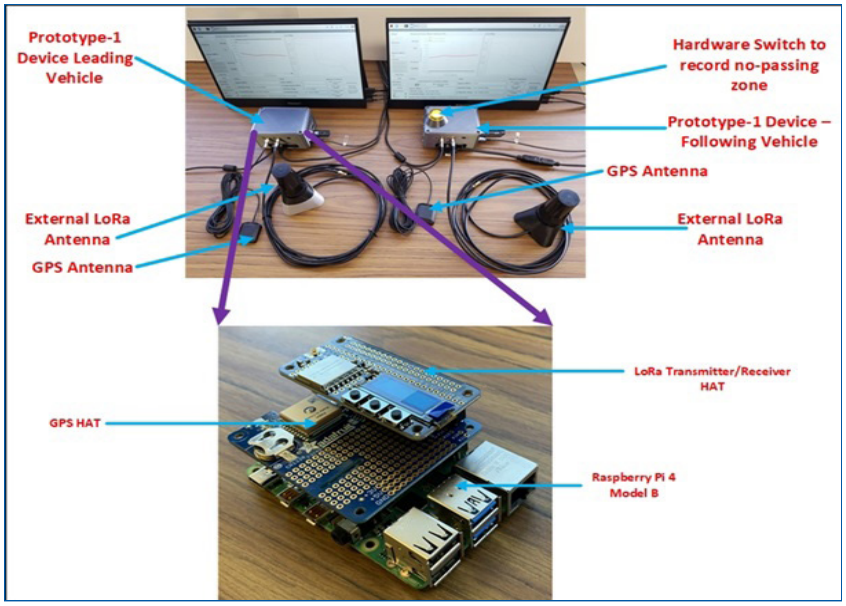
MOUNTAIN-PLAINS CONSORTIUM

MPC 24-535 | A. Farid, Z. Connell, J. Mock, S. Muknahallipatna, and K. Ksaibati

DEVELOPING PROTOTYPE SYSTEMS FOR ESTABLISHING TWO-LANE HIGHWAY PASSING AND NO-PASSING ZONES



A University Transportation Center sponsored by the U.S. Department of Transportation serving the Mountain-Plains Region. Consortium members:

Colorado State University
North Dakota State University
South Dakota State University
University of Colorado Denver
University of Denver
University of Utah
Utah State University
University of Wyoming

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
MPC-600		

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code
Developing a Prototype System for Establishing Passing and No-Passing Zones of Two-Lane Highways	5. Report Date: July 2024 6. Performing Organization Code:
7. Author(s) Ahmed Farid, Zephaniah Connell, James Mock, Suresh Muknahallipatna, and Khaled Ksaibati	8. Performing Organization Report No. MPC 24-535
9. Performing Organization Name and Address Department of Civil & Architectural Engineering Wyoming Technology Transfer Center University of Wyoming 1000 E. University Avenue, Dept. 3295 Laramie, Wyoming 82071 Department of Electrical and Computer Engineering University of Wyoming 1000 E. University Avenue, Dept. 3295 Laramie, Wyoming 82071	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Mountain-Plains Consortium North Dakota State University PO Box 6050, Fargo, ND 58108	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

Supported by a grant from the US DOT, University Transportation Centers Program
Supported by a grant from WYDOT RS02219

16. Abstract

Two-lane highways comprise a considerable percentage of the nation’s roads. A critical component required in the design of two-lane highways is the passing sight distance (PSD). In cases where it is inadequate, no-passing zones are established. There are multiple techniques employed for measuring the PSD in the field, and the Wyoming Department of Transportation (WYDOT) implements the two-vehicle method. However, WYDOT’s apparatus used to implement the method is no longer functional. Hence, this project was aimed at proposing two state-of-the-art prototypes of the two-vehicle method, and the first prototype, named Prototype 1, was replicated. The second prototype, Prototype 2, was designed to automate some of the functions of Prototype 1 by incorporating advanced intelligent transportation system devices. After the delivery of Prototype 1’s units and that of the latter to WYDOT, the former’s units were retrieved and upgraded such that their functionalities were similar to that of Prototype 2. As per the results of the testing of both prototypes, the equipment was not only efficient but also produced accurate results.

17. Key Word	18. Distribution Statement
Two-Lane Highways, Passing Sight Distance, Passing Zone, No-Passing Zone, Two-Vehicle Method, Intelligent Transportation Systems	Public distribution

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	63	n/a

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

DEVELOPING PROTOTYPE SYSTEMS FOR ESTABLISHING TWO-LANE HIGHWAY PASSING AND NO-PASSING ZONES

Dr. Ahmed Farid[1]
Zephaniah Connell[2]
James Mock[2]
Dr. Suresh Muknahallipatna[2]
Dr. Khaled Ksaibati[3]

[1]Department of Civil & Environmental Engineering
California Polytechnic State University
[2]Department of Electrical and Computer Engineering
University of Wyoming
[3]Wyoming Technology Transfer Center
University of Wyoming

July 2024

Acknowledgements

The authors thank the Wyoming Department of Transportation (WYDOT) and the Mountain-Plains Consortium (MPC) for funding this research

Disclaimer

ABSTRACT

Two-lane highways comprise a considerable percentage of the nation's roads. A critical component required in the design of two-lane highways is the passing sight distance (PSD). In cases where it is inadequate, no-passing zones are established. There are multiple techniques employed for measuring the PSD in the field, and the Wyoming Department of Transportation (WYDOT) implements the two-vehicle method. However, WYDOT's apparatus used to implement the method is no longer functional. Hence, this project was aimed at proposing two state-of-the-art prototypes of the two-vehicle method and the first prototype, named Prototype 1, was replicated. The second prototype, Prototype 2, was designed to automate some of the functions of Prototype 1 by incorporating advanced intelligent transportation system devices. After the delivery of Prototype 1's units and that of the latter to WYDOT, the former's units were retrieved and upgraded such that their functionalities were similar to that of Prototype 2. As per the results of the testing of both prototypes, the equipment was not only efficient but also produced accurate results.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

The passing sight distance (PSD) is a critical element required in the design of two-lane highways. Prior to passing, drivers should observe the opposing lane for a distance equivalent to the PSD to ensure that they could safely execute the overtaking maneuver. The PSD may be restricted by sight obstructions, such as buildings, vegetation, or hills around horizontal curves. In cases where the PSD is insufficient, passing-related crashes could occur. Restricted PSDs warrant the designation of no-passing zones, represented by solid yellow lines, or passing lanes.

This project was aimed at establishing passing/no-passing zones in the field according to the minimum required PSD. There are several methods for ascertaining the PSD in the field, and the Wyoming Department of Transportation (WYDOT) implements the two-vehicle method. The Range Tracker System used by WYDOT became nonfunctional due to its outdated Microsoft Disk Operating System (MS-DOS), and the manufacturer's discontinuation of the apparatus production. Therefore, the focus of this project was to develop two advanced prototypes of the two-vehicle method with cutting-edge intelligent transportation system (ITS) technologies for WYDOT's use.

In particular, Prototype 1 is a functional prototype developed, tested, and delivered to WYDOT to replace the Range Tracker System. Prototype 2 was designed to automate some of the functions of Prototype 1 and produce more accurate results as well.

The functions and components of Prototype 1 are as follows:

- Vehicle-to-vehicle (V2V) communication via wireless long range (LoRa) or the Institute of Electrical and Electronics Engineers' (IEEE's) 802.1p customs.
- Estimation of the PSD using the Global Positioning System (GPS) and speed data collected from both vehicles
- The switch needed to signal whether the lead vehicle is obscured behind sight obstructions, setting the beginning point of the no-passing zone, or visible after being out of view, setting the ending point of the no-passing zone with the use of the GPS devices

Prototype 1 was developed and tested on a section of WY-210 and another belonging to US-287. The no-passing zone plans outputted by the prototype and WYDOT's were compared. As per the comparison results, overall discrepancies of 3.1% and 7% were obtained for the eastbound and westbound lanes of WY-210's test section, respectively. Prototype 2 was developed by incorporating a fusion of two algorithms to automatically detect the beginning and end of the NPZ and record the GPS techniques. The two algorithms used terrain maps, GPS coordinates, and a computer vision device (CVD) to record the lead vehicle image and detect the NPZ offline continuously. Prototype 2 was designed in a way that, instead of operating the switch, the following vehicle was equipped with video cameras having machine vision systems that automatically detect the change in the lead vehicle's visibility status and hence the no-passing zone boundaries.

With multiple units of the state-of-the-art prototypes, WYDOT, counties, and local jurisdictions in Wyoming, such as the Wind River Indian Reservation, could continuously conduct their two-lane highway striping/re-striping operations without experiencing the difficulty arising from an equipment shortage. Also, WYDOT and local government agencies would be protected from liability when passing-related crashes occur.

1. INTRODUCTION

The passing sight distance (PSD) is a critical element required in two-lane highway design. A typical two-lane highway is shown in Figure 1.1. While driving on two-lane highways, drivers have to utilize the opposing traffic lane in order to pass slower-moving vehicles safely. Prior to passing, drivers should observe the opposing lane for a distance equivalent to the PSD to ensure that they safely execute the overtaking maneuver.

Figure 1.1 Two-lane highway**.** Source: (*1*)

The PSD is gauged from the driver's eye height, 3.5 ft from the road surface to another spot 3.5 ft from the surface as well (*2*, *3*). The PSD may be restricted by sight obstructions, such as buildings, vegetation, or hills around horizontal curves. Other obstructions include crest vertical curves or other structures (*4*). In cases where the PSD is insufficient, passing-related crashes could occur. Restricted PSDs warrant the designation of no-passing zones, represented by solid yellow lines, or passing lanes.

This project was aimed at establishing passing/no-passing zones in the field according to the minimum required PSD. The minimum PSD is strongly dependent on the roadway's posted speed limit. There are several methods for ascertaining the PSD in the field, and the Wyoming Department of Transportation (WYDOT) implements the two-vehicle method. Yet, their apparatus used to implement the method, the Range Tracker System, is no longer functional. Its operating system, the outdated Microsoft Disk Operating System (MS-DOS), ceased functioning properly and, regrettably, private firms did not manufacture a replacement apparatus. Therefore, the focus of this project was to develop two advanced prototypes of the two-vehicle method with cutting-edge intelligent transportation system (ITS) technologies. As per WYDOT, there are more than 29,000 miles of two-lane highways in Wyoming, which mainly pertain to those of state and national roads. WYDOT should continually re-evaluate those highways' passing/no-passing zone striping plans and establish such plans for new two-lane highways. The zone striping plans might fluctuate throughout the years due to changes in the minimum required PSD. With that, changes in the PSD could be a result of speed limit corrections, highway restructuring, crash experiences, building construction near horizontal curves restricting the PSD, vegetation growth near horizontal curves demarcating the PSD, and grievances from residents. PSD changes not only prompt the restriping of two-lane highways but also the re-positioning of signs. This contributes to construction costs. Hence, it is imperative that the developed prototypes used to establish passing/no-passing zone plans be accurate.

1.1 Objective

This study's objective is to develop two accurate, economical, long-lasting prototypes of the two-vehicle method (Prototypes 1 and 2) with state-of-the-art ITS equipment. In addition, a Quick Start Guide was outlined to train and educate the designated personnel. In particular, Prototype 1 was a functional prototype developed, tested, and delivered to WYDOT to replace the Range Tracker System. Multiple units of Prototype 1 were reproduced. Prototype 2 was designed to automate some of the functions of Prototype 1 and produce more accurate results as well. Once developed, tested, and provided to WYDOT, the Prototype 1 units were retrieved, upgraded to mimic the functionalities of Prototype 2, and re-delivered to WYDOT. With multiple units of the state-of-the-art prototypes, WYDOT, counties, and local jurisdictions in Wyoming, such as the Wind River Indian Reservation, could continuously conduct their two-lane highway striping/re-striping operations without experiencing the difficulty arising from an equipment shortage. Also, WYDOT and local government agencies would be protected from liability when passing-related crashes occur.

This report is organized as follows. Chapter 2 entails discussions of essential background information, while Chapter 3 describes Prototype 1's development, testing, replication, and delivery to WYDOT. Chapter 4 covers the development and testing of Prototype 2. Chapter 5 summarizes miscellaneous studies related to this project. Finally, Chapter 6 encompasses this project's conclusion and recommendations.

2. BACKGROUND

This chapter discusses the different PSD mathematical kinematics models developed and the PSD criteria for establishing the passing/no-passing zones. Note that there are other criteria for establishing such zones apart from the PSD, such as the proximity to intersections. Those criteria are discussed as well. The various methods implemented for measuring the PSD and documented studies that involve gauging of the PSD are covered in this chapter as well.

2.1 Passing Sight Distance Kinematics Models

Since the establishment of passing/no-passing zones are greatly dependent on the PSD, this section entails a summary of the previously proposed PSD mathematical kinematics models. Harwood et al. (2008) provided a review of previous studies involving the proposition of those models (*5–15*). An essential component that should be considered in ascertaining the PSD is the critical position concept. It is defined as the condition at which the passing vehicle is traveling adjacent to the overtaken vehicle and unable to back out from completing the overtaking maneuver (*16*). The most accurate models are those of Glennon (1988) and Hassan et al. (1996) since they account for the critical position (*6*, *8*). In the other studies, either the critical position concept was not accommodated, or erroneous assumptions were made regarding the PSD. The Glennon (1988) and Hassan et al. (1996) models yield PSD values that are in line with those of the American Association of State Highway and Transportation Officials' (AASHTO) Green Book and the Manual on Uniform Traffic Control Devices (MUTCD) (*2*, *4*). Yet, the Hassan et al. (1996) model produces exceedingly large estimates of the PSD for high-speed two-lane highways (*8*). Note that the WYDOT pavement marking manual's guidelines concerning two-lane highways (WYDOT Traffic Program, 2012) are consistent with those of the MUTCD (*2*, *3*).

2.2 Local Passing Sight Distance Standards

The minimum required PSD is dependent on the posted speed limit. As per the WYDOT pavement marking manual (WYDOT Traffic Program, 2012), the minimum PSDs are listed in Table 2.1.

For 65-mph roads, the minimum required PSD is 1,200 ft instead of 1,100 ft since it is assumed that the traffic could be light, prompting drivers to exceed the speed limit (*3*). However, as per WYDOT, an even more conservative value of 1,300 ft may be used for such roads. In cases where the available PSD is less than the minimum required PSD, a no-passing zone should be established. As previously stated, the PSD is measured 3.5 ft from the ground surface, representing the driver's eye height, to another point 3.5 ft from the surface as well.

Other than the PSD, care should be exercised to avoid having short passing zones between no-passing zones. Hence, road sections between successive no-passing zones that are shorter than those listed in Table 2.2 are designated as no-passing zones.

Table 2.1 Minimum Passing Sight Distances by Posted Speed Limit

Posted Speed Limit (mph)	Minimum Passing Sight Distance (ft)
25	450
30	500
35	550
40	600
45	700
50	800
55	900
60	1,000
65	1,200
70	1,200

Source: Wyoming Department of Transportation Traffic Program (2012)

Table 2.2 Minimum Road Section Lengths between No-Passing Zones

Posted Speed Limit (mph)	Road Section Length (ft)
25	280
30	320
35	370
40	410
45	500
50	550
55	650
60	700
65	850
70	850

Source: Wyoming Department of Transportation Traffic Program (2012)

It is possible that no-passing zones are too short, cuing drivers to flout the no-passing zone markings. In such cases, the no-passing zones may be extended or eliminated. The maximum no-passing zone lengths, at or below when eliminating the no-passing zones is warranted, are presented in Table 2.3.

Table 2.3 Maximum No-Passing Zone Lengths for Omitting No-Passing Zones

Posted Speed Limit (mph)	Maximum No-Passing Zone Length (ft)
25	75
30	90
35	105
40	120
45	135
50	150
55	165
60	180
65	195
70	210

Source: Wyoming Department of Transportation Traffic Program (2012)

There are different guidelines for opting to extend no-passing zones that are shorter than the ones listed in Table 2.3. For road sections with posted speed limits of 45 mph or higher and no-passing zone lengths that are shorter than those presented in Table 2.3, the no-passing zone lengths are lengthened to 500 ft. The supplementary length is appended to the beginning point of the no-passing zone (*3*). For road sections with posted speed limits of 40 mph or less and no-passing zones that are shorter than the ones listed in Table 2.3, the no-passing zones need not be elongated to 500 ft. Instead, 25-mph sections, 30-mph sections, 35-mph sections, and 40-mph sections are extended to 280 ft, 320 ft, 370 ft, and 410 ft, respectively. The added lengths adjoin the beginning point of the no-passing zone (*3*). If, on the other hand, the no-passing zone is to be discarded since its short length warrants, a field evaluation should be conducted to justify this decision (*3*).

2.3 Other Local Standards Governing Passing and No-Passing Zones

The PSD is not the only vital criterion needed in the designation of passing and no-passing zones. Other essential criteria include special locations—which are sections with passing lanes—locations characterized by transitions into or out of four-lane sections, sections with centerline channelization such as that shown in Figure 2.1, intersections, interchange ramps, railroad crossings, and other sections that warrant the designation of no-passing zones as per the discretion of the district traffic engineer (*3*).

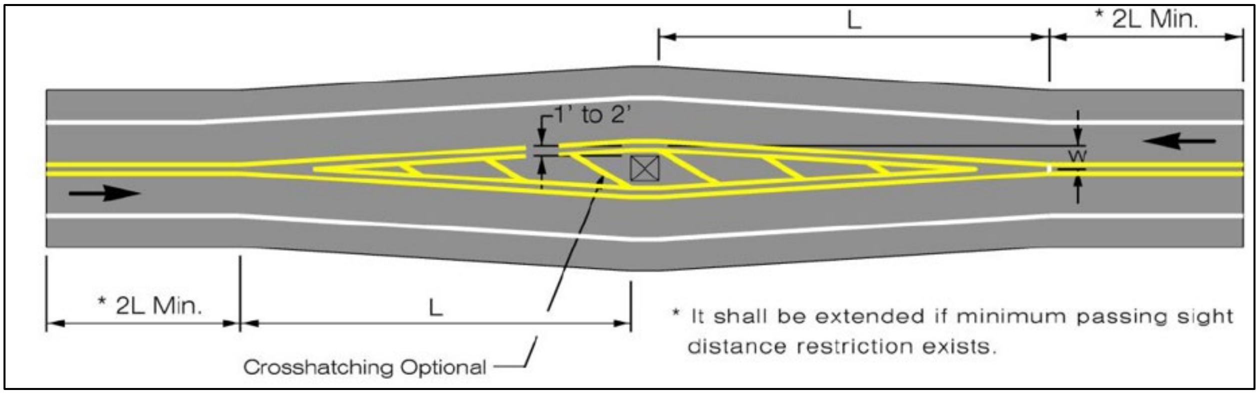


Figure 2.1 No-passing zone at a location with centerline channelization
Source: Wyoming Department of Transportation Traffic Program (2012)

The length of the no-passing zone at a location with a centerline channelization is as shown in Figure 2.1. For intersections and interchange ramps, the minimum passing zone lengths are listed in Table 2.4.

Table 2.4 Minimum Passing Zone Lengths for Special Locations

Posted Speed Limit (mph)	Minimum Passing Zone Length
25	280
30	320
35	370
40	410
45	500
50	550
55	650
60	700
65	850
70	850

Source: Wyoming Department of Transportation Traffic Program (2012)

For sections with passing lanes, a no-passing zone marking is designated on the side with the supplementary lane. The no-passing zone marking is extended a distance equivalent to that presented in Table 2.4 upstream of the passing lane taper's beginning point (*3*).

With railroad crossings, a no-passing zone marking should be striped from the railway line to a point upstream of the junction approach. Its location depends on the length of the no-passing zone. The no-passing zone lengths at railroad crossings are presented in Table 2.5. Likewise, this would be the case for the opposing traffic direction. Note that for gateless railroad crossings with posted speed limits that are 35 mph or lower, no-passing zones may be discarded (*3*).

Table 2.5 Minimum Passing Zone Lengths Needed for Railroad Crossings

Posted Speed Limit (mph)	Minimum Passing Zone Length
20	210
25	285
30	360
35	435
40	510
45	585
50	660
55	735
60	810
65	885

Source: Wyoming Department of Transportation Traffic Program (2012)

2.4 Passing Sight Distance Measurement Methods

There are multiple PSD measuring methods: walking, one-vehicle, two-vehicle, eyeball, laser rangefinder, and optical rangefinder, among others (*17*). In the walking method, two inspectors having poles with markings walk along the two-lane highway. The distance between both inspectors is the PSD and is maintained using a rope. Once the marking of the lead inspector's pole disappears behind a sight obstruction, the following inspector designates his position as the starting point of the no-passing zone. The inspectors proceed with their walk and, when the marking of the lead inspector's pole reappears, the following inspector designates his new position as the termination point of the no-passing zone. This technique is hazardous and laborious (*17*).

The one-vehicle method is more efficient than the walking method, albeit unsafe and less accurate. It requires a driver to travel at a low to moderate speed along the two-lane highway. Whenever the driver judges that the PSD is restricted, he or she parks to designate spots on the roadside, which are the no-passing zone's boundary points. The distance between the no-passing zone's beginning and end points are ascertained using an odometer (*17*, *18*).

The two-vehicle method is efficient and less risky relative to the walking and one-vehicle methods. In the two-vehicle method, two succeeding vehicles travel at the highway speed, and both are separated by a gap distance equivalent to the PSD. They are equipped with global positioning system (GPS) equipment to record their positions at a preset frequency. The vehicle speeds are computed using the GPS and timestamp data. The data collected by either vehicle are exchanged via radio and are depicted to the users by means of monitors. The following vehicle is also supplied with a switch that is used to signal whether the lead vehicle is visible or not depending on sight obstructions. When the lead vehicle disappears behind sight obstructions, the following vehicle's driver operates the switch to designate the beginning point of the no-passing zone. Similarly, when the lead vehicle returns to view, the following vehicle driver re-operates the switch to signal the ending point of the no-passing zone. The coordinates of both terminal points are recorded using the GPS devices (*17*). The following vehicle's driver manages multiple responsibilities, including focusing on the driving activities, operating the switch, ensuring that the equipment components are functioning properly, restarting them if required, and securing the predefined distance between both vehicles, which is the PSD. The equipment may exhibit bugs, and a passenger may aid the driver in conducting the field test (*19*). Other than the two-vehicle method, the eyeball method is another PSD data collection method. Yet, it is difficult to conduct along vertical curves (*17*, *18*). The laser rangefinder and optical rangefinder methods are other commonly employed techniques for collecting PSD data. The laser rangefinder method uses a laser rangefinder to gauge the distance to a spot where vehicles become invisible due to sight distance restrictions. Multiple recordings are logged, and the length of the no-passing zone is established. This method is uneconomical (*17*). The optical rangefinder method is similar to the laser rangefinder method except that the PSD data are collected using an optical rangefinder, which is cost competitive relative to the laser rangefinder (*17*). The PSD may also be obtained via computations using GPS data (*18*, *20*). In addition, Gargoum et al. (2018) utilized light detection and ranging (LiDAR) data to estimate the PSD, while Ma et al. (2018) proposed an algorithm used to envisage the PSD in real time (*21*, *22*). Brown and Hummer (2000) described the speed method as another way to evaluate the PSD, however, it is demanding. WYDOT employs the two-vehicle method since it is quick and less risky than some of the other methods. On the other hand, the walking method is hazardous, and the one-vehicle method is tedious. The eyeball method is problematic when conducted along vertical curves; the laser rangefinder, optical rangefinder and speed methods are taxing. The techniques of Namala and Rys (2006), Azimi and Hawkins (2012), Gargoum et al. (2018) and Ma et al. (2018) are not field-based methods.

2.5 Former Passing Sight Distance Data Collection Efforts

PSD methods were described in the previous section. Past studies involving PSD data collection were also discussed and critiqued (*18*, *20–22*). As such, they are not field-based procedures. In this section, Hutton and Cook's (2016) efforts involving the application of the two-vehicle method are elaborated and critically assessed as well (*19*).

In Cooper County, Missouri, Hutton and Cook (2016) implemented the two-vehicle method to collect PSD data pertaining to two-lane highways, thus, designate the passing/no-passing zones. The authors contrasted their results with the zone striping plans of the Missouri Department of Transportation (MoDOT). As per the study's findings, there were discrepancies between 9.8% and 22.3% depending on the field-testing location and the traffic lane. The discrepancies were mainly those in which the authors identified locations with adequate PSDs as passing zones while MoDOT designated them as no-passing zones. The research team encountered challenges as well. That is, the GPS equipment briefly halted, the power supply exhibited technical issues, and the communication between both vehicles diminished at crest vertical curves. The limitations of Hutton and Cook's (2016) equipment are surmounted in this project (*19*). The cutting-edge components of this project's apparatus are designed and tested to confirm they function smoothly.

3. DEVELOPMENT, TESTING, AND DELIVERY OF PROTOTYPE 1

This chapter encompasses the description of Prototype 1, used for implementing the two-vehicle method, the prototype's development, the elaboration of its testing procedure, the presentation of the testing results, and their discussion, as documented in Farid et al. (2021) (*23*). Subsequently, a section is dedicated to a discussion of the technical issues discovered in the prototype, how they were addressed, and the prototype's replication as per WYDOT's request.

3.1 Prototype 1's Description and Development

The intended functions and components of Prototype 1 are listed as follows:

- Vehicle-to-vehicle (V2V) communication via wireless long range (LoRa) or the Institute of Electrical and Electronics Engineers' (IEEE's) 802.1p customs
- Transmission of speed data from the lead vehicle to the following vehicle and vice versa at an appropriate frequency
- Estimation of the PSD using the GPS and speed data collected from both vehicles
- The switch needed to signal whether the lead vehicle is obscured behind sight obstructions, setting the beginning point of the no-passing zone, or visible after being out of view, setting the ending point of the no-passing zone with the use of the GPS devices
- A program with a graphical user interface (GUI) to present both vehicles' speeds, the recorded PSD, and a live map of the no-passing zone terminal points

There are multiple applications of wireless V2V communication technologies in transportation engineering, including those of traffic operations and safety. These emerging technologies must be reliable and exhibit reduced latency. The two main wireless V2V communication systems are the ITS-G5 (Europe) and the dedicated short range communication (DSRC) systems (U.S.), which are employed by following the IEEE 802.11p guidelines (*24*). The U.S. Department of Transportation (USDOT) suggests implementing DSRC based devices, such as the LocoMate mini-2. DSRC systems are commonly tuned to a dedicated spectrum of 75 MHz in the 5.9 GHz band with a communication buffer of 1 km (0.62 mi). Yet, when Prototype 1's devices were being developed, the communication equipment designed according to the IEEE 802.11p protocols exhibited low signal strength due to large environmental moisture contents. The communication buffer decreases from 1,500 ft at a moisture content of 20% to 200 ft at a content of 60%. Hence, multiple types of devices were explored to address this limitation, and the LoRa-based communication systems were found to operate well during conditions that were characterized by elevated moisture content. LoRa implemented a modulation system of the company Semtech, operable via chirp spread spectrum (CSS). The CSS could attain a communication buffer of 2 km (1.24 mi) using line antennas or a 20-km (12.43-mi) buffer using beam antennas. LoRa is permitted to function at frequencies of 915 MHz and 433 MHz in the nation, giving rise to a lengthy communication buffer and little signal waning (*25*). For this project, the LoRa Radio Bonnet, or hardware attached on top (HAT), tuned to 915 MHz and an auger antenna of Adafruit comprised the V2V communication equipment.

The Adafruit GPS HAT device with 66 channels and 10 Hz updates was utilized to log the vehicles' GPS coordinates and speeds every 0.1 second. A button was incorporated to save the GPS coordinates of the no-passing zone terminal points.

The Raspberry Pi 4 Model B system-on-chip (SoC) integrated system was chosen as the system computer to serve as the link between the LoRa and the GPS HATs. This task was essential for executing the calculations and outputting the GUI to the user. Prototype 1's devices are illustrated in Figure 3.1, which shows that the LoRa and GPS antennas are connected to their respective touchscreens. The LoRA and GPS HATs are attached to the Raspberry Pi.

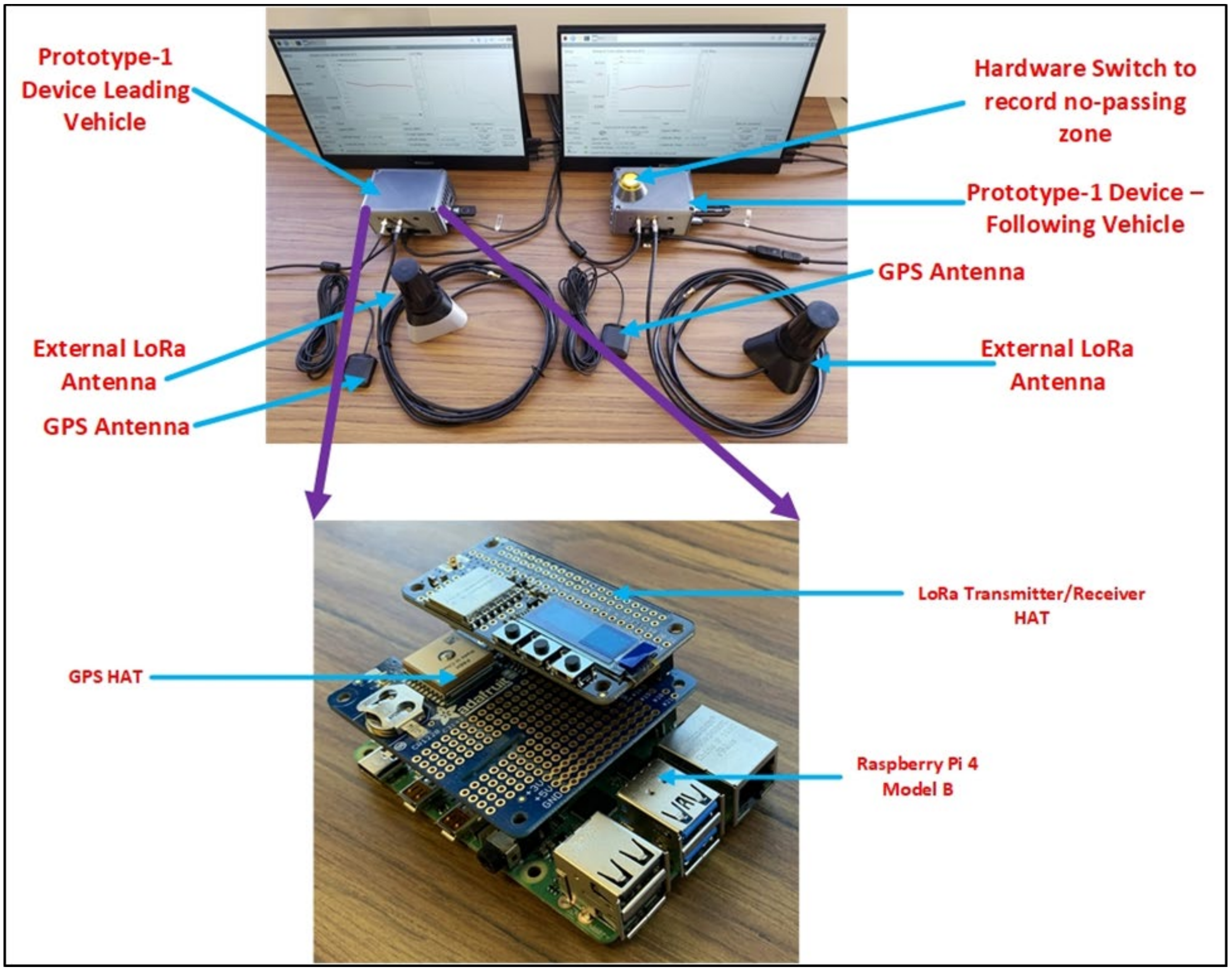


Figure 3.1 Prototype 1's components. Source: Farid et al. (2021) (*23*)

The computer software operating on the Raspberry Pi carried out the following functions:

- Exchange GPS and speed data between both vehicles
- Compute the gap distance between both vehicles
- Log the coordinates of the no-passing zone terminal points when the switch is operated
- Feature a GUI with a live map of the no-passing zone terminal points

The aforementioned features were enabled by employing Python 3.6 code, particularly the features of the PyQT graphic library, the System Development Kit (SDK) of the LoRa systems and the GPS equipment's SDK.

The communication between both lead and following vehicles must be efficient. Although the LoRa radio could operate in full-duplex mode, a software-handshake procedure was incorporated for smoothing communications between both vehicles. The prototype's equipment in the lead vehicle followed the procedure by transferring the speed and GPS coordinates data to the following vehicle. With that, a timer with a preset time limit was initiated. The following vehicle's equipment acquired the data and estimated its distance relative to the lead vehicle. The following vehicle also provided its position and speed data to the lead vehicle. If the lead vehicle obtained the data within the preset time limit, the lead vehicle estimated its distance relative to the following vehicle. On the other hand, if the lead vehicle did not obtain the data within the predefined time limit, the software-handshake procedure was restarted, securing sleek communications. In any case, the following vehicle attained the data from the lead vehicle first before exchanging its data.

Adjustments were made to the software to minimize errors in estimating the distances between both vehicles. The distance calculation could be performed every 0.35 seconds via the software-handshake procedure and gradually alter the LoRa radio's parameters. The 0.35-second time frame entailed the 0.1 second needed to attain fresh GPS coordinates, LoRa data, and processing time. For instance, the 0.35-second interval corresponding to a travel speed of 65 mph leads to an error of 33.36 ft in the estimated distance. This is because the GPS coordinates exchanged between both vehicles did not represent the present vehicle positions. Hence, this error needs to be mitigated. As such, the exchanged GPS coordinates data were augmented to incorporate data of the timestamps at which the coordinates were recorded. Also, a dead reckoning algorithm (*26*) was applied to estimate the distance with the use of the timestamp and speed data. The newly estimated distances were contrasted to those measured using laser equipment and, as per the contrast results, the computation error shrunk to ± 5 ft. However, since the GPS coordinates data were collected every 0.1 second, data of the estimated distances between both vehicles were erratic. Therefore, a Kalman filter algorithm was implemented to estimate the GPS coordinates of both vehicles at 0.05-second intervals by using the collected GPS coordinates data collected at 0.1-second intervals and the vehicle speed data. Both vehicles sent and received the GPS coordinates data estimated at 0.05-second intervals instead of those collected every 0.1 second. This led to more consistent estimates of the distances between both lead and following vehicles.

Concerning the touchscreens, the software's GUI was developed via the PyQT library. The GUI allows the user the choice to represent either the lead vehicle or the following vehicle. The user could enter the GPS coordinates of the beginning and termination points of the field test. The user could also label the file when starting the testing procedure for data storage purposes and access the roadway network map from a list of available state district maps. In addition, the user could choose the posted speed limit from a drop-down menu and the software would set the desired gap distance between both vehicles, namely the PSD (Table 2.1). The user could adjust the desired gap distance if needed. When conducting the testing procedure, the user is presented a real-time chart depicting the actual and desired distances between both vehicles, as shown in Figure 3.2. The operating status of the GPS equipment and the radio communications is also presented to the user. Furthermore, in addition to the switch (Figure 3.1), a special touchscreen button was incorporated to emulate the switch's function. Once the button is activated, the no-passing zone terminal point's coordinates are stored and the user receives a message indicating the lead vehicle's visibility status. This button is presented in Figure 3.3. Another menu was featured to permit the user to indicate being at a special location such as an intersection or a railroad crossing, warranting the designation of a no-passing zone. This menu is presented in Figure 3.4.

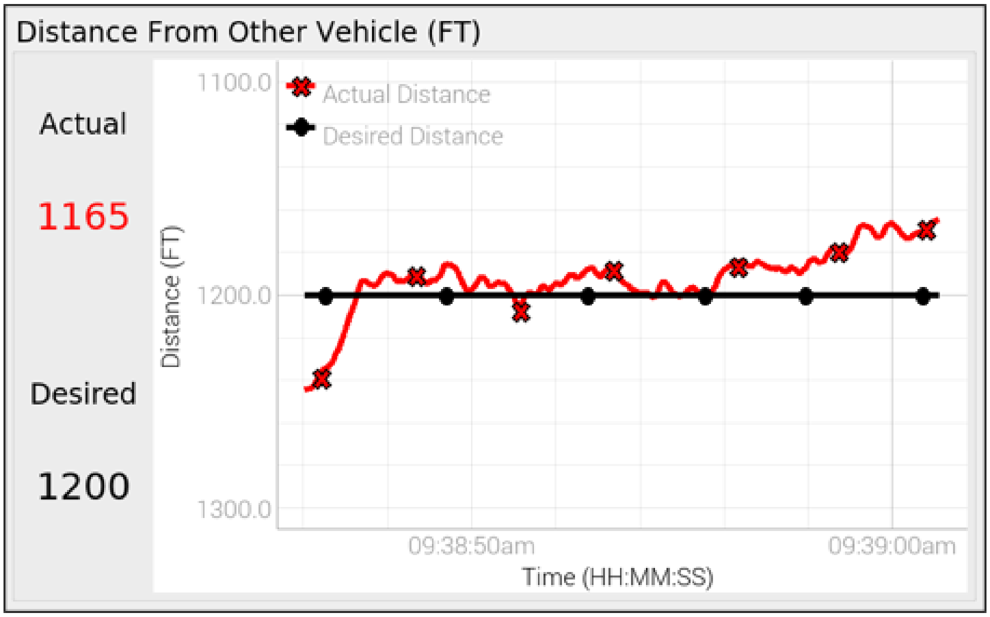


Figure 3.2 Real-time display of desired and estimated gap distances between lead and following vehicles

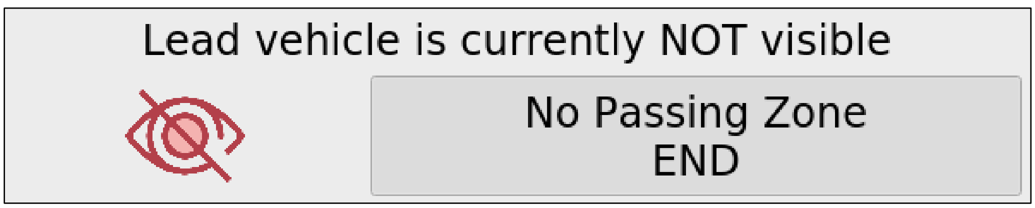


Figure 3.3 Presentation of the lead vehicle's visibility status

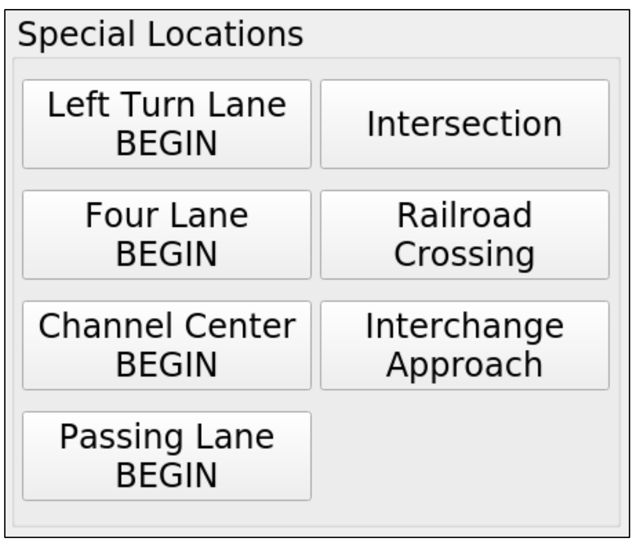


Figure 3.4 Menu for special locations warranting the striping of no-passing zones

The software also elongates short passing zones, sandwiched between no-passing zones, as no-passing zones (Table 2.2) according to the WYDOT pavement marking manual (*3*). A road map of the geocoded no-passing zone terminal points and special locations are presented to the user on the fly. The map could be saved as a Google Maps KMZ file or as ArcGIS SHP, SHX, and DBF files for post-processing purposes.

The software includes a supplementary feature, a button with a list of prescribed messages, such as “stop run,” for the test examiners to communicate with each other. This button was deemed essential since a substantial percentage of Wyoming’s two-lane highways are within areas that have no cellular coverage.

3.2 Prototype 1’s Testing Procedure

Two 20-mile stretches of two-lane highways on the outskirts of Laramie, Wyoming, were chosen as the Prototype 1 testing locations: Happy Jack Road, or simply WY-210, and US-287. Prototype 1 was tested along both travel directions of the aforementioned road segments covering 40 miles. Note that WY-210 is known for its hilly terrain, horizontal curves, and vegetation restricting the PSD, as shown in Figure 3.5.

Figure 3.5 Section of Happy Jack Road with restricting sight distance. Source: Google L.L.C. (2021) (*27*)

Since the PSD should be measured at a 3.5-ft height throughout its length, the lead vehicle’s taillights were measured to be 3.5 ft from the pavement surface, and a sedan was selected as the following vehicle to ensure that the driver’s eye height was 3.5 ft relative to the ground. Once the lead vehicle’s taillights disappeared due to sight distance restrictions, the following vehicle’s driver operated the switch. Similarly, once the lead vehicle’s taillights reappeared, the following vehicle’s driver operated the switch. When the field tests were carried out, it was ensured that the taillights of the lead vehicle were visible from distances beyond the PSD, provided that the lead vehicle was not obstructed by features blocking its view. The lead vehicle’s cruise control was designated at the desired speed—the posted speed limit—and the following vehicle’s driver secured the predetermined gap distance between both vehicles using the cruise control as well. Also, unlike the case of Hutton and Cook (2016), the equipment did not manifest any lapses (*19*).

3.3 Prototype 1's Testing Results and Discussion

After Prototype 1's testing, its outputted passing/no-passing zone plans were compared with the existing striped ones of WYDOT. The comparison results of the WY-210 and US-287 sections are presented in Table 3.1.

Table 3.1 No-Passing Zone Designation Comparison Results

WY-210		
Metric	**Eastbound**	**Westbound**
Overall Discrepancy (ft)	2,503	5,625
Route Length (ft)	80,647	
Overall Discrepancy (%)	3.1	7.0
Aggregate Length of No-Passing Zones Misidentified as Passing Zones (ft)	700	2,172
Aggregate Length of True No-Passing Zones (ft)	41,960	42,781
No-Passing Zones Misidentified as Passing Zones (%)	1.7	5.1
US-287		
Metric	**Southbound**	**Northbound**
Overall Discrepancy (ft)	248	628
Route Length (ft)	24,819	
Overall Discrepancy (%)	1.0	2.5
Aggregate Length of No-Passing Zones Misidentified as Passing Zones (ft)	153	628
Aggregate Length of True No-Passing Zones (ft)	10,154	10,274
No-Passing Zones Misidentified as Passing Zones (%)	1.5	6.1

Source: Farid et al. (2021) (*23*)

The WY-210 posted speed limit is 65 mph, prompting the selection of a desired gap distance between both vehicles of 1,200 ft (*3*). Yet, as per a discussion with WYDOT, a distance of 1,300 ft is desired. Furthermore, passing zones shorter than 850 ft would have to be designated as no-passing zones (*3*). Intersections, which prompt the designation of no-passing zones, were encountered throughout both WY-210 and US-287 test runs. The passing sight distance, minimum distance between no-passing zones and distance between no-passing zones and intersections were all considered in the designation of no-passing zones when conducting the field tests. Note that for all tests, manual calculations were conducted concerning short passing zones between no-passing zones. If they were found to be shorter than their minimum lengths, the passing zones were considered as no-passing zones. Overall discrepancies for the eastbound and westbound directions of WY-210's segment were 3.1% and 7%, respectively, as shown in Table 3.1. Some pertained to passing zones erroneously designated as no-passing zones while others belonged to no-passing zones mistakenly designated as passing zones. The difference in overall discrepancies of the eastbound and westbound directions' results could be attributed to differences in the features that restrict the PSD. These include hills, trees obstructing the sight distance around horizontal curves, vertical curves, and sections with a combination of horizontal and vertical curves. Also, the overall discrepancies could be because the desired distance between both lead and following vehicles was selected as 1,200 ft instead of 1,300 ft. In Hutton and Cook's (2016) results, overall discrepancies were 9.8% and higher depending on the location and lane. The no-passing zones incorrectly identified as passing zones were equally as important. Those errors were computed as the ratio of the aggregate footage of the no-passing zones, which were incorrectly identified as passing zones to the aggregate lengths of the true no-passing zones. Such errors were 1.7% and 5.1% for the eastbound and westbound lanes of WY-210's testing route, respectively. The delay in perception-reaction time (PRT) in activating the switch to designate the starting points of the no-passing zones could be another potential source of error.

In regard to testing Prototype 1 along US-287's segment, some locations had a posted speed limit of 55 mph while some had a limit of 65 mph and some had a limit of 70 mph. The corresponding PSDs selected were 900 ft, 1,200 ft, and 1,200 ft, respectively (*3*). Also, US-287 is known for its zones that are characterized by transitions into or out of four-lane sections and intersections. All criteria needed to establish passing/no-passing zones were considered in the field tests. As shown in Table 3.1, overall discrepancies of 1% and 2.5% were computed for the southbound and northbound directions of US-287's testing route, respectively. With that, no-passing zones that were erroneously designated as passing zones represented 1.5% and 6.1% of the aggregate lengths of the true no-passing zones of the southbound and northbound lanes, respectively. The discrepancies could possibly be attributed to delays in PRT and because the PSD of 1,200 ft was used instead of the conservative value of 1,300 ft for locations with 65-mph posted speed limits or higher.

3.4 Prototype 1's Mending and Replication

After Prototype 1 was tested, it was delivered to WYDOT and returned with feedback. The issues with the equipment pinpointed by WYDOT were the following:

- The software failed to mark locations with no-passing zones that were shorter than their minimum required lengths such that the geometric design engineer decided whether to elongate the zones or eliminate them.
- It was preferable that the GPS coordinates be converted into route and milepost information.

The previously mentioned issues were addressed and WYDOT requested that the project's contract be extended so as to replicate multiple units of Prototype 1. That is, several units were developed to enable WYDOT, counties, and local governments, such as the Wind River Indian Reservation, to continuously re-evaluate their two-lane highway zone striping plans without the hassle arising from a lack of prototypes. One of the Prototype 1 units was available at the Wyoming Technology Transfer/Local Technical Assistance Program (WYT2/LTAP) Center of the University of Wyoming and be loaned to any interested parties. A detailed guide, "Mapping Automation for Passing Zones (MAPZ): Quick Start Guide," with definitive instructions on how to operate Prototype 1 is provided in this report's appendix.

4. DEVELOPMENT, TESTING AND DELIVERY OF PROTOTYPE 2

This chapter is organized as follows. Prototype 2's development and testing procedure are elaborated. The testing results are presented and discussed as well. Subsequently, a section is dedicated to the issues exhibited by the equipment, the refurbishment of the equipment. and the upgrading of Prototype 1 to emulate the functionalities of Prototype 2

4.1 Prototype 2's Description and Development

In Prototype 1, the two-vehicle approach of determining the PSD was developed with the passenger in the following vehicle detecting the lead vehicle going in and out of view visually and recording the corresponding GPS coordinates and distance from the mile markers. WYDOT personnel used Prototype 1 devices (MAPZ) for over two years without major glitches and demonstrated the reliability and robustness of detecting the no-passing zones. However, the MAPZ devices require a passenger in the following vehicle to detect the beginning and end of a no-passing zone (NPZ) by determining the presence and disappearance of the lead vehicle and using a push button to trigger the device to record the corresponding GPS coordinates. Detecting the NPZ requires a second occupant (passenger) in addition to the driver of the following vehicle and can introduce errors due to inherent latency induced by the human operator. At highway speeds of 70 mph, a latency of 0.5 seconds in triggering the device to record the GPS coordinates can result in a 52-ft to 104-ft NPZ error. To eliminate the need for a passenger in the following vehicle and reduce error due to human latency, Prototype 2 was developed by incorporating a fusion of two algorithms to automatically detect the beginning and end of the NPZ and record the GPS techniques.

The two algorithms used terrain maps, GPS coordinates, and a computer vision device (CVD) to record the lead vehicle image and continuously detect the NPZ offline. The CVD was physically mounted on the front windshield at the head height of a passenger, as shown in Figure 4.1.

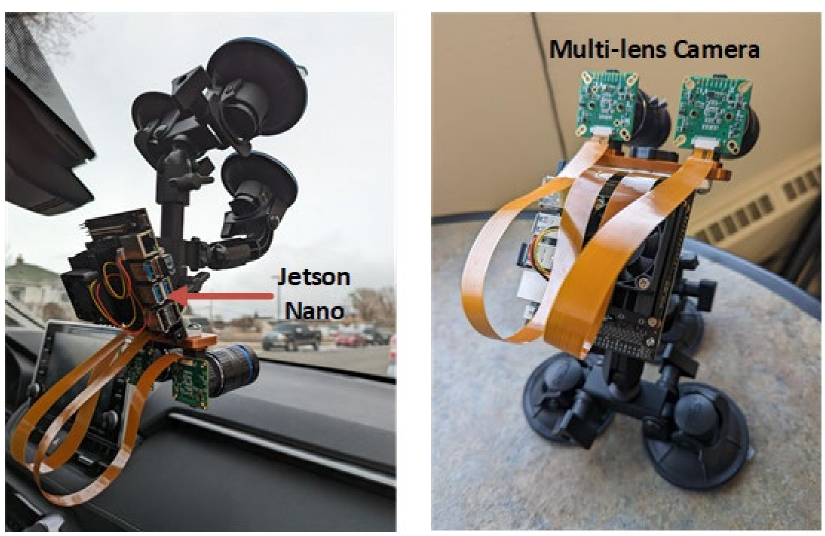


Figure 4.1 Computer vision device (CVD) to record lead vehicle

The CVD consisted of an embedded computer—the popular and commercially available Jetson Nano by NVidia—and two IMX477 cameras from Adafruit, as shown in Figure 4.1. The two cameras provided an overlapping 43.0° field of view (FOV), translating into an 850-ft view at a distance of 1200 ft. Using the two cameras maximized the time the lead car was visible when a highway was winding, as shown in

Figure 4.2. As shown in Figure 4.1, if only a single camera was used, the lead vehicle was not visible due to the limited FOV, even though a passenger could see the lead vehicle due to the sight line.

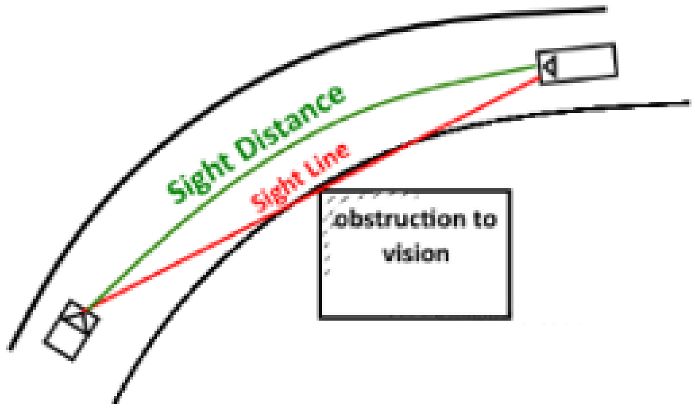


Figure 4.2 Sightline of the lead vehicle on a winding road

The Prototype 1 MAPZ device (provided to WYDOT) uses only the latitude and longitude of the GPS coordinate to maintain the desired separation distance. To detect the NPZ autonomously, the software on the Prototype 1 MAPZ device was modified to record the latitude, longitude, and altitude of the GPS coordinates and continuously transmit the GPS coordinates to the Jetson Nano over the WiFi hotspot. The Jetson Nano records a video at six frames per second and saves each frame tagged with its GPS coordinate on a flash drive on the Jetson. The Prototype 2 data collection process to perform autonomous offline two-vehicle NPZ data collection is discussed below:

- One modified MAPZ device and the CVD device should be mounted in the following vehicle, and the second modified MAPZ device should be mounted in the lead vehicle.
- Initially, with the following vehicle stationary, the lead vehicle should be driven until the separation distance corresponding to the highway speed limit is reached.
- The two lenses on the CVD device should be adjusted to ensure that the lead vehicle is visible and the lenses point at 3 ft from the ground level on the lead vehicle.
- On driving both vehicles at the highway speed and maintaining the required distance, the MAPZ device continuously records the GPS coordinates (latitude, longitude, and altitude) while the CVD records a video of the lead vehicle, the area surrounding the road, and any oncoming vehicles. The video recording is displayed on the laptop in real time for verification.
- After completing the drive, the data file containing the drive GPS coordinates and drive video is processed using two algorithms.

4.1.1 Autonomous NPZ Detection using Terrain Maps and GPS Coordinates

The United States Geological Survey (USGS) provides access to different U.S. terrain maps. Geo Tagged Image File Format (GeoTIFF) and LiDAR maps are a few of the terrain maps USGS has in its database that can also be downloaded. The GeoTIFF maps are images gathered using satellite imagery, with each pixel containing the landscape's latitude, longitude, and altitude, whereas the terrain maps based on LiDAR lack altitude information. Hence, the GeoTIFF terrain maps were used to implement the NPZ detection. Using The National Map (TNM) Downloader on the USGS website, the terrain map in GeoTIFF format of an area can be downloaded (*28*), as shown in Figure 4.3. By drawing a box around Albany County, WY, and using the Extent button and searching for 3D elevation maps, the terrain map of Albany County was downloaded as a GeoTIFF terrain map, as demonstrated in Figure 4.4.

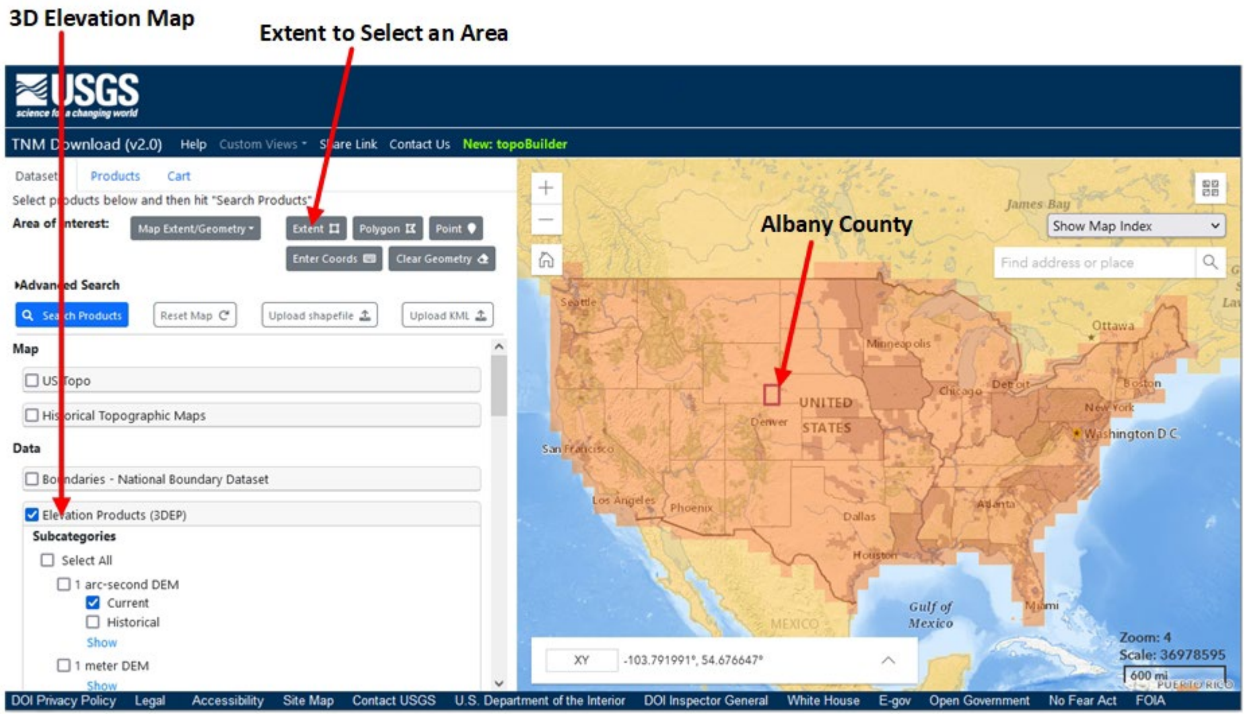


Figure 4.3 USGS TNM Downloader of Terrain Maps. (Source: USGS, 2023)

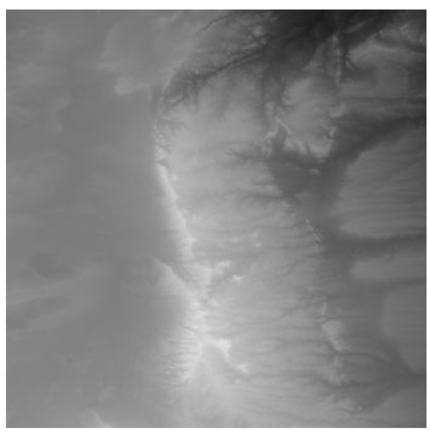


Figure 4.4 Terrain Map of Albany County. Source: (*28*)

A software program developed in Python reads the downloaded terrain map and the GPS coordinates of the lead-follow vehicles collected during the drive as inputs. Using the read GPS coordinates and the terrain map, the software detected the locations of the lead-follow vehicles on the terrain map at each sampling instance, as shown in Figure 4.5. The location of the lead-follow vehicles on the WY-210 highway at a sampling instance is demonstrated in Figure 4.5. The location's altitude of the lead-follow vehicle was increased by 3 ft to account for the observer's location in the following vehicle and observation point on the lead vehicle.

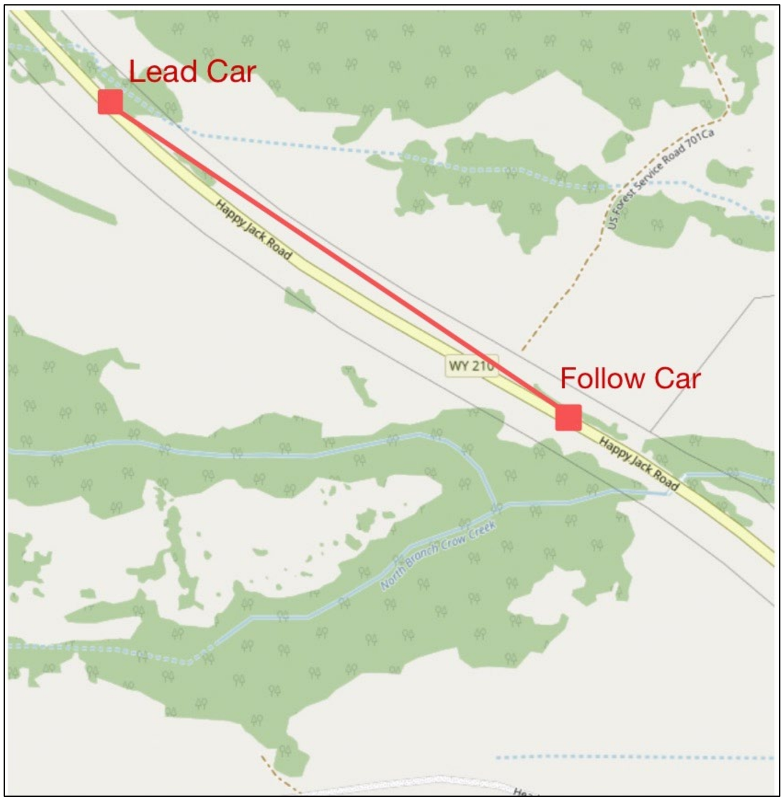


Figure 4.5 Software detection of the lead and follow vehicles on the terrain map

Figure 4.5 shows that the line of sight was not along the WY-210 terrain, indicating that the elevation and other features, such as vegetation near WY-210, dictated whether the following vehicle can view the lead vehicle. Next, the software searched for GPS coordinates of the terrain map located on the line of sight and determined whether any GPS coordinates on the line had an altitude higher than the altitude of the lead vehicle, the following vehicle, or both. If any GPS coordinate of the terrain map on the line-of-sight line had an altitude higher than the lead or following vehicle's altitude, the lead vehicle was not visible from the following vehicle, and the software marked the GPS coordinates of the vehicles at that sampling instance as an NPZ otherwise visible. However, in cases where the view of the following vehicle was obstructed by vegetation along the line-of-sight and there were no altitude violations, the algorithm incorrectly indicated that the lead vehicle was visible. The error is because the GeoTIFF terrain map does not contain the elevation and other information about vegetation near a highway. This kind of error was fixed in Prototype 2. For instance, Prototype 2 utilized the second algorithm to analyze the GPS-tagged video frames collected by the CVD, and thus the roadside vegetation errors were addressed.

4.1.2 Deep Learning-based Lead Vehicle Detection

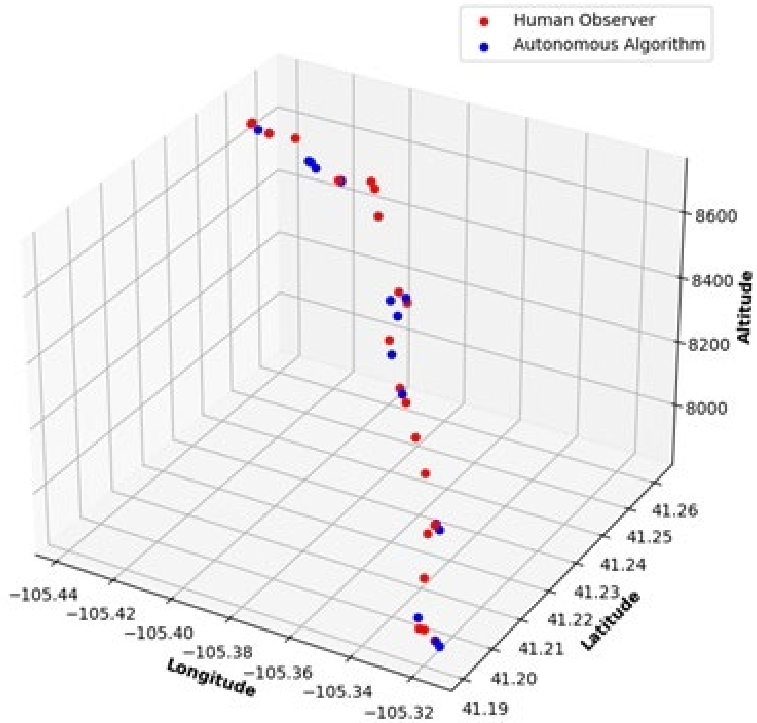
Several deep learning models are available in the literature for detecting objects in a video frame, such as the famous efficient "You Only Look Once" (YOLO) real-time object detection. The YOLO model is fast and efficient since it can detect and locate objects in a single pass of the input image frame. While developing Prototype 2, a new deep learning model was established based on the YOLO v7 with the training dataset generated on Wyoming highways. The training dataset was generated by conducting several NPZ driving trials on multiple highways around Laramie. A total of 7,400 images were collected and labeled. The labeling task involves identifying the presence of the back side of the lead vehicle and its location in the image, which is labor-intensive. The 7,400 images consisted of those with the back side of the lead vehicle visible up to 3 ft from the ground level, with the back side of the lead vehicle not visible, with oncoming vehicles, and on winding roads.

The YOLO v7 architecture was modified to suit the resolution of the images in the training dataset and trained without any prior training information. The machine model was trained to detect the back side of the lead vehicle if the back side was visible and also determine the location of the back side in the image. Furthermore, the model was trained not to detect any oncoming vehicles. Combined with autonomous NPZ detection using terrain maps and GPS coordinates, it is possible to eliminate the effect of any vehicles between the following and lead vehicles.

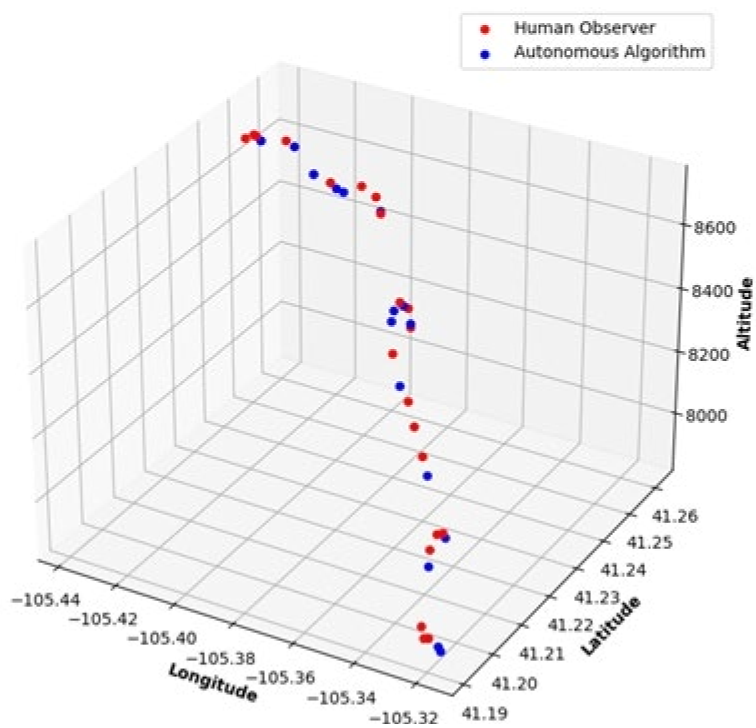
4.2 Prototype 2's Testing Results and Discussion

After training, new data were collected by conducting several NPZ driving trials. The new data were used to determine the performance of the autonomous NPZ detection and new deep learning model algorithms. The video and GPS data were collected while driving on Happy Jack Road, and a human observer marked the beginning and end of NPZs using the push button on the modified MAPZ device (i.e., Prototype 2).

The collected GPS data were first fed to the Python software. The beginning and ending GPS coordinates of no-passing zones were then computed. Figure 4.6(a) shows the beginning NPZ GPS coordinates detected by the autonomous NPZ algorithm and the human observer. Figure 4-6(b) shows that the GPS coordinates of the beginning of NPZ detected by the autonomous NPZ algorithm and human observer were highly correlated. It can be seen that the autonomous NPZ algorithm identified locations as the beginning of the NPZ, whereas the human observer failed to mark the locations. Also, it can be observed that there were differences in the beginning locations of NPZs marked by the autonomous NPZ algorithm and the human observer. The difference can be attributed to human observer latency.



a) Starting GPS locations from the autonomous algorithm and the human observer



b) Ending GPS locations from the autonomous algorithm and the human observer

Figure 4.6 Starting and ending GPS locations from the autonomous algorithm and the human observer

Case 1: Lead Vehicle Visible – Passing Zone

The passing zone detection by the deep learning and autonomous algorithms is shown in Table 4.1. Both algorithms indicate that the lead vehicle was visible in both trials. The deep learning algorithm draws a bound box around the detected lead vehicle. Both algorithms agree that the lead vehicle was visible and in a passing zone for the two test cases, as demonstrated in Figure 4.7.

Table 4.1 Passing Zone Detection

Speed Limit	Actual Speed	Desired Separation Distance	Actual Separation Distance	Follow - Latitude	Follow - Longitude	Follow - Altitude	Lead - Latitude	Lead - Longitude	Lead - Altitude	Deep Learning Algorithm	Autonomous Algorithm
70	60.7	1200	1247	41.19127	-105.315	7867.65	41.19179	-105.32	7898.78	VISIBLE	VISIBLE
70	49.8	1200	1100	41.24349	-105.436	8716.13	41.24048	-105.436	8709.79	VISIBLE	VISIBLE

Figure 4.7 Lead vehicle visible indicating passing zone

Case 2: Lead vehicle not visible, indicating NPZ

The no-passing zone detection by the deep learning and autonomous algorithms is shown in Table 4.2. Both algorithms indicate that the lead vehicle was not visible in both trials. Both algorithms agree that the lead vehicle was not visible, and the vehicles were in a no-passing zone for the two test cases, as demonstrated in Figure 4.8.

Table 4.2 No-passing Zone Detection

Speed Limit	Actual Speed	Desired Separation Distance	Actual Separation Distance	Follow - Latitude	Follow - Longitude	Follow - Altitude	Lead - Latitude	Lead - Longitude	Lead - Altitude	Deep Learning Algorithm	Autonomous Algorithm
70	66.8	1200	1236	41.24774	-105.382	8279.19	41.25061	-105.384	8217.4	NOT VISIBLE	NOT VISIBLE
70	59.5	1200	1240	41.25913	-105.403	8418.23	41.26152	-105.407	8474.87	NOT VISIBLE	NOT VISIBLE

Figure 4.8 Lead vehicle not visible indicating no passing zone

Case 3: NPZ disagreement between deep learning and autonomous algorithms

Table 4.3 shows that for all three trial cases, the autonomous algorithm indicates that the lead vehicle was visible and the vehicles were in the passing zone. However, the deep learning algorithm indicates that the lead vehicle was not visible and the vehicles were in the NPZ.

Table 4.3 Deep Learning Model Contradicting Autonomous Algorithm – NPZ

Speed Limit	Actual Speed	Desired Separation Distance	Actual Separation Distance	Follow - Latitude	Follow - Longitude	Follow - Altitude	Lead - Latitude	Lead - Longitude	Lead - Altitude	Deep Learning Algorithm	Autonomous Algorithm
70	54.4	1200	1354	41.23342	-105.373	8243.73	41.23588	-105.377	8266.94	NOT VISIBLE	VISIBLE
70	64.6	1200	1110	41.25122	-105.385	8193.08	41.25227	-105.389	8179.89	NOT VISIBLE	VISIBLE
70	56.4	1200	1432	41.23814	-105.379	8337.46	41.24201	-105.38	8364.83	NOT VISIBLE	VISIBLE

Figure 4.9 shows that roadside vegetation blocked the lead vehicle, and hence the deep learning algorithm correctly indicates that the vehicles are in the no-passing zone for Trial 1. The autonomous algorithm indicates that the lead vehicle was visible using the terrain map data from USGS. However, the USGS terrain map data did not consider the vegetation along the roadside.

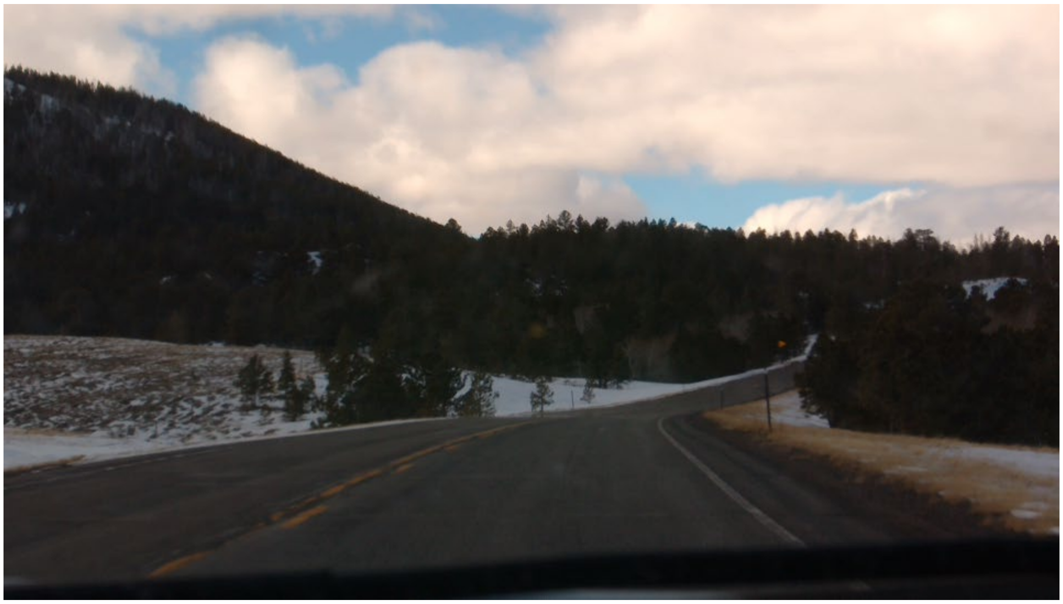


Figure 4.9 Lead vehicle not visible due to vegetation (Trial 1)

Figures 4.10 and 4.11 show that the limited field of view of the cameras in the following vehicle and the winding road resulted in the deep learning algorithm incorrectly indicating that the lead vehicle was not visible and vehicles were in the no-passing zone for both trials 2 and 3. However, the autonomous algorithm correctly indicates that the lead vehicle was visible and the vehicles were in the passing zone using terrain map data that are not affected by the field of view limitations.

Figure 4.10 Lead vehicle not visible due to limited field of view (Trial 2)

Figure 4.11 Lead vehicle not visible due to limited field of view (Trial 3)

4.3 Mending of Prototype 2 and Upgrading of Prototype 1

Prototype 2 is more advanced than Prototype 1. It features cutting-edge ITS-devices that automatically declare whether the lead vehicle disappears or return to view designating the no-passing zone boundaries. The development of Prototype 2 requires machine vision artificial intelligence (AI) algorithms embedded into video cameras used by the following vehicle's driver. Furthermore, automated voice messages instructing the following vehicle's driver to increase or decrease speed to maintain the predetermined distance between both vehicles make the results more reliable and accurate. With efficient functionalities in Prototype 2, the following vehicle's driver was relieved of multiple duties and more accurate passing/no-passing zone striping plans were outputted. This is because the PRT, required to operate the switch, was minimized. It can be concluded that by utilizing the output from both algorithms and examining the associated individual GPS-tagged frames, Prototype 2 users can determine the correct outcome with supporting data.

5. RELEVANT MISCELLANEOUS STUDIES

This project was aimed at developing state-of-the-art prototypes of the two-vehicle method for WYDOT and local jurisdictions. The development and testing of Prototype 1 was documented in a scientific peer-reviewed research article (Farid et al., 2021), while the effort culminating in the delivery of Prototype 2 was also accomplished (*23*). While the project was underway, three other research articles related to two-lane highways were produced and disseminated. One (Farid and Ksaibati, 2020) was about the severities of two-lane highway passing-related crashes, another (Farid et al., 2021) compared the performances of two advanced statistical methods that could be used to evaluate two-lane highway crash severities, and the third (Haq et al., 2021) was about gauging the PSD when passing multiple oil and gas trucks on two-lane highways (*29*–*31*).

5.1 Modeling the Severities of Two-Lane Highway Passing-Related Crashes

In a study by Farid and Ksaibati (2020), two-lane highway passing-related crash severities were assessed via a random parameter, or mixed (Eluru et al., 2008; Mannering et al., 2016), ordinal probit structure (*30*, *32*, *33*). Crash, traffic, roadway characteristics, and other data were collected from the WYDOT Critical Analysis Reporting Environment (CARE) package for 2008-2017. The records showed 132 single-vehicle passing-related crashes and 195 multiple-vehicle passing-related crashes sampled for the study. Separate analyses were conducted for each type. Marginal effects were computed for the factors that gave rise to both single- and multiple-vehicle passing-related crashes. A marginal effect is the average change in injury severity risk due to a factor's influence. For instance, the marginal effect of motorcycle involvement might indicate that the presence of a motorcycle increased the risk of incurring severe injury, and hence lower that of incurring possible injury. Concerning the results of the single-vehicle passing-related crash data analysis, the marginal effects are presented in Table 5.1.

Table 5.1 Marginal Effects' Results of the Single-Vehicle Passing-Related Crash Data Analysis

Crash Severity	Crash Contributing Factors' Marginal Effects (%)				
	Loss of Control	Rollover	Motorcycle Presence	Proper Restraint Use	Rainy or Snowy Weather
Possible or No Injury	-14.90	-7.92	-22.24	66.07	46.12
Suspected Minor Injury	-11.60	-3.95	-34.58	-27.16	-12.69
Fatal or Suspected Serious Injury	26.50	11.87	56.81	-38.91	-33.43

Source: Farid and Ksaibati (2020) (*30*)

As shown in Table 5.1, single-vehicle passing-related crashes involving loss of control, overturning, or motorcycles were likely to result in fatalities/severe injuries provided that all else was fixed. On the other hand, single-vehicle passing-related crashes involving proper use of safety restraints and precipitation had a lower chance of being severe when all else was controlled.

Regarding passing-related multiple-vehicle crashes, the corresponding marginal effects are listed in Table 5.2. As shown in Table 5.2, opposite-direction collisions and the presence of a motorcycle raised the chance of leading to fatalities/severe injuries granted that all else was controlled. Also, traffic volumes exceeding 3,000 veh/day, proper use of the seat belt, rainy conditions, and snowy conditions decreased the likelihood of observing severe passing-related multiple-vehicle crashes provided that all else was unchanged.

Table 5.2 Marginal Effects' Results of the Multiple-Vehicle Passing-Related Crash Data Analysis

Crash Severity	Crash Contributing Factors' Marginal Effects (%)				
	Opposite-Direction Crash	Motorcycle Presence	Proper Restraint Use	Traffic Volume ≥ 3,000 veh/day	Rainy or Snowy Weather
Possible or No Injury	-51.37	-57.98	21.08	21.65	17.02
Suspected Minor Injury	3.69	0.06	-11.09	-11.46	-8.56
Fatal or Suspected Serious Injury	47.68	57.93	-9.99	-10.19	-8.47

Source: Farid and Ksaibati (2020) (*30*)

As per inferences drawn from the study's results, it was recommended that seat belt laws be strictly enforced, sufficient signs along two-lane highways be deployed, and dynamic message signs warning drivers against inclement weather be implemented. This was because, in the minority of multiple-vehicle passing-related crashes that occurred during rainy or snowy conditions, fatalities and severe injuries were likely to be sustained.

5.2 Comparison of Two Appropriate Statistical Methods Used for Modeling Two-Lane Highway Crash Severities

Farid et al. (2021) compared the performances of two advanced statistical regression modeling techniques when evaluating the injury severities of two-lane highway crashes in Wyoming (*29*). They were the uncorrelated random parameters ordinal probit model with interaction effects and the correlated random parameters ordinal probit model (*34*). The advantage of both modeling structures is that they capture the interrelationships among the parameters influencing crash severity. Data of multiple-vehicle crashes, roadway conditions, and other pertinent characteristics were collected from WYDOT's CARE package from 2007 to 2017. In total, 2,115 records of multiple-vehicle crash records were collected for the study. As per the study's findings, the uncorrelated random parameters model with interaction effects exhibited a better fit. It specifies a latent propensity that is equivalent to a linear combination of the products of the parameters and their coefficients as obtained using simulated maximum likelihood estimation. The parameters are the crash contributing factors. The latent propensity represents the mean of a normal distribution with a standard deviation of one. Two thresholds, ψ_0 set as zero and ψ_1 estimated via simulated maximum likelihood estimation, demarcate the crash injury severity categories on the normal distribution curve. For the study, the categories were 1) fatal or suspected serious injury, 2) suspected minor injury or possible injury, and 3) no-injury. Hence, parameters with positive coefficients would, on average, raise the risk of incurring fatalities/serious injuries while those with negative coefficients induced the opposite effect. The model also permits some of the parameters to be random. In particular, random parameters' coefficients would be allowed to vary across the data points assuming that they followed normal distributions. The coefficients' degrees of variation depend on the estimated standard deviations of their distributions (*32*, *33*). The model's performance is typically assessed using the log-likelihood ratio test that compares its log-likelihood with that of a model with the constant term only, also known as the null model. Log-likelihoods provide an indication of model fit. The log-likelihood ratio test statistic, χ^2, is computed as negative twice the difference of both model's log-likelihoods. The number of degrees of freedom is the count of parameters in the former model, including the standard deviations of the random parameters' distributions and the threshold, ψ_1, but not the constant term. The 95th percentile confidence level was used for incorporating the parameters. The results of the uncorrelated random parameters ordinal probit model with interaction effects are presented in Table 5.3.

Table 5.3 Results of the Uncorrelated Random Parameters Model with Interaction Effects

Parameter	**Coefficient**	**P-Value**
Constant	-0.100	0.151
Crash Attributes		
Speeding	0.228	0.013
Head-On Collision	0.879	< 0.001
Standard Deviation of Random Parameter's Distribution	1.048	< 0.001
Sideswipe Intersecting-Direction or Opposite-Direction Collision	0.209	0.012
Standard Deviation of Random Parameter's Distribution	0.475	< 0.001
Motorcycle Involved	0.856	< 0.001
Standard Deviation of Random Parameter's Distribution	0.368	< 0.001
Hit-and-Run Crash	-0.726	< 0.001
Commercial Vehicle Involved	-0.013	0.875
Standard Deviation of Random Parameter's Distribution	0.558	< 0.001
Driver's Attributes		
Driving under the Influence	0.760	< 0.001
Standard Deviation of Random Parameter's Distribution	0.353	0.002
Proper Use of Safety Restraints	-0.618	< 0.001
Distracted Driving	0.233	0.010
Roadway Conditions' Attributes		
Wet, Icy or Snowy Road	-0.225	0.001
Standard Deviation of Random Parameter's Distribution	0.219	< 0.001
Interaction Effects		
Motorcycle Involvement × Driving under the Influence	-1.080	0.021
Standard Deviation of Random Parameter's Distribution	1.254	0.016
Speeding × Motorcycle Involvement	0.534	0.092
Standard Deviation of Random Parameter's Distribution	1.457	< 0.001
Speeding × Commercial Vehicle Involvement	0.049	0.761
Standard Deviation of Random Parameter's Distribution	0.820	< 0.001
Head-On Collision × Driving under the Influence	1.783	< 0.001
Standard Deviation of Random Parameter's Distribution	2.369	< 0.001
Head-On Collision × Commercial Vehicle Involvement	0.211	0.407
Standard Deviation of Random Parameter's Distribution	0.944	< 0.001
Sideswipe Opposite-Direction or Intersecting-Direction × Motorcycle Involvement	0.088	0.768
Standard Deviation of Random Parameter's Distribution	1.940	< 0.001
Sideswipe Opposite-Direction or Intersecting-Direction × Speeding	-0.032	0.847
Standard Deviation of Random Parameter's Distribution	0.276	0.038
Threshold		
ψ_1	1.457	< 0.001
Model Fit Summary		
Log-Likelihood	-1,601.012	
Log-Likelihood of Null Model	-1,833.414	
Log-Likelihood Ratio χ^2	464.803	
Degrees of Freedom	30	
P-Value	< 0.001	

Adapted from: Farid et al. (2021)

As shown in Table 5.3, the correlated random parameters ordinal probit model's results indicated that the fit was appropriate compared with that of the null model. According to the study's findings, driving too fast for the conditions, the presence of a motorcycle, head-on crashes, sideswipe-opposite-direction crashes, broadside crashes, alcohol/drug use, driving while being sidetracked, the interaction effect of driving too fast and the presence of a motorcycle, the interaction effect of a head-on crash and alcohol/drug use, and the interaction effect of the presence of a commercial vehicle, and a head-on crash increased the chance of leading to fatalities/critical injuries assuming all else was controlled. Conversely, absconding from the crash scene, appropriately fastening safety restraints, wet pavement surfaces, and the interaction effect of alcohol/drug use and the presence of a motorcycle decreased the likelihood of giving rise to fatalities/severe injuries assuming all else was unchanged. It was plausible that motorcyclists executed a defensive maneuver prior to colliding with a vehicle driven by a drunken driver. Note that other parameters, such as time of day, day of the week (weekday or weekend), presence of a horizontal curve, and adverse weather conditions (rain, fog, snow, etc.), were incorporated into the model. However, they were not found to influence crash injury severity risk. With that, suggestions were made to address the factors that increased the chance of resulting in unfavorable consequences on the road. The suggestions pertained to roadway design, enforcement, and driver's education measures.

Computing Passing Sight Distances for Overtaking Truck Platoons

In the third study conducted by Haq et al. (2021), the authors estimated the PSD for passing a platoon of two, three, or even four oil and gas trucks on a two-lane highway (*31*). Note that the PSD is required to pass a single vehicle ahead (*2–4*, *16*). However, in Wyoming, oil and gas firms promote the platooning of their trucks, making passing difficult. The mathematical kinematics PSD prediction models (Forbes, 1990; Glennon, 1988; Harwood and Glennon, 1976; Hassan et al., 1996; Lieberman, 1982; Ohene and Ardekani, 1988; Rilett et al., 1990; Saito, 1984; Van Valkenburg and Michael, 1971; Wang and Cartmel, 1998; Weaver and Glennon, 1972) were reviewed and the Glennon (1988) was selected to predict the PSDs for the study (*5–15*). This was because the other models were either founded upon flawed hypothetical assumptions or produced faulty PSD results for a variety of conditions. The Glennon (1988) model was implemented to predict the PSDs for passing a platoon of two, three, and four oil and gas trucks on a 70-mph two-lane highway. Various intra-platoon truck spacings were considered as well, leading to multiple scenarios (*6*). The estimated PSDs, presented in Figure 5.1, were considerably greater than the one needed to pass a single vehicle, which is 1,200 ft (*2*, *3*). Yet, WYDOT prefers using the conservative value of 1,300 ft. Note that, in the figure, the spacings are the intra-platoon spacings.

Figure 5.1 Computed passing sight distances for overtaking oil and gas truck platoons on a 70-mph two-lane highway. Source: Haq et al. (2021) (*31*).

The PSD results, obtained using the Glennon (1988) model, were compared with those of microsimulations run in VISSIM Version 9 (PTV Group, 2016) (*6*, *35*). The microsimulation results were validated by data representative of traffic patterns and speeds belonging to a segment of US-287. The segment selected was south of Laramie, Wyoming, and nearly 15 miles long. The differences between the PSDs predicted using the Glennon (1988) model and those outputted from VISSIM (PTV Group, 2016) were below 3%. Also, the microsimulation results indicated that passenger car drivers would not pass platoons of four oil and gas trucks with an intra-platoon spacing of 50 ft or wider on a 70-mph two-lane highway. It was recommended that another study be carried out to assess the feasibility of increasing the frequency of constructed passing or climbing lanes.

6. CONCLUSION AND RECOMMENDATIONS

Two-lane highways represent a considerable proportion of U.S. highways. Passing sight distance (PSD) is a fundamental component needed in the design of two-lane highways. At locations where the available PSD is shorter than the minimum required PSD, a no-passing zone should be striped. Other criteria for striping no-passing zones are passing lanes, locations with centerline channelization, transitions into/out of four-lane highways, intersections, interchange ramps, railroad crossings, and other locations that warrant the striping of such markings. There are multiple methods of measuring the PSD in the field; WYDOT implements the two-vehicle method, which specifies two successive vehicles traveling at the highway speed and spaced a distance equivalent to the PSD. Both vehicles have GPS devices, radio communication devices, and a monitor to display the data. Both vehicles compute their speeds using the GPS data collected and exchange all data with one another. The following vehicle is also instrumented with a switch. The driver of the following vehicle operates the switch to signal when the lead vehicle is no longer visible due to sight obstructions, indicating the beginning point of the no-passing zone. Likewise, when the lead vehicle returns to view, the switch is operated once more to declare the ending point of the no-passing zone. However, WYDOT's apparatus became nonfunctional and needed to be replaced. Therefore, this project aimed to develop two advanced prototypes of the two-vehicle method with state-of-the-art ITS devices and deliver them to WYDOT. The second prototype was designed to be more advanced than the first. Multiple units of Prototype 1 were reproduced and delivered to WYDOT. Near the completion of the project, Prototype 1's units were recalled and upgraded such that they were similar to Prototype 2.

This project's efforts contributed to that of Hutton and Cook (2016), who also implemented the two-vehicle method. Yet their equipment exhibited glitches (*19*). Brown and Hummer (2000) conducted a review of the field-based PSD data collection techniques (*17*). Other previous studies involved estimating the PSD by means of non-field-based methods (*18*, *20*, *21*, *33*). Yet, the two-vehicle method was carried out for this project since it is a field-based method preferred by WYDOT. More importantly, cutting-edge equipment was used to develop the two-vehicle method's prototypes, and it was ensured that the devices functioned well, unlike in the case of Hutton and Cook (2016).

Prototype 1 was developed and tested on a section of WY-210 and another belonging to US-287. The no-passing zone plans outputted by the prototype and WYDOT's were compared. As per the comparison results, overall discrepancies of 3.1% and 7% were obtained for the eastbound and westbound lanes of WY-210's test section, respectively. Concerning US-287's testing route, the overall discrepancies were 1% and 2.5% for the southbound and northbound directions, respectively. The discrepancies were possibly due to prolonged perception-reaction time (PRT) of the inspection team's personnel when declaring the no-passing zones' beginning points, the use of a less conservative, albeit valid, PSD value, or glitches that WYDOT later identified. Nevertheless, the overall discrepancies were lower than those of Hutton and Cook (2016). The glitches were addressed and WYDOT requested the replication of Prototype 1. Hence, multiple units of the equipment were delivered to WYDOT and one of the units was retained at the WYT2/LTAP Center for loaning to interested entities.

Prototype 2 was designed to be more innovative than Prototype 1 in that it automates some of its functions and produces more accurate results. Instead of operating a switch, the following vehicle was equipped with video cameras having machine vision systems that automatically detect the change in the lead vehicle's visibility status and hence the no-passing zone boundaries. This is less burdensome on the following vehicle's driver. Also, accurate results are computed since the PRT, associated with operating the switch, is substantially reduced. Afterward, Prototype 1's units were retrieved and upgraded such that their functionalities were similar to those of Prototype 2. With multiple prototypes, WYDOT and its counties and local governments, such as the Wind River Indian Reservation, could consistently establish and re-establish their two-lane highway zone striping plans without the impediment arising from deficient equipment.

Other than the development and delivery of the two-vehicle method's state-of-the-art prototypes, several two-lane highway studies were conducted and publicized in scientific peer-reviewed journals (*23*, *30*, *31*). Farid and Ksaibati (2020) investigated the severities of passing-related crashes on two-lane highways. Farid et al. (2021) compared of the performances of two rigorous statistical regression techniques when modeling two-lane highway crash severities (*29*, *30*). Haq et al. (2021) focused on computing PSDs for passing a platoon of oil and gas trucks on a 70-mph two-lane highway (*31*).

Recommendations are made for this project. One is to maintain the relationship with WYDOT should they require modifications to any of the prototypes provided. WYDOT may also request additional units of the prototypes. Equally important is the fact that any of the delivered equipment may malfunction in the future. In that case, the devices may be recalled and mended.

7. REFERENCES

1. Risa, J. "See the Status of the Worst Oroville-Gridley Area Roads, As Voted by Readers." *Enterprise-Record, MediaNews, Inc.*, , 2018. https://www.chicoer.com/2018/02/25/see-the-status-of-the-worst-oroville-gridley-area-roads-as-voted-by-readers/ (Accessed August 24, 2021)
2. Federal Highway Administration. *Manual on Uniform Traffic Control Devices*. U.S. Department of Transportation, Washington, D.C., 2012.
3. Wyoming Department of Transportation Traffic Program. *Pavement Marking Manual*. Wyoming Department of Transportation, Cheyenne, Wyoming, 2012.
4. American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets 7th Edition*. American Association of State Highway and Transportation Officials, Washington, D.C., 2018.
5. Forbes, G. "The Origin of Minimum Passing Sight Distances for No-Passing Zones." *ITE journal*, Vol. 60, No. 12, 1990, pp. 20–24.
6. Glennon, J. C. "New and Improved Model of Passing Sight Distance on Two-Lane Highways." *Transportation Research Record*, Vol. 1195, 1988, pp. 132–137.
7. Harwood, D. W., and J. C. Glennon. "Framework for Design and Operation of Passing Zones on Two-Lane Highways." *Transportation Research Record*, Vol. 601, 1976, pp. 45–50.
8. Hassan, Y., S. M. Easa, and A. O. Abd El Halim. "Passing Sight Distance on Two-Lane Highways: Review and Revision." *Transportation Research Part A: Policy and Practice*, Vol. 30, No. 6, 1996, pp. 453–467. https://doi.org/10.1016/0965-8564(95)00032-1.
9. Lieberman, E. B. "Model for Calculating Safe Passing Distances on Two-Lane Rural Roads." *Transportation Research Record*, No. 869, 1982.
10. Ohene, F. A., and S. A. Ardekani. "Minimum Passing Sight Distance for Completing or Aborting the Passing Maneuver." *Institute of Transportation Engineers Journal*, Vol. 58, No. 7, 1988, pp. 29–33.
11. Rilett, L. R., B. G. Hutchinson, and M. Whitney. "Mechanics of the Passing Maneuver and the Impact of Large Trucks." *Transportation Research Part A: General*, Vol. 24, No. 2, 1990, pp. 121–128. https://doi.org/10.1016/0191-2607(90)90019-3.
12. Saito, M. "Evaluation of the Adequacy of the MUTCD Minimum Passing Sight Distance Requirement for Aborting the Passing Maneuver." *ITE Journal*, Vol. 54, No. 1, 1984, pp. 18–22.
13. Van Valkenburg, G. W., and H. L. Michael. *Criteria for No-Passing Zones*. Purdue University, Joint Highway Research Project, 1971.
14. Wang, Y., and M. P. Cartmell. "New Model for Passing Sight Distance on Two-Lane Highways." *Journal of Transportation Engineering*, Vol. 124, No. 6, 1998, pp. 536–545. https://doi.org/10.1061/(ASCE)0733-947X(1998)124:6(536).
15. Weaver, G. D., and J. C. Glennon. "Design and Striping for Safe Passing Operations." *Highway Research Record*, No. 390, 1972.
16. Harwood, D. W., and C. Sun. *Passing Sight Distance Criteria*. Transportation Research Board, 2008.
17. Brown, R. L., and J. E. Hummer. "Determining the Best Method for Measuring No-Passing Zones." *Transportation Research Record*, Vol. 1701, No. 1, 2000, pp. 61–67. https://doi.org/10.3141/1701-08.
18. Namala, S. R., and M. J. Rys. *Automated Calculation of Passing Sight Distance Using Global Positioning System Data*. Kansas. Dept. of Transportation, 2006.
19. Hutton, J. M., and D. J. Cook. *Developing a System to Identify Passing and No Passing Zone Boundaries on Rural Two-Lane Highways*. Missouri. Dept. of Transportation, 2016.
20. Azimi, M., and H. Hawkins. *Automating the Process for Locating No-Passing Zones Using Georeferencing Data.* Southwest Region University Transportation Center (US), 2012.

21. Gargoum, S. A., K. El-Basyouny, and J. Sabbagh. "Assessing Stopping and Passing Sight Distance on Highways Using Mobile LiDAR Data." *Journal of Computing in Civil Engineering*, Vol. 32, No. 4, 2018, p. 04018025. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000753.
22. Ma, Y., Y. Zheng, J. Cheng, L. Guo, and Y. Zhang. "A Novel Real-Time Visualization Algorithm for Computing Three-Dimensional Sight Distance." 2018.
23. Farid, A., Z. Connell, J. Mock, S. Muknahallipatna, and K. Ksaibati. "Introducing a New Apparatus for Designating Two-Lane Highway Passing and No-Passing Zones." *Transportation Research Record*, Vol. 2675, No. 6, 2021, pp. 420–428. https://doi.org/10.1177/0361198121994112.
24. Ouya, A., B. M. De Aragon, C. Bouette, G. Habault, N. Montavont, and G. Z. Papadopoulos. "An Efficient Electric Vehicle Charging Architecture Based on LoRa Communication." 2017. https://doi.org/10.1109/SmartGridComm.2017.8340723.
25. Orfanidis, C., L. M. Feeney, M. Jacobsson, and P. Gunningberg. "Investigating Interference between LoRa and IEEE 802.15. 4g Networks." 2017. https://doi.org/10.1109/WiMOB.2017.8115772.
26. Omar, H. M., Z. Yanzhong, Z. Bo, and H. U. Gul. "Integration of GPS and Dead Reckoning Navigation System Using Moving Horizon Estimation." 2016. https://doi.org/10.1109/ITNEC.2016.7560421.
27. Google L.L.C. 2021 Google Maps. https://www.google.com/maps. Accessed August 26, 2021.
28. United States Geological Survey (USGS). TNM Download (v2.0). 2023. Retrieved from https://apps.nationalmap.gov/downloader/#/.
29. Farid, A., A. Alrejjal, and K. Ksaibati. "Two-Lane Highway Crash Severities: Correlated Random Parameters Modeling Versus Incorporating Interaction Effects." *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2675, No. 11, 2021, pp. 565–575. https://doi.org/10.1177/03611981211018473.
30. Farid, A., and K. Ksaibati. "Modeling Two-Lane Highway Passing-Related Crashes Using Mixed Ordinal Probit Regression." *Journal of Transportation Engineering, Part A: Systems*, Vol. 146, No. 9, 2020, p. 04020092. https://doi.org/10.1061/JTEPBS.0000428.
31. Haq, M. T., A. Farid, and K. Ksaibati. "Estimating Passing Sight Distances for Overtaking Truck Platoons–Calibration and Validation Using VISSIM." *International Journal of Transportation Science And Technology*, Vol. 11, No. 2, 2022, pp. 255–267. https://doi.org/10.1016/j.ijtst.2021.03.009.
32. Eluru, N., C. R. Bhat, and D. A. Hensher. "A Mixed Generalized Ordered Response Model for Examining Pedestrian and Bicyclist Injury Severity Level in Traffic Crashes." *Accident Analysis & Prevention*, Vol. 40, No. 3, 2008, pp. 1033–1054. https://doi.org/10.1016/j.aap.2007.11.010.
33. Mannering, F. L., V. Shankar, and C. R. Bhat. "Unobserved Heterogeneity and the Statistical Analysis of Highway Accident Data." *Analytic Methods in Accident Research*, Vol. 11, 2016, pp. 1–16. https://doi.org/10.1016/j.amar.2016.04.001.
34. Fountas, G., P. C. Anastasopoulos, and M. Abdel-Aty. "Analysis of Accident Injury-Severities Using a Correlated Random Parameters Ordered Probit Approach with Time Variant Covariates." *Analytic Methods in Accident Research*, Vol. 18, 2018, pp. 57–68. https://doi.org/10.1016/j.amar.2018.04.003.
35. PTV Group. PTV VISSIM Version 9. PTV Group, Karlsruhe, Germany, 2016.

8. APPENDIX

Mapping Automation for Passing Zones (MAPZ): Quick Start Guide

Step 1: With the vehicle off and parked, locate the 12V DC power socket and plug in the AC power inverter.

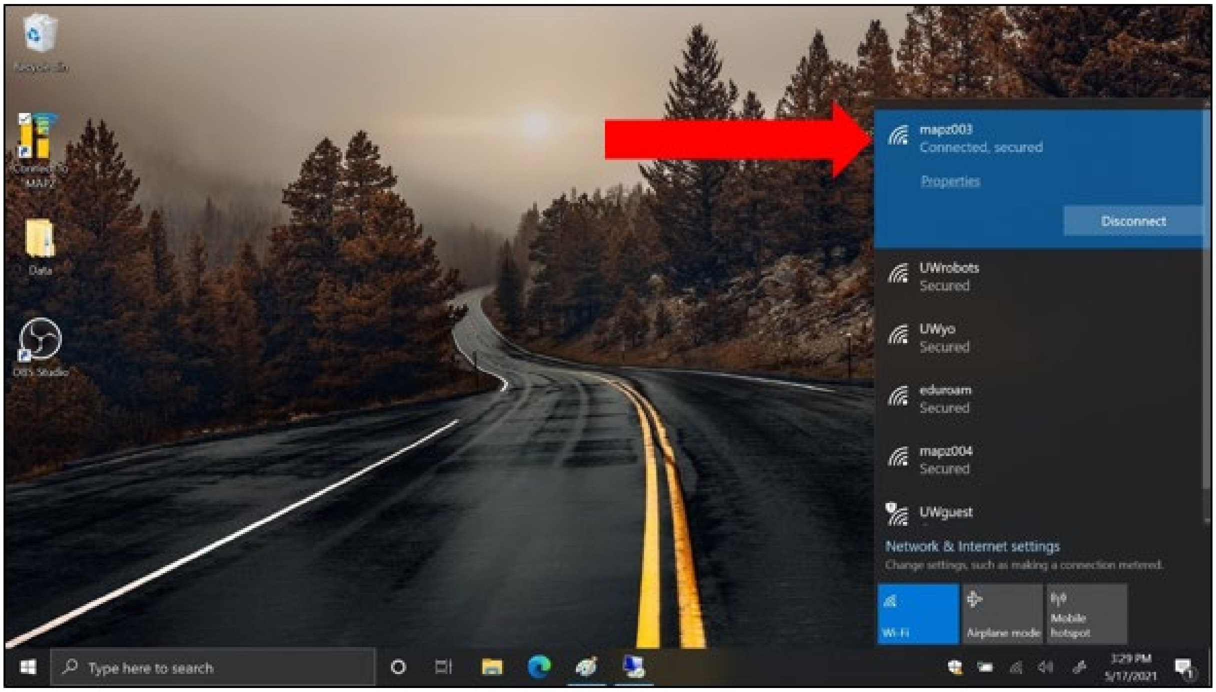
Step 2: Plug the MAPZ device into the AC Inverter. Place the MAPZ device and the inverter on the floor of the passenger's seat.

Step 3: Raise the Wi-Fi antennas on the top of the MAPZ device.

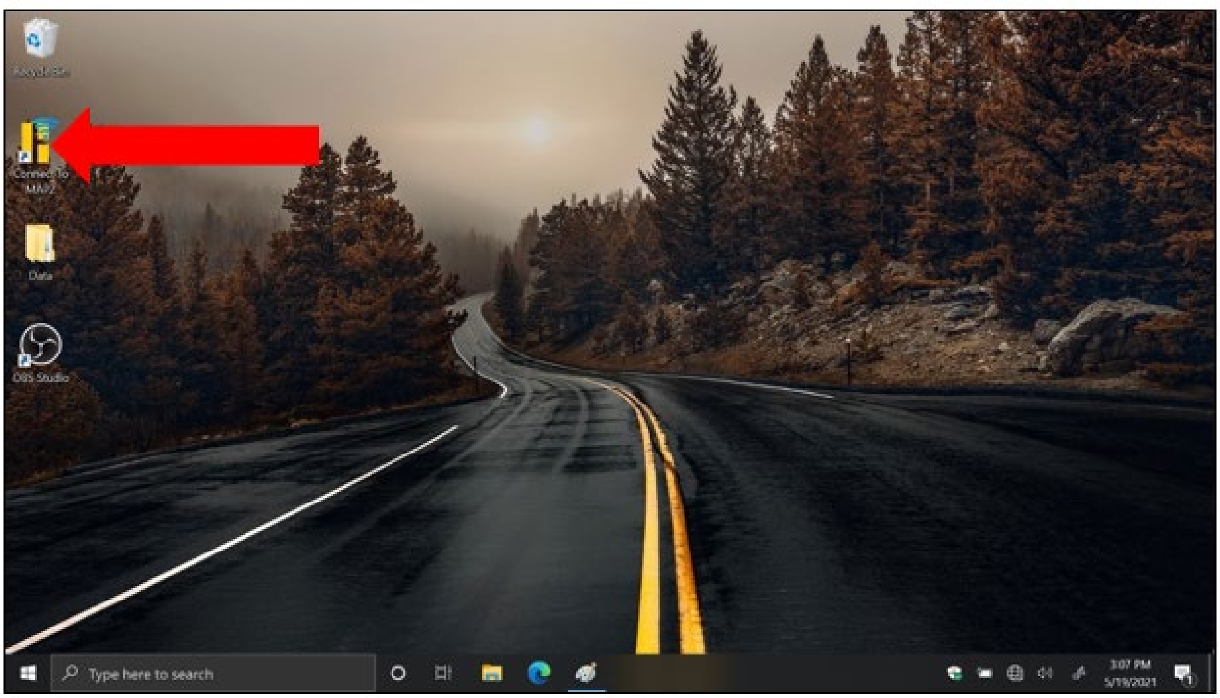
Step 4: Attach the antennas to the roof of the vehicle.

Step 5: Route the cables through the door frame so they are not pinched.

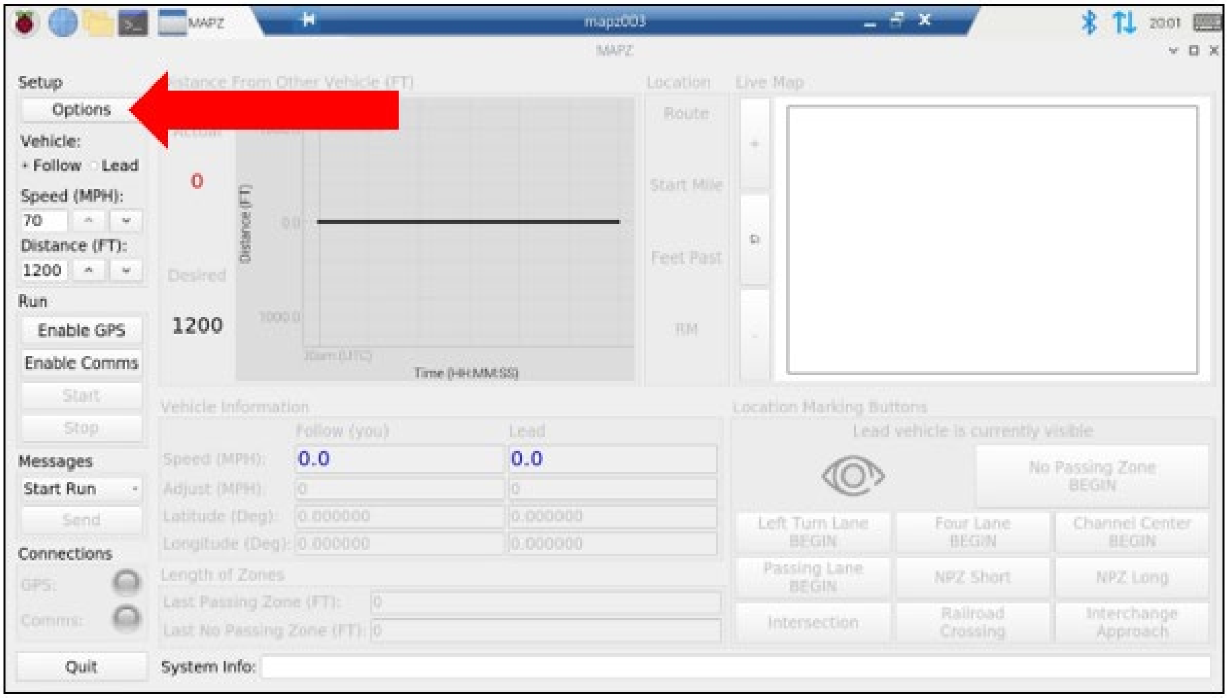
Step 6: Turn on the vehicle. Turn on the inverter by flipping the power switch to the on position. Turn on the MAPZ device by pressing down the power button on the top of the device till it latches.



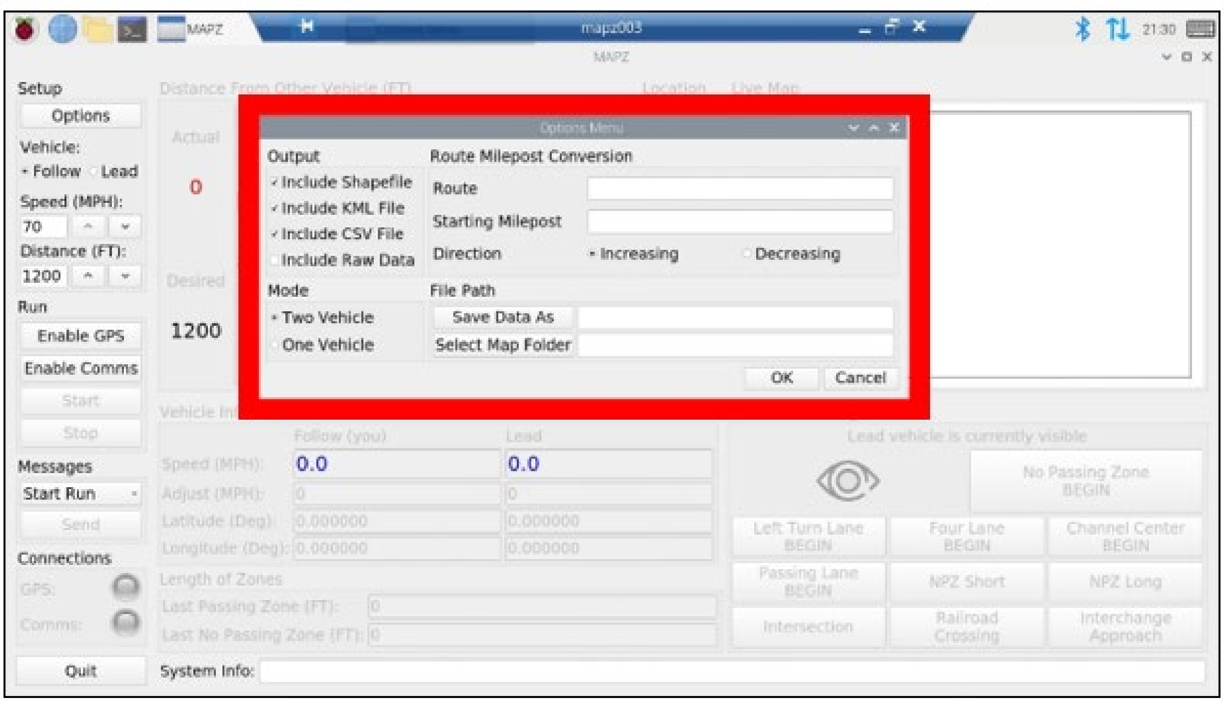
Step 7: Once the device is powered on, ensure your laptop is connected to the MAPZ network.



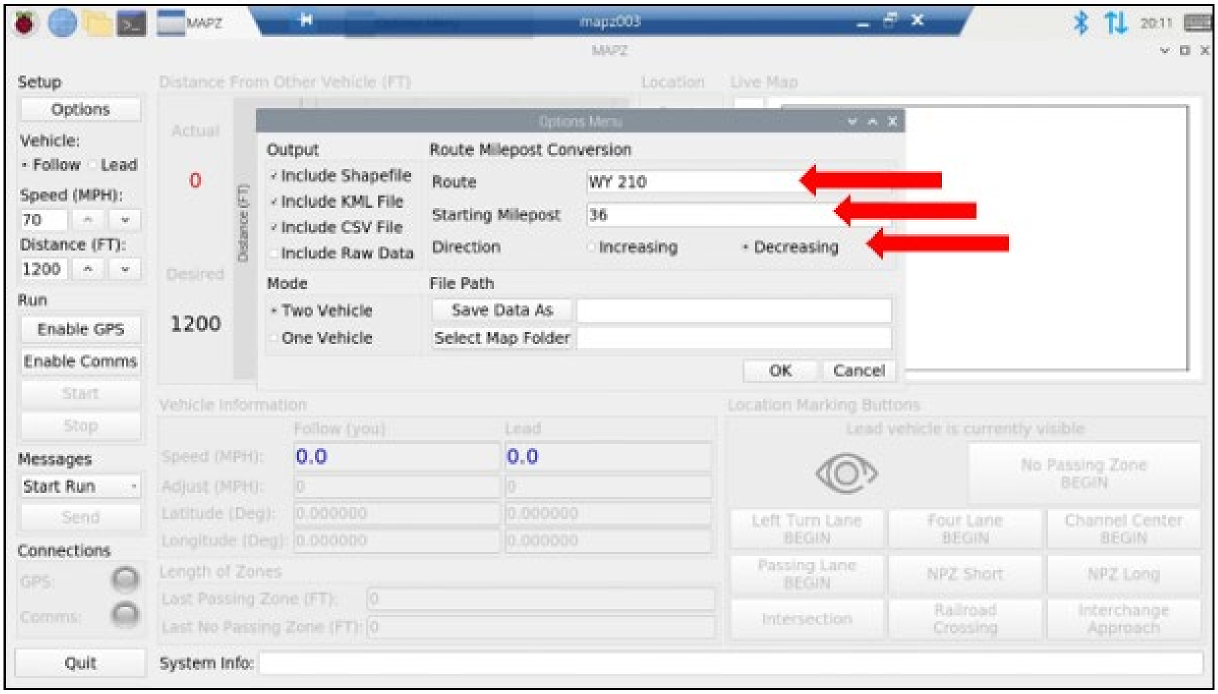
Step 8: Start the MAPZ software by double clicking the “Connect to MAPZ” icon.



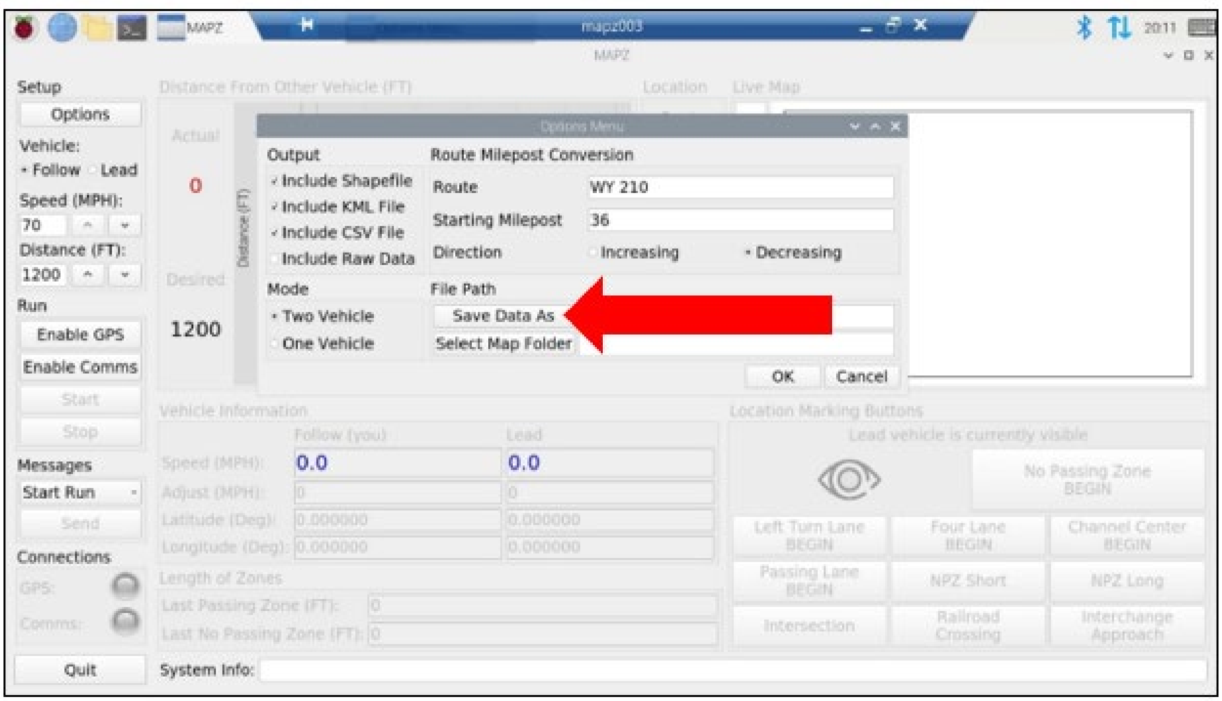
Step 9A: Once the device is connected, this screen will appear. To begin the setup process, click on the "Options" button.



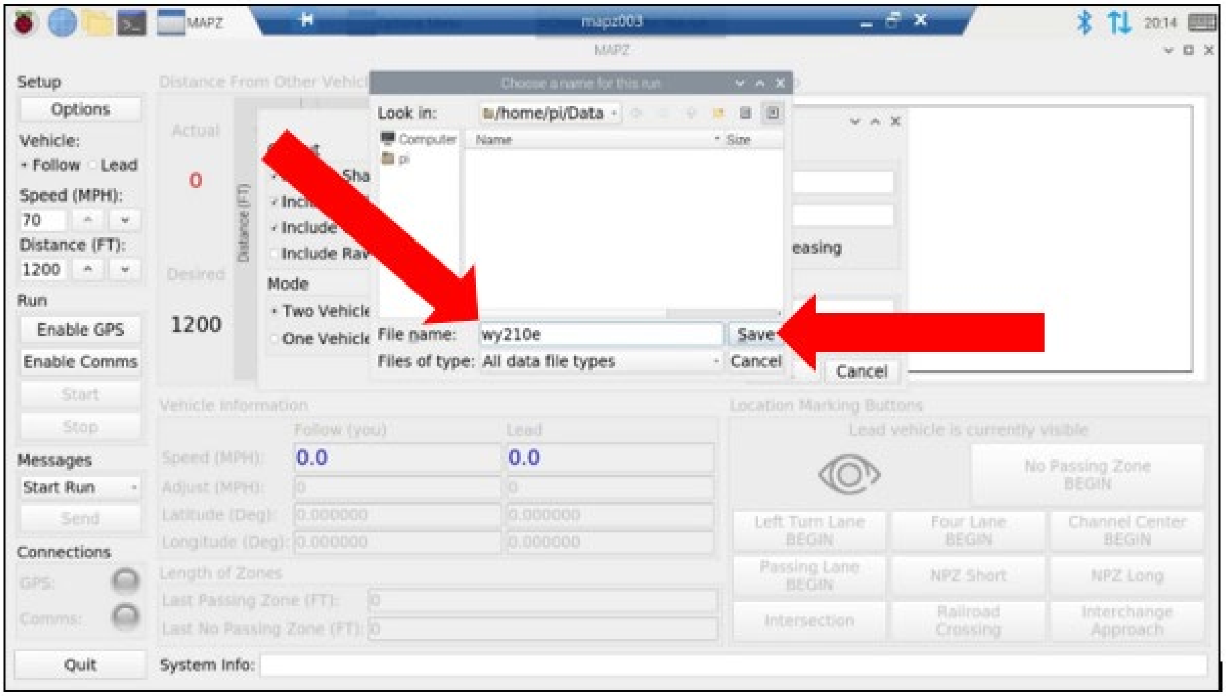
Step 9B: After clicking the "Options" button the options menu will appear.



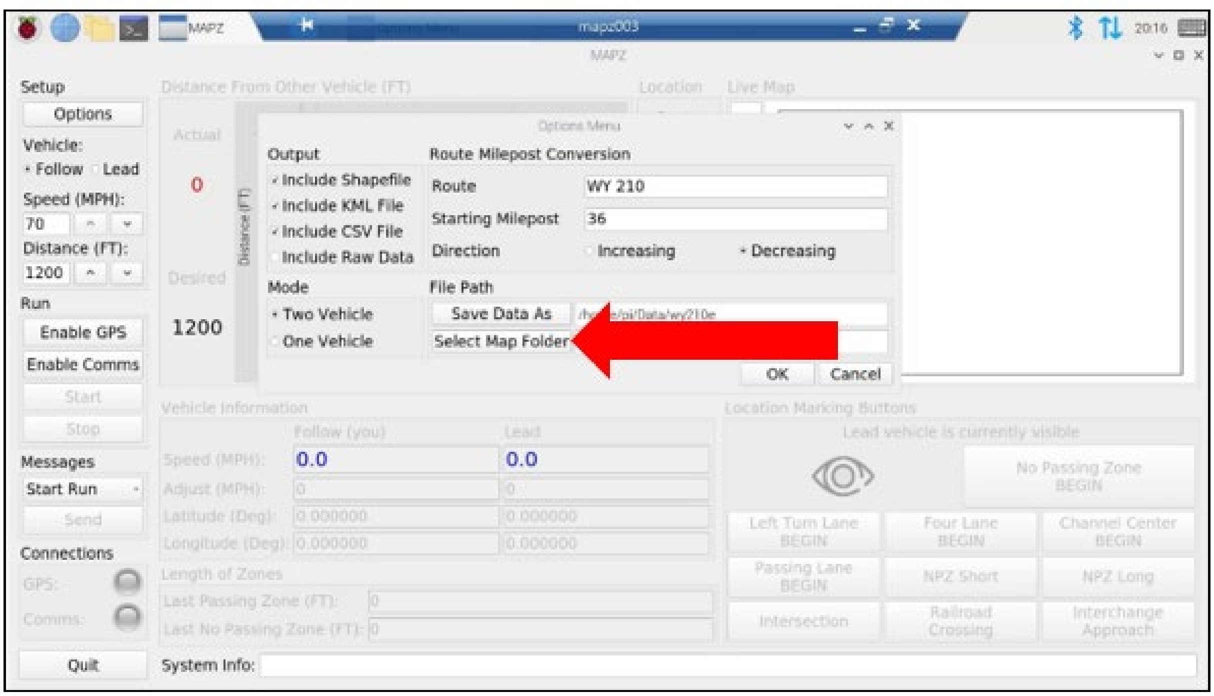
Step 10: Enter the highway/road name in the "Route" dialog box. Next, enter the starting mile maker in the "Starting Milepost" dialog box. Then select if the mile markers increase or decrease.



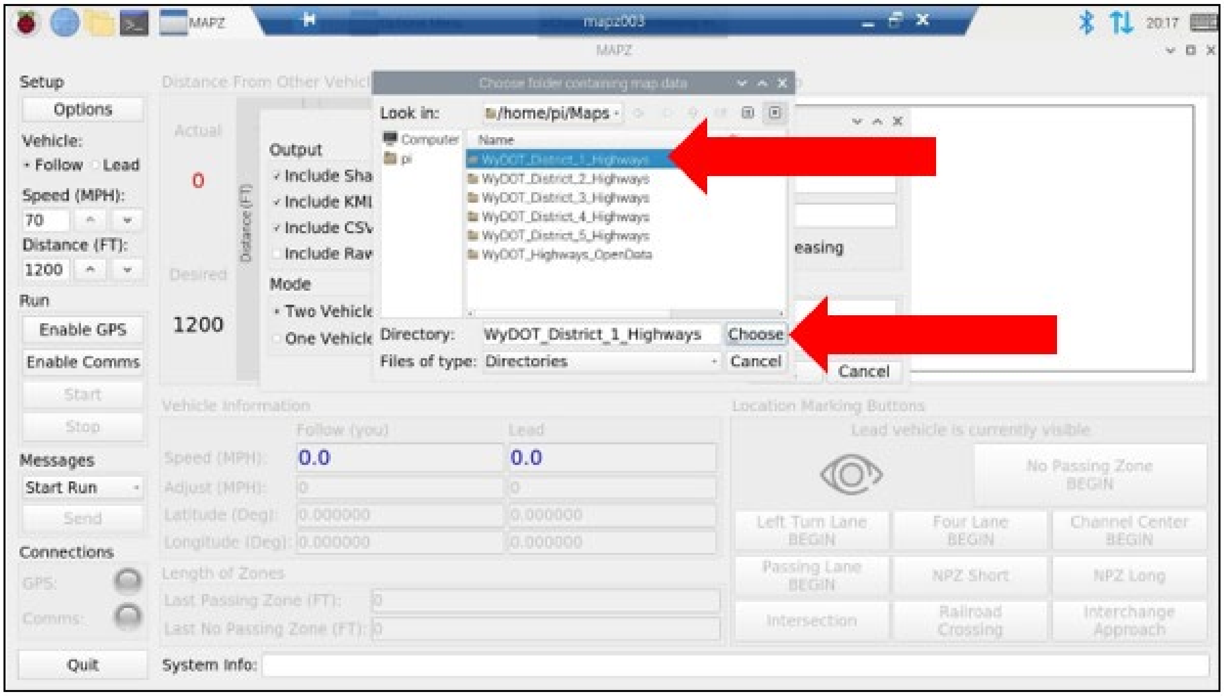
Step 11A: Click on the "Save Data As" button to open the save menu.
*Skip this step if operating as lead vehicle.



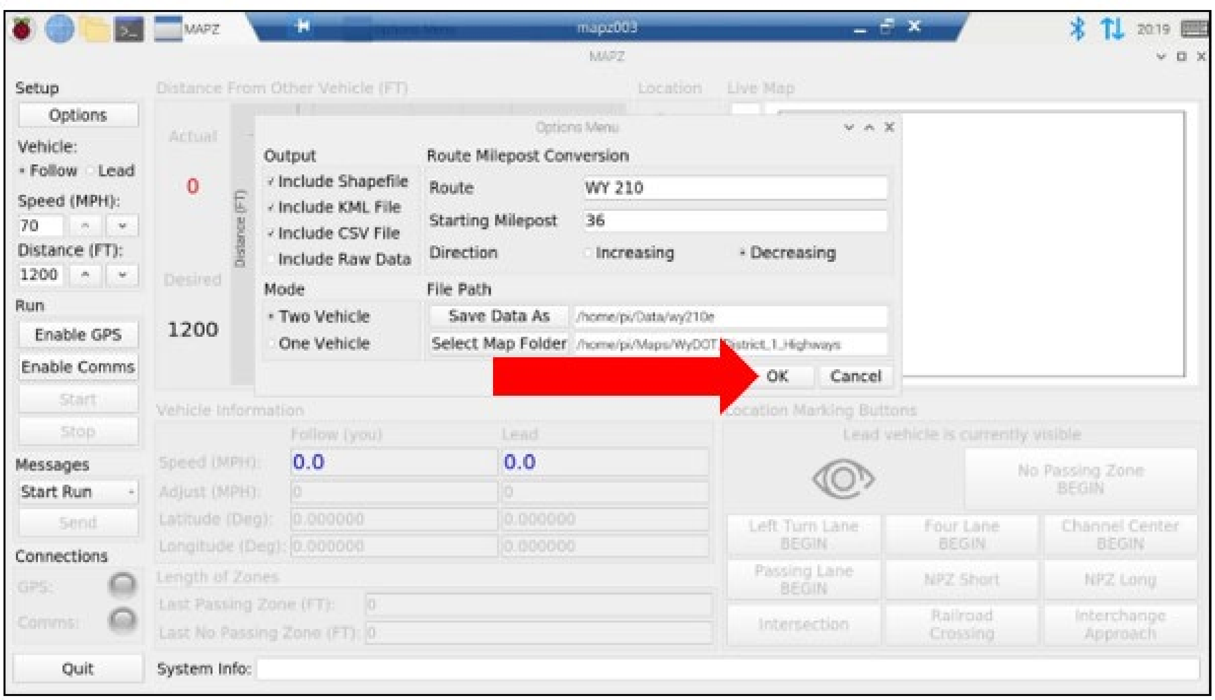
Step 11B: Enter a filename into the “File Name” dialog box. Then click on the save button to exit the save menu.



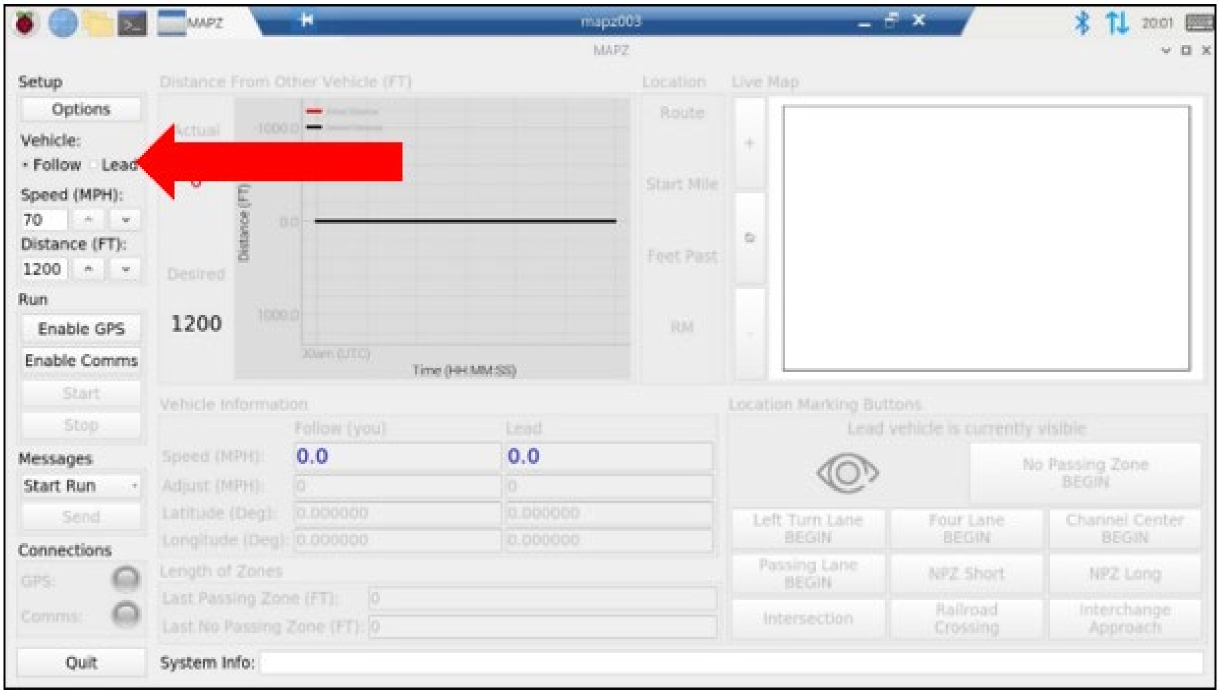
Step 12A: To add a live map, click on the “Select Map Folder” button to open the map menu.



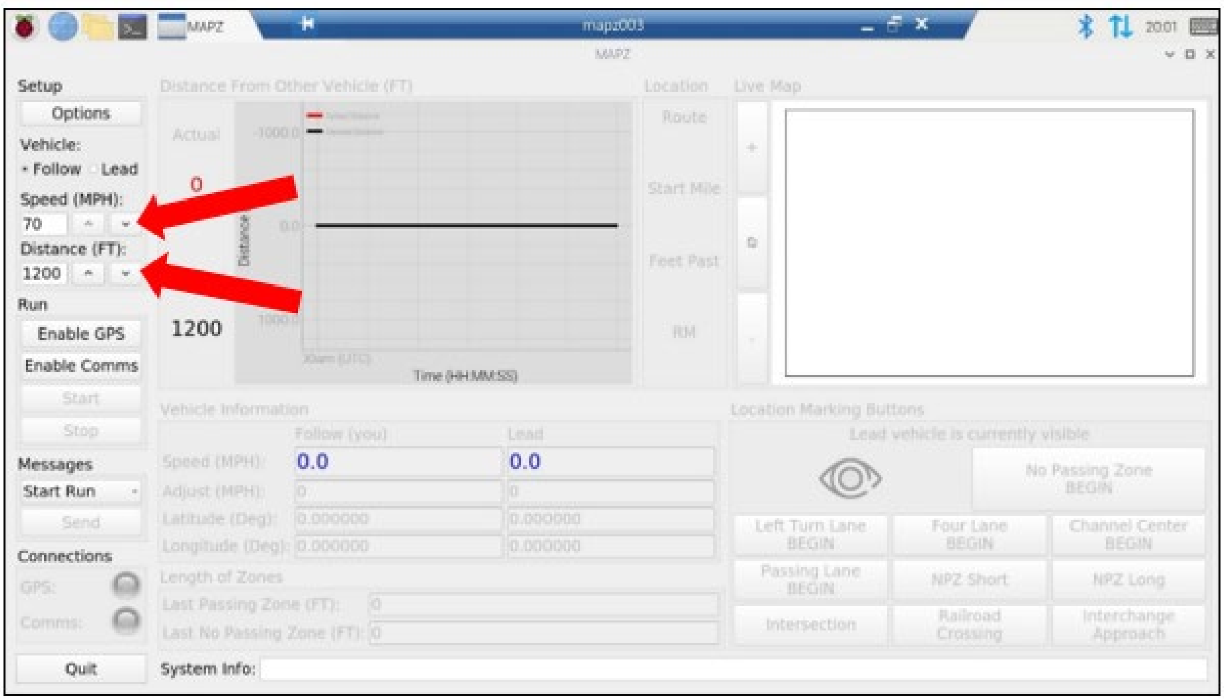
Step 12B: Select the district the highway/road is located in. Then click on “Choose” to exit the map menu.



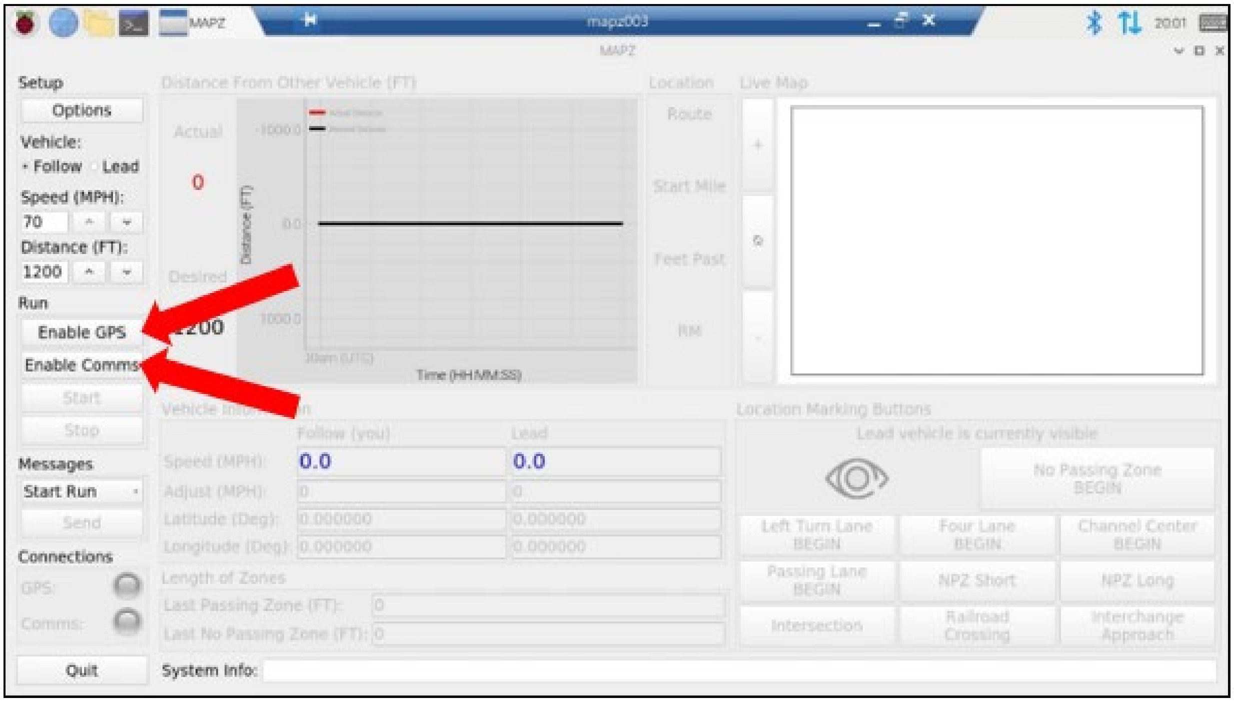
Step 13: Click on “OK” to exit the options menu.



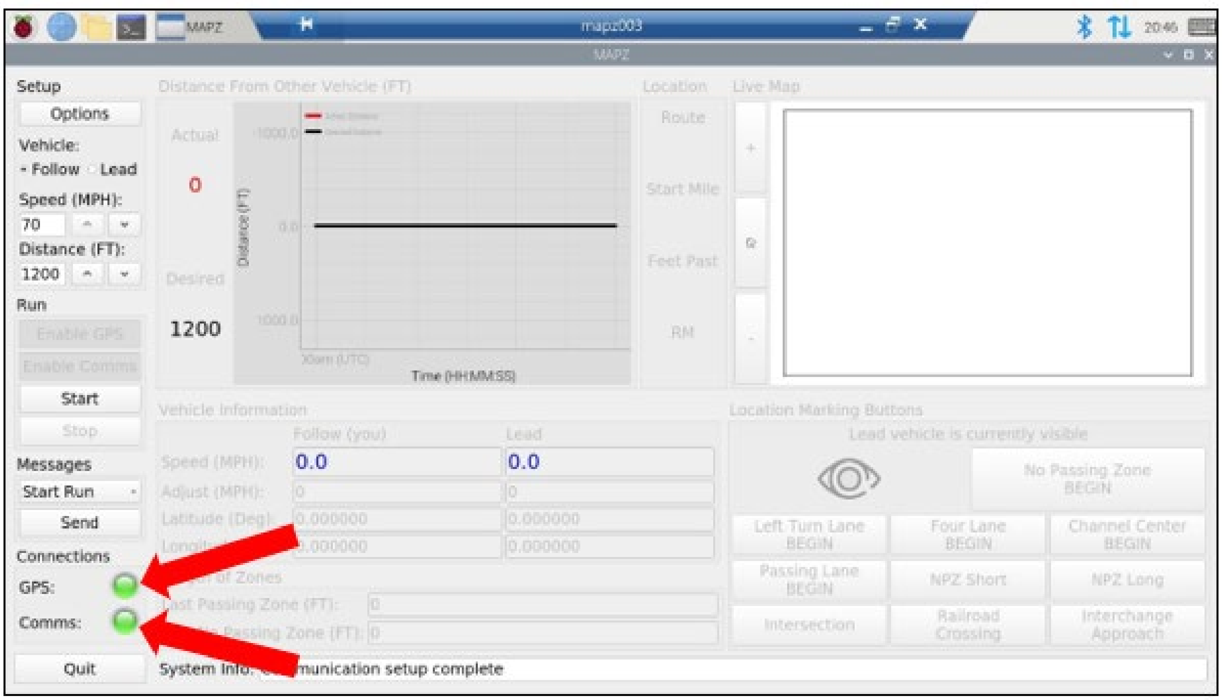
Step 14: Select vehicle position. By default, "Follow" is selected.



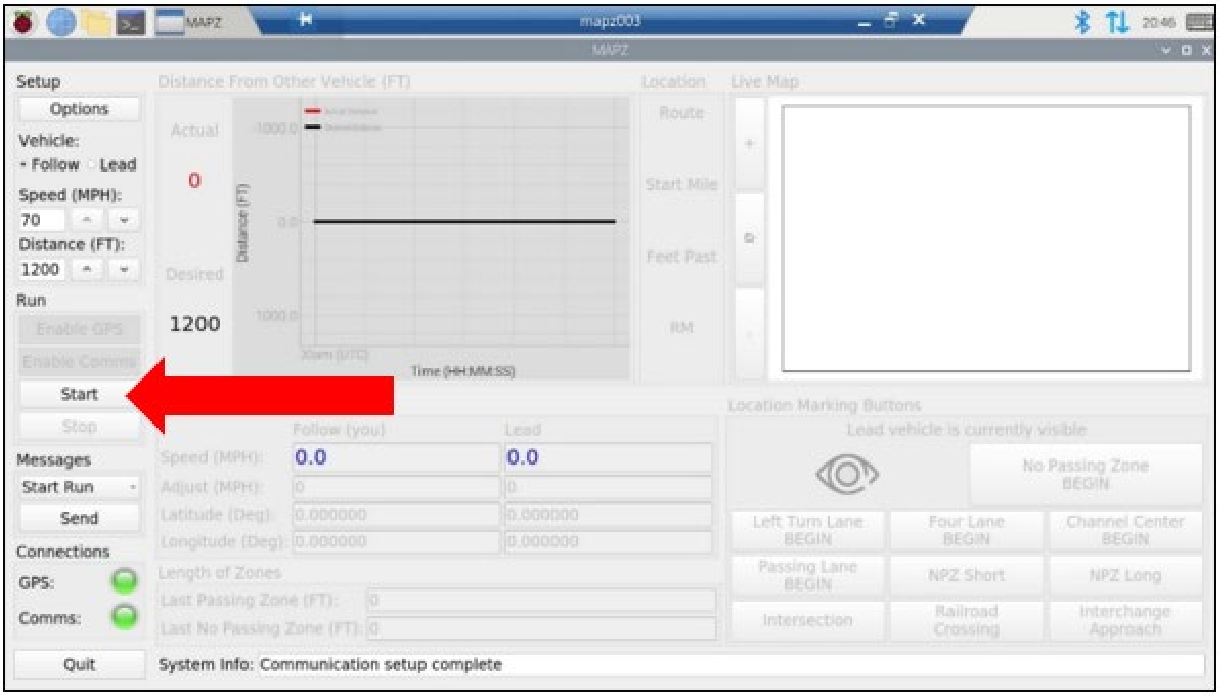
Step 15: Change the desired speed limit by using the arrow buttons to the right of the "Speed" dialog box. Changing the set speed will automatically change the set distance. Distance can be set manually as well using the arrows under "Distance."



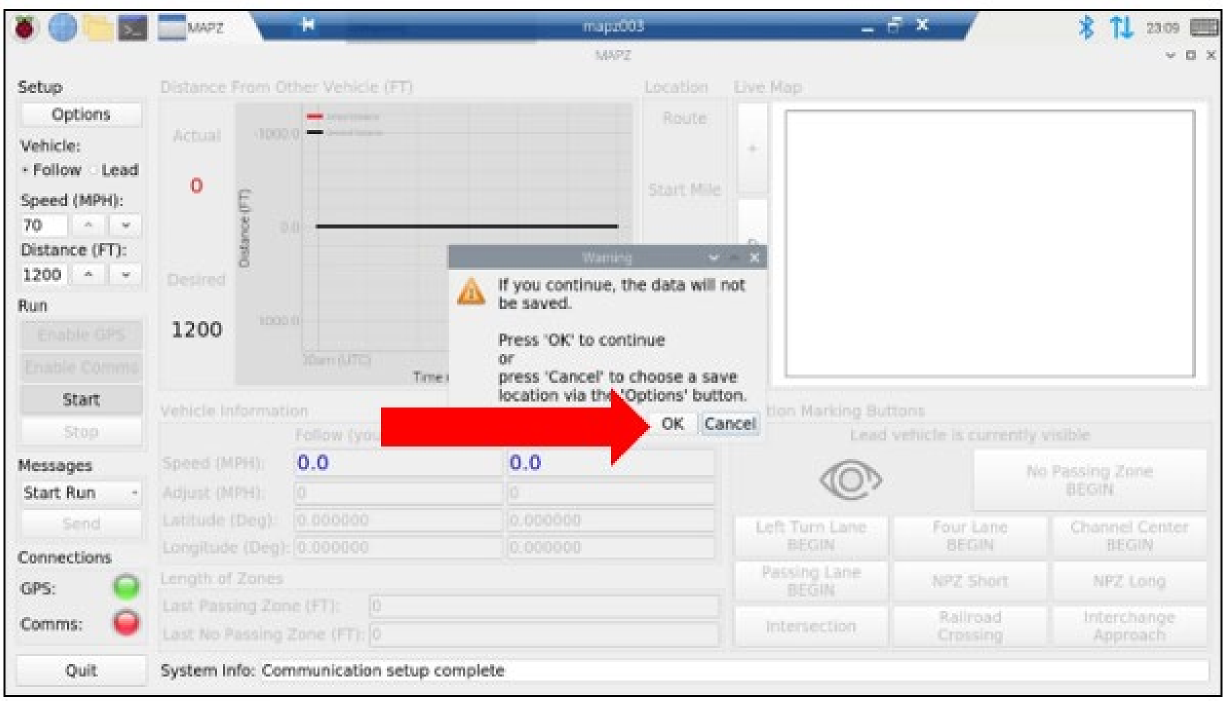
Step 16A: Click “Enable GPS” and “Enable Comms.”



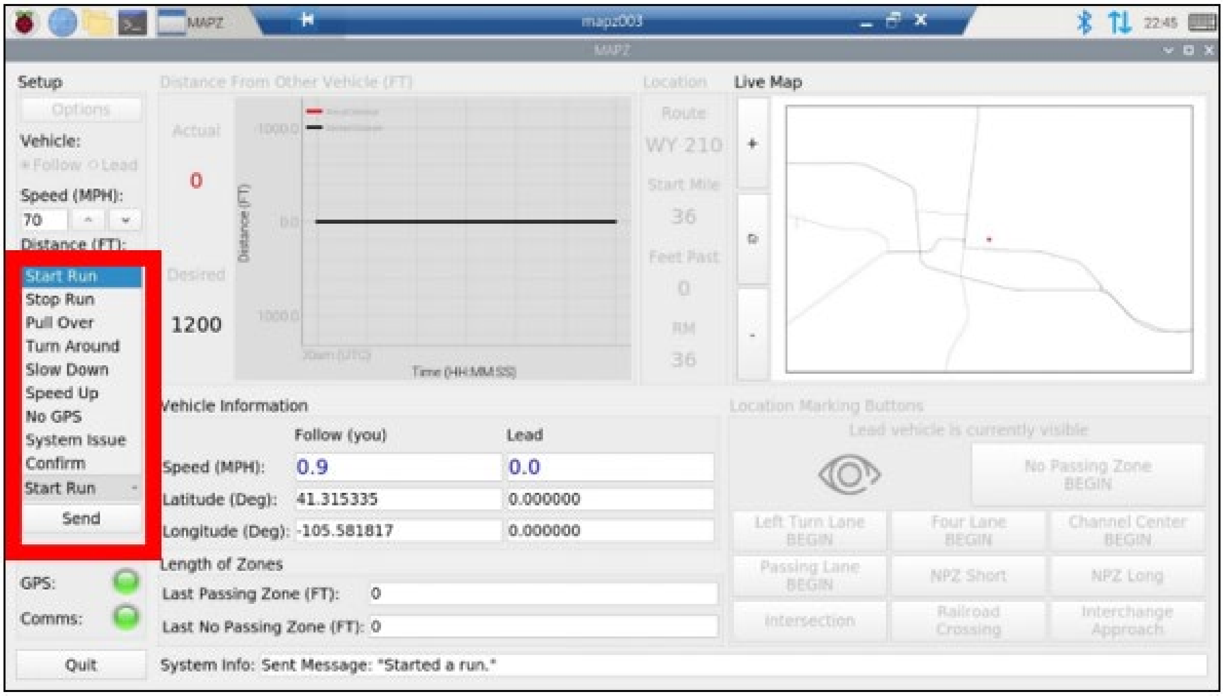
Step 16B: Once GPS and Comms have been enabled, the status indicators under “Connections” will change color. Green indicates that the device is working properly and red indicates that the device is not successful in acquiring GPS or communicating with the other vehicle.



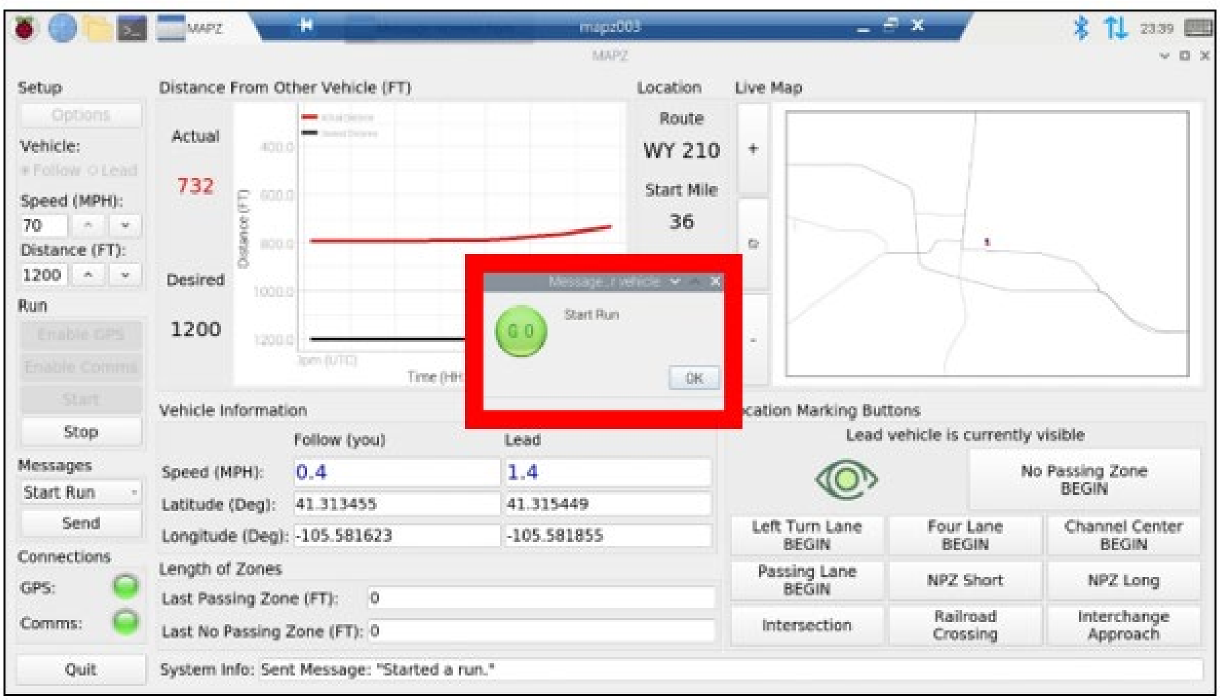
Step 17A: If both indicators are green, it is ok to begin the run. Begin the run by clicking the “Start” button.



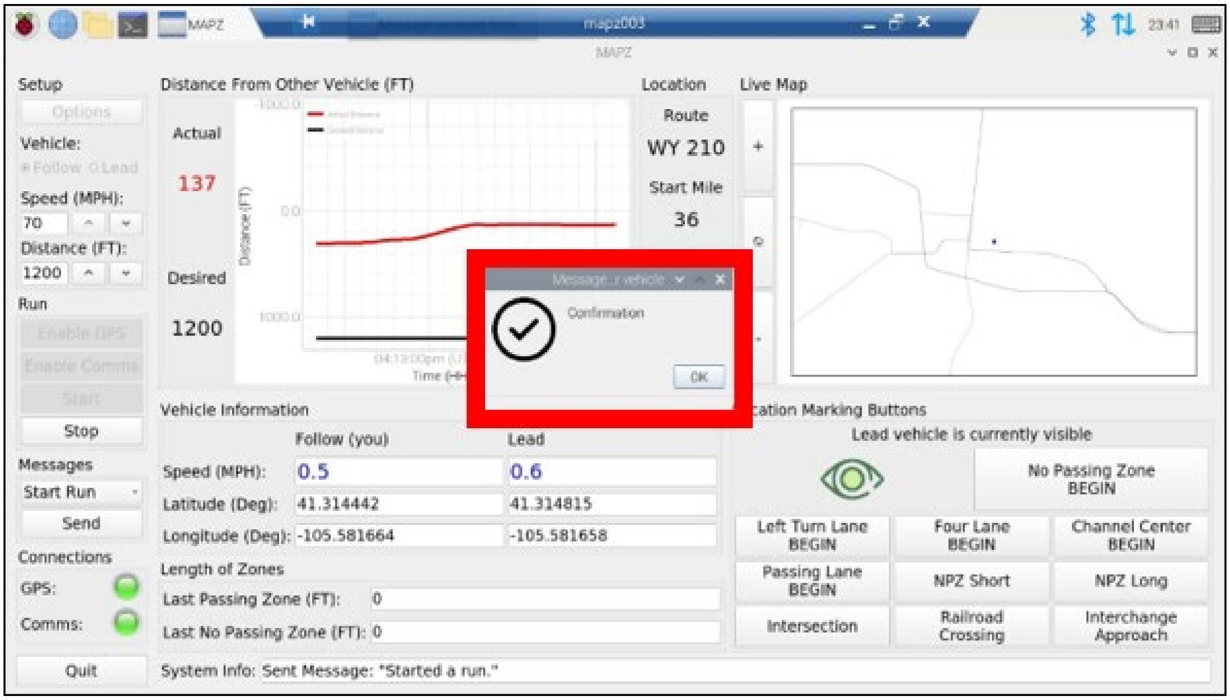
Step 17B: If operating as lead vehicle, a warning message will appear. Click “OK” to start the run.



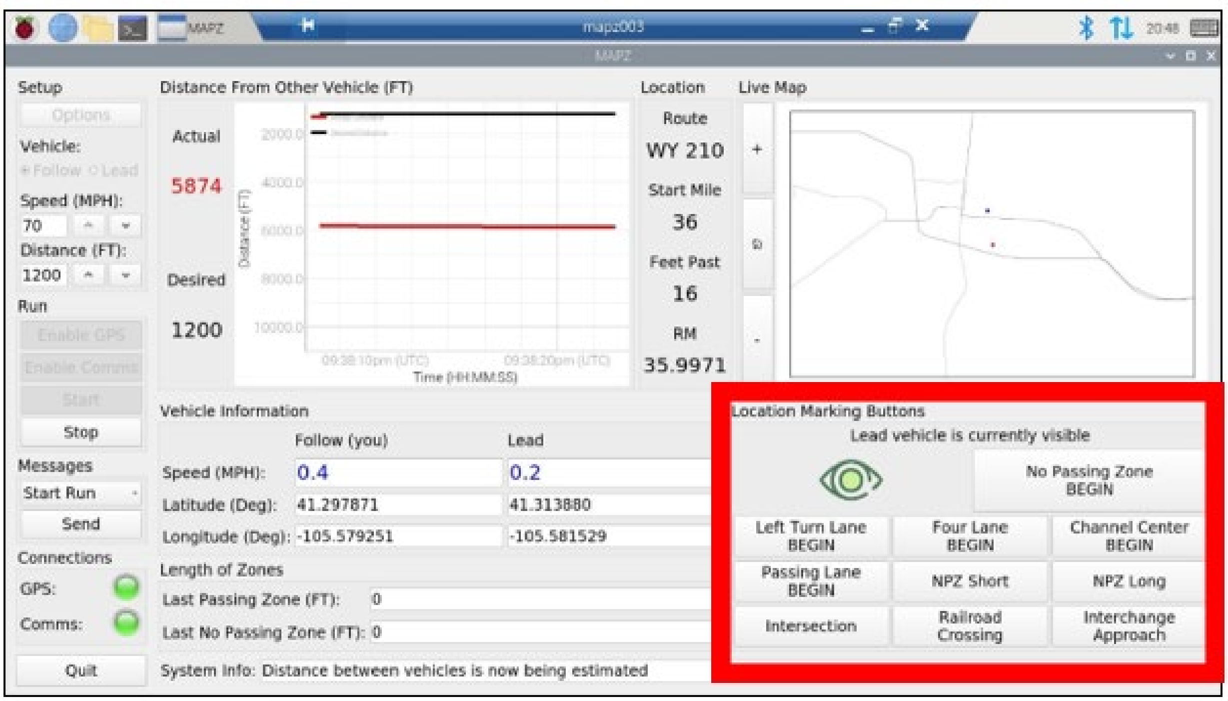
Messages can be sent between vehicles via the "Messages" section. A drop-down menu is used to select the message. Once a message is selected, click "Send" to transmit the message.



The other vehicle will receive a pop-up with the sent message. Click "OK" to close the message.

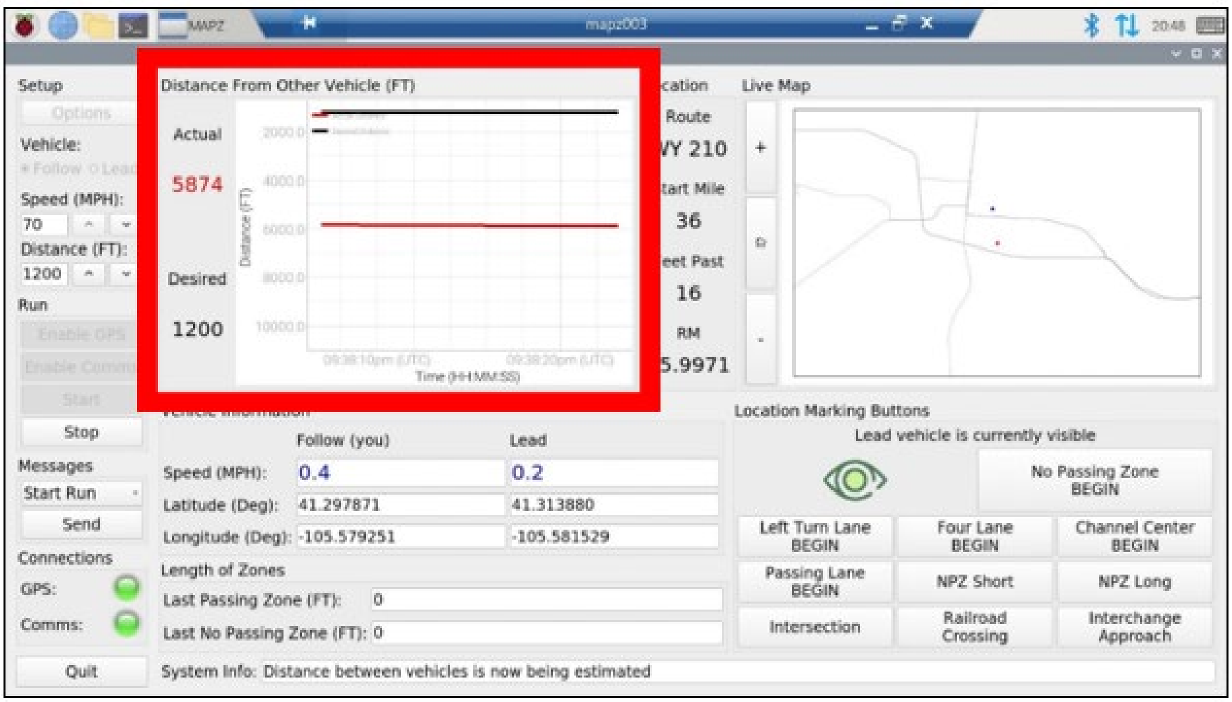


A confirmation message is included in the drop-down menu to acknowledge messages.

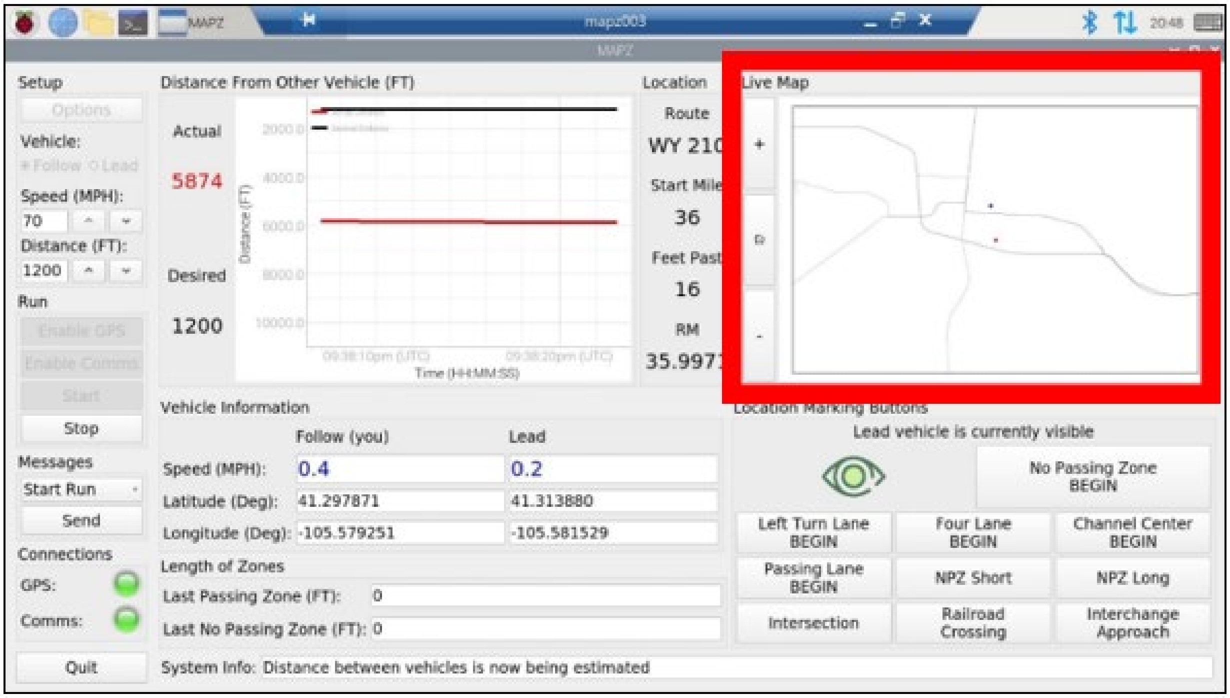


Location is marked with the "Location Marking Buttons." Marked locations will appear on the live map.

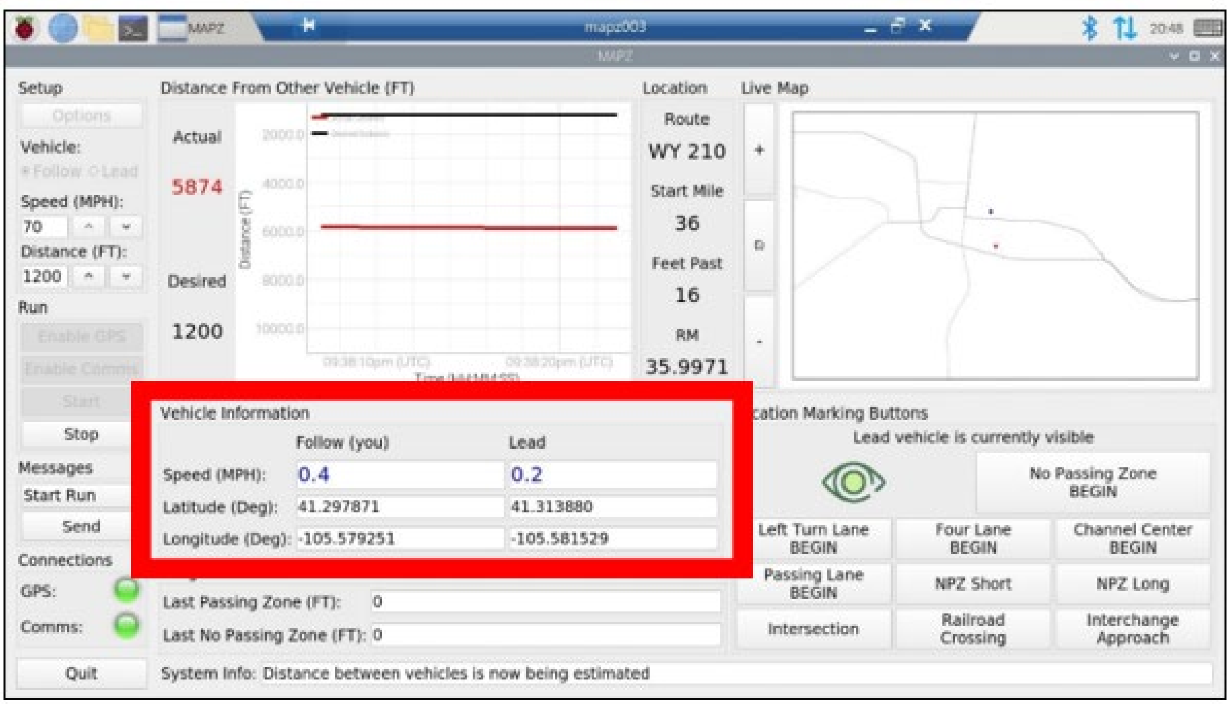
The passing zones can also be marked with the handheld button connected to the MAPZ device.



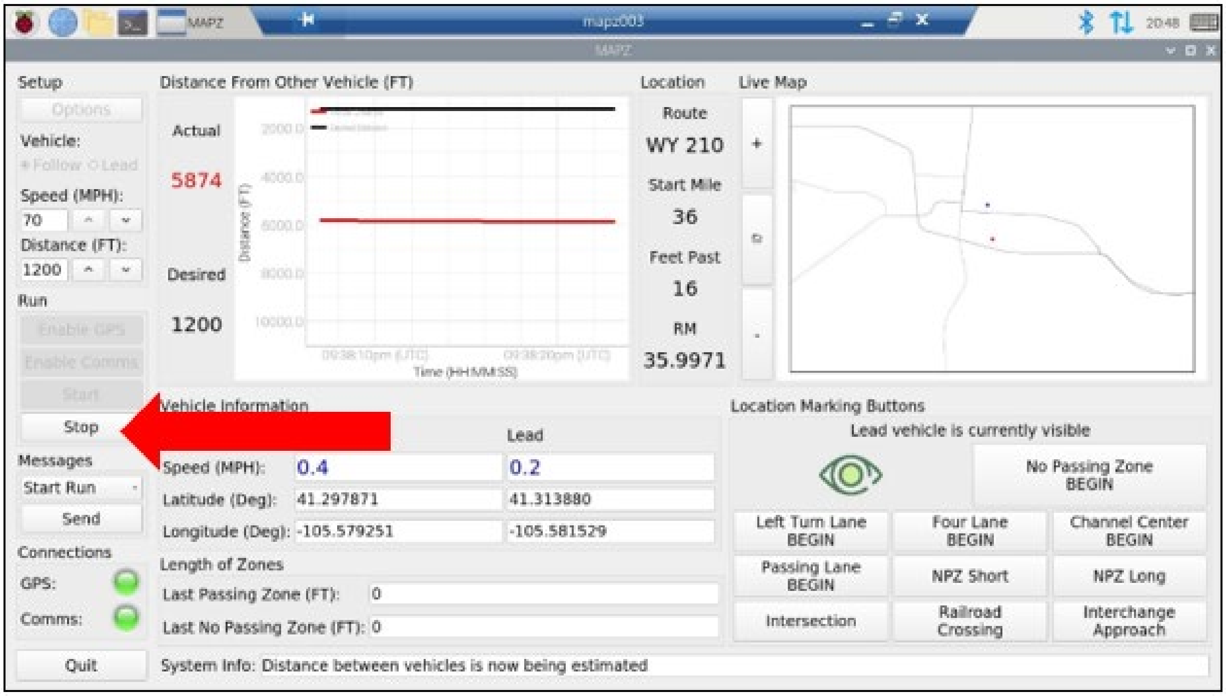
The “Distance from Other Vehicle” section displays the actual and desired vehicle distance.



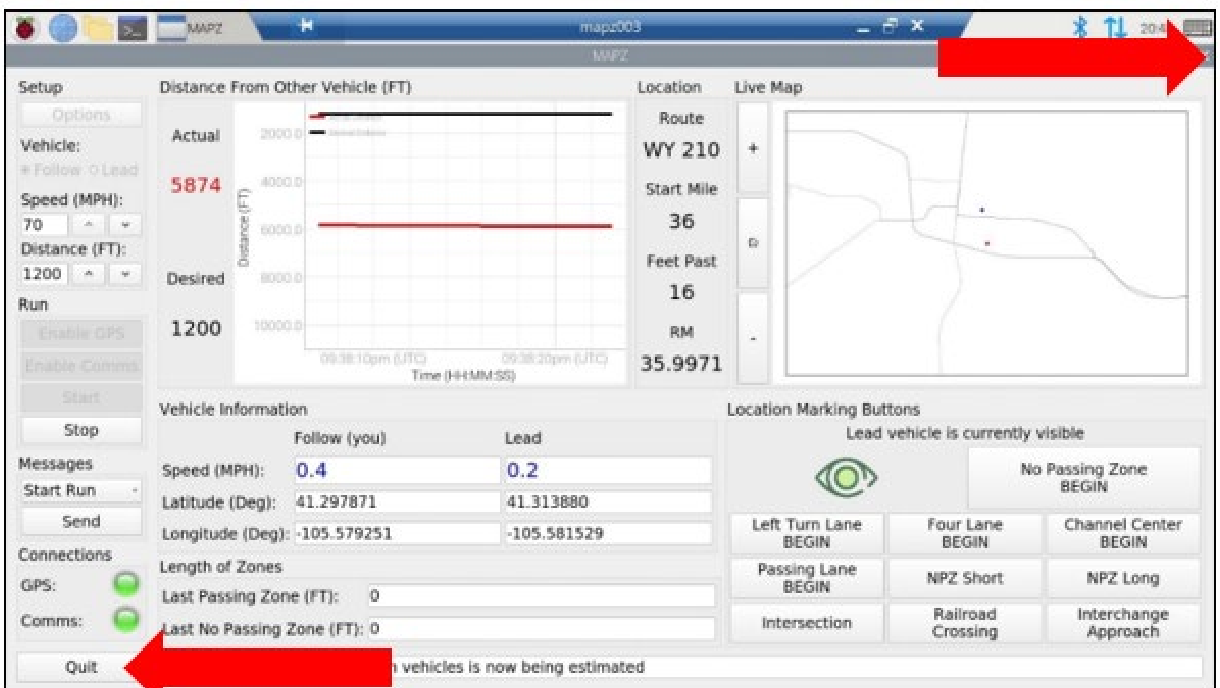
The "Live Map" displays the road, the location of both vehicles, and marked points in real time. The "+" and "-" buttons can be used to zoom in and out of the map.



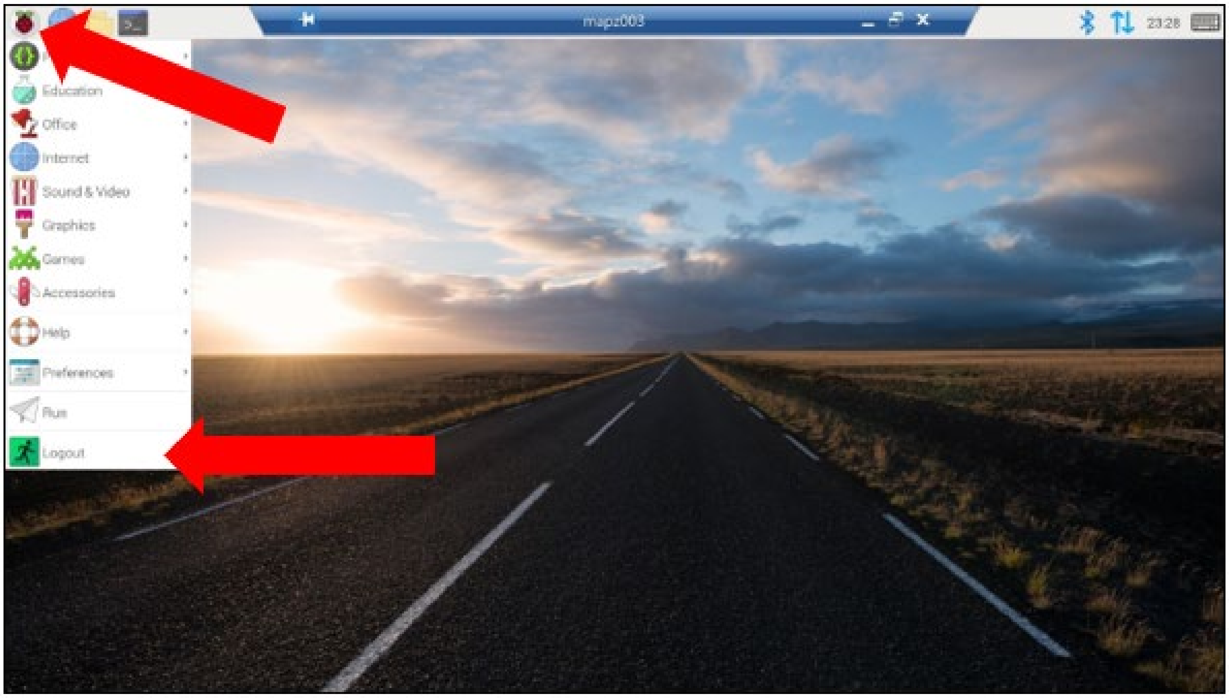
The "Vehicle Information" section displays the speed and GPS coordinates of both vehicles.



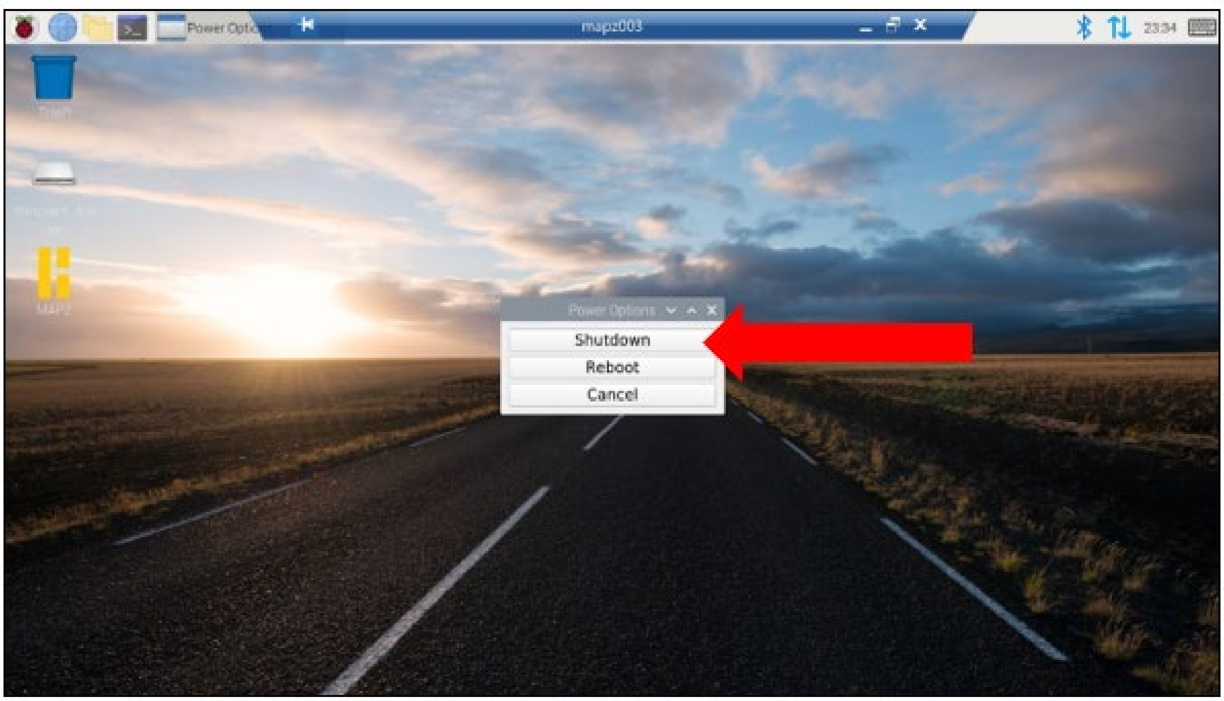
Step 18: To stop the run, click the “Stop” button.



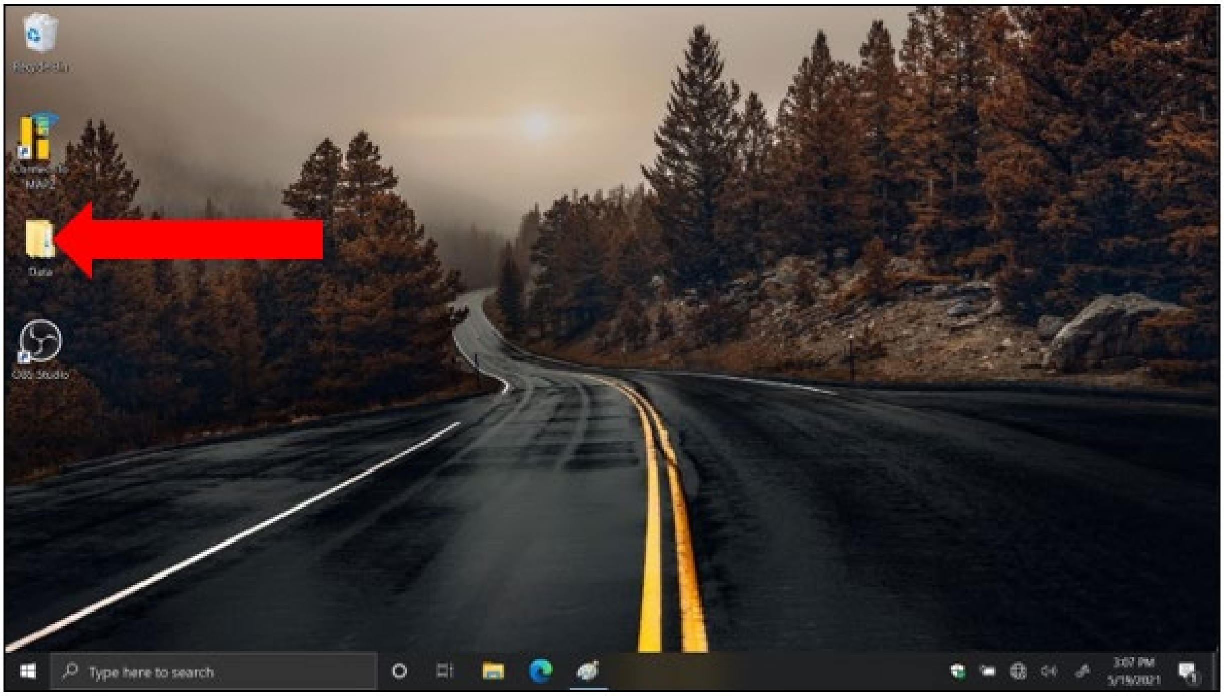
Step 19: To quit the program, click the “Quit” button or the “X” at the top right of the screen. If a run is in progress the data will be saved before the program closes.



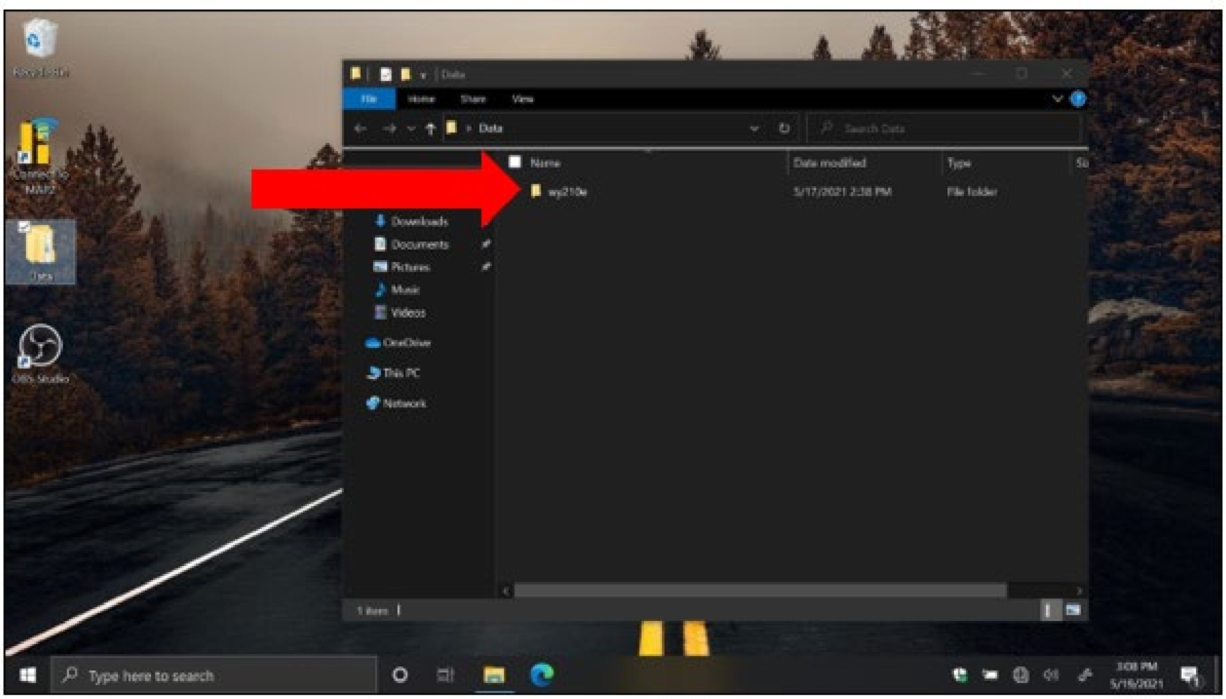
Step 20A: To shut down the MAPZ device, click on the raspberry icon at the top left of the screen. Then, click on "Logout."



Step 20B: Once the "Power Options" menu appears click on the "Shutdown" button. It is now safe to depress the power button on the top of the MAPZ device.



Step 21A: The run data are saved to a folder named “Data” on the desktop.



Step 21B: A folder with the name selected in step 11B will now be present.
*To modify the run data, they must be copied to another folder first.