FINAL REPORT

WY-WY2306F

Wyoming Department of Transportation, State of Wyoming

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

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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 that are employed for measuring the PSD in the field and the Wyoming Department of Transportation (WYDOT) implements the two-vehicle method. However, WYDOT's apparatus that is 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 were not only efficient but also produced accurate results.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
^oC	Celsius	1.8C+32	Fahrenheit	^oF
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AI	Artificial Intelligence
CARE	Critical Analysis Reporting Environment
CSS	Chirp Spread Spectrum
DOT	Department of Transportation
DSRC	Dedicated Short Range Communication
GPS	Global Positioning System
GUI	Graphical User Interface
HAT	Hardware Attached on Top
IEEE	Institute of Electrical and Electronics Engineers
ITS	Intelligent Transportation System
LiDAR	Light Detection and Ranging
LoRa	Long Range
MoDOT	Missouri Department of Transportation
MS-DOS	Microsoft Disk Operating System
MUTCD	Manual on Uniform Traffic Control Devices
PRT	Perception-Reaction Time
PSD	Passing Sight Distance
SDK	Software Development Kit
SoC	System-on-Chip
V2V	Vehicle-to-Vehicle
WYDOT	Wyoming Department of Transportation
WYT2/LTAP	Wyoming Technology Transfer/Local Technical Assistance Program

CHAPTER 1: INTRODUCTION

The passing sight distance (PSD) is a critical element required in the design of two-lane highways. A typical two-lane highway is shown in Figure 1. While driving on two-lane highways, drivers would have to utilize the opposing traffic lane in order to pass slower-moving vehicles safely. Prior to passing, drivers ought to observe the opposing lane for a distance equivalent to the PSD to ensure that they could safely execute the overtaking maneuver.

Figure 1: Two-lane highway.
Source: Johnson (2018).

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 (Federal Highway Administration, 2012; Wyoming Department of Transportation Traffic Program, 2012). 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 (American Association of State Highway and Transportation Officials, 2018). In cases where the PSD is insufficient, passing related crashes would 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, called the Range Tracker System, became no longer

functional. Its operating system, the outdated Microsoft Disk Operating System (MS-DOS), ceased functioning properly and, regrettably, private firms would 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 in excess of 29,000 miles of two-lane highways in Wyoming, which mainly pertain to those of state and national roads. WYDOT ought to persistently 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, restructuring of highways, crash experiences, construction of buildings near horizontal curves restricting the PSD, growth of vegetation near horizontal curves demarcating the PSD, and grievances from residents. Changes in the PSD not only prompt the restriping of two-lane highways but also the re-positioning of signs. This would contribute to construction costs. Hence, it would be imperative that the developed prototypes, used for establishing the passing/no-passing zone plans, be accurate.

Objective

The objective of this study was 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 would be 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 units of Prototype 1 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, would be able to continuously conduct their two-lane highway striping/re-striping operations without experiencing the difficulty arising from a shortage in the equipment. Also, WYDOT and local government agencies would be protected from liability when passing related crashes occur.

This report is organized as follows. The subsequent chapter, Chapter 2, entails discussions of essential background information while Chapter 3 comprises the description of 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.

CHAPTER 2: BACKGROUND

This chapter entails a discussion of 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 that are implemented for measuring the PSD and documented studies that involved the gauging of the PSD are covered in this chapter as well.

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 (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). An essential component that ought to be considered in ascertaining the PSD is the concept of the critical position. It is defined as the condition at which the passing vehicle is traveling adjacent to the overtaken vehicle and will not be able to back out from completing the overtaking maneuver (Harwood et al., 2008). The most accurate models are those of Glennon (1988) and Hassan et al. (1996) since they take into account the critical position. 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's) Green Book (American Association of State Highway and Transportation Officials, 2018) and the Manual on Uniform Traffic Control Devices, MUTCD (Federal Highway Administration, 2012). Yet, the Hassan et al. (1996) model produces exceedingly large estimates of the PSD for high-speed two-lane highways. It should be noted that the WYDOT pavement marking manual's guidelines concerning two-lane highways (Wyoming Department of Transportation Traffic Program, 2012) are consistent with those of the MUTCD (Federal Highway Administration, 2012).

Local Passing Sight Distance Standards

The minimum required PSD is dependent on the posted speed limit. As per the WYDOT pavement marking manual (Wyoming Department of Transportation Traffic Program, 2012), the minimum PSDs are listed in Table 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 (Wyoming Department of Transportation Traffic Program, 2012). 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 ought to 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 ought to be exercised so as to avoid having short passing zones between no-passing zones. Hence, road sections between successive no-passing zones that are shorter than the ones listed in Table 2 would be designated as no-passing zones.

Table 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: 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 be 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 which the elimination of the no-passing zones is warranted are presented in Table 3.

Table 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 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 3, the no-passing zone lengths would be lengthened to 500 ft. The supplementary length would be appended to the beginning point of the no-passing zone (Wyoming Department of Transportation Traffic Program, 2012). 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 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 would be extended to 280 ft, 320 ft, 370 ft and 410 ft, respectively. The added lengths would adjoin the beginning point of the no-passing zone (Wyoming Department of Transportation Traffic Program, 2012). If, on the other hand, the no-passing zone is to be discarded since its short length warrants so, a field evaluation ought to be conducted to justify this decision (Wyoming Department of Transportation Traffic Program, 2012).

Other Local Standards Governing Passing and No-Passing Zones

The PSD is not the only vital criterion that is 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, 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 (Wyoming Department of Transportation Traffic Program, 2012).
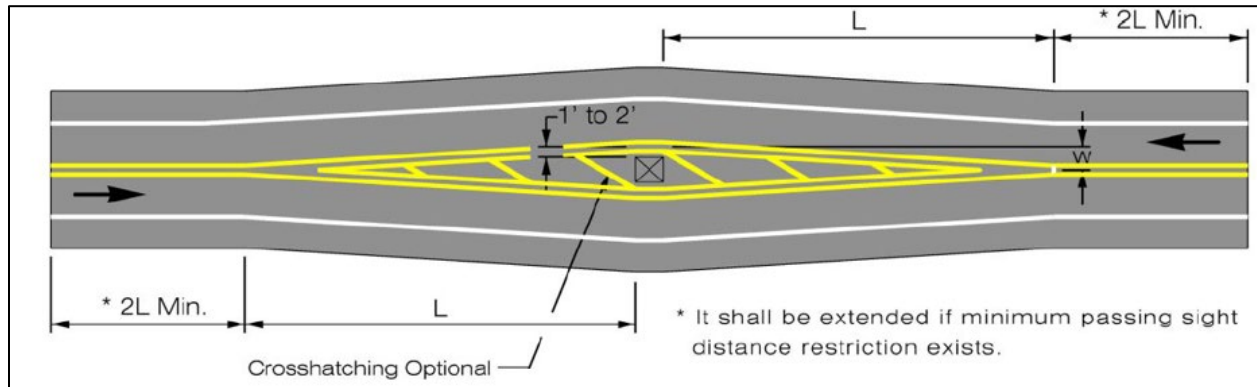

Figure 2: No-passing zone at a location with centerline channelization.
Source: Wyoming Department of Transportation Traffic Program (2012).

The length of the no-passing zone at a location with a centerline channelization is as shown in Figure 2. For intersections and interchange ramps, the minimum passing zone lengths are listed in Table 4.

Table 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 provided the supplementary lane. The no-passing zone marking is extended a distance equivalent to that presented in Table 4 upstream of the passing lane taper's beginning point (Wyoming Department of Transportation Traffic Program, 2012).

When it comes to railroad crossings, a no-passing zone marking ought to be stripped 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 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 (Wyoming Department of Transportation Traffic Program, 2012).

Table 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).

Passing Sight Distance Measurement Methods

There are multiple PSD measuring methods, which are the walking, one-vehicle, two-vehicle, eyeball, laser rangefinder, and optical rangefinder methods, among others (Brown and Hummer, 2000). 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 (Brown and Hummer, 2000).

The one-vehicle method is more efficient than the walking method albeit unsafe and less accurate. It requires a driver traveling 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 (Brown and Hummer, 2000; Namala and Rys, 2006).

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 data 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 (Brown and Hummer, 2000). The following vehicle's driver ought to manage 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 (Hutton and Cook, 2016).

Other than the two-vehicle method, the eyeball method is another PSD data collection method. Yet, it is difficult to conduct along vertical curves (Brown and Hummer 2000; Namala and Rys, 2006). The laser rangefinder and optical rangefinder methods are other commonly employed techniques for collecting PSD data. The laser rangefinder method requires the use of 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 (Brown and Hummer, 2000). 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 (Brown and Hummer, 2000). The PSD may also be obtained via computations involving the use of GPS data (Azimi and Hawkins, 2012; Namala and Rys, 2006). 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. Another method that is employed for evaluating the PSD, namely the speed method, was described by Brown and Hummer (2000). However, it is demanding.

The PSD data collection method employed by WYDOT is the two-vehicle method since it is quick and not as risky as 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 while 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.

Former Passing Sight Distance Data Collection Efforts

In the previous section, the PSD methods were described. Also, past studies involving PSD data collection (Azimi and Hawkins, 2012; Gargoum et al., 2018; Namala and Rys, 2006; Ma et al., 2018) were discussed and critiqued. 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.

In Cooper County, Missouri, Hutton and Cook (2016) implemented the two-vehicle method to collect PSD data pertaining to two-lane highways, and 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 percent and 22.3 percent 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 would be surmounted in this project. The cutting-edge components of this project's apparatus would be designed and tested to confirm that they would function smoothly.

CHAPTER 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). 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.

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 Global Positioning System (GPS) and speed data collected from both vehicles
- The switch needed to signal whether the lead vehicle would be 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) that would 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 ought to 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 (Ouya et al., 2017). The U.S. Department of Transportation (DOT) 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 would decrease from 1,500 ft at a moisture content of 20 percent to 200 ft at a content of 60 percent. 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 would implement 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 would be 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 (Orfanidis et al., 2017). 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.

A GPS HAT device of Adafruit 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 shown in Figure 3. As shown in Figure 3, the LoRa and GPS antennas would be connected to their respective touchscreens. The LoRA and GPS HATs would be attached to the Raspberry Pi.
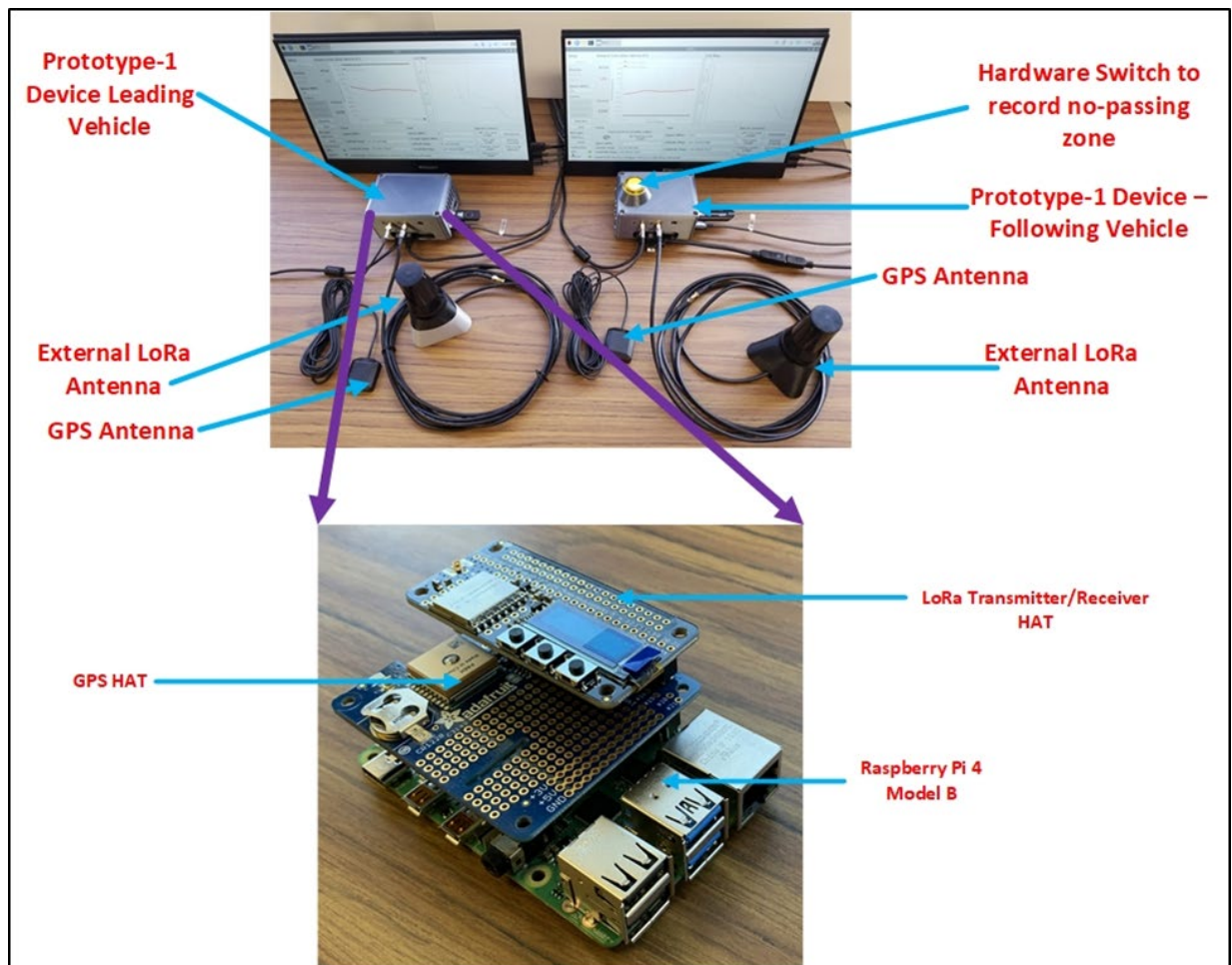

Figure 3: Prototype 1's components.
Source: Farid et al. (2021).

The computer software operating on the Raspberry Pi would carry 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 would be 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 ought to 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 would follow the procedure by transferring the speed and GPS coordinates data to the following vehicle. With that, a timer with a preset time limit, would be initiated. The following vehicle's equipment would acquire the data and estimate its distance relative to the lead vehicle. The following vehicle would also provide its position and speed data to the lead vehicle. If the lead vehicle obtained the data within the preset time limit, the lead vehicle would estimate 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 would be restarted securing sleek communications. In any case, the following vehicle would attain 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 second via the software-handshake procedure and gradually alter the LoRa radio's parameters. The 0.35 second time frame would entail 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 would give rise 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 would have 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 (Omar et al., 2016) 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 would be collected every 0.1 second, data of the estimated distances between both vehicles would be erratic. Therefore, a Kalman filter algorithm was implemented to estimate the GPS coordinates of both vehicles at 0.05-second intervals by making use of the collected GPS coordinates data collected at 0.1-second intervals and the vehicle speed data. Both vehicles would send and receive the GPS coordinates data estimated at

0.05-second intervals instead of those collected every 0.1 second. This would lead 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 would allow the user to select whether he or she would represent 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 dropdown menu and the software would set the desired gap distance between both vehicles, namely the PSD (Table 1). The user could adjust the desired gap distance if needed. When conducting the testing procedure, the user would be presented a real-time chart depicting the actual and desired distances between both vehicles as shown in Figure 4. The operating status of the GPS equipment and the radio communications would also be presented to the user. Furthermore, in addition to the switch (Figure 3), a special touchscreen button was incorporated to emulate the switch's function. Once the button would be activated, the no-passing zone terminal point's coordinates would be stored and the user would be provided a message indicating the lead vehicle's visibility status. This button is presented in Figure 5. Another menu was featured to permit the user to indicate that he or she was at a special location, such as an intersections or a railroad crossing, warranting the designation of a no-passing zone. This menu is presented in Figure 6.
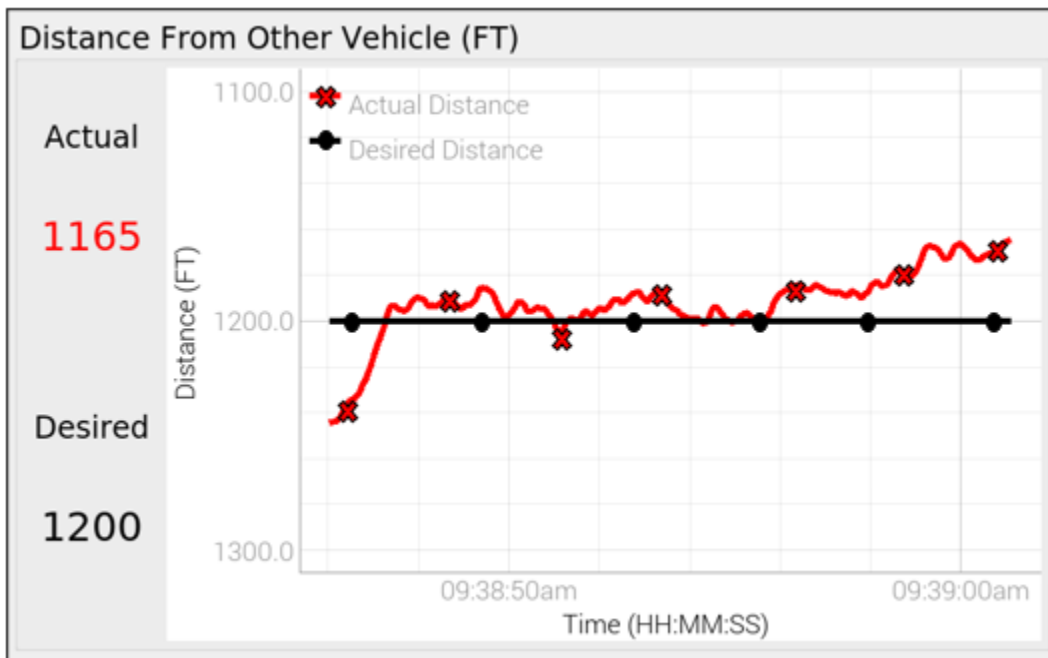

Figure 4: Real-time display of desired and estimated gap distances between lead and following vehicles.
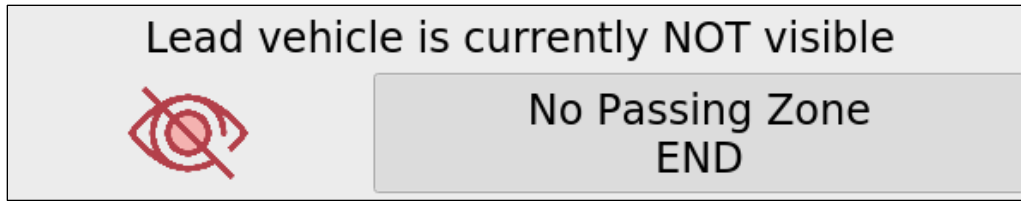
14

Figure 5: Presentation of the lead vehicle's visibility status.
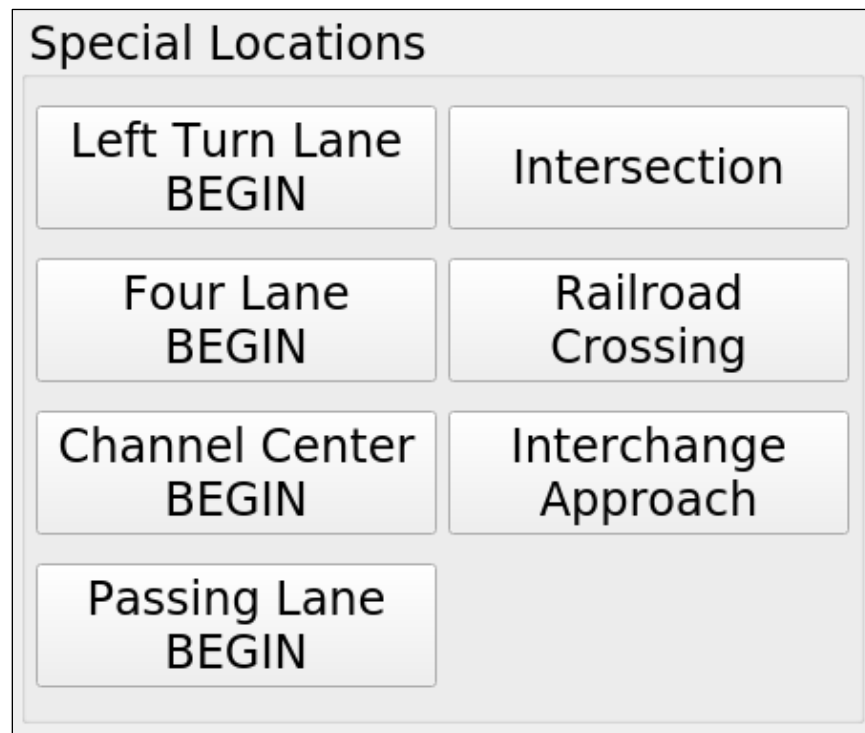

Figure 6: Menu for special locations warranting the striping of no-passing zones.

The software also elongates short passing zones, sandwiched between no-passing zones, as no-passing zones (Table 2) according to the WYDOT pavement marking manual (Wyoming Department of Transportation Traffic Program, 2012). A road map of the geocoded no-passing zone terminal points and special locations would be 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.

A supplementary feature included in the software was 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.

Prototype 1's Testing Procedure

Two stretches of two-lane highways comprising twenty miles on the outskirts of Laramie, Wyoming were chosen as the testing locations of Prototype 1. They were those of 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 7.

Figure 7: Section of Happy Jack Road with restricting sight distance.
Source: Google L.L.C. (2021).

Since the PSD ought to be measured at a height of 3.5 ft 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 would disappear due to sight distance restrictions, the following vehicle's driver would operate the switch. Similarly, once the lead vehicle's taillights would reappear, the following vehicle's driver would operate 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 view. Furthermore, the lead vehicle's cruise control was designated at the desired speed, which would be the posted speed limit, and the following vehicle's driver would secure 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.

Prototype 1's Testing Results and Discussion

After the testing of Prototype 1, 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 6.

Table 6: 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).

For WY-210, the posted speed limit is 65 mph prompting the selection of a desired gap distance between both vehicles of 1,200 ft (Wyoming Department of Transportation Traffic Program, 2012). Yet, as per a discussion with WYDOT, a distance of 1,300 ft would be desired. Furthermore, passing zones that would be shorter than 850 ft would have to be designated as no-passing zones (Wyoming Department of Transportation Traffic Program, 2012). Intersections, which would prompt the designation of no-passing zones, were encountered throughout the test runs of both WY-210 and US-287. The PSD, distance between no-passing zones and intersections were all considered in the designation of no-passing zones when conducting the field tests. It should be noted that, for all tests, manual calculations were conducted concerning short passing zones in 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 percent and 7 percent, respectively as shown in Table 6. Some pertained to passing zones which were erroneously designated as no-passing zones while others belonged to no-passing zones which were 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 which would restrict the PSD. They would 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 a result of the fact that 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 percent and higher depending on the location and lane. Equally important were the no-passing zones that were incorrectly identified as passing zones. 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 percent and 5.1 percent 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.

When it comes to the testing of Prototype 1 along US-287's segment, some locations had a posted speed limit of 55 mph while some locations 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 (Wyoming Department of Transportation Traffic Program, 2012). 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 6, overall discrepancies of 1 percent and 2.5 percent 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 percent and 6.1 percent 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 the fact that 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.

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 would decide 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 enabling WYDOT, Wyoming's 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. With that, one of the units of Prototype 1 would be 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, titled "Mapping Automation for Passing Zones (MAPZ): Quick Start Guide,"

with definitive instructions on how to operate Prototype 1 is provided in the appendix of this report.

CHAPTER 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

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. The 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-pass zone (NPZ) by determining the presence and disappearance of the lead vehicle and using a pushbutton switch 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 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 detect the NPZ offline continuously. The CVD was physically mounted on the front windshield at the head height of a passenger, shown in Figure 1.
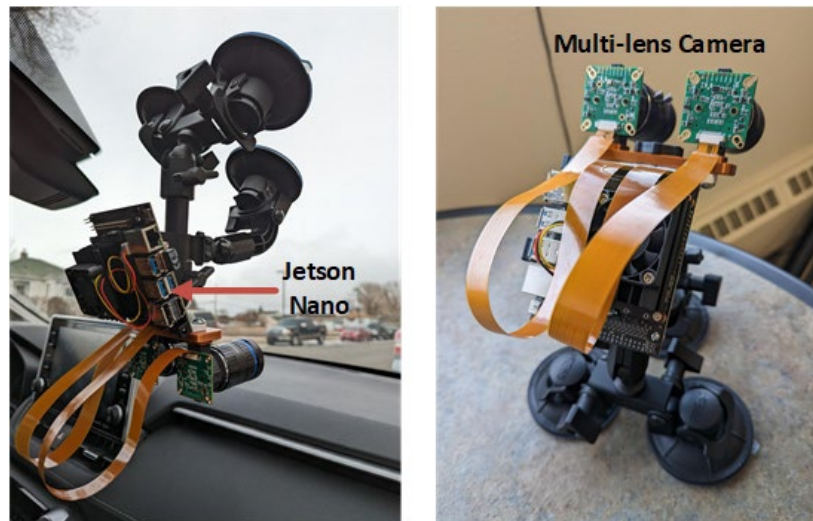

Figure 8: Computer Vision Device (CVD) to record Lead Vehicle.

The CVD consists of an embedded computer, the popular and commercially available Jetson Nano by NVidia, and two IMX477 cameras from Adafruit, shown in Figure 1. The two cameras provide an overlapping 43.0 degree field of view (FOV), translating into an 850 ft view at a distance of 1200 ft. Using the two cameras maximizes the time the lead car would be visible when a highway is winding, as shown in Figure 2. As shown in Figure 1, if only a single camera is used, the lead vehicle would not be visible due to the limited FOV, even though a passenger could see the lead vehicle due to the sight line.
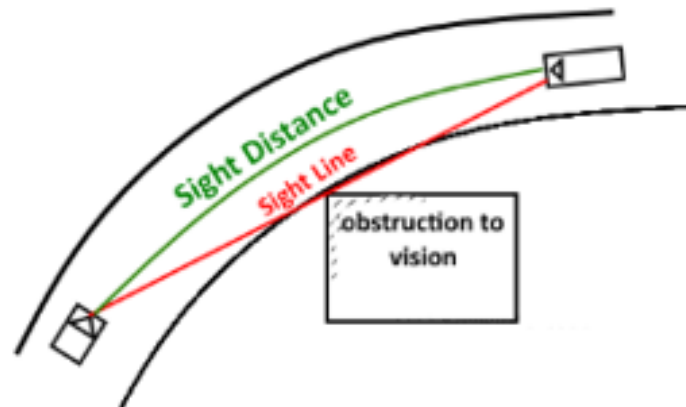
Figure 9: Sightline of the Lead Vehicle on a winding road.

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 data collection process of Prototype 2 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:

1. Autonomous NPZ Detection using Terrain Maps and GPS Coordinates

The United States Geological Survey (USGS) provides access to different terrain maps of the United States. Geo Tagged Image File Format (GeoTIFF) and lidar maps are a few of the terrain maps that 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, as shown in Figure 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.
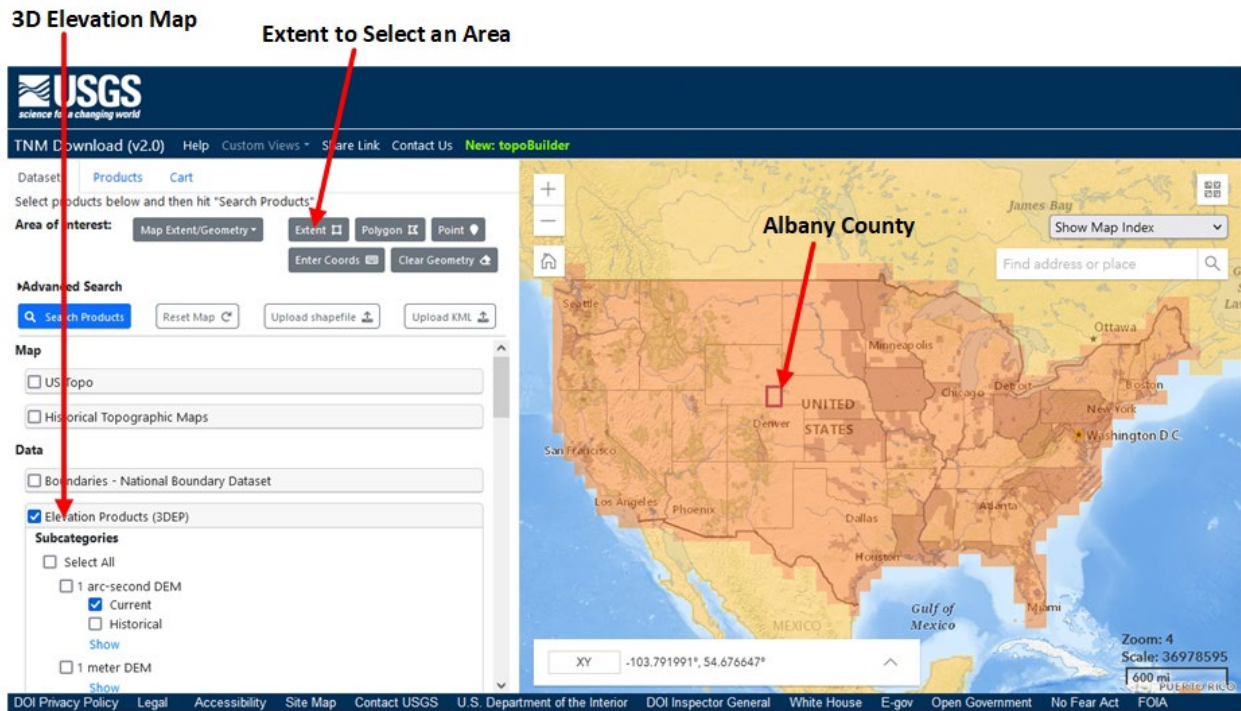
Figure 10: USGS TNM Downloader of Terrain Maps.
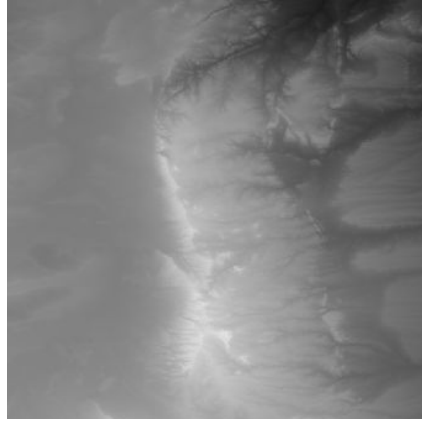(Source: USGS, 2023)

Figure 11: Terrain Map of Albany County.
(Source: USGS, 2023)

A software program was developed in Python that 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 5. The location of the lead-follow vehicles on the WY-210 highway at a sampling instance is demonstrated in Figure 5. The locations' 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.
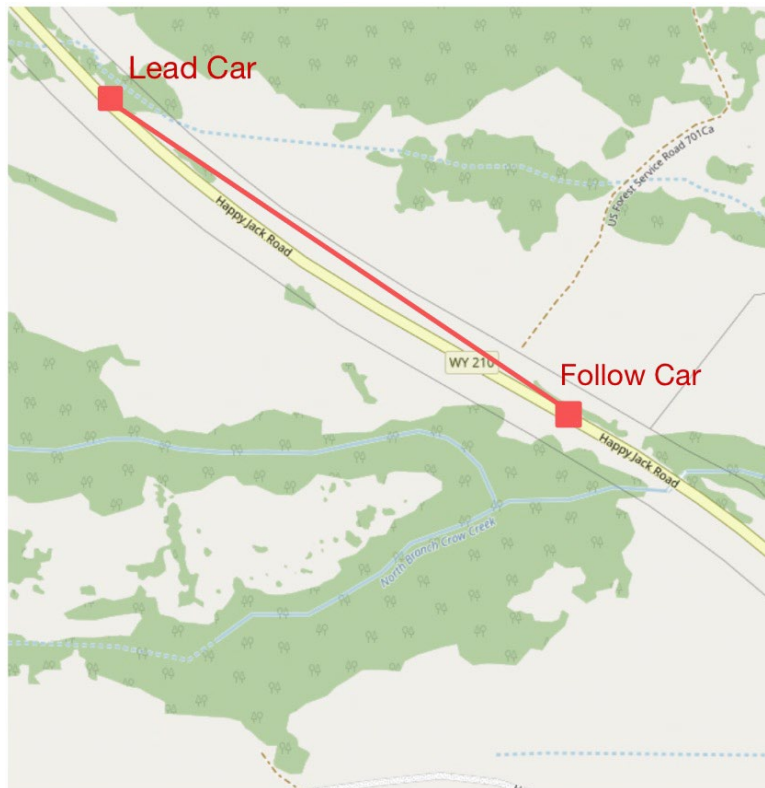
Figure 12: Software detection of the Lead and Follow Vehicles on the Terrain Map.

Figure 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, would dictate 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 have an altitude higher than the altitude of the lead vehicle, the following vehicle, or the both. If any GPS coordinate of the terrain map on the line of sight line has an altitude higher than the lead or following vehicles altitude, the lead vehicle would not be visible from the following vehicle, and the software marks the GPS coordinates of the vehicles at that sampling instance as an NPZ otherwise visible. However, if vegetation blocks the view of the following vehicle along the line-of-sight line and there are no altitude violations, the algorithm would provide with the output that the lead vehicle is visible, which is an error. The error is due to the GeoTIFF terrain map not containing the elevation and other information about the 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.

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 data set generated on Wyoming highways. The training data set 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 images with the back side of the lead vehicle visible up to 3 ft from the ground level, images with the back side of the lead vehicle not visible, images with oncoming vehicles, and images on winding roads.

The YOLO v7 architecture was modified to suit the resolution of the images in the training data set 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.

**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 no-pass zones using the push button on the modified MAPZ device (i.e., Prototype 2).

The collected GPS data was first fed to the Python software. Then, the beginning and ending GPS coordinates of no-pass zones were computed. Figure 6 shows the beginning NPZ GPS coordinates detected by the autonomous NPZ algorithm and the human observer. Figure 6 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 NPZ marked by the autonomous NPZ algorithm and human observer. The difference can be attributed to human observer latency.
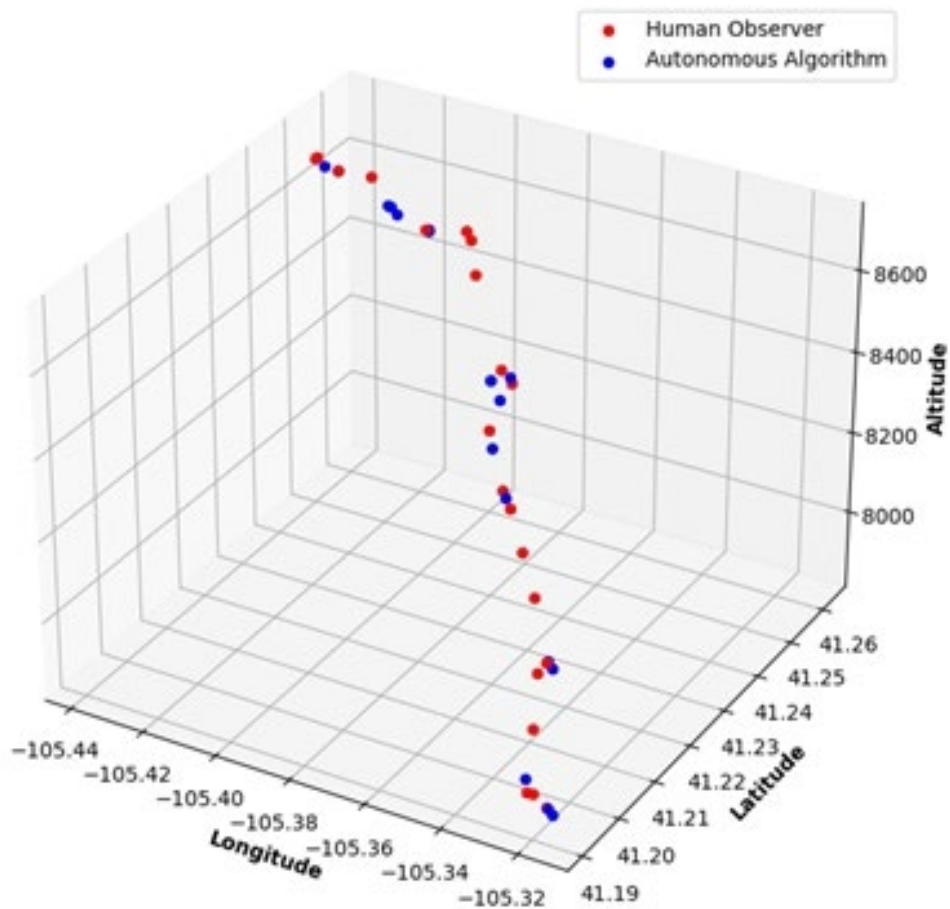
a) Starting GPS Locations from the Autonomous Algorithm and the Human Observer
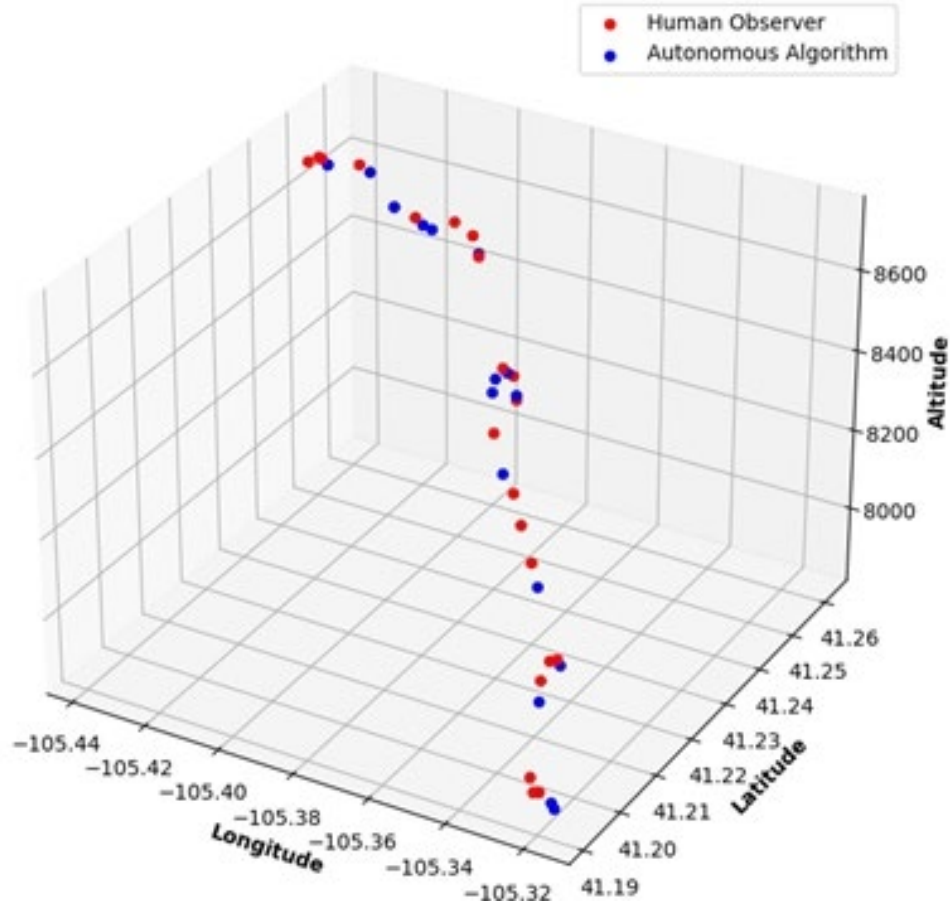
b) Ending GPS Locations from the Autonomous Algorithm and the Human Observer

Figure 13: 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 7. 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 14.

Table 7: 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 14: Lead Vehicle Visible indicating Passing Zone.

Case 2: Lead vehicle not visible, indicating No-Pass Zone

The no passing zone detection by the deep learning and autonomous algorithms is shown in Table 8. 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 15.

Table 8: 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
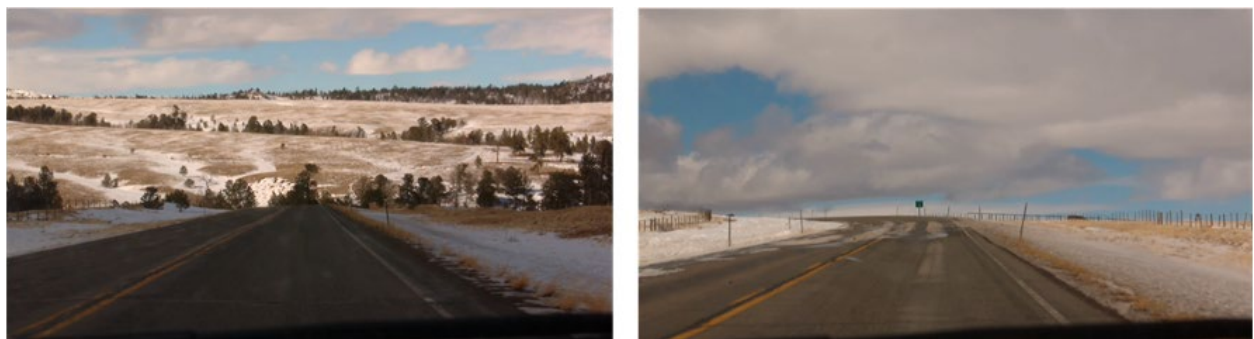
Figure 15: Lead Vehicle not Visible indicating No Passing Zone.

Case 3: No-Pass Zone disagreement between Deep Learning and Autonomous Algorithms

Table 9 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 no-pass zone.

Table 9: 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 16 shows that the 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 16: Lead Vehicle not Visible due to Vegetation (Trial 1).

Figures 17 and 18 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 the terrain map data that is not affected by the field of view limitations.

Figure 17: Lead Vehicle not Visible due to Limited Field of View (Trial 2).

Figure 18: Lead Vehicle not Visible due to Limited Field of View (Trial 3).

Mending of Prototype 2 and Upgrading of Prototype 1

Prototype 2 is more advanced than Prototype 1. It features with cutting-edge ITS-devices that would automatically declare whether the lead vehicle would disappear 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 delivered to the following vehicle's driver instructing him or her to increase or decrease speed to maintain the predetermined distance between both vehicles would 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 attributed to the fact of 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, the user of Prototype 2 can determine the correct outcome with supporting data.

CHAPTER 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. 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, one (Farid et al., 2021) was about comparing the performances of two advanced statistical methods that could be used for evaluating two-lane highway crash severities, and the third (Haq et al., 2021) was about gauging the PSD when it comes to passing multiple oil and gas trucks on a two-lane highway.

Modeling the Severities of Two-Lane Highway Passing Related Crashes

In the study of Farid and Ksaibati (2020), the severities of two-lane highway passing related crashes were assessed via a random parameters, or mixed (Eluru et al., 2008; Mannering et al., 2016), ordinal probit structure. Crash, traffic, roadway characteristics and other data were collected from the WYDOT Critical Analysis Reporting Environment (CARE) package for the years 2008-2017. There were records of 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 would give 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 would increase 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 10.

Table 10: 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).

As shown in Table 10, 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.

When it comes to passing related multiple-vehicle crashes, the corresponding marginal effects are listed in Table 11. As shown in Table 11, 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 11: 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 $\geq$ 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).

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.

Comparison of Two Decent 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. They were the uncorrelated random parameters ordinal probit model with interaction effects and the correlated random parameters ordinal probit model (Fountas et al., 2018). 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 for the years 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 would induce 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 follow normal distributions. The coefficients' degrees of variation would depend on the estimated standard deviations of their distributions (Eluru et al., 2008; Mannering et al., 2016). The model's performance is typically assessed using the log-likelihood ratio test that compares its log-likelihood to 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 12.

Table 12: 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	

Parameter	Coefficient	P-Value
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 12, the correlated random parameters ordinal probit model's results indicated that the fit was appropriate compared to 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. On the contrary, 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 would increase 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. Note that the PSD is required to pass a single vehicle ahead (American Association of State Highway and Transportation Officials, 2018; Federal Highway Administration, 2012; Harwood et al., 2008; Wyoming Department of Transportation Traffic Program, 2012). However, in Wyoming, oil and gas firms promote the platooning of their trucks rendering 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) were selected to predict the PSDs for the study. 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 spacing's were considered as well

leading to multiple scenarios. The estimated PSDs, presented in Figure 19, were considerably greater than the one needed to pass a single vehicle. It is 1,200 ft (Federal Highway Administration, 2012; Wyoming Department of Transportation Traffic Program, 2012). Yet, WYDOT would prefer using the conservative value of 1,300 ft. Note that, in the figure, the spacing's are the intra-platoon spacing's.

Figure 19: Computed passing sight distances for overtaking oil and gas truck platoons on a 70-mph two-lane highway.
Source: Haq et al. (2021).

The PSD results, obtained using the Glennon (1988) model, were compared to those of microsimulations run in VISSIM Version 9 (PTV Group, 2016). 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 its length was nearly fifteen miles. The differences between the PSDs predicted using the Glennon (1988) model, and those outputted from VISSIM (PTV Group, 2016), were below three percent. 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.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

Two-lane highways represent a considerable proportion of the highways in the U.S. A fundamental component needed in the design of two-lane highways is the PSD. At locations where the available PSD is shorter than the minimum required PSD, a no-passing zone ought to 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 would warrant the striping of such markings. There exists multiple methods of measuring the PSD in the field and WYDOT implements the two-vehicle method. It specifies two successive vehicles traveling at the highway speed and spaced a distance equivalent to the PSD. Both vehicles would be equipped with GPS devices, radio communication devices, and a monitor to display the data. Both vehicles would compute their speeds using the GPS data collected and exchange all data with one another. The following vehicle would also be instrumented with a switch. The driver of the following vehicle would operate the switch to signal that the lead vehicle became no longer visible by being obscured by sight obstructions indicating the beginning point of the no-passing zone. Likewise, when the lead vehicle would return to view, the switch would be operated once more to declare the ending point of the no-passing zone. Yet, WYDOT's apparatus became no longer functional and needed to be replaced. Therefore, this project was aimed at developing two advanced prototypes of the two-vehicle method with state-of-the-art ITS devices and delivering them to WYDOT. The latter was designed to be more advanced than the former. Multiple units of Prototype 1 were reproduced and delivered to WYDOT as well. Near the completion of the project, Prototype 1's units were recalled and upgraded such that they would be 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. Brown and Hummer (2000) conducted a review of the field-based PSD data collection techniques. There were other previous studies involving the estimation of the PSD by means of non-field based methods (Azimi and Hawkins, 2012; Gargoum et al., 2018; Ma et al., 2018; Namala and Rys, 2006). 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 were integrated 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 percent and 7 percent 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 percent and 2.5 percent for the southbound and northbound directions, respectively. The discrepancies were possibly due to prolonged PRTs 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, which were later identified by

WYDOT. 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 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. This would be less burdensome on the following vehicle's driver. Also, accurate results would be computed since the PRT, associated with operating the switch, would be substantially reduced. Afterwards, Prototype 1's units were retrieved and upgraded such that their functionalities would be similar to those of Prototype 2. With multiple prototypes, WYDOT, Wyoming's counties and local governments, such as the Wind River Indian reservation, would be able to persistently establish and re-establish their two-lane highway zone striping plans without the impediment arising from a deficiency in the 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 (Farid and Ksaibati, 2020; Farid et al., 2021; Haq et al., 2021). That of Farid and Ksaibati (2020) was about investigating the severities of passing related crashes on two-lane highways while that of Farid et al. (2021) involved the comparison of the performances of two rigorous statistical regression techniques when modeling two-lane highway crash severities. The study of Haq et al. (2021) was focused on computing PSDs for passing a platoon of oil and gas trucks on a 70-mph two-lane highway.

Recommendations are made for this project. One is to maintain the relationship with WYDOT in case they require modifications to any of the prototypes provided. They 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.

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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.
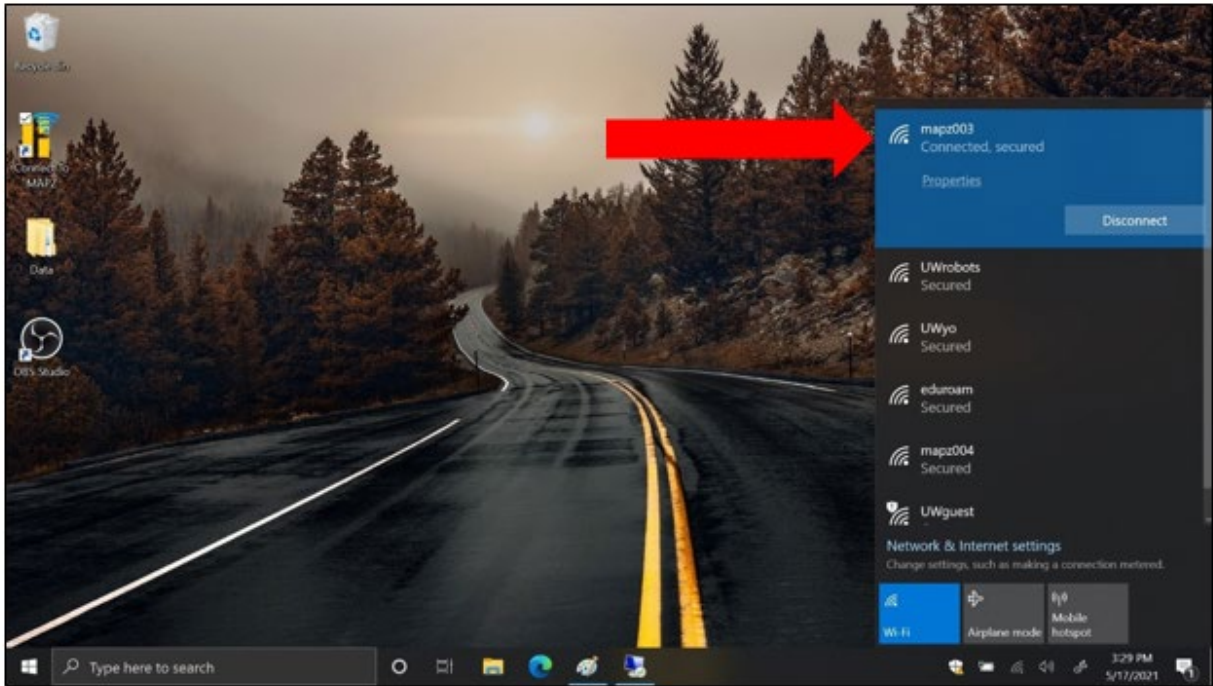
Step 7: Once the device is powered on, ensure your laptop is connected to the MAPZ network.
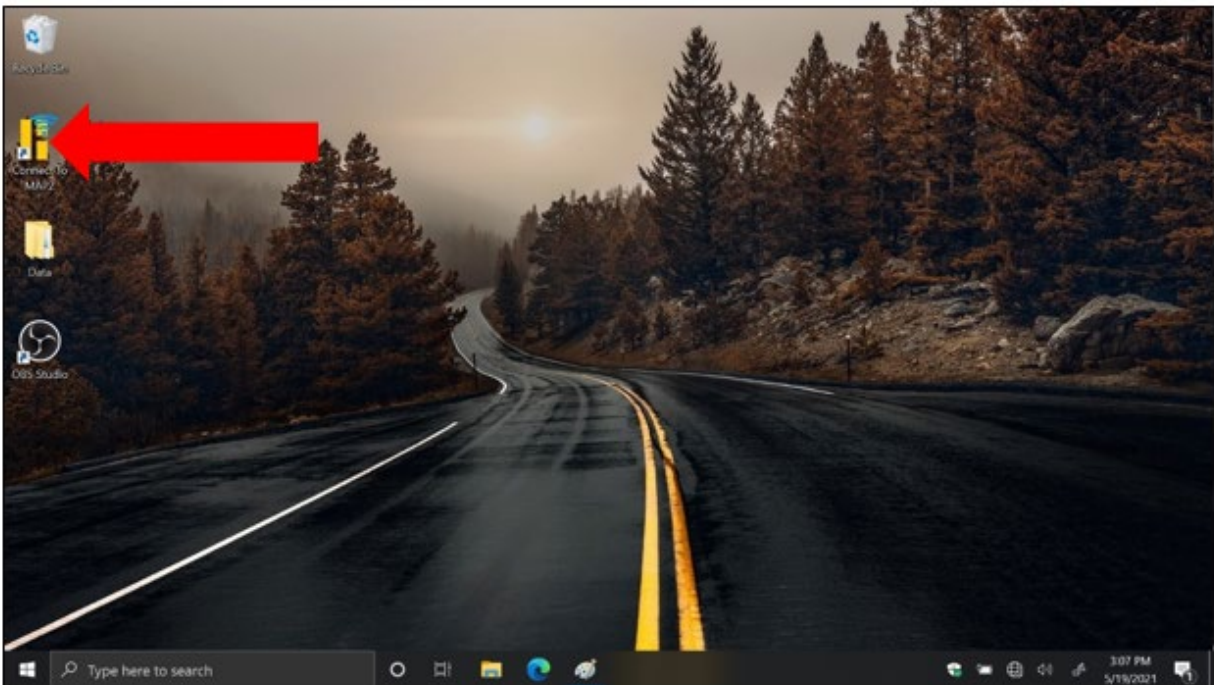
Step 8: Start the MAPZ software by double the clicking the "Connect to MAPZ" icon.
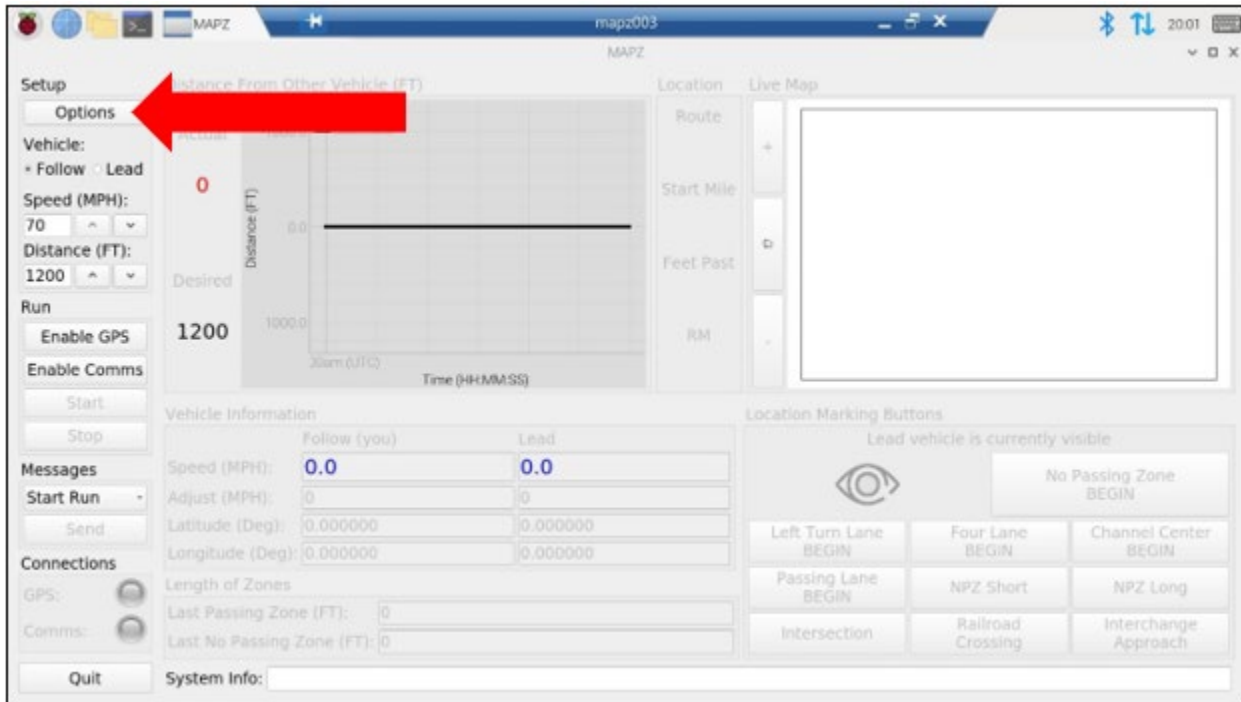
Step 9A: Once the device is connected this screen will appear. To begin the setup process, click on the "Options" button.
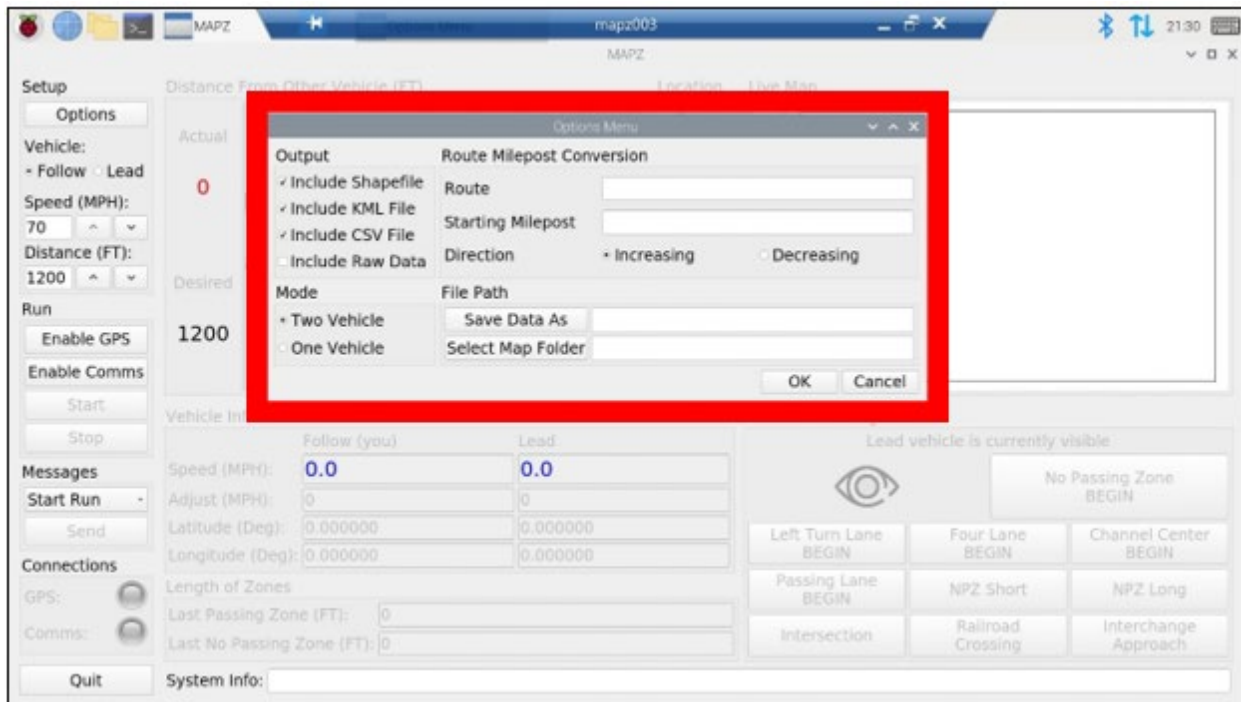
Step 9B: After clicking the "Options" button the options menu will appear.
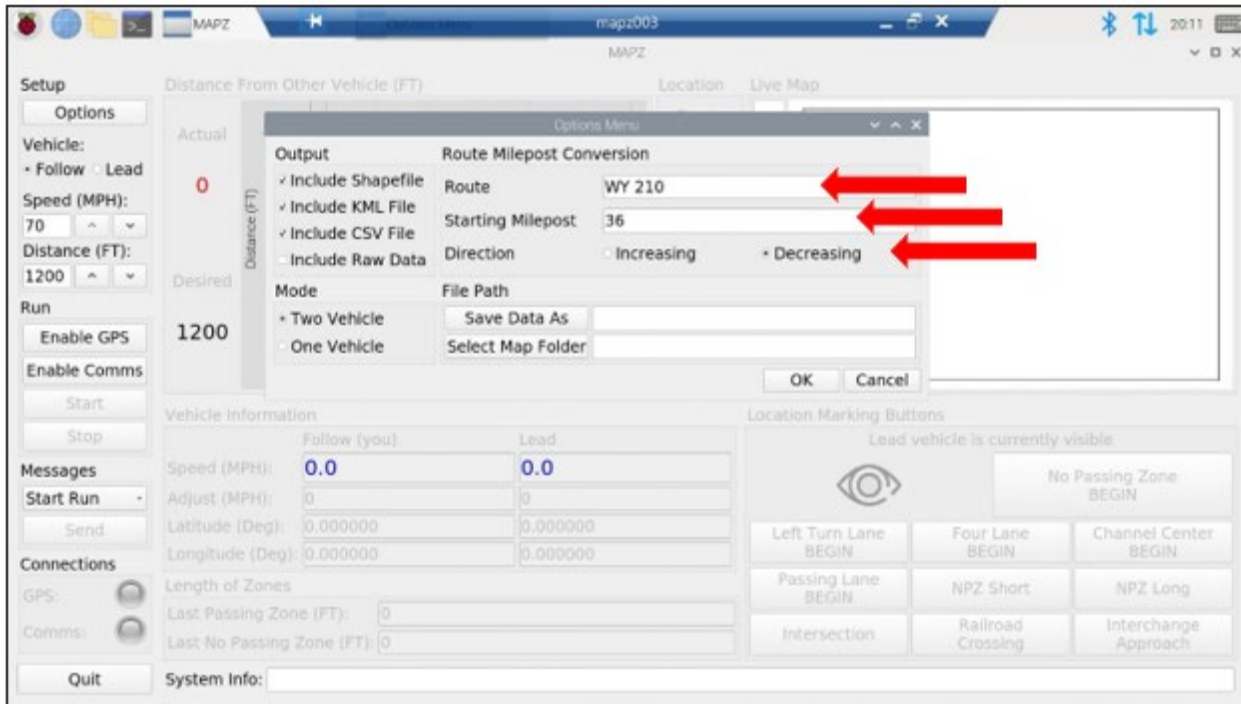
Step 10: Enter the highway/road name in the "Route" dialog box. Next, enter the Starting mile maker in the "starting Milepost" dialog box. Then select if the mile markers increase or decrease.
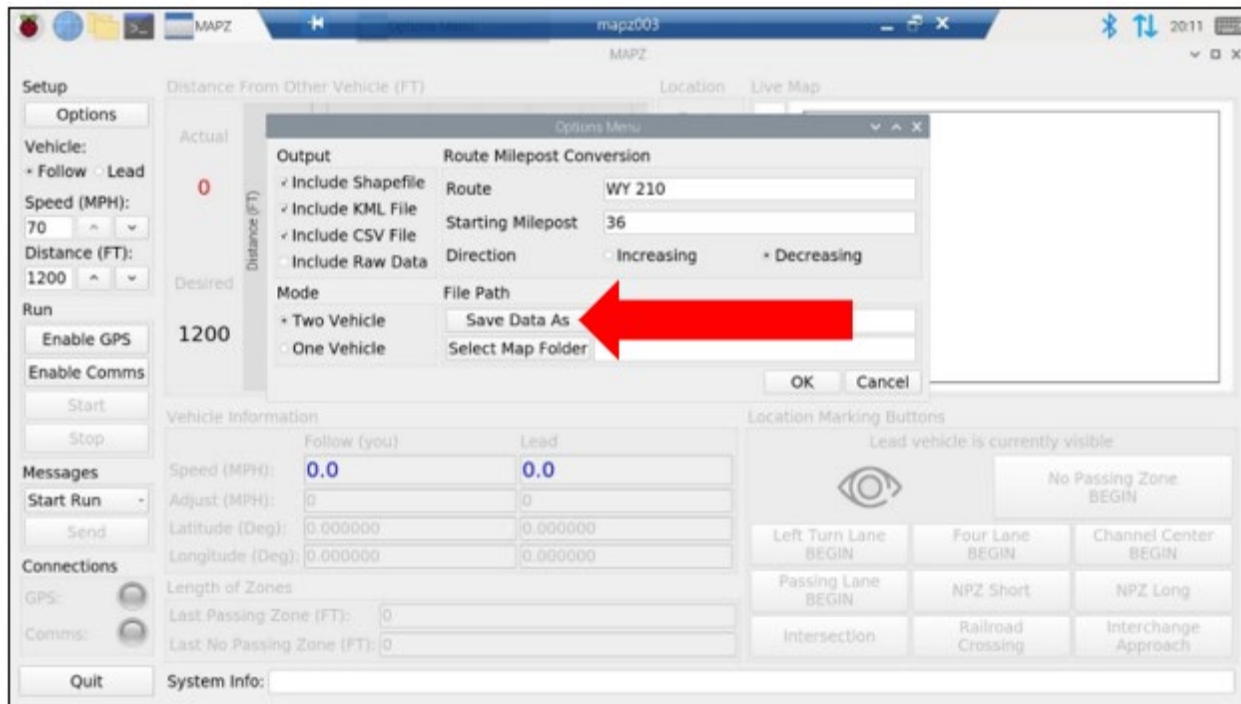
Step 11A: Click on the "Save Data As" button to open the save menu.

*Skip this step if operating as lead vehicle.
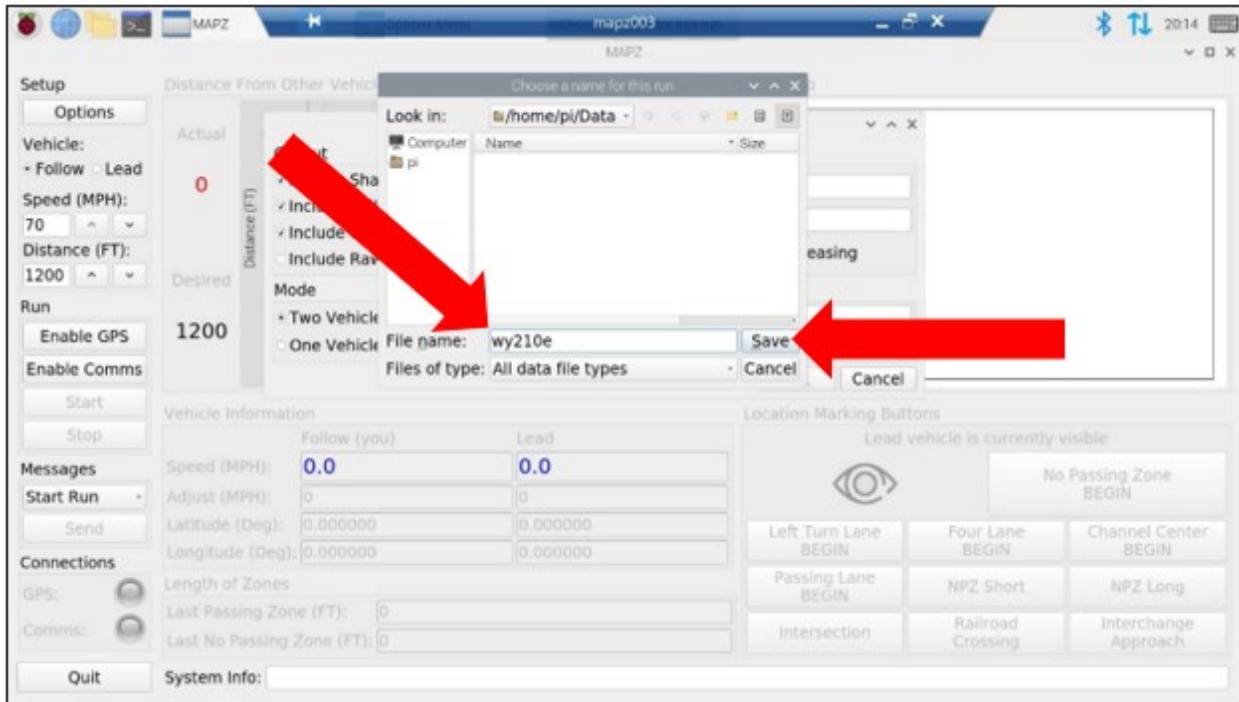
Step 11B: Enter a filename into the "File Name" dialog box. Then click on the save button to exit the save menu.
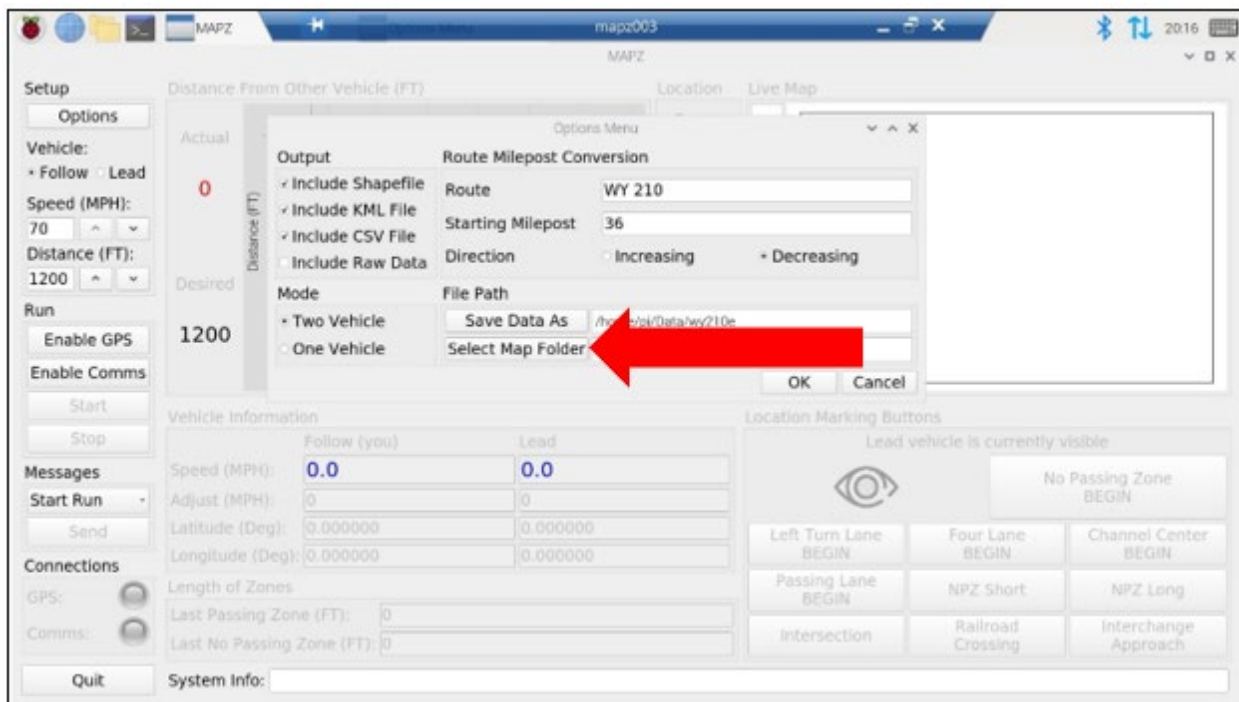
Step 12A: To add a live map, click on the "Select Map Folder" button to open the map menu.
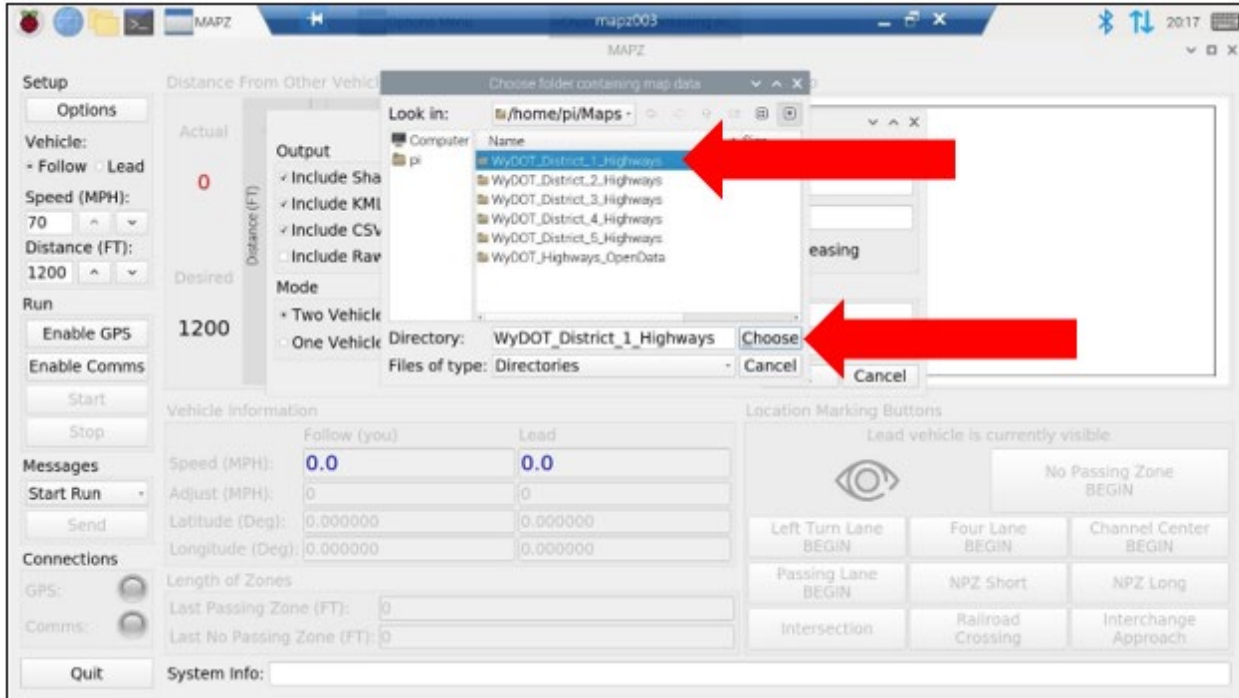
Step 12B: Select the district the highway/road is located in. Then click on "Choose" to exit the map menu.
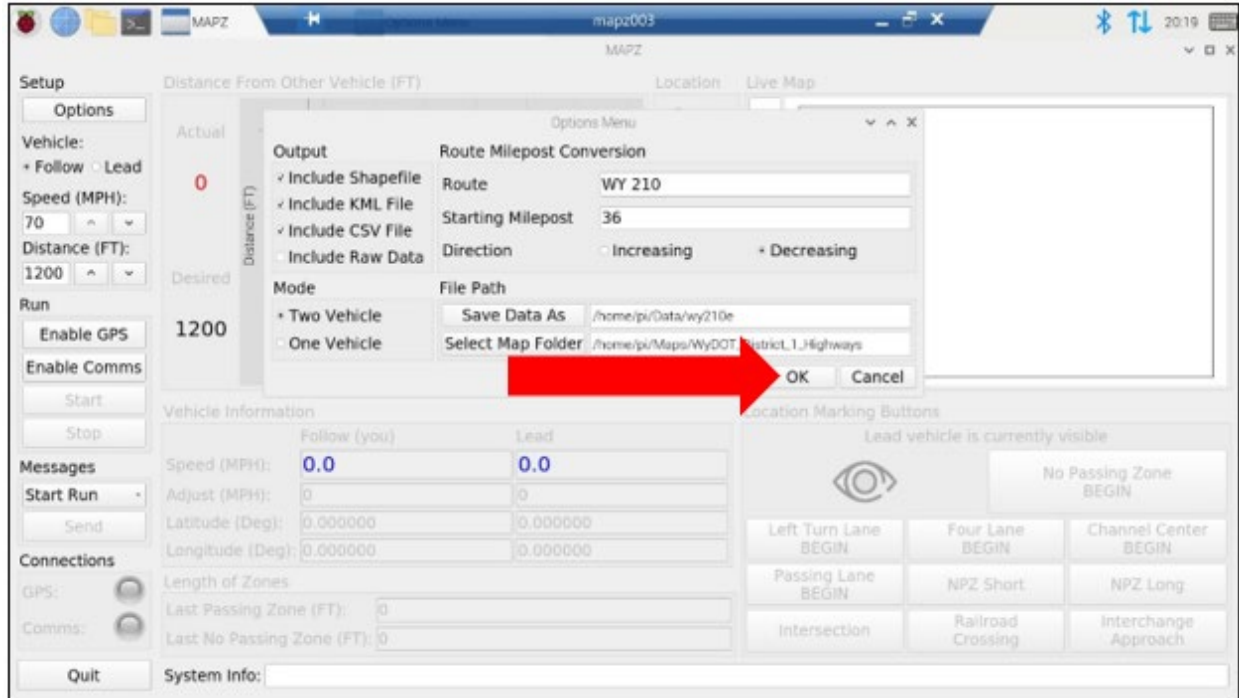
Step 13: Click on "Ok" to exit the options menu.
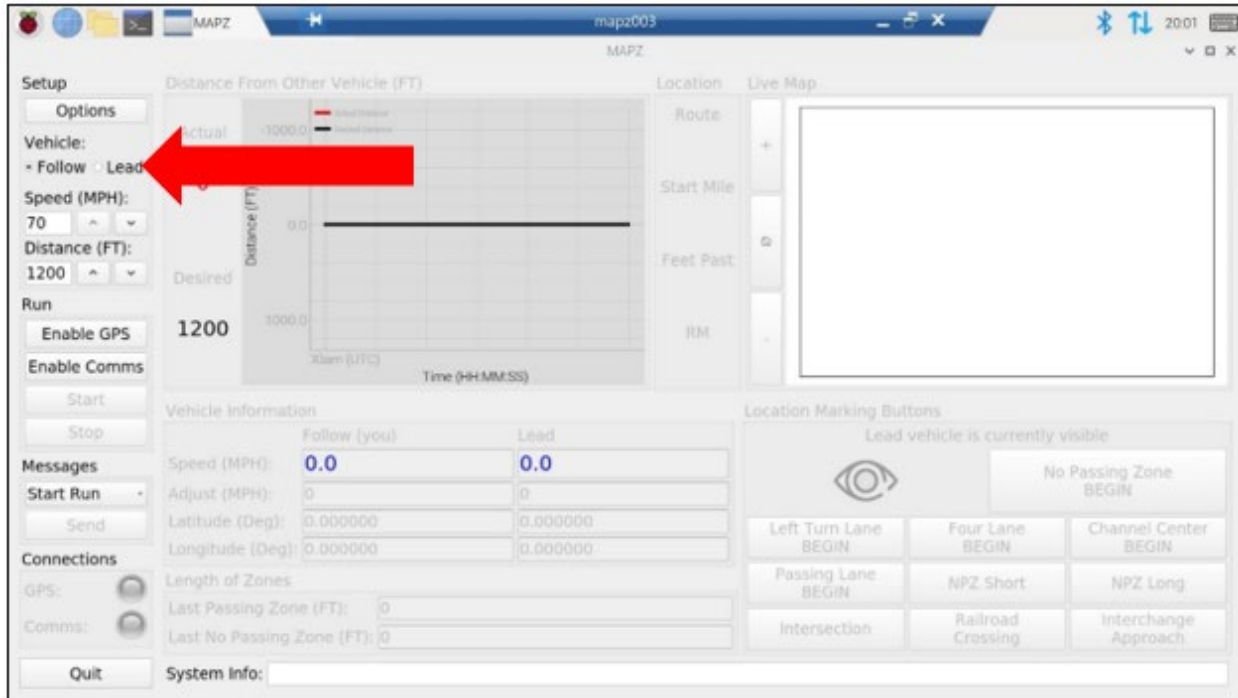
Step 14: Select vehicle position. By default, "Follow" is selected.
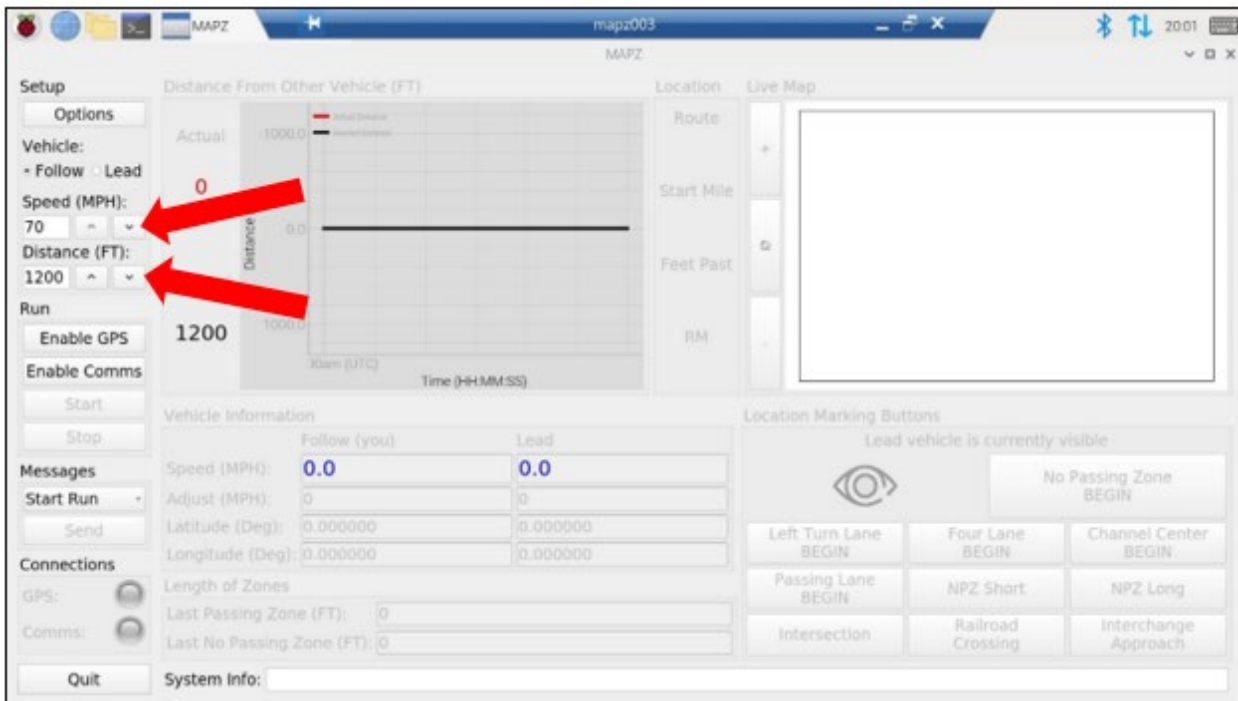
Step 15: Change the desired speed limit by using the arrow buttons to the right of the "Speed" dialog box. Changing the set speed will automatically change the set distance. Distance can be set manually as well using the arrows under "Distance."
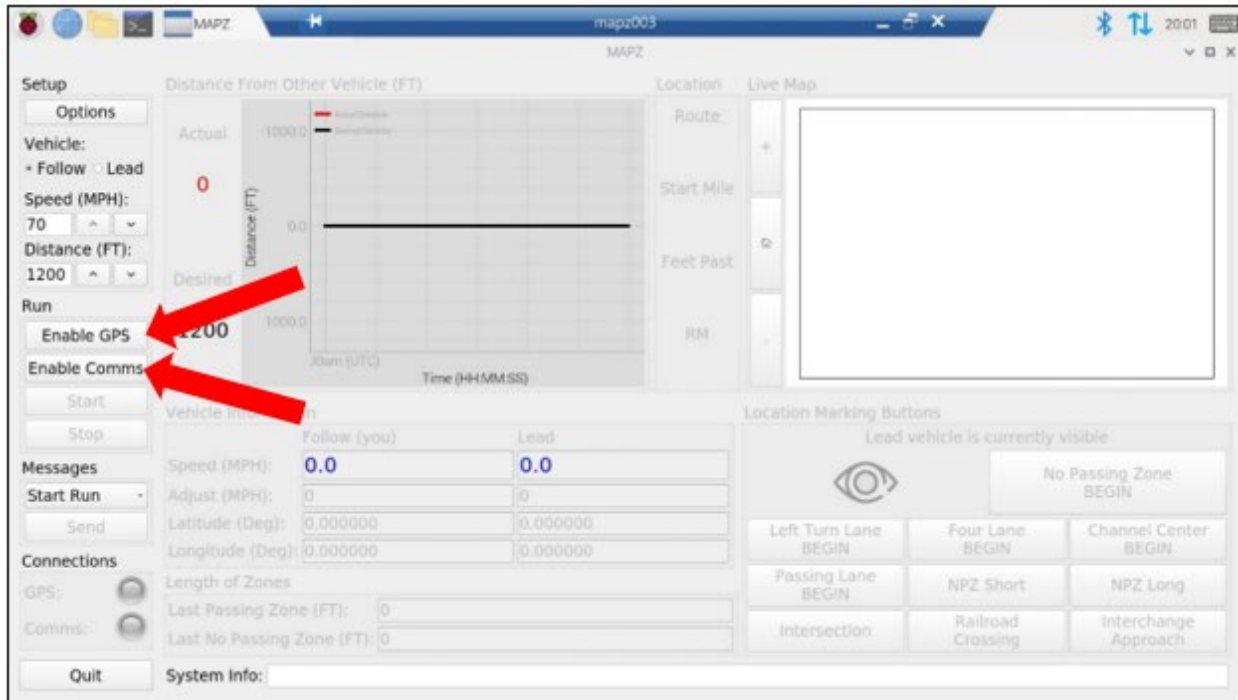
Step 16A: Click "Enable GPS" and "Enable Comms."
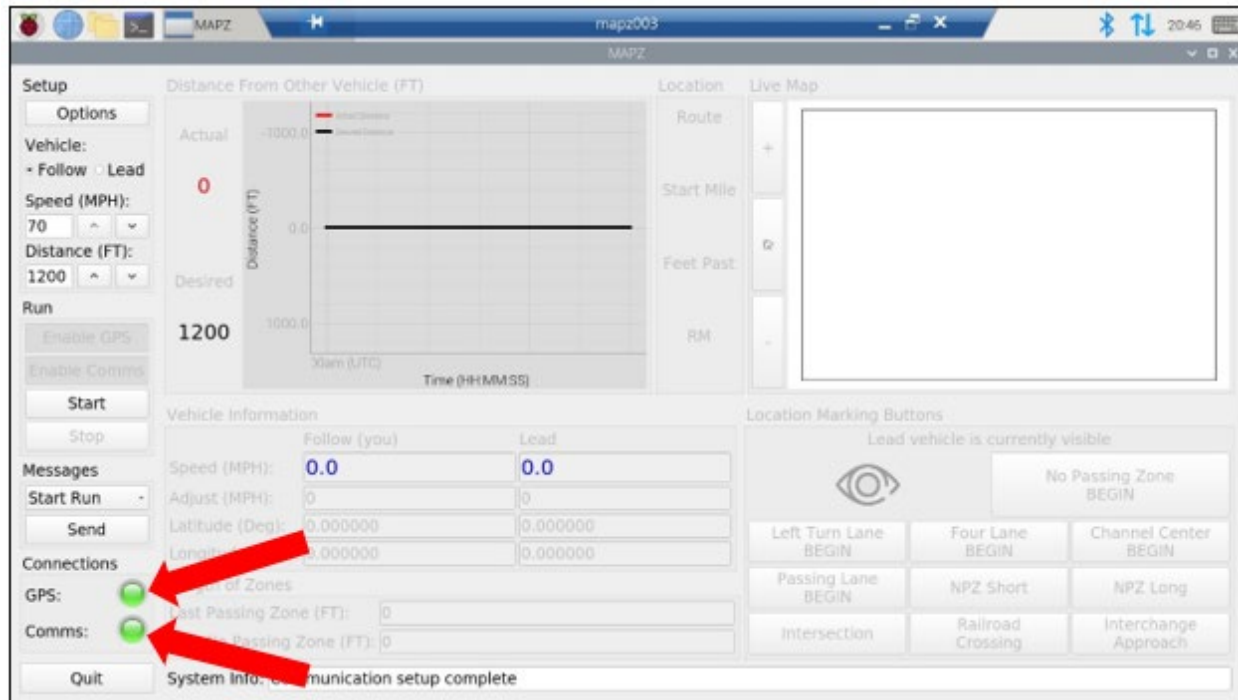
Step 16B: Once GPS and Comms have been enabled, the status indicators under "Connections" will change color. Green indicates that the device is working properly and red indicates that the device is not successful in acquiring GPS or communicating with the other vehicle.
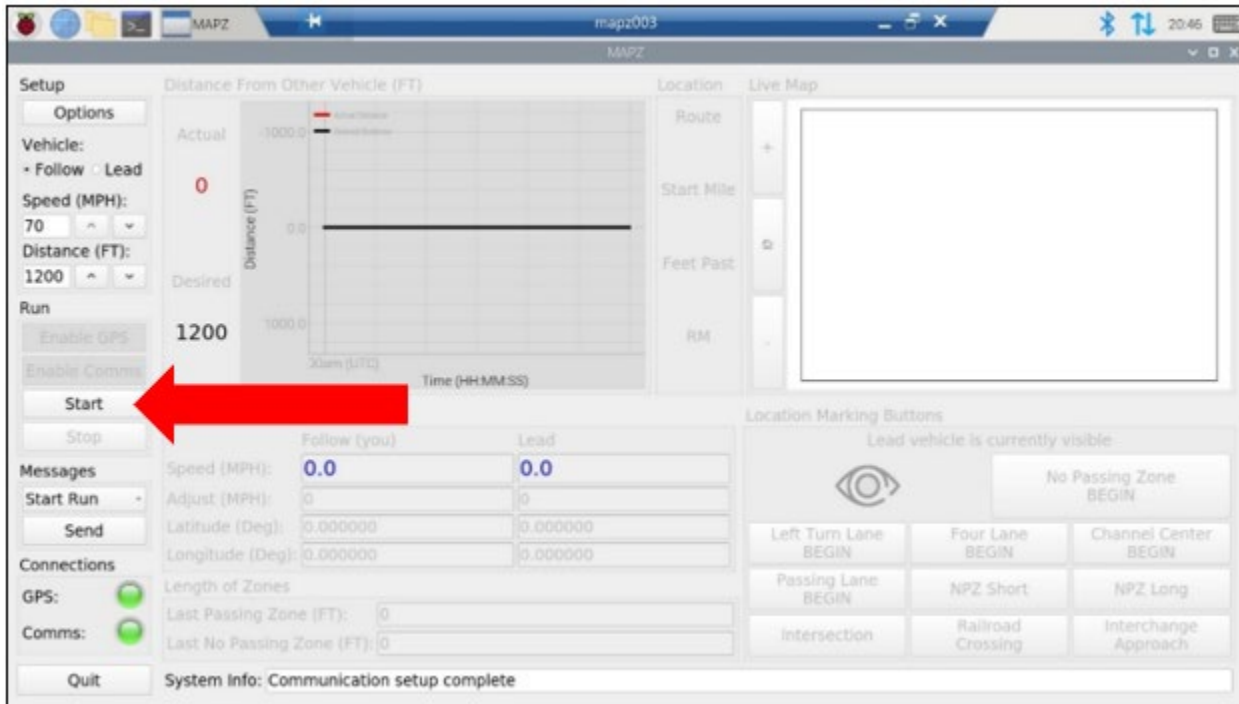
Step 17A: If both indicators are green it is ok to begin the run. Begin the run by clicking the "Start" button.
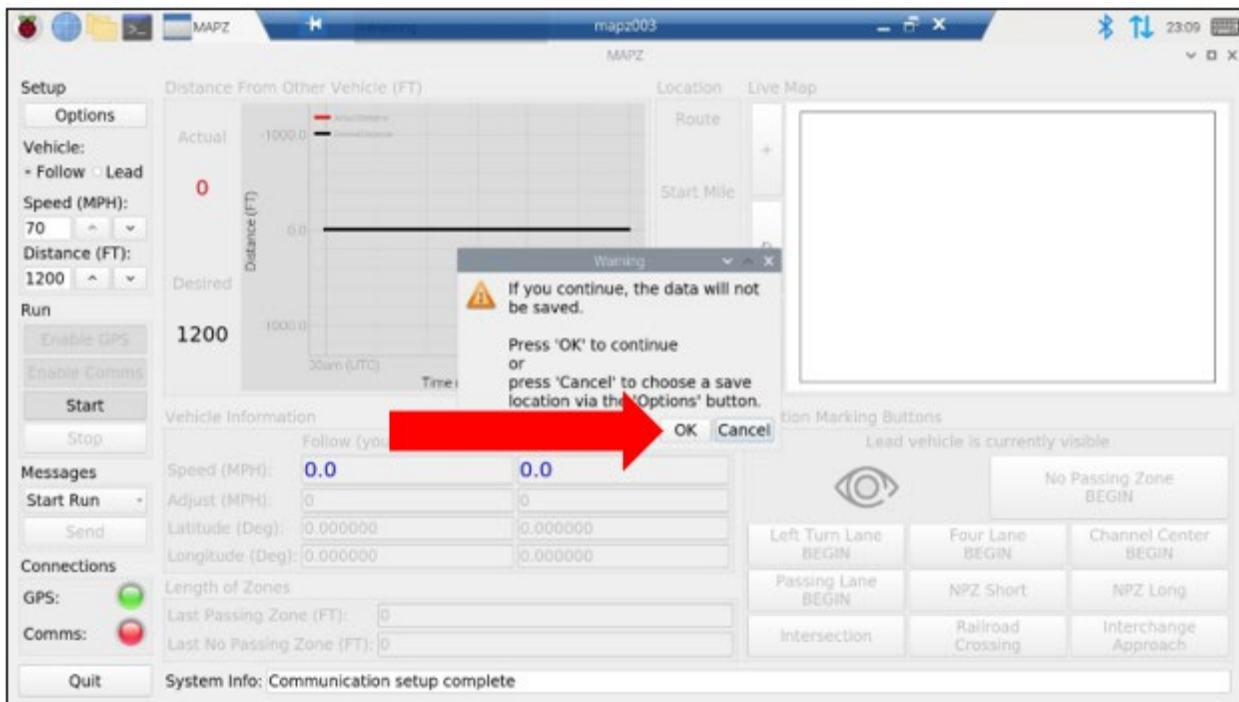
Step 17B: If operating as lead vehicle a warning message will appear. Click "OK" to start the run.

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.
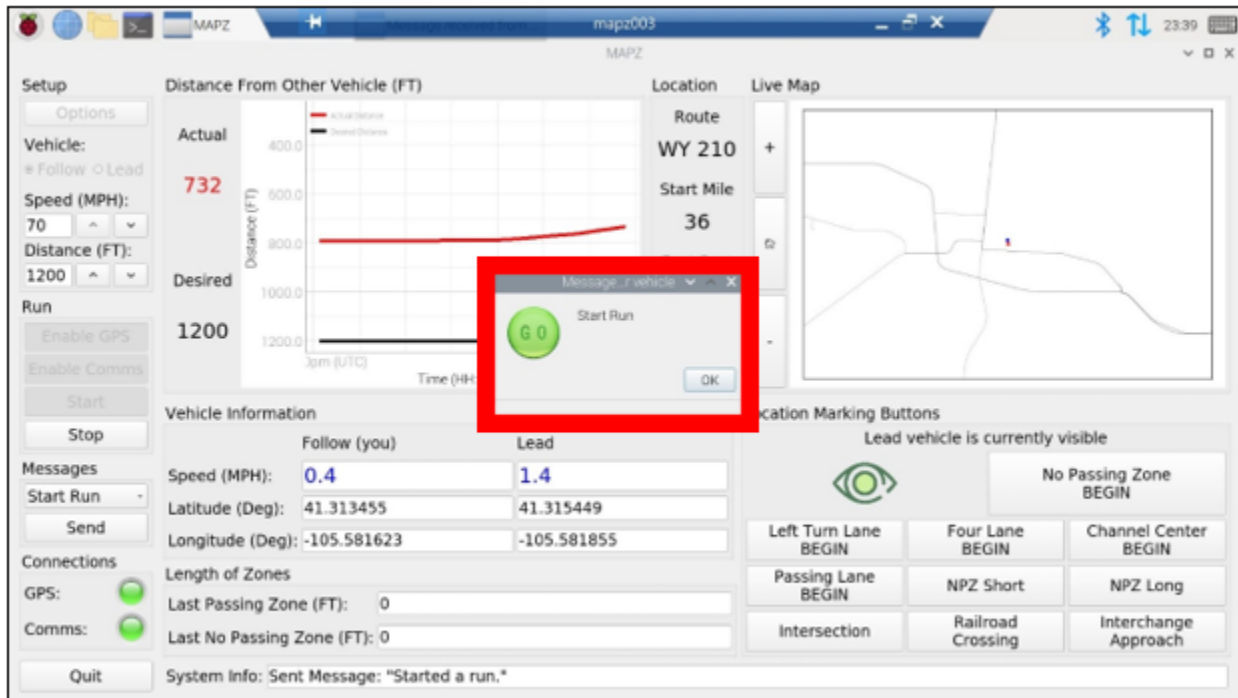
The other vehicle will receive a pop-up with the sent message. Click "OK" to close the message.
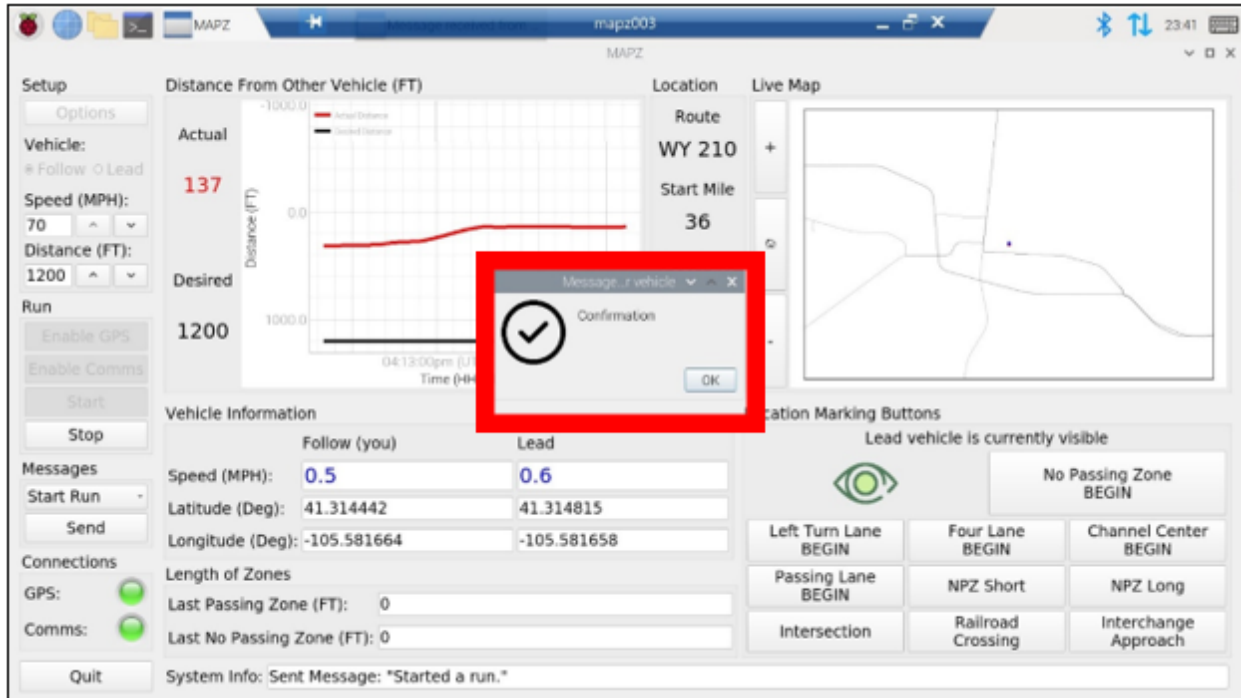
A confirmation message is included in the drop down menu to acknowledge messages.
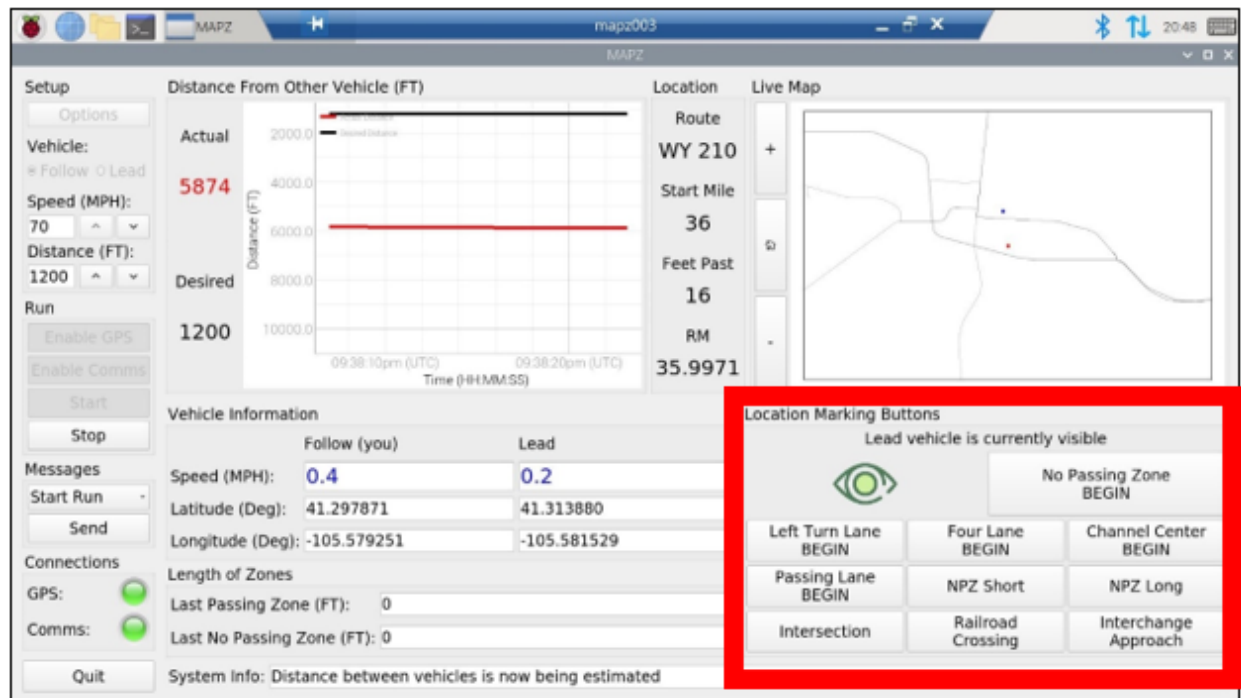
Location are marked with the "Location Marking Buttons". Marked locations will appear on the live map.

The passing zones can also be marked with the handheld button connected to the MAPZ device.
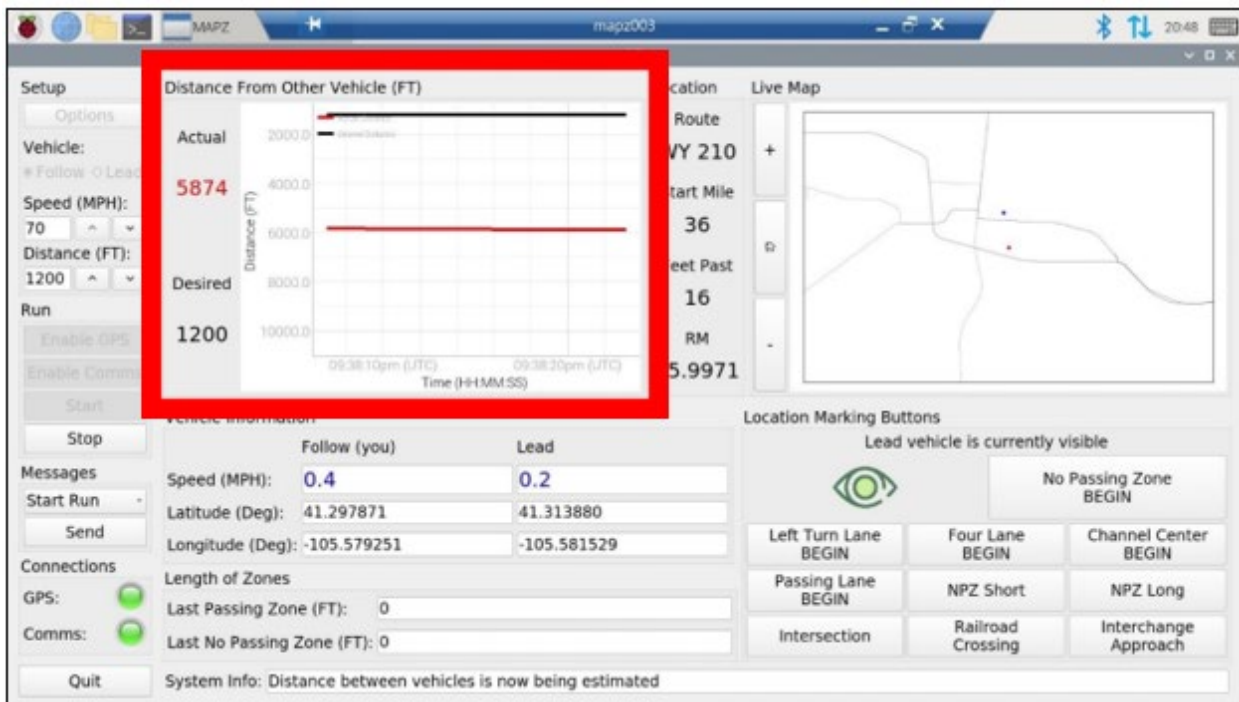
The "Distance from Other Vehicle" section displays the actual and desired vehicle distance.

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.
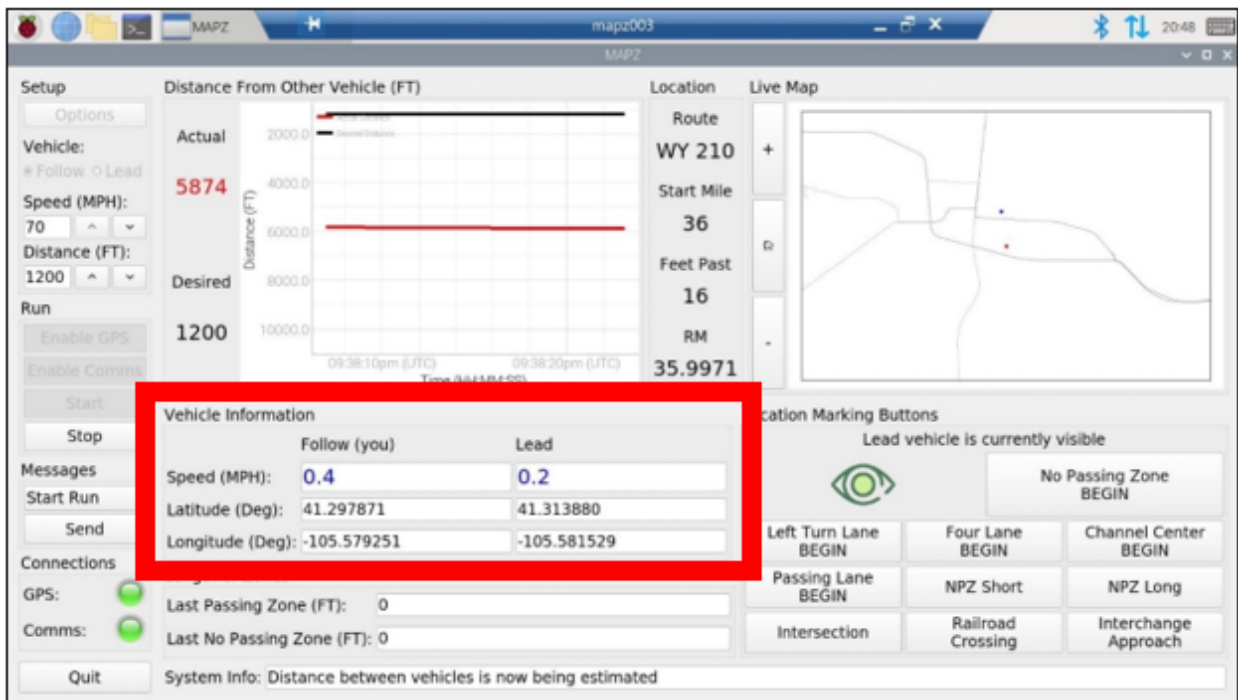
The "Vehicle Information" section displays the speed and GPS coordinates of both vehicles.
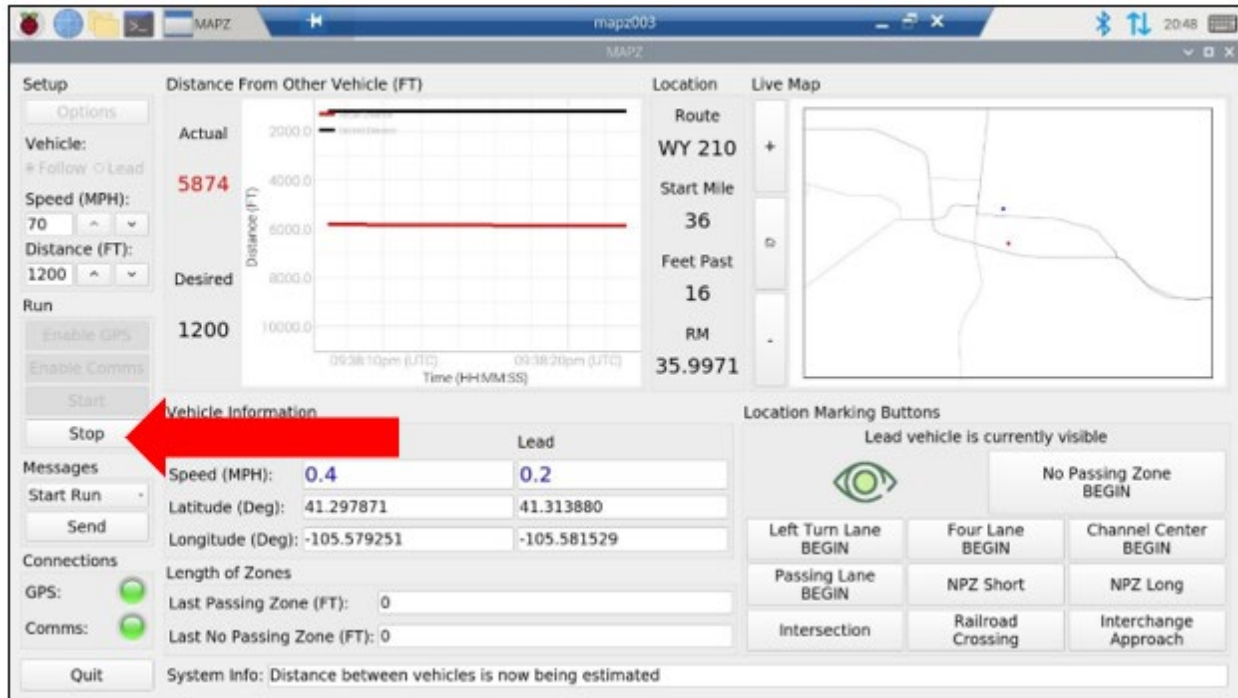
Step 18: To stop the run click the "Stop" button.
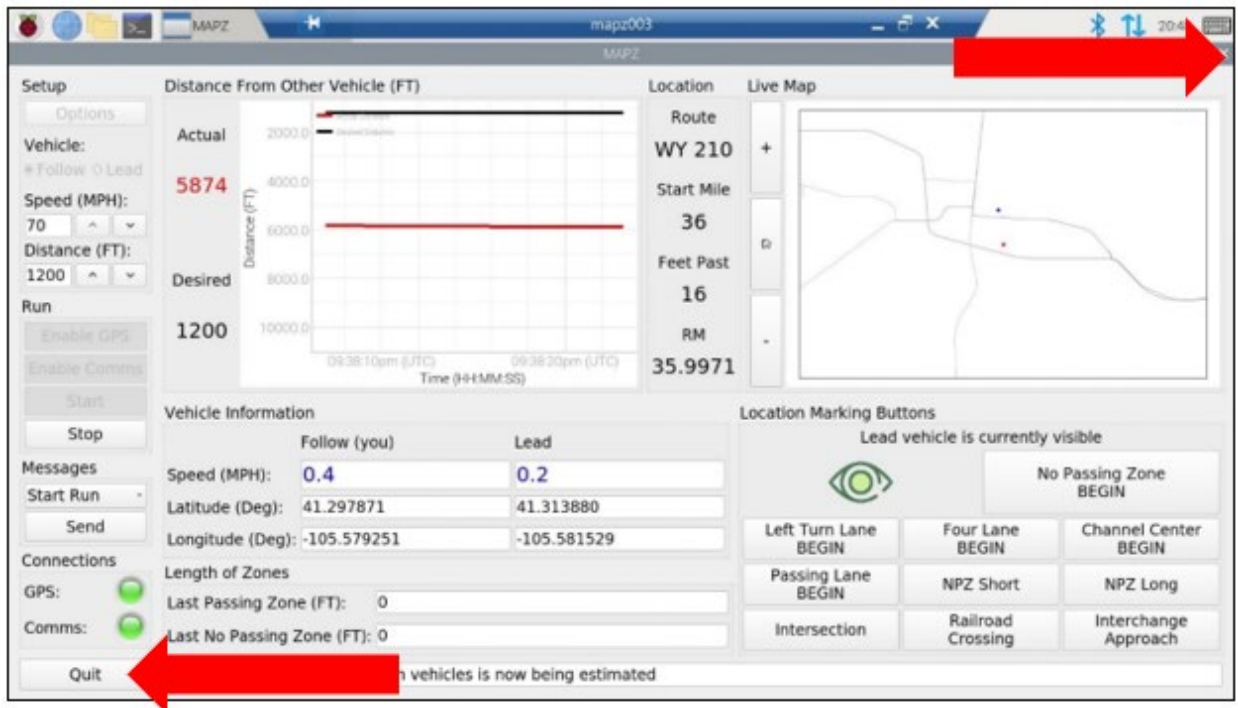
Step 19: To quit the program click the "Quit" button or the "X" at the top right of the screen. If a run is in progress the data will be saved before the program closes.
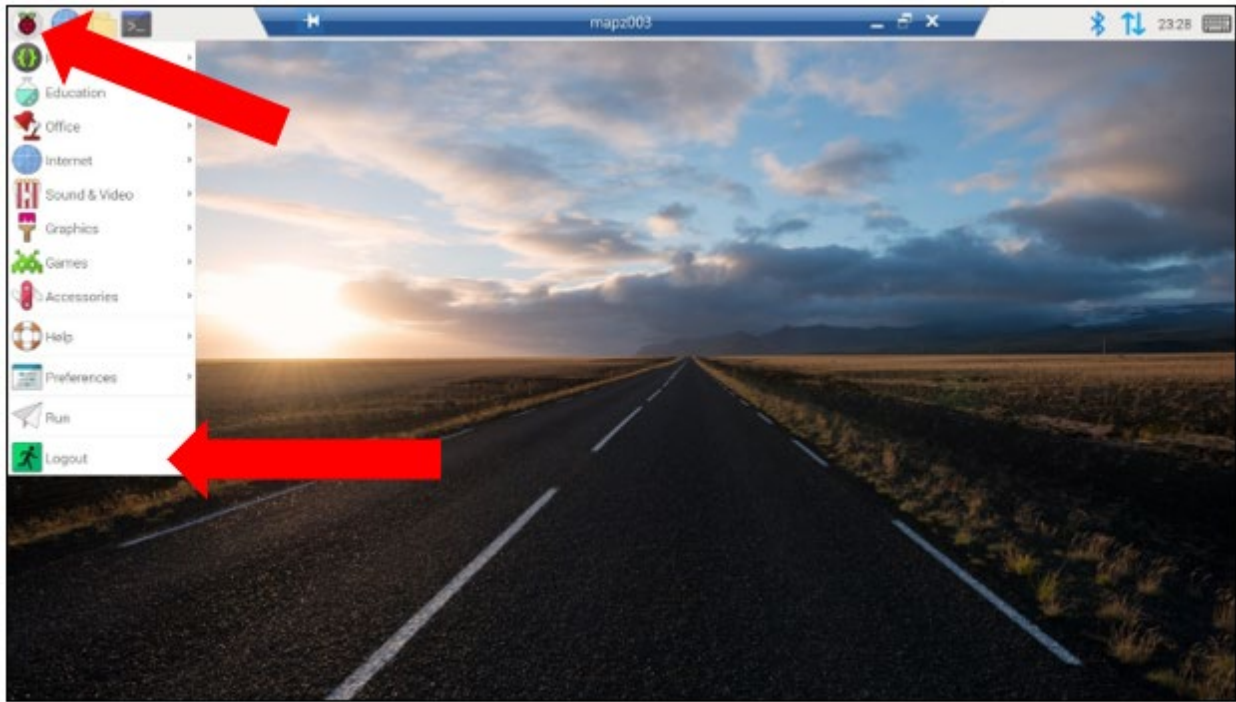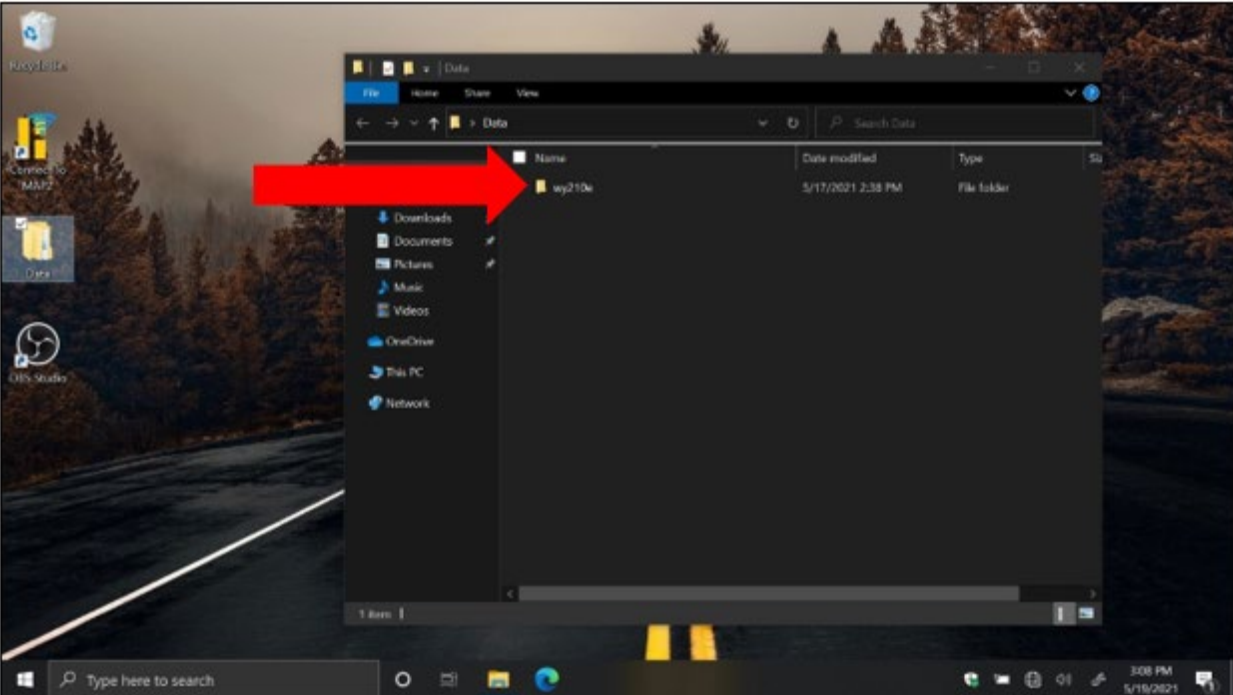
Step 20A: To shut down the MAPZ device click on the raspberry icon at the top left of the screen. Then, click on "Logout".
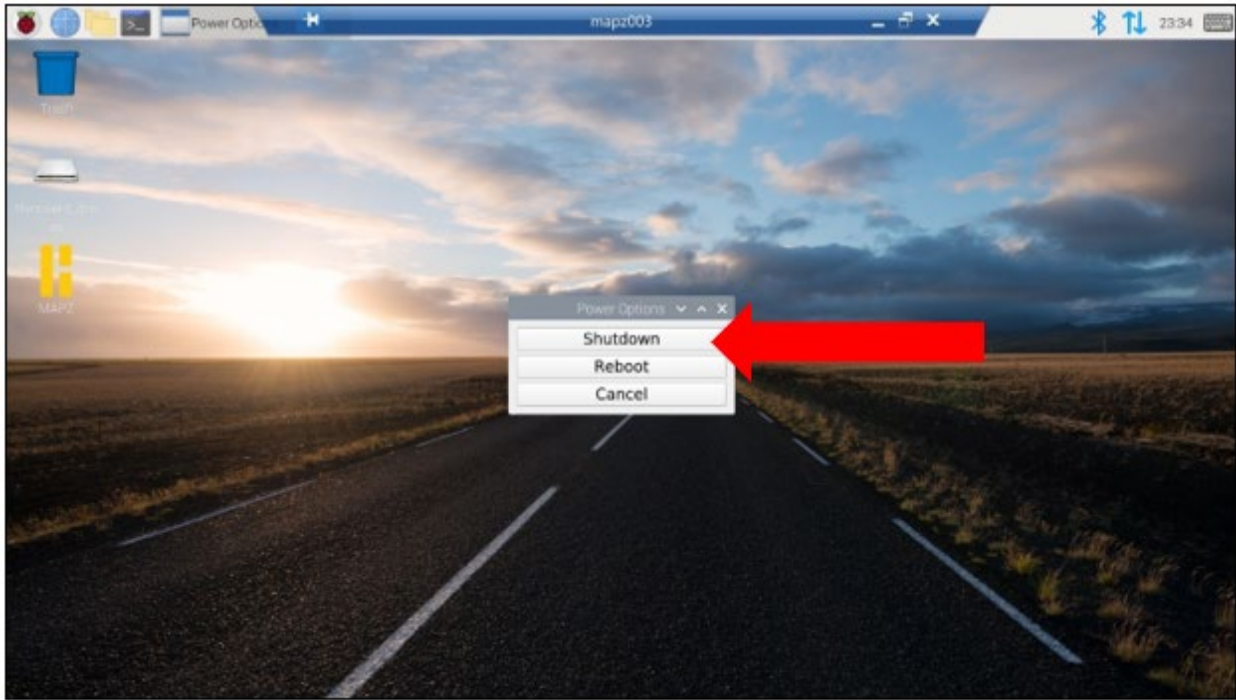
Step 20B: Once the "Power Options" menu appears click on the "Shutdown" button. It is now safe to depress the power button on the top of the MAPZ device.
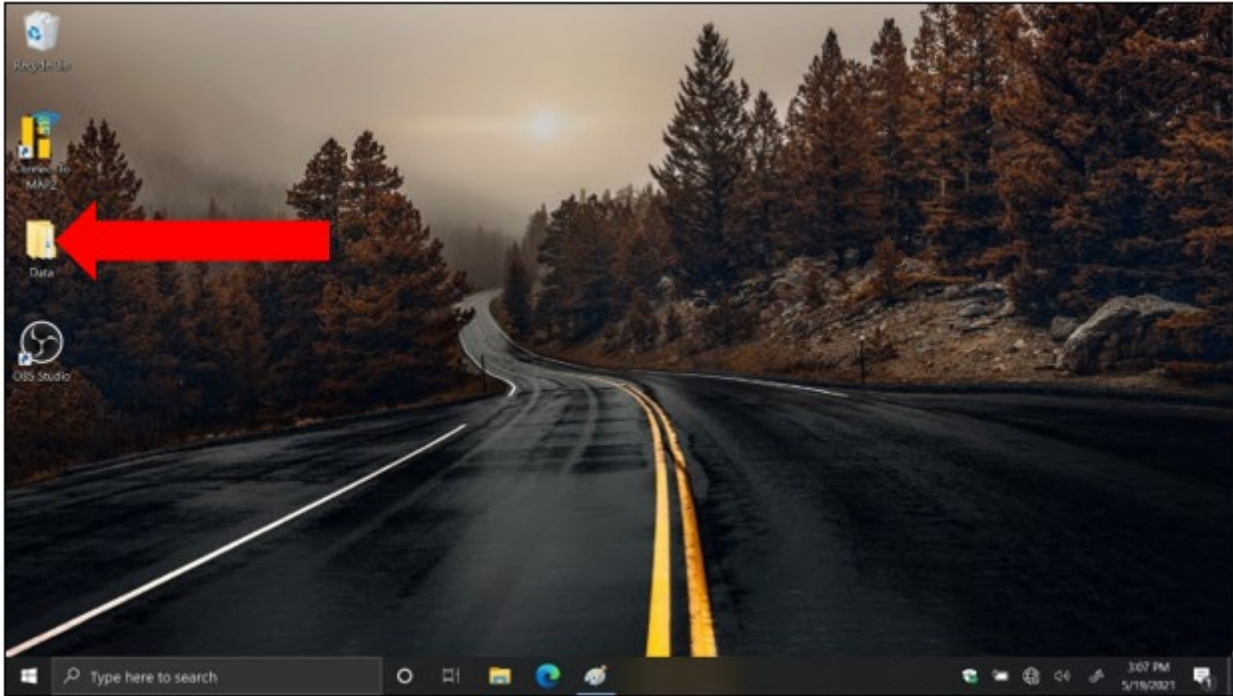
Step 21A: The run data is saved to a folder named "Data" on the desktop.

Step 21B: A folder with the name selected in step 11B will now be present.

*To modify the run data it must be copied to another folder first.