceptable Range	
38.907118	-92.795783	Dash	Dash	Following Vehicle Out of Range	-6
38.90681	-92.795973	Dash	Solid	Following Vehicle Out of Range	19
38.904353	-92.797685	Solid	Solid	Vehicles Within Acceptable Range	
38.902068	-92.80073	Solid	Dash	Vehicles Within Acceptable Range	
38.901055	-92.80329	Dash	Dash	Vehicles Within Acceptable Range	
38.895663	-92.81062	Solid	Dash	Vehicles Within Acceptable Range	
38.895355	-92.810928	Dash	Dash	Vehicles Within Acceptable Range	
38.895138	-92.811165	Dash	Solid	Vehicles Within Acceptable Range	
38.89336	-92.813107	Solid	Solid	Vehicles Within Acceptable Range	
38.889802	-92.817393	Solid	Dash	Following Vehicle Out of Range	-1
38.888347	-92.821762	Solid	Solid	Vehicles Within Acceptable Range	
38.8882	-92.821937	Solid	Dash	Vehicles Within Acceptable Range	
38.885817	-92.823178	Dash	Dash	Vehicles Within Acceptable Range	
38.876408	-92.827195	Dash	Solid	Vehicles Within Acceptable Range	
38.874442	-92.828975	Solid	Solid	Following Vehicle Out of Range	82
38.872673	-92.830632	Solid	Dash	Following Vehicle Out of Range	-9
38.87058	-92.832518	Dash	Dash	Vehicles Within Acceptable Range	
38.869665	-92.833393	Dash	Solid	Following Vehicle Out of Range	-7
38.867895	-92.834948	Dash	Dash	Vehicles Within Acceptable Range	
38.8676	-92.835185	Solid	Dash	Following Vehicle Out of Range	63
38.865297	-92.836207	Dash	Dash	Vehicles Within Acceptable Range	
38.861908	-92.837655	Dash	Solid	Vehicles Within Acceptable Range	
38.861623	-92.837755	Dash	Dash	Vehicles Within Acceptable Range	
38.861542	-92.83779	Solid	Dash	Vehicles Within Acceptable Range	
38.859975	-92.838447	Dash	Dash	Vehicles Within Acceptable Range	
38.858885	-92.838925	Dash	Solid	Vehicles Within Acceptable Range	
38.857338	-92.83956	Dash	Dash	Vehicles Within Acceptable Range	
38.85658	-92.839883	Solid	Dash	Vehicles Within Acceptable Range	
38.855045	-92.840523	Dash	Dash	Following Vehicle Out of Range	-29
38.85118	-92.841305	Dash	Solid	Following Vehicle Out of Range	-28
38.848423	-92.841355	Solid	Solid	Following Vehicle Out of Range	53
38.846405	-92.841672	Solid	Dash	Vehicles Within Acceptable Range	
38.845918	-92.841752	Dash	Dash	Vehicles Within Acceptable Range	
38.843678	-92.842113	Dash	Solid	Following Vehicle Out of Range	-4
38.842733	-92.842273	Solid	Solid	Following Vehicle Out of Range	-63

Table A-2. Route B

Route	B
Forward Run Direction	S
Reverse Run Direction	N
County Start	Cooper
County End	Cooper
Forward Run Start Time	6/7/2016 11:43
Forward Run Start	J
Forward Run End	Moniteau Co Line
Reverse Run Start Time	6/7/2016 11:58
Reverse Run Start	Mon Co Line
Reverse Run End	J
Number of Passing Zones Removed	10

Striping Changes in the Forward Direction					
Latitude	Longitude	Reverse Stripe	Forward Stripe	Range Status	Difference from Acceptability
38.788112	-92.78898	Dash	Solid		
38.787963	-92.780522	Dash	Dash	Following Vehicle Out of Range	-199
38.78596	-92.780577	Dash	Solid	Following Vehicle Out of Range	97
38.783312	-92.78066	Solid	Solid	Vehicles Within Acceptable Range	
38.782662	-92.78068	Solid	Dash	Following Vehicle Out of Range	15
38.78021	-92.78073	Solid	Solid	Following Vehicle Out of Range	-4
38.780013	-92.780733	Dash	Solid	Vehicles Within Acceptable Range	
38.77824	-92.780782	Dash	Dash	Vehicles Within Acceptable Range	
38.777617	-92.780793	Solid	Dash	Vehicles Within Acceptable Range	
38.775653	-92.780837	Dash	Dash	Vehicles Within Acceptable Range	
38.773057	-92.780852	Dash	Solid	Following Vehicle Out of Range	-16
38.771405	-92.780923	Dash	Dash	Vehicles Within Acceptable Range	
38.770612	-92.780948	Solid	Dash	Following Vehicle Out of Range	-3
38.76916	-92.780987	Solid	Solid	Following Vehicle Out of Range	-6
38.768715	-92.780998	Dash	Solid	Vehicles Within Acceptable Range	
38.767312	-92.781035	Dash	Dash	Vehicles Within Acceptable Range	
38.766675	-92.781055	Solid	Dash	Vehicles Within Acceptable Range	
38.764758	-92.781098	Dash	Dash	Following Vehicle Out of Range	-6
38.761357	-92.781178	Dash	Solid	Vehicles Within Acceptable Range	
38.759332	-92.781217	Dash	Dash	Vehicles Within Acceptable Range	
38.758888	-92.781223	Solid	Dash	Following Vehicle Out of Range	68
38.756785	-92.781258	Dash	Dash	Following Vehicle Out of Range	-12
38.754772	-92.781305	Dash	Solid	Following Vehicle Out of Range	-10
38.752978	-92.78144	Dash	Dash	Following Vehicle Out of Range	1
38.75228	-92.78146	Solid	Dash	Vehicles Within Acceptable Range	
38.751697	-92.781477	Solid	Solid	Vehicles Within Acceptable Range	
38.750273	-92.781527	Dash	Solid	Following Vehicle Out of Range	63
38.7493	-92.781553	Dash	Dash	Vehicles Within Acceptable Range	
38.74917	-92.781553	Solid	Dash	Following Vehicle Out of Range	69
38.746723	-92.781525	Dash	Dash	Vehicles Within Acceptable Range	
38.742542	-92.781532	Dash	Solid	Vehicles Within Acceptable Range	
38.740833	-92.781643	Solid	Solid	Following Vehicle Out of Range	-120
38.73897	-92.786247	Solid	Dash	Following Vehicle Out of Range	-12
38.736542	-92.786395	Dash	Dash	Following Vehicle Out of Range	-28
38.734885	-92.786435	Dash	Solid	Following Vehicle Out of Range	-10
38.73234	-92.78654	Solid	Solid	Following Vehicle Out of Range	147
38.732065	-92.786548	Solid	Dash	Following Vehicle Out of Range	69
38.730282	-92.787208	Solid	Solid	Vehicles Within Acceptable Range	
38.729858	-92.787422	Solid	Dash	Following Vehicle Out of Range	-6
38.729645	-92.78752	Dash	Dash	Following Vehicle Out of Range	-17
38.728563	-92.788038	Solid	Dash	Following Vehicle Out of Range	-49
38.728053	-92.788283	Solid	Solid	Following Vehicle Out of Range	-48
38.727542	-92.788513	Dash	Solid	Following Vehicle Out of Range	-30
38.725705	-92.789442	Solid	Solid	Following Vehicle Out of Range	83
38.720908	-92.791403	Dash	Solid	Following Vehicle Out of Range	-53
38.719637	-92.791422	Solid	Solid	Following Vehicle Out of Range	-16
38.719015	-92.791437	Solid	Dash	Vehicles Within Acceptable Range	
38.716803	-92.791482	Solid	Solid	Following Vehicle Out of Range	-4
38.716567	-92.791485	Dash	Solid	Vehicles Within Acceptable Range	
38.714543	-92.791423	Solid	Solid	Following Vehicle Out of Range	-17
38.710773	-92.790347	Dash	Solid	Following Vehicle Out of Range	-25
38.710047	-92.790203	Dash	Dash	Following Vehicle Out of Range	-28
38.709165	-92.790017	Solid	Dash	Vehicles Within Acceptable Range	
38.708768	-92.789935	Solid	Solid	Vehicles Within Acceptable Range	
38.707793	-92.789728	Dash	Solid	Vehicles Within Acceptable Range	
38.706725	-92.789333	Solid	Solid	Following Vehicle Out of Range	-5
38.70153	-92.787022	Solid	Dash	Vehicles Within Acceptable Range	
38.699575	-92.787063	Solid	Solid	Vehicles Within Acceptable Range	

Table A-2. Route B (continued)

			38.69902	-92.78708	Dash	Solid	Following Vehicle Out of Range	-15
			38.69812	-92.7871	Dash	Dash	Vehicles Within Acceptable Range	
			38.696882	-92.787145	Solid	Dash	Vehicles Within Acceptable Range	
			38.69611	-92.787168	Solid	Solid	Vehicles Within Acceptable Range	
			38.695493	-92.787187	Dash	Solid	Vehicles Within Acceptable Range	
			38.693705	-92.78713	Solid	Solid	Following Vehicle Out of Range	-18
			38.693338	-92.786377	Solid	Dash	Following Vehicle Out of Range	54
			38.693285	-92.784805	Solid	Solid	Following Vehicle Out of Range	12
			38.69326	-92.78342	Dash	Solid	Vehicles Within Acceptable Range	
			38.693218	-92.781495	Solid	Solid	Following Vehicle Out of Range	-15
			38.692568	-92.777845	Solid	Dash	Following Vehicle Out of Range	23
			38.69017	-92.77792	Dash	Dash	Vehicles Within Acceptable Range	
			38.689678	-92.777923	Dash	Solid	Following Vehicle Out of Range	-27
			38.687142	-92.777907	Solid	Solid	Vehicles Within Acceptable Range	
			38.687073	-92.77791	Solid	Dash	Vehicles Within Acceptable Range	
			38.685857	-92.777977	Solid	Solid	Vehicles Within Acceptable Range	

Table A-3. Route EE

Route	EE
Forward Run Direction	E
Reverse Run Direction	W
County Start	C
County End	C
Forward Run Start Time	6/7/2016 15:36
Forward Run Start	87
Forward Run End	179
Reverse Run Start Time	6/7/2016 15:47
Reverse Run Start	179
Reverse Run End	87
Number of Passing Zones Removed	9

Striping Changes in the Forward Direction					
Latitude	Longitude	Reverse Stripe	Forward Stripe	Range Status	Difference from Acceptability
38.815052	-92.590583	Dash	Dash		
38.818193	-92.590497	Dash	Solid	Following Vehicle Out of Range	-4
38.819737	-92.590447	Dash	Dash	Vehicles Within Acceptable Range	
38.820782	-92.590415	Solid	Dash	Following Vehicle Out of Range	59
38.822257	-92.590372	Dash	Dash	Vehicles Within Acceptable Range	
38.822785	-92.590355	Dash	Solid	Following Vehicle Out of Range	-1
38.825348	-92.590192	Solid	Solid	Vehicles Within Acceptable Range	
38.825795	-92.587285	Solid	Dash	Following Vehicle Out of Range	-27
38.825652	-92.584222	Solid	Solid	Vehicles Within Acceptable Range	
38.82564	-92.583912	Dash	Solid	Following Vehicle Out of Range	-4
38.825507	-92.580928	Solid	Solid	Vehicles Within Acceptable Range	
38.828953	-92.571673	Solid	Dash	Following Vehicle Out of Range	-9
38.830772	-92.571558	Solid	Solid	Following Vehicle Out of Range	-26
38.831457	-92.571538	Dash	Solid	Following Vehicle Out of Range	-24
38.833288	-92.571495	Solid	Solid	Vehicles Within Acceptable Range	
38.835352	-92.571435	Solid	Dash	Following Vehicle Out of Range	11
38.837832	-92.571357	Dash	Dash	Vehicles Within Acceptable Range	
38.843538	-92.571183	Dash	Solid	Vehicles Within Acceptable Range	
38.845665	-92.571112	Dash	Dash	Vehicles Within Acceptable Range	
38.846138	-92.571093	Solid	Dash	Vehicles Within Acceptable Range	
38.848328	-92.571033	Dash	Dash	Vehicles Within Acceptable Range	
38.851322	-92.570963	Dash	Solid	Vehicles Within Acceptable Range	
38.853887	-92.570748	Solid	Solid	Vehicles Within Acceptable Range	
38.854288	-92.566373	Solid	Dash	Vehicles Within Acceptable Range	
38.856202	-92.563652	Dash	Dash	Following Vehicle Out of Range	-10
38.85638	-92.563385	Dash	Solid	Following Vehicle Out of Range	-10
38.858047	-92.561085	Solid	Solid	Following Vehicle Out of Range	-24
38.857853	-92.555527	Dash	Solid	Following Vehicle Out of Range	-3
38.857403	-92.55315	Solid	Solid	Vehicles Within Acceptable Range	
38.857353	-92.552892	Solid	Dash	Vehicles Within Acceptable Range	
38.857193	-92.551197	Solid	Solid	Vehicles Within Acceptable Range	
38.85711	-92.549115	Dash	Solid	Vehicles Within Acceptable Range	
38.857075	-92.547685	Solid	Solid	Vehicles Within Acceptable Range	
38.859112	-92.541498	Solid	Dash	Following Vehicle Out of Range	n/a
38.85951	-92.538847	Dash	Dash	Vehicles Within Acceptable Range	
38.85963	-92.538163	Dash	Solid	Vehicles Within Acceptable Range	
38.860138	-92.534803	Solid	Solid	Following Vehicle Out of Range	53

Table A-4. Route J

Route	J
Forward Run Direction	E
Reverse Run Direction	W
County Start	Cooper
County End	Cooper
Forward Run Start Time	6/7/2016 11:08
Forward Run Start	B
Forward Run End	O
Reverse Run Start Time	6/7/2016 11:29
Reverse Run Start	O
Reverse Run End	B
Number of Passing Zones Removed	6

Striping Changes in the Forward Direction					
Latitude	Longitude	Reverse Stripe	Forward Stripe	Range Status	Difference from Acceptability
38.79584	-92.85586	Solid	Solid		
38.78818	-92.78355	Solid	Dash	Vehicles Within Acceptable Range	
38.78817	-92.78166	Solid	Solid	Vehicles Within Acceptable Range	
38.78817	-92.78027	Dash	Solid	Vehicles Within Acceptable Range	
38.78817	-92.77942	Dash	Dash	Vehicles Within Acceptable Range	
38.78817	-92.77871	Solid	Dash	Vehicles Within Acceptable Range	
38.78818	-92.77685	Solid	Solid	Following Vehicle Out of Range	-34
38.78818	-92.77624	Dash	Solid	Following Vehicle Out of Range	-18
38.7882	-92.7746	Dash	Dash	Vehicles Within Acceptable Range	
38.7882	-92.77396	Solid	Dash	Vehicles Within Acceptable Range	
38.78818	-92.77252	Solid	Solid	Vehicles Within Acceptable Range	
38.78818	-92.77138	Dash	Solid	Vehicles Within Acceptable Range	
38.78817	-92.76974	Dash	Dash	Vehicles Within Acceptable Range	
38.78817	-92.7693	Solid	Dash	Vehicles Within Acceptable Range	
38.78818	-92.76746	Dash	Dash	Vehicles Within Acceptable Range	
38.78822	-92.75952	Dash	Solid	Vehicles Within Acceptable Range	
38.78825	-92.75696	Dash	Dash	Vehicles Within Acceptable Range	
38.78826	-92.75638	Solid	Dash	Vehicles Within Acceptable Range	
38.78829	-92.75377	Dash	Dash	Vehicles Within Acceptable Range	
38.78831	-92.75142	Dash	Solid	Vehicles Within Acceptable Range	
38.78833	-92.74907	Dash	Dash	Vehicles Within Acceptable Range	
38.78834	-92.7486	Solid	Dash	Vehicles Within Acceptable Range	
38.78836	-92.74607	Dash	Dash	Vehicles Within Acceptable Range	
38.78838	-92.74427	Dash	Solid	Vehicles Within Acceptable Range	
38.7884	-92.74167	Dash	Dash	Vehicles Within Acceptable Range	
38.7884	-92.74126	Solid	Dash	Following Vehicle Out of Range	-8
38.78844	-92.73844	Dash	Dash	Following Vehicle Out of Range	-5
38.78848	-92.7356	Dash	Solid	Vehicles Within Acceptable Range	
38.78852	-92.73262	Dash	Dash	Vehicles Within Acceptable Range	
38.78852	-92.73247	Solid	Dash	Vehicles Within Acceptable Range	
38.78854	-92.72947	Dash	Dash	Vehicles Within Acceptable Range	
38.78856	-92.72295	Dash	Solid	Vehicles Within Acceptable Range	
38.78823	-92.71954	Solid	Solid	Following Vehicle Out of Range	-5
38.78711	-92.71457	Solid	Dash	Vehicles Within Acceptable Range	
38.78701	-92.71131	Dash	Dash	Vehicles Within Acceptable Range	
38.78684	-92.70646	Dash	Solid	Following Vehicle Out of Range	-23
38.78673	-92.70397	Dash	Dash	Vehicles Within Acceptable Range	
38.78671	-92.7034	Solid	Dash	Vehicles Within Acceptable Range	
38.78658	-92.70007	Dash	Dash	Following Vehicle Out of Range	-4
38.78649	-92.69783	Dash	Solid	Vehicles Within Acceptable Range	
38.78637	-92.69465	Solid	Solid	Following Vehicle Out of Range	63
38.78624	-92.6922	Solid	Dash	Vehicles Within Acceptable Range	
38.7861	-92.68901	Dash	Dash	Vehicles Within Acceptable Range	
38.78596	-92.6851	Dash	Solid	Following Vehicle Out of Range	n/a
38.786	-92.68445	Solid	Solid	Vehicles Within Acceptable Range	
38.78606	-92.68332	Dash	Solid	Vehicles Within Acceptable Range	
38.786	-92.68098	Dash	Dash	Following Vehicle Out of Range	n/a
38.78598	-92.68053	Solid	Dash	Following Vehicle Out of Range	56
38.78587	-92.67817	Solid	Solid	Following Vehicle Out of Range	n/a
38.78586	-92.67793	Dash	Solid	Vehicles Within Acceptable Range	
38.7858	-92.67673	Dash	Dash	Following Vehicle Out of Range	n/a
38.78575	-92.67552	Solid	Dash	Vehicles Within Acceptable Range	
38.78567	-92.67366	Dash	Dash	Vehicles Within Acceptable Range	
38.78556	-92.67139	Solid	Dash	Following Vehicle Out of Range	-9
38.78543	-92.669	Dash	Dash	Following Vehicle Out of Range	-3
38.78537	-92.66798	Dash	Solid	Vehicles Within Acceptable Range	
38.78528	-92.66632	Dash	Dash	Following Vehicle Out of Range	29
38.78526	-92.66592	Solid	Dash	Vehicles Within Acceptable Range	
38.78515	-92.66358	Dash	Dash	Vehicles Within Acceptable Range	
38.7849	-92.65803	Dash	Solid	Following Vehicle Out of Range	-1
38.78476	-92.65498	Solid	Solid	Following Vehicle Out of Range	-9
38.78632	-92.65136	Dash	Solid	Vehicles Within Acceptable Range	
38.78797	-92.65134	Solid	Solid	Following Vehicle Out of Range	151

Table A-5. Route T

Route	T
Forward Run Direction	S
Reverse Run Direction	N
County Start	Cooper
County End	Cooper
Forward Run Start Time	6/7/2016 12:17
Forward Run Start	B
Forward Run End	Mnt End
Reverse Run Start Time	6/7/2016 12:27
Reverse Run Start	Mnt End
Reverse Run End	B
Number of Passing Zones Removed	12

Striping Changes in the Forward Direction					
Latitude	Longitude	Reverse Stripe	Forward Stripe	Range Status	Difference from Acceptability
38.788053	-92.74238	Solid	Solid		
38.786365	-92.74236	Solid	Dash	Following Vehicle Out of Range	-256
38.784637	-92.74239	Dash	Dash	Following Vehicle Out of Range	-10
38.781377	-92.74246	Dash	Solid	Vehicles Within Acceptable Range	
38.778903	-92.74251	Dash	Dash	Following Vehicle Out of Range	-30
38.77861	-92.74252	Solid	Dash	Vehicles Within Acceptable Range	
38.77749	-92.74255	Dash	Dash	Vehicles Within Acceptable Range	
38.77574	-92.7426	Dash	Solid	Vehicles Within Acceptable Range	
38.77449	-92.74263	Dash	Dash	Vehicles Within Acceptable Range	
38.773193	-92.74268	Dash	Solid	Following Vehicle Out of Range	32
38.773112	-92.74268	Solid	Solid	Vehicles Within Acceptable Range	
38.77219	-92.74272	Solid	Dash	Following Vehicle Out of Range	23
38.772058	-92.74273	Dash	Dash	Vehicles Within Acceptable Range	
38.770538	-92.74278	Solid	Dash	Following Vehicle Out of Range	-4
38.76992	-92.7428	Solid	Solid	Vehicles Within Acceptable Range	
38.76963	-92.74281	Dash	Solid	Vehicles Within Acceptable Range	
38.768505	-92.74285	Dash	Dash	Vehicles Within Acceptable Range	
38.76732	-92.74289	Solid	Dash	Following Vehicle Out of Range	-1
38.765942	-92.74293	Dash	Solid	Following Vehicle Out of Range	-13
38.763402	-92.743	Solid	Solid	Vehicles Within Acceptable Range	
38.761822	-92.74305	Solid	Dash	Vehicles Within Acceptable Range	
38.760197	-92.74308	Solid	Solid	Following Vehicle Out of Range	-1
38.759213	-92.74311	Dash	Solid	Following Vehicle Out of Range	58
38.757632	-92.74314	Solid	Solid	Following Vehicle Out of Range	65
38.739662	-92.72179	Solid	Dash	Following Vehicle Out of Range	-30
38.738473	-92.72173	Solid	Solid	Following Vehicle Out of Range	-82
38.737792	-92.72178	Solid	Dash	Following Vehicle Out of Range	-91
38.736627	-92.72185	Solid	Solid	Following Vehicle Out of Range	-58
38.735637	-92.7219	Dash	Solid	Following Vehicle Out of Range	-81
38.734353	-92.72195	Solid	Solid	Following Vehicle Out of Range	-134