DRIVER'S SAFETY ASSESSMENT IN TWO-LANE RURAL ROAD WORK ZONES

SAFETY RESEARCH USING SIMULATION

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16. Abstract

Temporary traffic control in work zones, often referred to as TTC, lead to several challenges in terms of safety for both crew workers and drivers in both rural and urban settings. The changes imposed by the work zone in the road operating conditions or alignment geometry, including the presence of temporary signs, channelizing devices, and barriers, lane merging, shifting or closing tapers, width changes, and equipment, personnel, and materials on the roadway, increase the driver workload and the risk of crashes. This report presents the results of a driving simulator research project that investigated the potential safety implications associated with severe injuries and fatalities related to the use of GPS while driving on a two-lane rural highway with work zones consisting of one-lane closures due to operations and maintenance activities. Specifically, the effects of distractions caused by the audible messages of an active GPS while approaching or entering the advanced warning area of the TTC and the drivers' compliance with work zone regulations on the workspace were investigated.

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Acronyms

AASHTO	American Association of State Highway and Transportation Officials
AGC	Associated General Contractors
ASCE	American Society of Civil Engineers
DOT	Department of Transportation
FHWA	Federal Highway Administration
GPS	Global Positioning System
IRB	Institutional Review Board
ITE	Institute of Transportation Engineers
MSP	Mobility Service Providers
MUTCD	Manual on Uniform Traffic Control Devices
NADS	National Advanced Driving Simulator
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Transportation Safety Administration
O/M	Operations and Maintenance
PEW	Pew Research Center
PRHTA	Puerto Rico Highway and Transportation Authority
PRT	Perception and Reaction Time
RSS	Road Safety and Simulation
RTI	Real Time Technologies, Inc.
SDLP	Standard Deviation of Lateral Position
TA	Typical Application
TCD	Traffic Control Devices
TNC	Transportation Network Companies
TRB	Transportation Research Board
TTC	Temporary Traffic Control

UPRM	University of Puerto Rico at Mayagüez
US-DOT	United States Department of Transportation
UTC	University Transportation Center

Abstract

Temporary traffic control in work zones, often referred to as TTC, lead to several challenges in terms of safety for both crew workers and drivers in both rural and urban settings. The changes imposed by the work zone in the road operating conditions or alignment geometry, including the presence of temporary signs, channelizing devices, and barriers, lane merging, shifting or closing tapers, width changes, and equipment, personnel, and materials on the roadway, increase the driver workload and the risk of crashes. This report presents the results of a driving simulator research project that investigated the potential safety implications associated with severe injuries and fatalities related to the use of GPS while driving on a two-lane rural highway with work zones consisting of one-lane closures due to operations and maintenance activities. Specifically, the effects of distractions caused by the audible messages of an active GPS while approaching or entering the advanced warning area of the TTC and the drivers' compliance with work zone regulations on the workspace were investigated. Twenty-four subjects were selected to participate in the study using the UPRM driving simulation. The scenarios had two consecutive work zones with one of them in a horizontal curve. Half of the scenarios included the presence of flaggers, one at the beginning and another at the end of each work zone. Furthermore, the scenarios presented hazardous situations with incoming traffic in the opposite direction when the driver tries to pass the area closed due to the construction. The design of both TTCs in the simulation experiment followed the corresponding suggestions presented in typical applications of the MUTCD. However, it has been observed that in some instances in the real world, TTCs on two-lane rural roads do not follow the MUTCD recommendations. The variables of speed and lateral position for each subject were analyzed along the work zone. The results indicate that drivers are more likely to encroach in the workspace following the GPS routing directions in two-lane rural roads, suggesting that additional or stricter precautions and measures must beimplemented in the TTC to mitigate the safety impact of distracted drivers. At least 25% of subjects encroached the workspace while using an active GPS. Also, the results demonstrated that upon reaching the lane closure of the work zone in their firstrun, 54% of the subjects continued driving straight ahead ignoring the temporary construction work zone signs.

Keywords: Driving Behavior, Driving Simulation, Distractions, Work Zones, Temporary Traffic Control, Highway Safety, Human Factors.

CHAPTER 1: INTRODUCTION

1.1 Background

Constructing new roads and maintaining the desired state of good repair of highway facilities requires the continuous efforts of all the agencies involved in the development and maintenance of our transportation systems. Temporary traffic control in highway work zones, often referred to as TTC, are an integral part of these activities (1). Maintaining safe and efficient work zones is also a priority. However, every year we are witnessing fatalities and crashes in work zones affecting drivers as well as construction workers. Just in 2018, 124 workers suffered fatalities in work zones in the United States (2). Driver distractions are the most recurrent error that leads to crashes in work zones according to Bai and Li (3). Distraction occurs when drivers focus their attention on activities other than driving. A change in attention can be caused by a variety of factors classified into three groups: visual, manual, and cognitive distractions. Drivers experience many distractions while driving such as using cell phones, fiddling with the radio, eating, and interacting with other passengers. Distracted driving caused 2,841 fatalities in 2018 (4). As a unifying distraction, cell phones, and other electronic devices, impair all drivers in causing higher mental workloads (5). In 2019, 81% of adults in the United States own a smartphone compared to 35% in 2011 (2).

The use of smartphone applications, such as road navigation systems with a Global Positioning System (GPS), has increased the use of cell phones while driving. In a survey performed by State Farm (6), 65% of the participants stated that listening to directions from a navigation system was one of the activities they engaged in while driving. Besides, cell phones and portable devices like a GPS have complex interfaces that need interaction with the driver to operate the device, thus increasing theworkload. When drivers perform this activity, they must: touch and interact with the device to visualize the route, input or change an address, or change the route, and may get distracted by the voice navigation (7). Drivers' dependence on GPS has increased over the years. Just one of the main Transportation Network Companies (TNC) reports 15 million transactions per day (8). Dependence on GPS has the potential to create a new level of distraction, threatening the safety of road users in urban settings, and in particular, in road construction zones. Drivers using their private vehicle working for a TNC have increased complexity in their driving task. They may be unfamiliar with the driving environment, have unknown occupants in their cars from which they must listen to instructions and monitor their behavior, and look at the GPS App in their vehicles while driving, creating a potential safety problem.

Two-lane rural work zones with a one-lane closure create a situation where the vehicle going in the direction that the lane that is closed is forced to change its trajectory by moving to the lane open in the opposite direction. Tymvios and Oosthuysen investigated the difference in speed between distracted drivers and non-distracted drivers while passing around work zones in an urban area of a two-lane road with one lane temporarily closed (9). The results showed no difference in speeds between distracted drivers and non-distracted drivers. This behavior is of concern because several researchers have found that distracted drivers have a slower reaction time, and therefore, would need a longer distance to come to a full stop (8, 9, 10).

1.2 Problem Statement

Work zones generate several challenges in terms of safety for both workers and drivers. The complex geometry imposed by the TTC, including the presence of temporary signs, channelizing devices, lane changes, lane reduction, traffic flow, and modifications to the road configuration increases the risk of crashes. A study conducted by the Associated General Contractors (AGC) revealed that 54% of contractors reported that a motor vehicle crashed into their construction work zones during the past year. Also, the study showed that 25% of workers were injured and 3% lost their lives. These data show that vehicle intrusions into the workspace are a significant safety concern, which is exacerbated by the presence of distracted drivers and speeding.

Previous studies conducted at UPRM using the driving simulator regarding the impact of GPS usage on a smartphone while driving in a work zone/TTC in a high-speed divided highway have concluded that smartphone usage increases distractions that may lead to serious and fatal crashes. For example, 16.7% of the subjects using GPS encroached into the workspace, compared to 8.3% of the subjects who did not use GPS. The geometric and operational characteristics of rural two-lane roads without access control are significantly different to high-speed divided highways. Therefore, this research project will assess driver’s safety issues including GPS distractions while driving on a work zone in a two-lane rural highway.

1.3 Research Objectives

The main objective of this study is to evaluate if the use of GPS varies significantly the potential safety implications associated with serious injuries and fatalities. Specifically, the effects of distractions caused by the audible messages of the active GPS while approaching or entering the advanced warning area of the TTC in a two-lane highway, and the probability of driver error maneuvers when approaching the STOP/SLOW instructions by the flagger will be investigated. The specific objectives of this research are to:

- Evaluate driving behavior when approaching different work zone conditions on a two-lane highway segment that included one lane closure.
- Provide conclusions and recommendations regarding whether having an active GPS while traversing the rural highway work zones affects driver performance and road safety.

1.4 Report Organization

The organizational structure of this report consists of five chapters. Chapter 2 contains a review of published literature related to crash statistics, distraction while driving, and TTC. Chapter 3 explains the methodological procedure used in this investigation. Chapter 4 includes the results of the statistical analysis of the driving simulator data coupled with observational data. Lastly, Chapter 5 provides conclusions and research recommendations. References, acknowledgments, and appendices are included at the end of the report.

CHAPTER 2: LITERATURE REVIEW

2.1 National Crash Statistics

The National Highway Traffic Safety Administration (NHTSA) reported 2,994 fatalities in 2017 as a result of distracted driving and 799 associated with work zones. NHTSA defines distracted driving as any activity that diverts attention from driving, including talking or texting, eating, and drinking, talking to occupants in the vehicle, fiddling with the stereo, entertainment, or navigation system (10). The increase in workload due to the presence of the TTC in conjunction with a distracted driver can potentially increase the risk of crashes because drivers may not be aware of changes that occur in road geometry and the presence of workers performing tasks in the area.

2.2 Legal Restrictions of Smartphone Use While Driving

Using smartphones while driving is prohibited by law in Puerto Rico with the exception of these particular circumstances:

- Drivers can use a smartphone without a hands-free mode when the vehicle is completely stopped and is not impeding traffic.
- Drivers can use a smartphone when calls or communications are generated to law enforcement or related agencies.
- Drivers can use a smartphone in cases of medical or safety emergencies, including situations of immediate risk to health, life, or property; when using the GPS, or when starting or ending a call.

It is pertinent to note that the law does not apply to drivers of official vehicles that are attending emergency situations (Esq Migdalia Millet 2012; “Vehicle and Traffic Law of Puerto Rico’ [Law 22-2000, as amended]” 2017) (11).

2.3 Distracted Driving while using Smartphones.

A study conducted by State Farm in 2016 shows that even though drivers are aware of the dangers of using smartphones while driving, they still engage in said behavior. Fifty percent of surveyed drivers indicated that they talk on a hand-held cell phone while driving and 35% of drivers send text messages while driving. When asked about the main reason for using smartphones while driving, 49% indicated that it is an efficient use of time and 34% indicated that they text while driving out of habit (6).

Multiple studies have found that using smartphones while driving has a negative effect on the following five driver actions:

- Reaction time to detect an event: Drivers distracted by having smartphone conversations take 42% longer to detect an event in their peripheral vision. This applies to both hands-free and handheld phone conditions (12).
- Braking aggressively: Drivers distracted by having smartphone conversations brake more aggressively than non-distracted drivers to reduce their initial speed when an unexpected situation appears (12). Aggressive braking to decelerate by inattentive drivers is a factor highly associated with rear-end collisions; that is the main crash type occurring on highway work zones (13).
- Longer Perception and Reaction Time (PRT): Bellinger et al. studied PRT for twenty-seven young individuals using a simulated environment and found that drivers distracted by smartphone conversations had a 7.1% longer PRT.
- Unconscious time compensation: Bellinger et al. concluded that distracted drivers used an unconscious time compensation with a faster movement to the brake pedal, resulting in a more intense braking deceleration.
- Slower response and more intense braking when performing dual-tasks: Bellinger et al. identified a lower response and more intense braking for dual-task drivers when compared to those who faced only one task (13).

2.4 Temporary Traffic Control and The Manual on Uniform Traffic Control Devices (MUTCD)

Temporary Traffic Control (TTC) plans are used in highway work zones to provide an optimal functionality of the roadway, a safe and effective movement to road users when the normal function of a roadway is suspended, and to protect road users, workers, responders to traffic incidents, and equipment. TTC plans guarantee the safety and continuity of movement for motor vehicles, cyclists, pedestrians, and transit services along the work zone and provide access to adjacent property and utilities (1). To warn and inform users of the changing road conditions and channel traffic along the work zone, the following traffic control devices are often required: warning signs, cones or drums, temporary pavement markings, and flaggers.

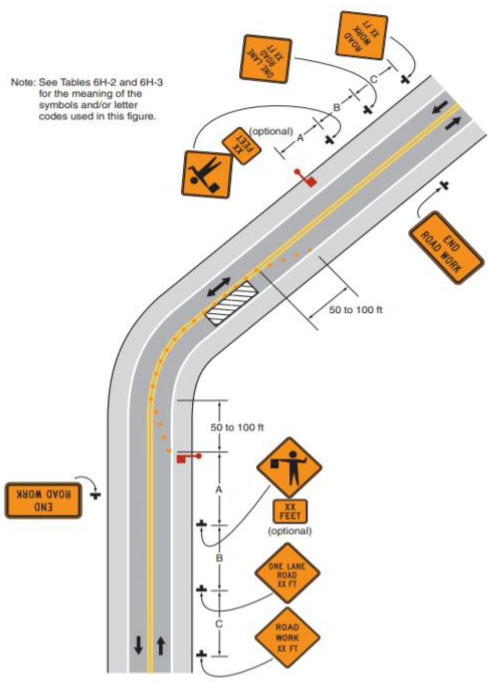
The Manual on Uniform Traffic Control Devices (MUTCD) is a national reference guide to install and maintain traffic control devices in work zones. As defined by the MUTCD (1), "*a TTC zone is an area of a highway where road user conditions* *are changed because of a work zone, an incident zone or a planned special event through the use of TTC devices, uniformed law enforcement officers, or other authorized personnel.*" The MUTCD provides a series of typical applications (TAs) that can be used taking into account the road configuration, work activity, road user volume and speed, the location of the work, and road vehicle mix. The MUTCD defines four main areas for a temporary highway construction work zone (14):

- Advance Warning Area: "*The advance warning area is the section of highway where road users are informed about the upcoming work zone or incident area*".
- Transition Area: "*The transition area is that section of highway where road users are redirected out of their normal path. Transition areas usually involve strategic use of tapers*".
- Activity Area: "*The activity area is the section of the highway where the work activity takes place. It consists of the workspace, the traffic space, and the buffer space*".
- Termination Area: "*The termination area is the section of the highway where road users are returned to their normal driving path. The termination area extends from the downstream end of the work area to the last TTC device such as END ROAD WORK signs, if posted*".

2.5 Lane Closure on a Two-Lane Road

This study used the MUTCD Typical Application (TA)-10. This application was used because the work zone included a lane closure of a two-lane road. MUTCD TA-10 states that to close a lane on a two-lane highway, it is necessary to coordinate traffic movements at each end. Traffic needs to be controlled by flaggers. If visibility allows seeing from one end to the other, the traffic can be controlled by a single flagger on low volume roads. If there is no visibility, two flaggers must be present and communicate with each other to coordinate the movement. The location of the flagger to indicate the driver to stop should be on the side of the road or in the closed lane. The flagger station must be located in a place that allows sufficient visibility for a driver to stop at the intended stopping point. Figure 1 shows the MUTCD TA-10. As shown in the figure, the two-lane road work zone includes two flaggers due to the obstructed visibility caused by the horizontal curve.

Figure 6H-10. Lane Closure on a Two-Lane Road Using Flaggers (TA-10)



Typical Application 10

Figure 1: Lane Closure on a Two-Lane Road Using Flaggers (MUTCD, 2009)

2.6 Driving Simulators

Driving simulators are an innovative and cost-effective research tool to evaluate drivers' behavior in a wide variety of research fields such as human factors, transportation, psychology, medicine, computer science, training, and other driving activities (15). Driving simulators have been used in research with the goal of evaluating scenarios where physical harm or potential crashes may occur without exposing subjects to harmful situations. By using driving simulators, researchers can anticipate and evaluate road safety issues by analyzing the behavior of subjects in simulated scenarios and existing conditions. In surface transportation, several driving simulators studies have used speed, lane position, and acceleration data as measures to evaluate driving behavior.

CHAPTER 3: METHODOLOGY

The research methodology was divided in six tasks as shown in Figure 2. The first task was a literature review which included the relevant research findings and information related to distractions and their impact on road safety, construction work zones on rural two-lane roads, and the use of driving simulators. The second task was getting the Institutional Review Board (IRB) approval for the simulation study. The third task was the development of the scenario of a rural two-lane road, similar to the existing roadway conditions of highway PR-108, located in the western region of Puerto Rico. The design of the scenario included the closing of one of the travel lanes using proper temporary traffic control devices, with the TTC plan layout following guidelines provided by the MUTCD.

The fourth task was data collection. A group of 24 subjects between 18 and 70 years of age, with a valid driver's license and more than 18 months of driving experience, were recruited to drive in the simulator. Using the driving simulator, driver's behavior was evaluated in terms of speed, lateral position, and reaction time in the work zone of the two-lane road. In addition to the data collected using the driver simulator, an observer was taking notes of the subjects' reactions while driving on each scenario. Particular interest was placed on the reactions before, during, and afterthe subjects encounter each one of the two work zones presented in each scenario.

The fifth task was to perform the statistical analysis of the behavior observed in the driving simulator experiments.

Finally, the sixth task was to write the final report that includes all the pertinent findings of the study.

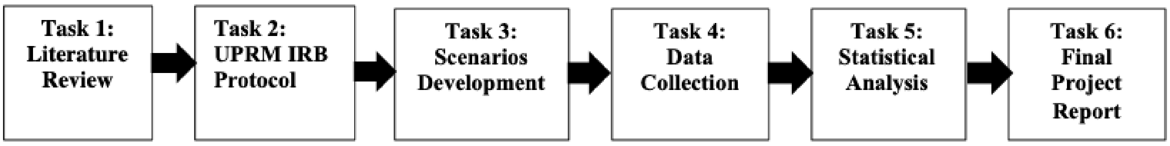


Figure 2: Research Methodology

3.1 Research Hypothesis

The general hypothesis of this study was that:

Drivers subjected to a driving distraction (i.e., navigation task) while traversing a work zone will exhibit worse performance (more unsafe behavior) than those who do not have a distraction while driving along the same two-lane road work zone.

3.2 Driving Simulator Equipment

The driving simulator equipment used in the study is configured as a driving cockpit simulator with three primary parts described below:

- The vehicle – The cockpit consists of a car seat, a gear shifter, a steering wheel, and pedals, placed in a wood frame with wheels for mobile application. The steering wheel with turn signal control is attached to the wooden countertop. The gear shifter is on the car seat's right hand and the brake and accelerator pedals on the cockpit floor below the countertop.
- The projection – consist of a screen with a 120° field of view and three overhead projectors with a ten degrees deflection between them.
- Control center – hardware consists of a desktop with NVIDIA GeForce GTX 1080 graphics card to reproduce the simulation and a laptop to control it. The software consists of RTI SimCreator/SimVista simulation software.

3.3 Experimental Design

The factors used for the scenarios were: with or without GPS distraction, and with or without a flagger. Based on these variables, a total of four scenarios were created. The scenarios' description is shown in Table 1.

Scenario	Presence of GPS	Presence of Flagger
1	No	Yes
2	No	No
3	Yes	Yes
4	Yes	No

Table 1: Scenarios' Description

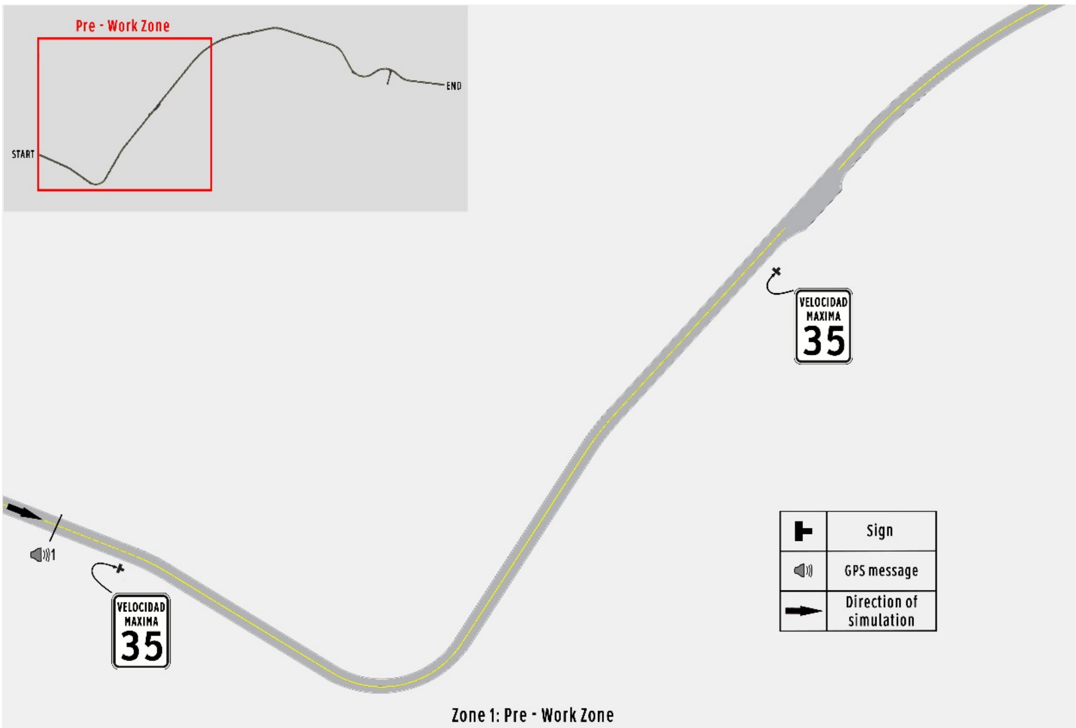
A randomization strategy was used to assign the viewing order of the scenarios to counterbalance the effects of fatigue and the learning curve. All of the participants completed the four scenarios in a different order.

3.4 Scenario Development

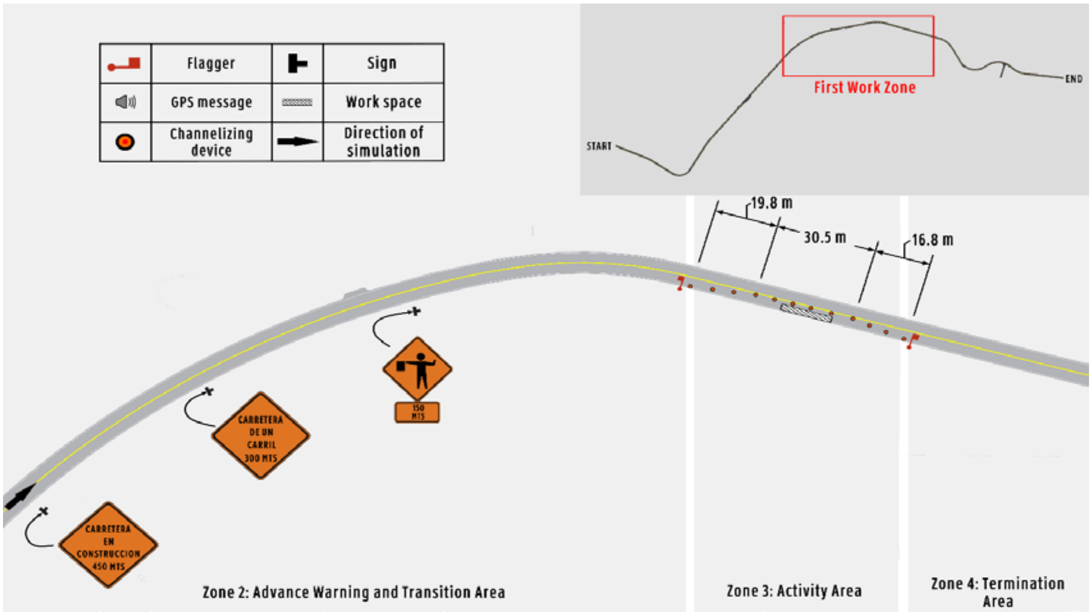
A base scenario was created based on the geometric and operational characteristics of the existing two-lane rural highway PR-108 located in the western region of Puerto Rico. This base scenario has a 1.8 km long highway section with nine horizontal curves segments and a 7.7 m-wide roadway cross-section with 3.2-m wide lanes. The segment has a posted speed limit of 35 mph. The beginning of the work zone is located 1.2 km from the start of the simulation. From the base road scene, the four scenarios described above were developed. Figure 3 shows the cross-section of the simulated scenarios.

Figure 3: View of the Simulated Roadway with Active GPS and Flagger Condition

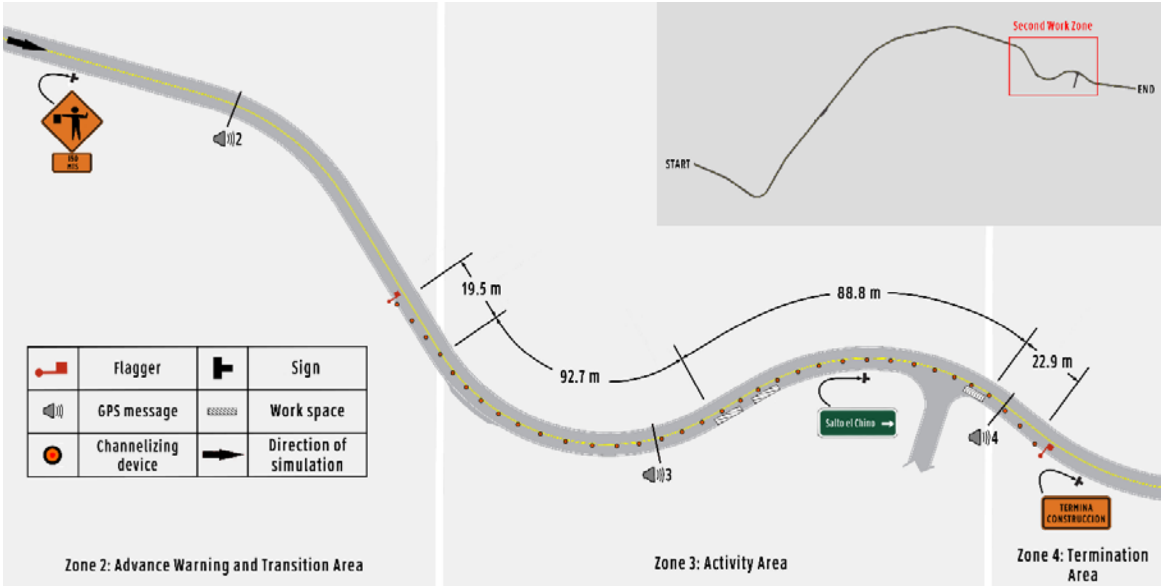
Figure 4 illustrates a plan view sketch of the base scenario with the corresponding work zone components. The scenario includes a pre-work zone and two continuous work zones. The pre-work zone shown in Figure 4a includes the first GPS message and the posted speed limit and is used to allow the driver to get in a normal driving condition before arriving at the advance warning and transition area of the first one-lane closure work zone. The workspace is defined by the presence of workers and construction equipment located in the right lane. A series of channelizing devices separate the work zone from the available lane that alternates for vehicles traversing both directions. The TTC plan presented in Figure 4b and Figure 4c were designed in compliance with the MUTCD TA-10, but using Spanish-text signs.



(a) Pre – Work Zone alignment



(b) TTC Plan for the First Work Zone



c) TTC plan for the second work zone

Figure 4: Plan View of the Roadway and Work Zone Conditions

The GPS used as a distraction includes four-voice instructions. These instructions told the driver that he was heading to one of the exits that were blocked by the work zones. The locations where each message is triggered in scenarios that have GPS are shown in Figure 2. The instructions provided by the GPS are:

- "Continue on PR-108 for a kilometer and a half"
- "After 300 meters, turn right towards Salto el Chino"
- "Turn right towards Salto el Chino"
- "Recalculating… head north on PR-108 towards Camino las Hortensias… after 300 meters turn right towards Camino las Hortensias"

To determine the effect of the GPS as a distraction in work zones, the research established a conflicting decision for drivers whether to follow GPS instructions and turn into the exit that was blocked by the work zone or to ignore the GPS instructions and continue driving along the road without exiting. For the drivers who were not using GPS, the instructions were given verbally before the simulation run. Drivers were instructed to start driving at the specified exit that corresponds to the "Salto del Chino" road. For subjects who had the GPS active, the voice messages indicated to the drivers as they passed by the side of the work zone should take the exit. Of course, the second work zone was in the way. Therefore, taking the exit meant encroaching into the workspace in the TTC.

CHAPTER 4: DRIVING SIMULATOR STUDY

This chapter presents the characteristics of the subjects that participated in the experiments and the results of the analysis of the data obtained from the experiments. The analysis includes the data collected by the driving simulator and the data collected from the observations of the subjects' reaction when entering and traversing the work zones.

4.1 Subjects

All subjects that participated in the study have a valid motor vehicle driver license in Puerto Rico and are between the ages of 18-70. The study followed the UPRM Institutional Review Board (IRB) ethics regulations.

The 24 participants conducted 4 different scenarios. At the beginning of the simulation, the participants were given visual instructions on where they should go. Upon reaching the work zone, the driver had to decide to continue or stop to assess whether a vehicle was approaching from the opposite direction. In the scenarios with the flagger, the participant must wait for getting authorization to pass through the area. At approximately 1.6 km there is a destination sign that notifies the driver of the exit they need to take. The work zone blocks this exit on purpose. The driver has to recognize the modifications on the road imposed by the work zone and decide whether to continue (e.g., the correct and safe decision) or encroach the work space (e.g., the wrong and hazardous decision). In the scenarios where there is an active GPS that does not take into account the presence of the work zones, the driver receives audible instructions indicating to take the exit as simulating that the GPS system does not have updated information about the existing road conditions. Since the work space is blocking the exit, the driver faces the same dilemma, to encroach or not the work zone space. The expected correct behavior would be to continue along the roadway and look for alternate ways to reach their destination.

4.2 Experimental Results and Data Analysis

Once the 24 subjects completed the corresponding runs for each scenario, the results collected by the driver simulator were organized in a database using R Studio. The database was further analyzed using the Power BI data visualization tool. The data collected from the observations of the subjects were organized into a database in Excel for further analysis.

Figure 5 presents the percentage of subjects who invaded the lane in the opposite direction when reaching the first construction zone without stopping. The horizontal axis shows the order in which the drivers ran the scenarios. In this case, the order is essential because, as shown in the figure, the first time the drivers face the simulation, they react differently from the subsequent runs. When the subjects drove the scenario for the first time, 54% of the subjects reaching the work zone invaded the opposite lane without stopping. These subjects reached the work zone, and instead of stopping to see if a vehicle was coming from the other direction, they continued straight on. More subjects stopped and proceeded with caution in the second work zone and subsequent runs. As mentioned above, in the first work zone, 54% invaded the opposite lane, while in the second work zone, only 35% invaded it without caution. More drivers stopped to wait for a safe gap in the opposite lane when they reached the work zone in the second run. The percentage is even lower for subsequent runs. This indicates that drivers were driving as usual when they approached the first work zone for the first time, but were more cautious once they learned that oncoming traffic would not stop because they were invading their lane. The learning curve was fast in most of the cases. However, some subjects still invaded the opposite direction without stopping even in their fourth run.

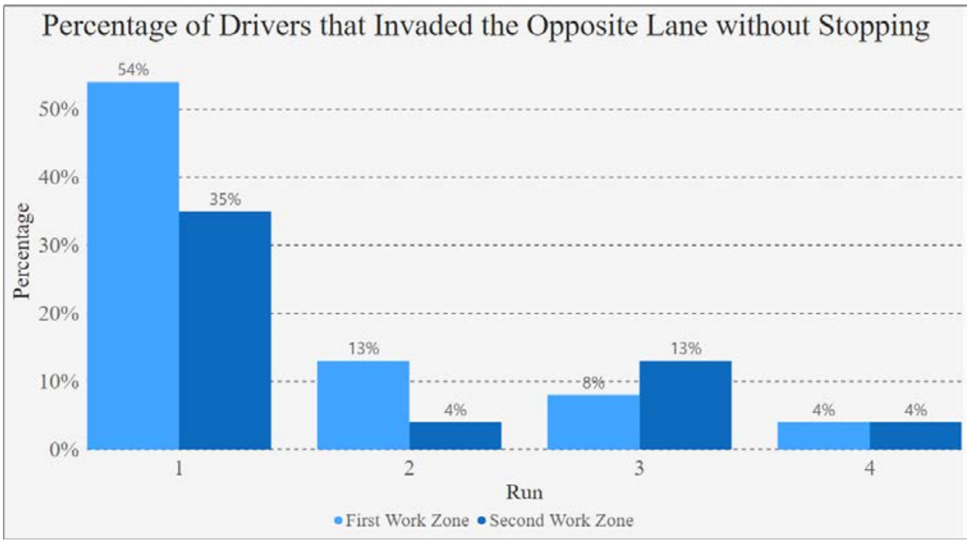


Figure 5: Drivers Invading the Opposite Lane Without Stopping

Three main reactions were observed once the drivers arrived at the work zone. The first reaction was to continue straight ahead without stopping, as shown in Figure 5. The second reaction was that when some drivers invaded the opposite lane, they crashed into the opposing vehicle. Finally, the third reaction was that when they invaded the opposite lane, subjects stopped when they saw the vehicle coming from the opposite direction and backed up and moved away to let the opposing vehicle go by.

Figure 6 presents the percentage of drivers who crashed when invading the opposite lane adjacent to the work zone. The highest percentage of drivers that crashed occurred the first time they ran the scenario. For the next runs, the percentage of subjects who crash was lower. However, this situation still occurred even when subjects knew that a vehicle could come from the opposite direction. Figure 7 shows the percentage of drivers who backed up when they invaded the opposite lane and a vehicle came from the other direction. It is interesting to see that even in runs two and four, some subjects tried to invade the opposite lane without caution but decided to back up once the vehicle came from the opposite direction. The exhibited behavior is very dangerous and that was precisely the intent of this experiment.

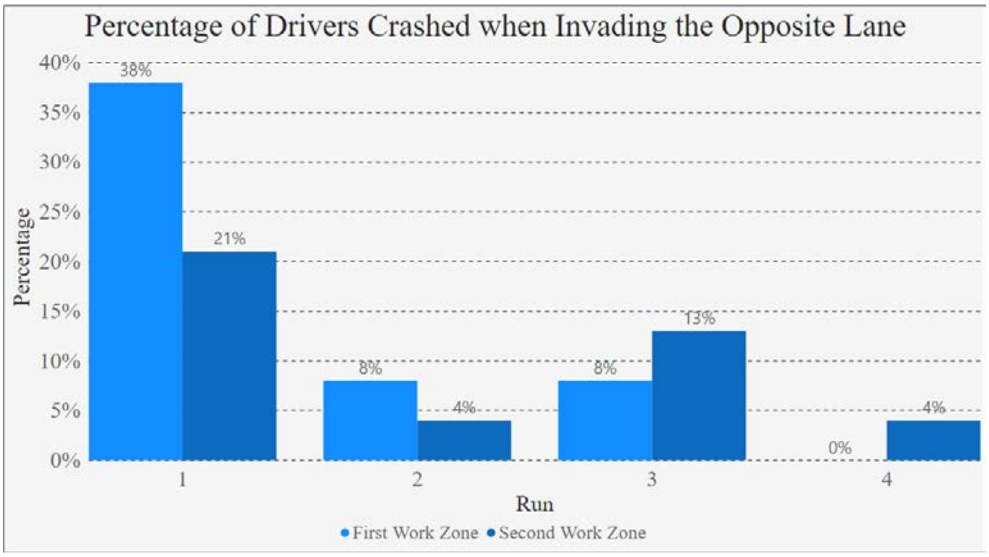


Figure 6: Percentage of Crashes after Invading the Opposite Lane

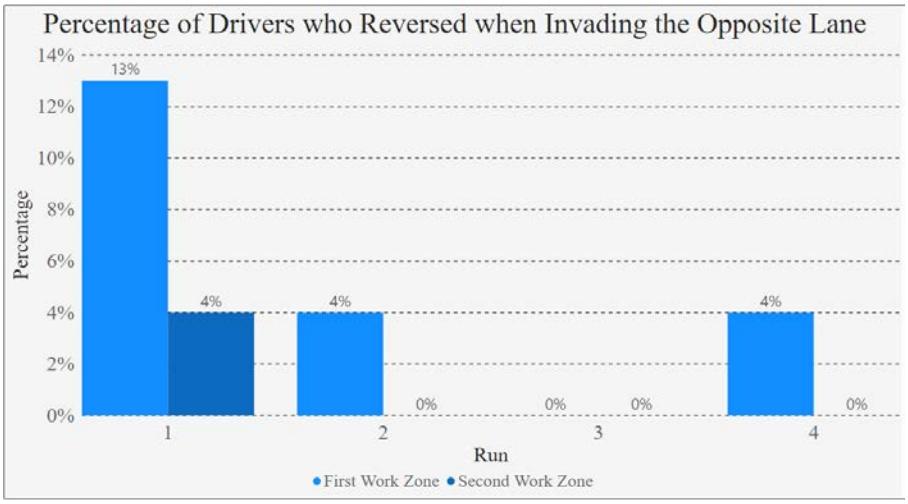
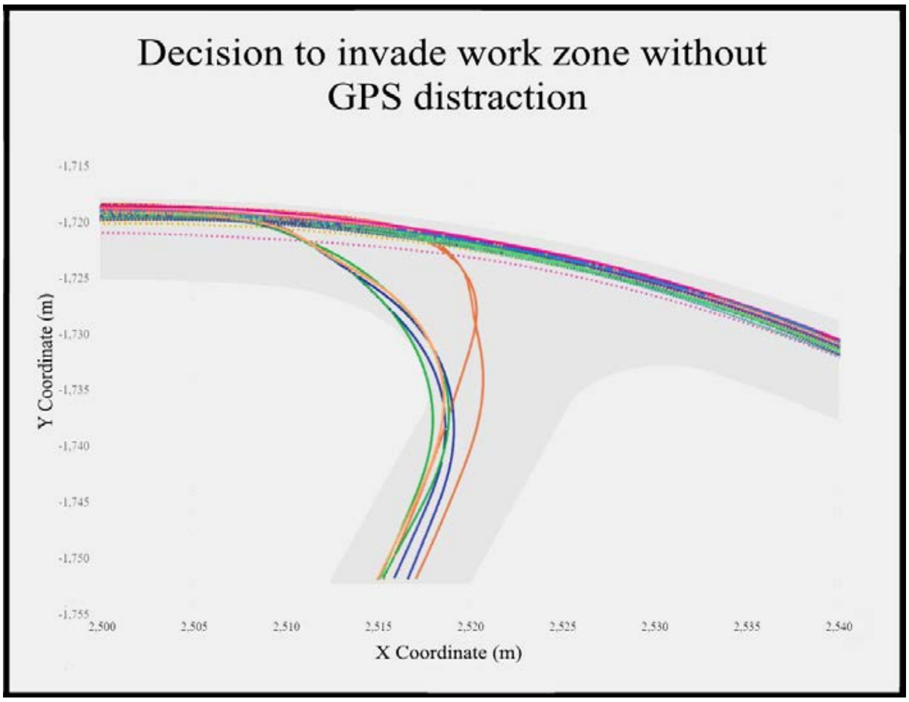
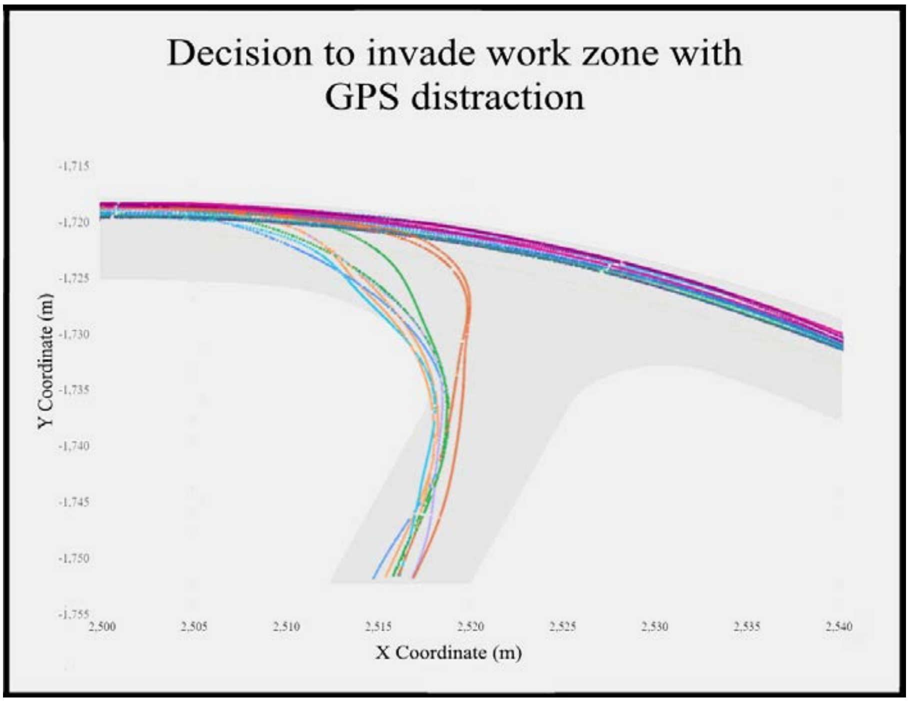


Figure 7: Percentage of Reverse Maneuvers after Invading the Opposite Lane

Figures 8A and 8B show the vehicles' trajectories corresponding to the runs without GPS and with GPS. Figure 8A corresponds to the runs without GPS (Scenarios 1 and 2), and Figure 8B corresponds to the runs with GPS (Scenarios 3 and 4). In total, 48 runs are represented in the two figures. There were 24 subjects running the scenarios. As shown, 17% of the subjects without GPS correspond to the subjects who exited the roadway by encroaching the work space at least once. In comparison, 25% of the subjects with GPS encroached the work space at least once. Therefore, the use of GPS has an additional effect in this case. There is an 8% increase in runs in which the subjects encroached the work zone due to the GPS distraction.



A) Trajectories of the vehicles corresponding to the runs without GPS

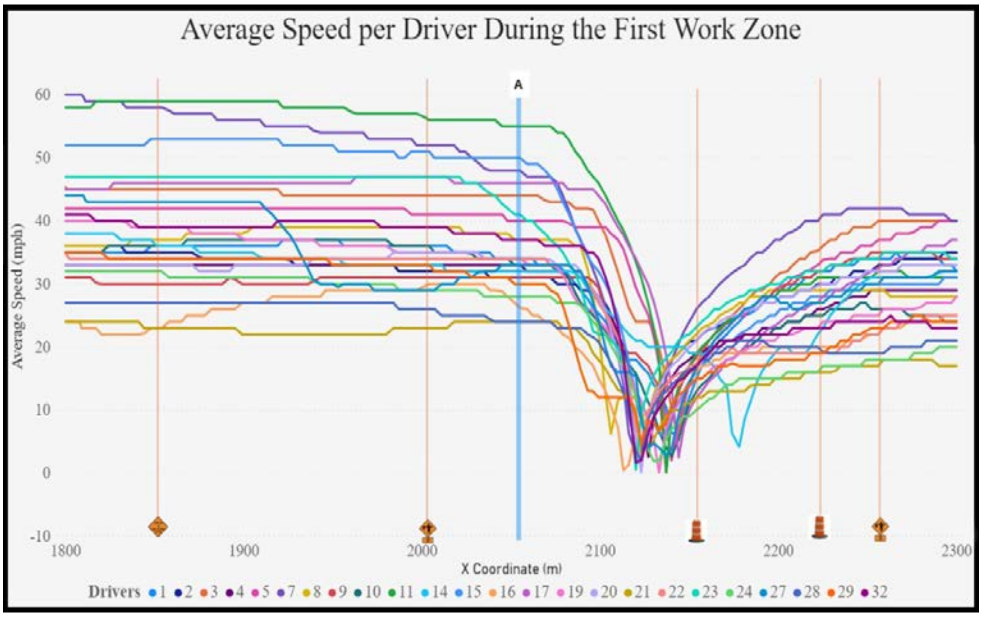


B) Trajectories of the vehicles corresponding to the runs with GPS

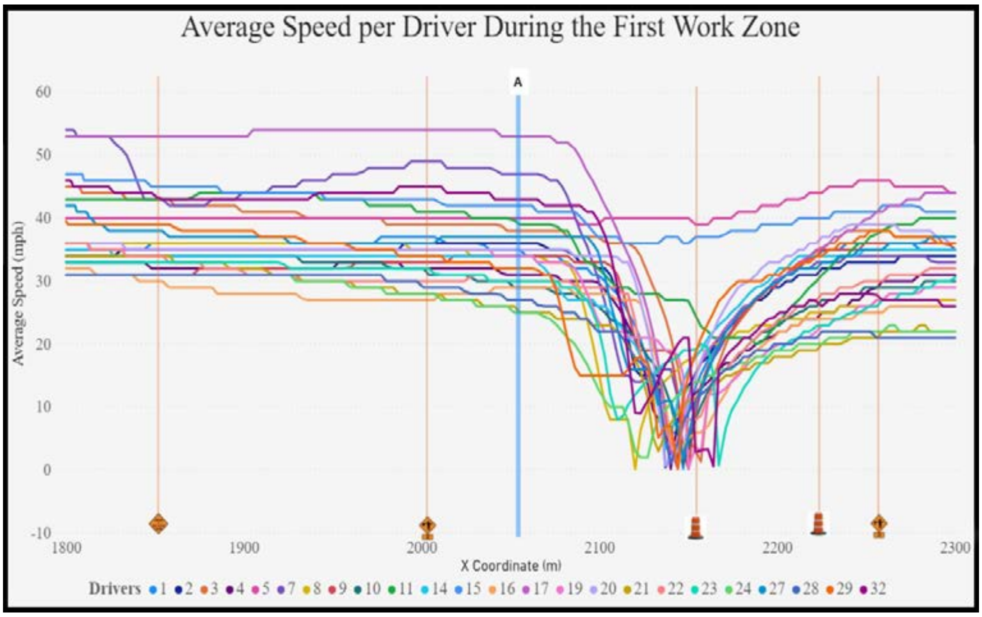
Figure 8: Vehicle Trajectories at the Location of the Exit Road.

Figure 9 shows the speed profile of the drivers through the first work zone. The figure is divided into four figures (A, B, C, D) corresponding to Scenarios 1, 2, 3, and

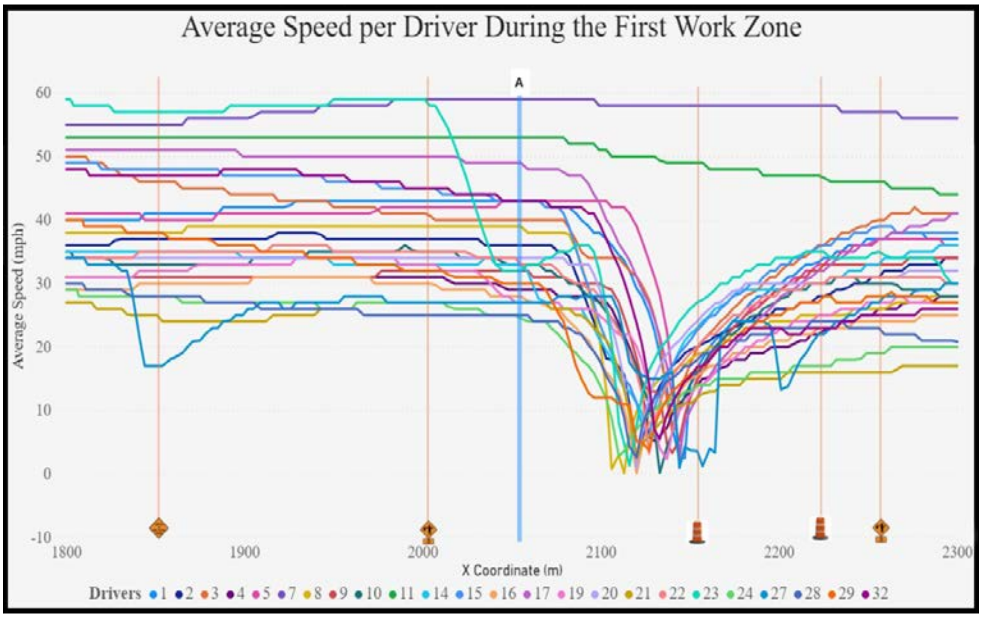
4, respectively. As indicated in the experimental design, in Scenarios 1 and 3, a flagger with a STOP/SLOW paddle is located at the beginning of the merging taper. The point "A" in the figures, represents the point from which the drivers first perceive the work zone, approximately 100 meters away from the first drum. As shown in these figures, most of the subjects stop when they arrive at the work zone. The figures show the TTC devices from the first work zone on the horizontal axis. As it can be seen, two of the drivers did not stop even though there was a flagger. For these two drivers, this scenario corresponds to their first run. In other words, it was the first time they saw the situation, and it could be inferred that they continued straight on without stopping for that reason. In Scenarios 2 and 4, corresponding to Figures 9B and 9D, it is observed that there were eight drivers out of the 24 who did not make a full stop. In these scenarios, there was no flagger. Therefore, the analysis indicates that the flagger's presence contributes to the subjects slowing down and stopping before reaching the work zone. Another important element to appreciate in these graphs is that the drivers stop at different points before the work zone. For this reason, when the average speed is calculated at different points, a speed of zero is not reached because the place where each subject made a full stop may be different along the road.



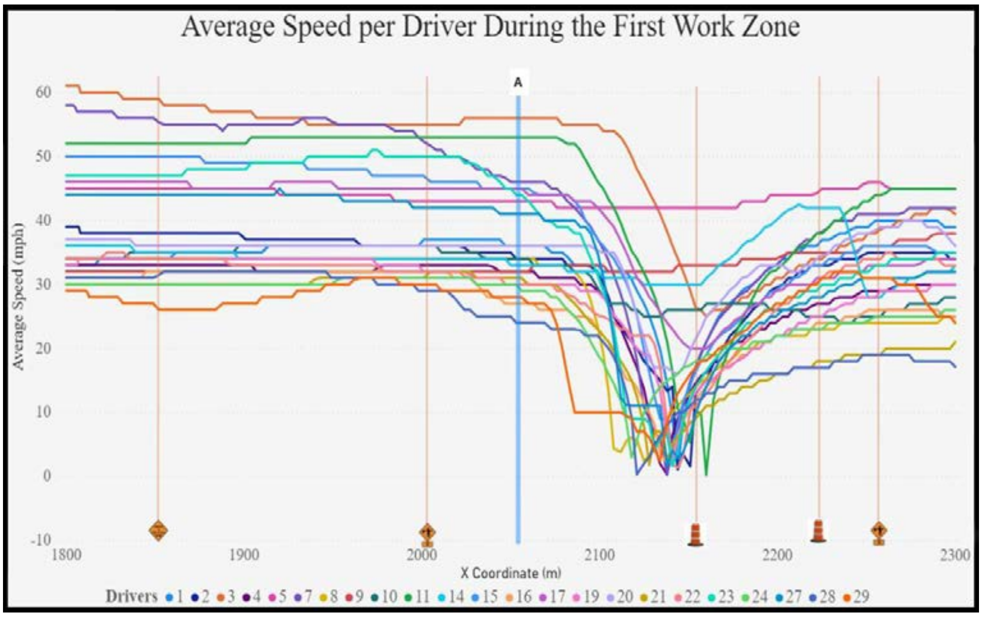
A) Average Speed Profile - Scenario 1



B) Average Speed Profile - Scenario 2



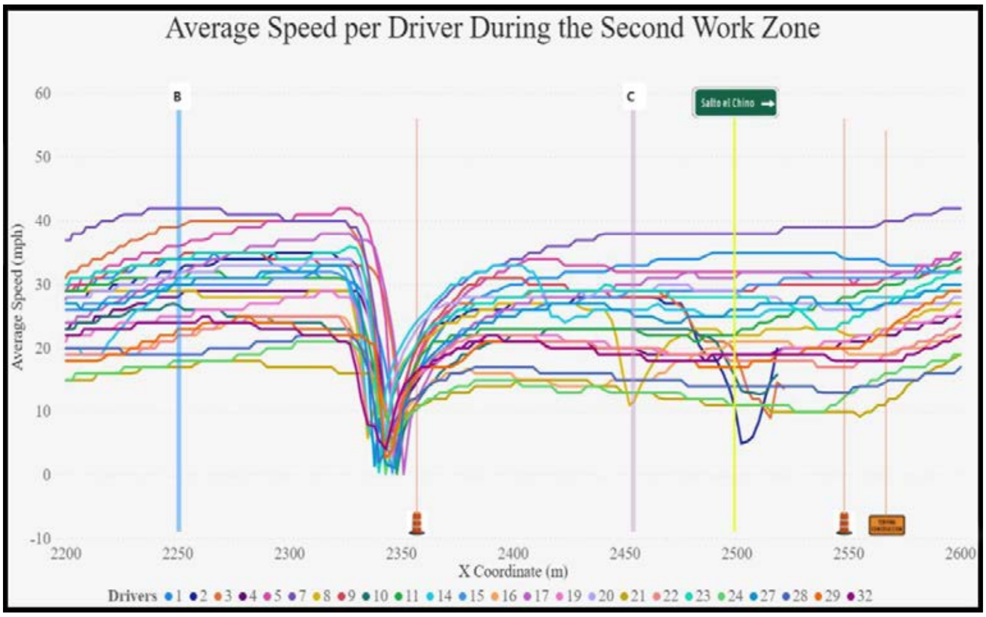
C) Average Speed Profile - Scenario 3



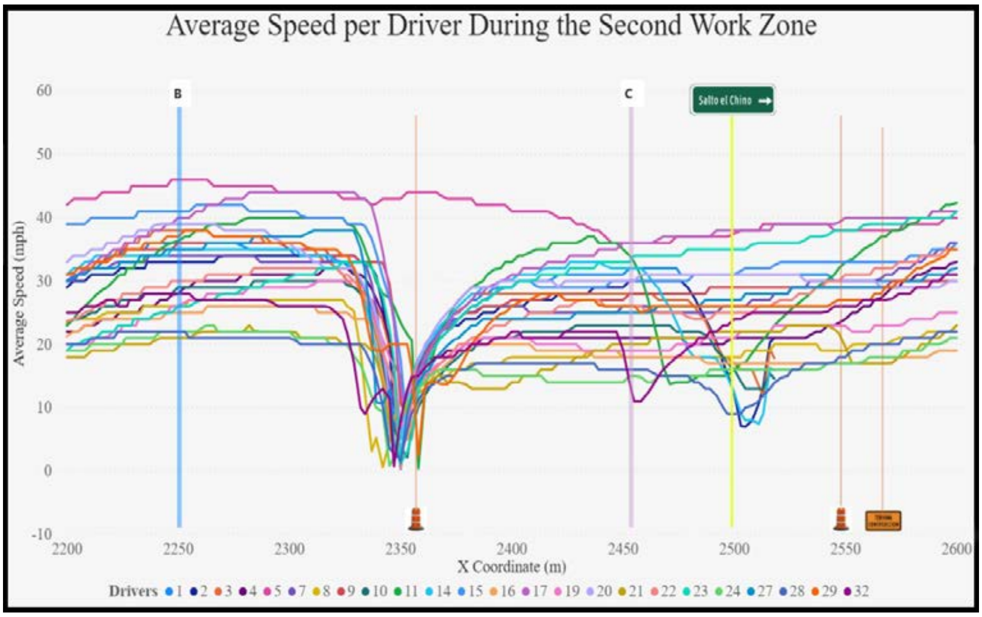
D) Average Speed Profile - Scenario 4

Figure 9: Speed Profiles Along the First Work Zone

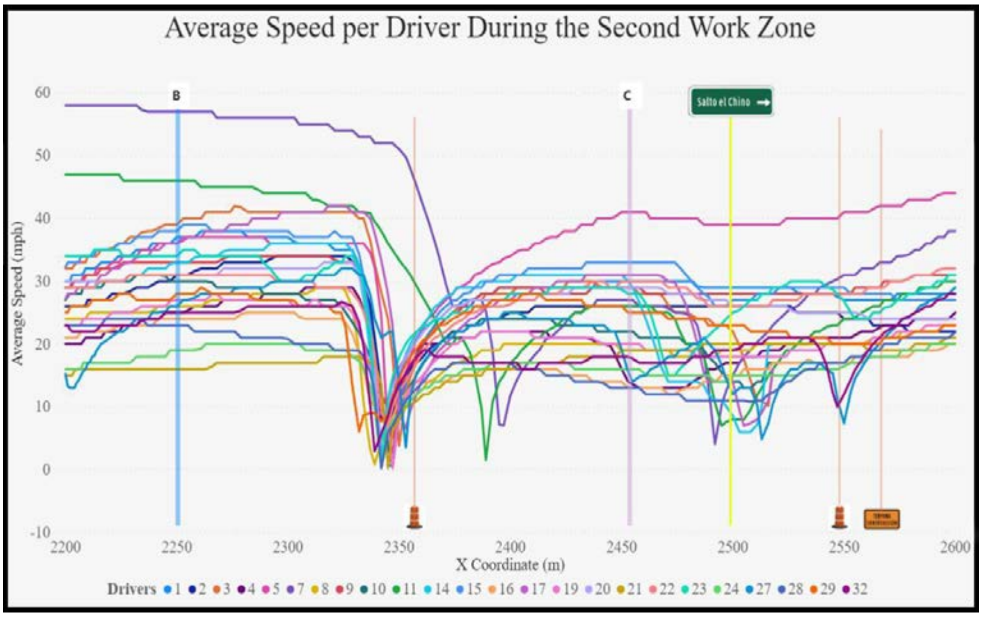
Figure 10 presents the speed profiles in the four scenarios for the second work zone. In these figures, line "B" indicates the point from which the sequence of channelizing devices or the flagger is visible. The line marked with the letter "C" indicates the point from which the destination sign of the "Salto del Chino" exit road is visible, which is where the subjects are supposed to exit. In these figures, when the subjects see the destination sign to the "Salto del Chino", they slow down, and some of them stop. Other subjects enter the lane encroaching the work space; however, most subjects continue looking for a possible alternate route. Similar to what happened in the first work zone, several subjects continue driving straight without stopping when they reach the point where the lane is closed, therefore invading the opposite lane without caution. In Scenario 3, only 8.3% of the subjects that saw the flagger scenario as theirfirst run did not stop. In the scenarios where there was no flagger, 25% of the subjectsdid not stop when they reached the point where the lane is closed. This result indicatesthat the presence of the flagger contributes to increasing safety in this type of two-lanerural work zone. In other words, the presence of flaggers have a positive effect wherethere is a closed lane and vehicles must use the lane in the opposite direction to passthe area where the construction is taking place.



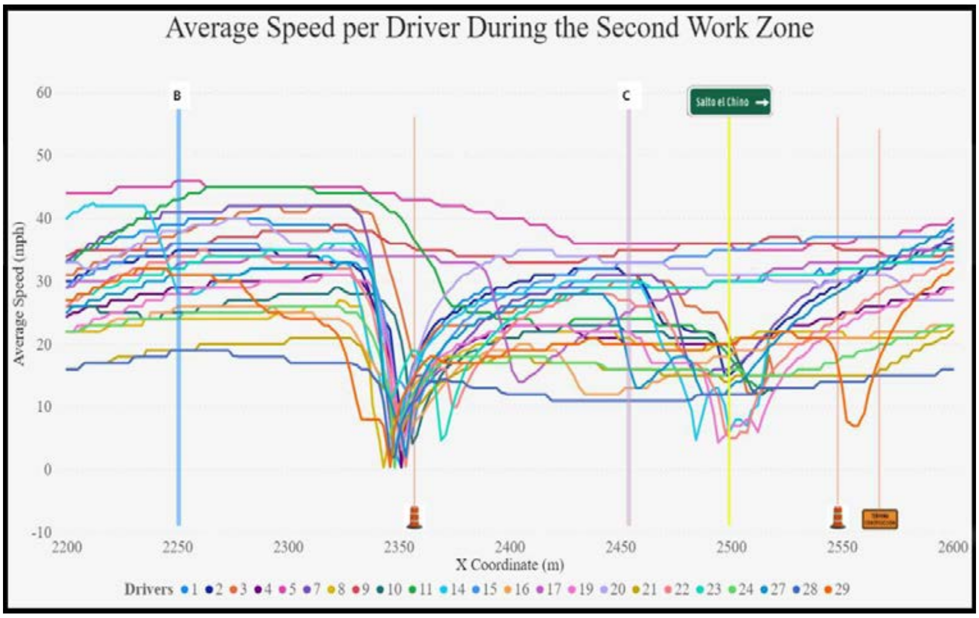
A) Average Speed Profile - Scenario 1



B) Average Speed Profile - Scenario 2



C) Average Speed Profile - Scenario 3



D) Average Speed Profile - Scenario 4

Figure 10: Speed Profiles Along the Second Work Zone

Figure 11 presents the average speed profiles for each of the scenarios. At the start of the profile, the drivers gain speed until reaching an average speed approximately equal to the 35-mph speed limit. As shown, at the beginning of all the scenarios, there is a decrease in the average speed that is related to a sharp horizontal curve of approximately 90º. This horizontal curve is shown in Figure 4. After this curve, a sequence of tangents and smooth curves continues until it reaches the work zone.

In the work zone, the different segments are presented together with the signs that correspond to the advance warning zone and then where the first workspace begins. At this point, the speed profiles drop significantly down to an average speed of about 10 mph. As indicated in the figures above, the individual drivers slow down to zero and come to a full stop. Because they stopped at different points along the road before reaching the point where the work zone blocks the lane, the average speed drops substantially, but does not reach zero.

After passing the first work zone, speeds increase again. Since the next work zone is close, the next noticeable reduction in the average speed profile begins there. It can even be observed that the average speeds decrease to a value lower than that on the first work zone. In this case, some scenarios have an average speed of 8 mph, and afterward, the vehicles continue their route but arrive at the point where they should deviate from taking the exit to the "Salto del Chino." At this point, it can be observed that the subjects also slow down to decide what to do: some of them enter the work zone, but most of them continue straight ahead and then continue to accelerate. On average, the speed continues to increase until the end of the simulation.

The average speeds of the other scenarios are similar. The variability observed in the analysis above is only between subjects (Figures 8 and 9). However, the average speed does not present high variability. By making statistical estimates, one can identify if there are significant average speed differences between scenarios when the subjects arrive at each work zone.

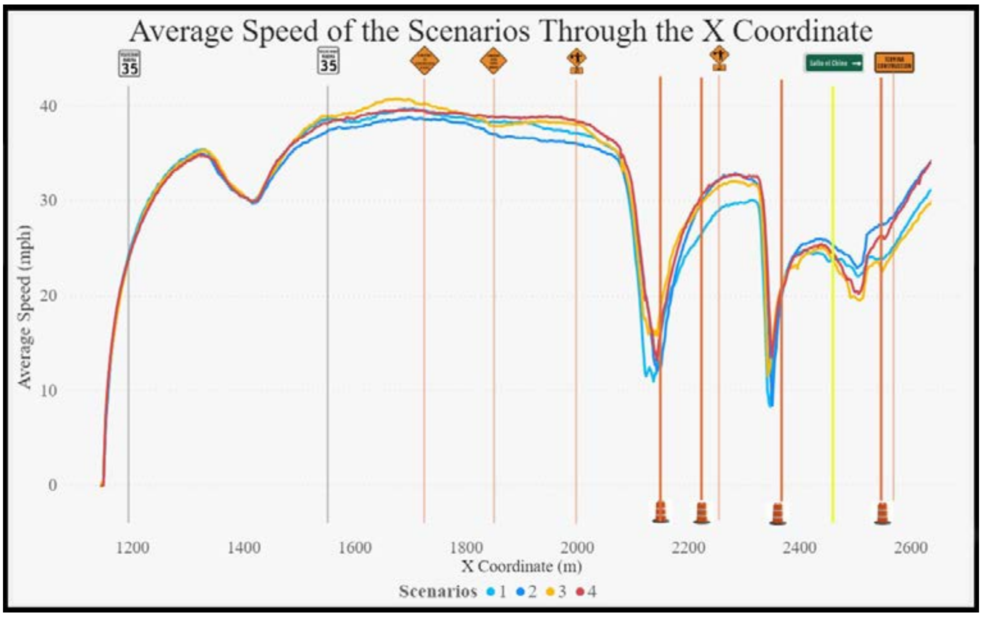
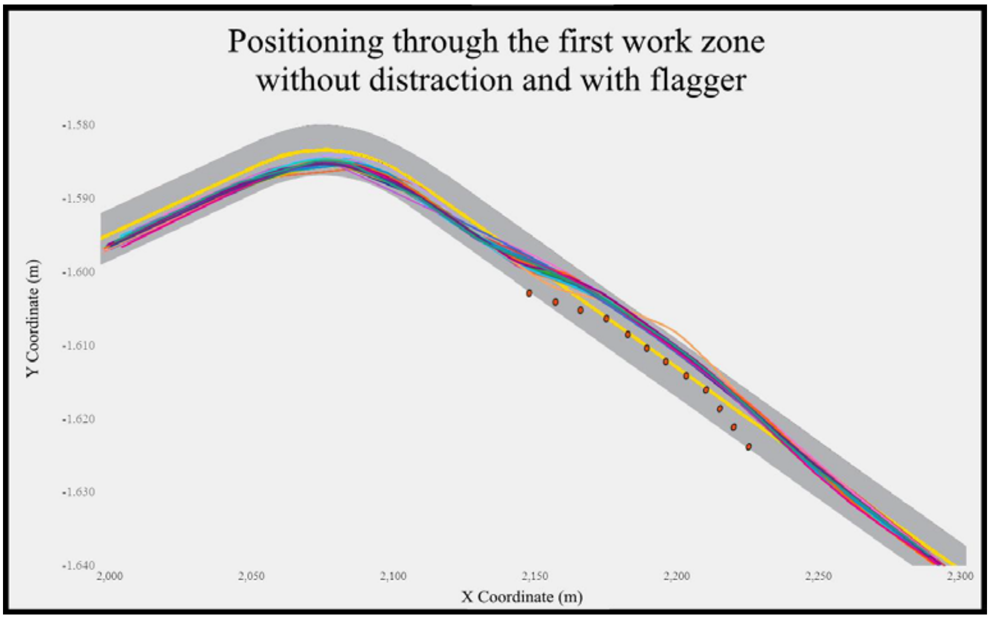
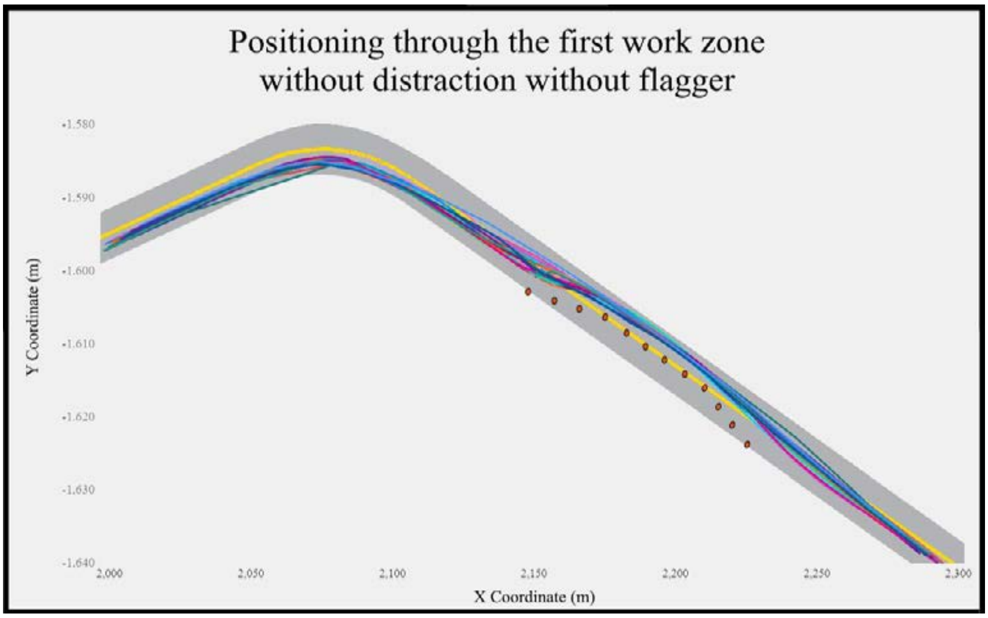


Figure 11: Average Speed Profiles per Scenario

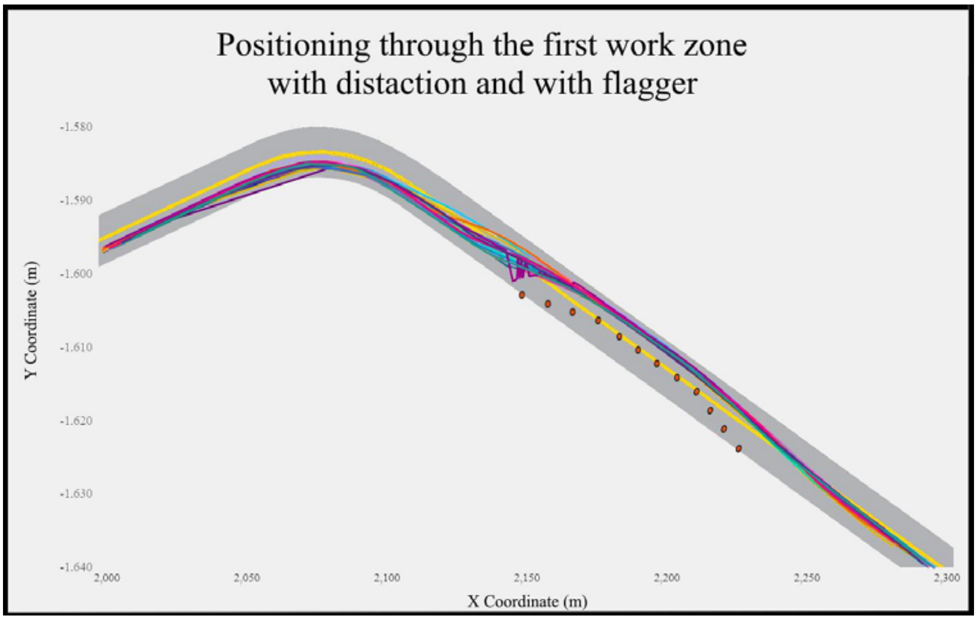
Figure 12 shows the path of the vehicles according to the coordinates registered in the simulator for the first work zone. It is divided into four figures (a,b,c,d),which correspond to the four scenarios. It can be observed that when one driver entersthe opposite lane and encounters the oncoming vehicle decides to move and pull off the road in order to avoid the collision. In other cases, drivers somewhat deviated, but crashed with the oncoming vehicle. Figure 12B shows a little more dispersion in the vehicles' position upon arrival at the work zone. Due in part to the fact that some of these drivers reverse when encountering traffic coming from the other direction in Figure 12C, similar dispersion is observed in the same position in the scenario without a flagger. In Figure 12D, it is observed that one driver passes at high speed when meeting the opposing vehicle, invading the work area, and hitting the drums that were separating the lane from the work area. The subject drivers then continue avoiding the traffic coming from the other direction. It is remarkable in this figure observing the importance of the flagger and the people's reactions when they see the traffic coming from the other direction when they decide to take action and apply the brakes or make an evasive maneuver to avoid crashing with the coming vehicle from the opposite direction.



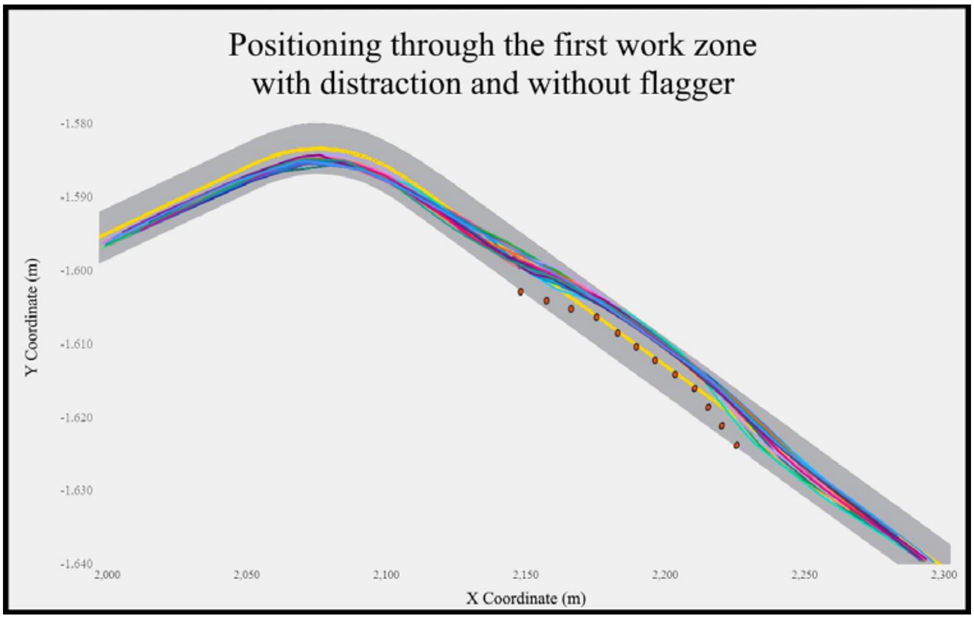
(a) Plan view of the first work zone - Scenario 1



(b) Plan view of the first work zone - Scenario 2



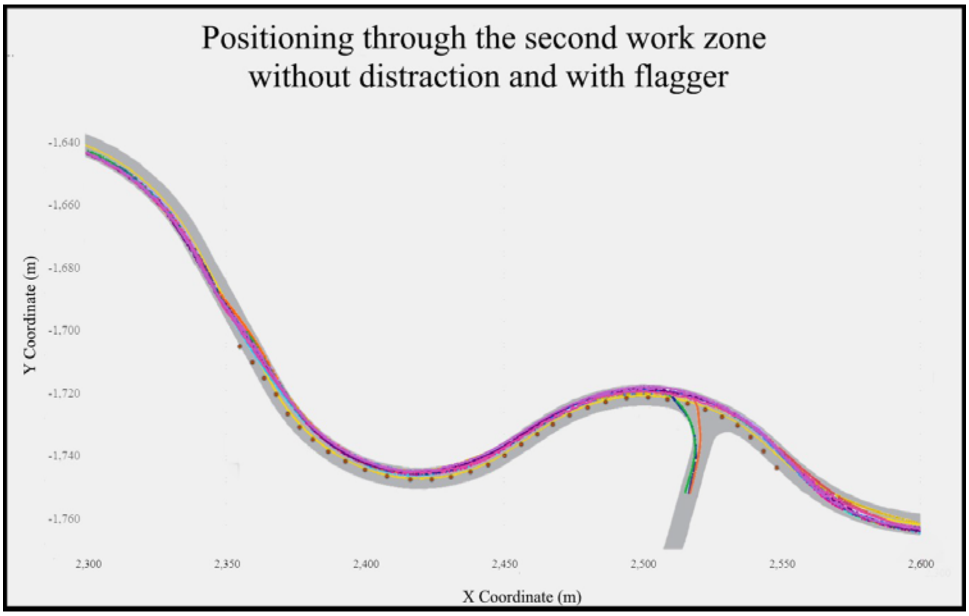
(c) Plan view of the first work zone - Scenario 3



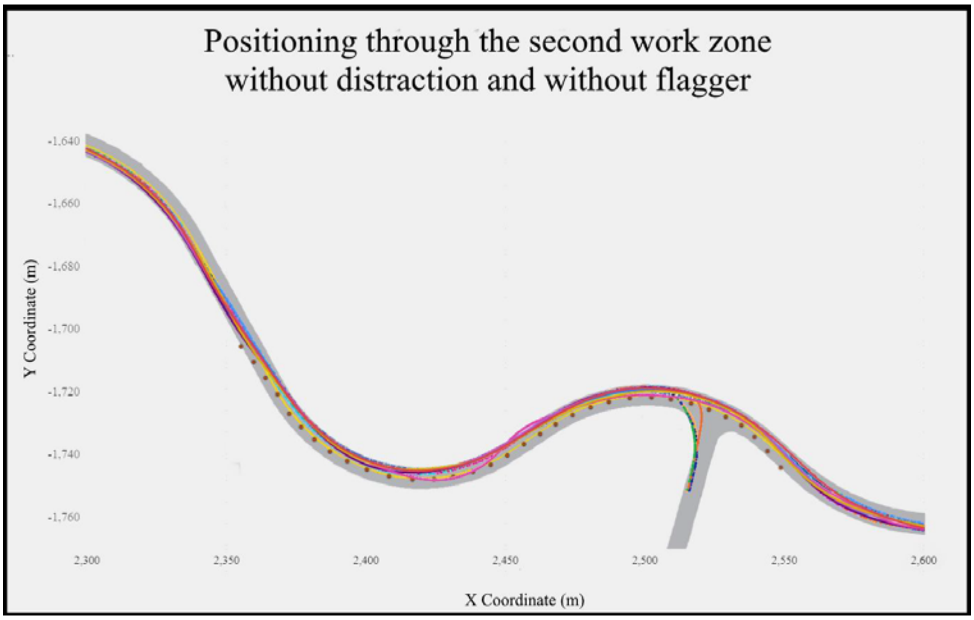
(d) Plan view of the first work zone - Scenario 4

Figure 12: Plan View of the First Work Zone for the Scenarios

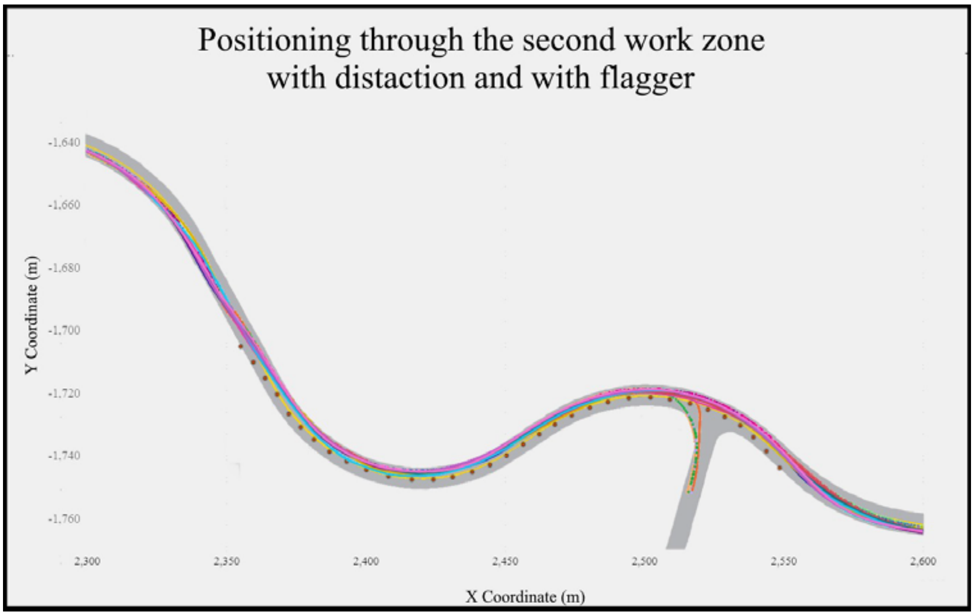
Figure 13 shows the path of the vehicles according to the coordinates recorded in the simulator corresponding to the second work zone. This work zone includes the exit street to “Salto El Chino”. This is the street where the drivers had been instructed to exit in the case of those subjects who did not have GPS. For subjects with GPS, the auditive and visual cues of the GPS confirmed that this was the exit and provided the indication that they should take the exit. Therefore, despite the channelizing devices delimiting the area, some drivers encroached the work zone space. The analysis can be seen in more detail in Figures 8 analyzed previously, but similar dispersion is also observed upon arrival at the drums used to delineate the transition and workspace. The dispersion in the vehicles' trajectories upon arrival is because, in some cases, they reversed when they noticed that vehicles were coming from the opposite direction.



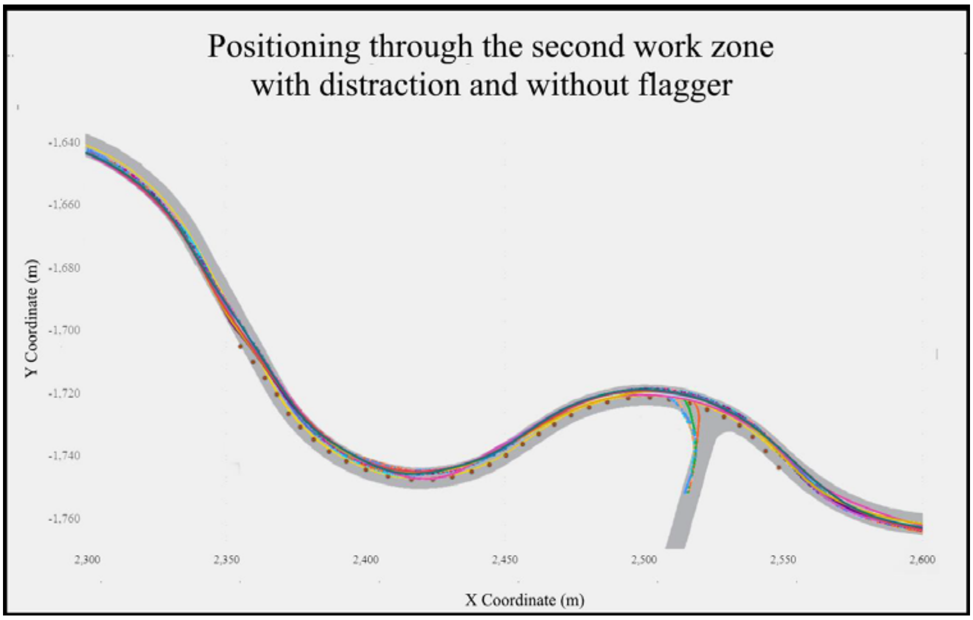
(a) Plan view of the second work zone - Scenario 1



(b) Plan view of the second work zone - Scenario 2



(c) Plan view of the second work zone - Scenario 3



(d) Plan view of the second work zone - Scenario 4

Figure 13: Plan View of the Second Work Zone for All Scenarios

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Major Findings

This project assessed the impact of GPS usage in smartphones while driving in a two-lane roadway with a one-lane closure in a work zone using a driving simulator. Four scenarios were evaluated considering two major factors, namely with and without GPS, and with and without a flagger. In addition, an observational study was conducted to determine the subject's reactions when approaching and traversing the work zones. The major conclusions associated with the driving simulator are:

- In scenarios with the active GPS, two out of the four audible messages (50%) instructed subjects to encroach the workspace that was closed due to the presence of the TTC plan. Subjects had to decide whether to follow the GPS instructions (creating a hazardous situation) or to ignore the GPS. The results showed that 25% of the subjects encroached into the work zone.
- In scenarios where the flagger is present, subjects make a full stop when they reach the construction zones. In Scenario 3, only two out of the 24 subjects continued straight without stopping. On the scenarios with no flagger, 8 out of the 24 subjects continued straight without stopping. This result shows the positive impact of having a flagger in the construction zone.
- In Scenarios 3 and 4 (active GPS), 25% of the subjects encroached into the work zone compared to 17% of the subjects who did not have the GPS (Scenarios 1 and 2). Even though the exit road was blocked by the channelizing devices in the TTC plan, subjects followed the GPS instructions and encroached into the work zone.
- Receiving contradictory information between the GPS instructions and the TTC plan led subjects to hesitate on what to do (follow GPS instructions or encroach into the work zone) which resulted in a higher probability of hazardous maneuvers by subjects.
- The lack of real-time updates for the GPS from the short-term TTC closure in the rural two-lane road provided contradictory information to subjects which resulted in potential safety-related risks to drivers, road users, and workers.
- In terms of speed variability, there was no significant difference among the scenarios evaluated with regard to the dispersion of subjects with GPS as compared with those driving without GPS.

- In terms of lane position, upon reaching the lane closure of the work zone in their first run, four different reactions were observed.
    - Eleven subjects (46%) stopped when they reached the lane closure of the work zone.
    - Thirteen subjects (54%) continued driving straight ahead ignoring the construction work zone signs. Out of these 13 subjects:
        - Nine subjects (38% of the total population) continued driving straight ahead and crashed into incoming traffic.
        - Four subjects (12% of the total population) continued driving straight ahead and upon realizing that traffic was coming in the opposite direction, immediately backed up.
        - One subject (4% of the total population) continued driving ahead and performed an evasive maneuver to avoid crashing with the opposing traffic.
- The hesitation of deciding what to do when encountering an unexpected situation generated a dangerous behavior in drivers, indicating that the simulation scenarios created in this experiment achieved the intent of the researchers.

5.2 Recommendations and Future Research

A driving simulation experiment was used to evaluate user behaviour while going through a construction work zone in a two-lane rural road. The long-term goal is to improve road user and worker safety by increasing the level of understanding about driver behaviour through work zones with and without GPS. This research provided the basis for understanding how subjects behave when facing a choice of following directions given by a GPS and encountering a hazardous situation, or disregarding the directions given by the GPS to avoid a hazardous situation. As stated in the results, when a flagger was present, subjects were more likely to stop when they reached the construction zone.

It is recommended that all the concerning entities in the public and private sectors associated with performing maintenance and construction activities on the highway system provide updated work zone data to the companies that manage and administer the information provided by GPS technologies and smartphone applications. This coordination would solve the safety-related issues associated with hesitation and extra workload to drivers in conflicting decision situations. All the parties involved should address these issues considering the potential liability implications associated with the life of road users and workers.

Future studies should investigate the negative impact of providing contradictory information to subjects while driving through work zones. Future studies should also focus on raising awareness about the essential role that flaggers play and the dangers that they are exposed to when drivers are distracted.

ACKNOWLEDGMENTS

This material is based upon work supported by the Safety Research Using Simulation (SaferSim) University Transportation Center and funded by the U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology under Grant No.1001814551. Any opinions, findings or conclusions expressed in this material are those of the authors and do not necessarily reflect the views of the U.S. Department of Transportation. The authors are greatly thankful to the subjects who participated in this study.

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Appendices

Appendix A. Informed Consent

ESTUDIO DE SIMULACIÓN

FORMULARIO DE CONSENTIMIENTO INFORMADO

Investigador Principal: Edgardo Concepcion Carrasco

Título de Proyecto: Driver' Safety Assessment in Two-Lane Rural Roads Work Zones

1. ¿QUÉ ES ESTE FORMULARIO?

Esto es un Formulario de Consentimiento Informado. Le proveerá información acerca de este estudio para que usted pueda tomar una decisión informada sobre su participación. Usted debe tener 18 años de edad o más para dar *consentimiento* informado.

2. ¿QUIÉN ES ELEGIBLE PARA PARTICIPAR?

Individuos que se encuentran entre las edades de 18 a 70 años y han tenido una licencia de conducir por al menos 18 meses. Conductores que han experimentado cinetosis (mareo por movimiento), ya sea en su propio vehículo como pasajero o conductor, o en otros modos de transporte, no deberían participar.

3. **¿QUIÉN PATROCINA ESTE ESTUDIO?**

Este estudio es patrocinado por el Centro de Investigación en Transporte (UTC, por sus siglas en inglés) financiado por la Oficina de Tecnología de Investigación (OSTR, por sus siglas en inglés) bajo la Administración Federal de Carreteras (FHWA, por sus siglas en inglés).

4. ¿CUÁL ES EL PROPÓSITO DE ESTE ESTUDIO?

El propósito de este estudio es evaluar el impacto del uso de teléfono celular mientras al manejar utilizando diversos escenarios y configuraciones que representan una carretera rural de Puerto Rico.

5. ¿DÓNDE ESTE ESTUDIO TOMARÁ LUGAR Y CUÁNTO DURARÁ?

Esta sesión de estudio se llevará a cabo en el Laboratorio de Ingeniería de Transportación de la Universidad de Puerto Rico en Mayagüez, localizado en el Edificio de Ingeniería Civil y Agrimensura, salón 102-F. El estudio durará aproximadamente 45 minutos por participante e incluirá cuestionarios y uso del simulador.

6. ¿QUÉ SE ME PEDIRÁ HACER?

i) Se le pedirá que llene un breve cuestionario antes y después del experimento.

ii) El investigador le enseñará cómo manejar el simulador y le proveerá instrucciones generales para los escenarios de simulación. Durante la simulación, usted deberá operar los controles del simulador del vehículo de la misma manera que usted manejaría los de cualquier otro vehículo, y manejar por el mundo simulado como corresponde. Usted debe de seguir los límites de velocidad y las reglas estándares de la carretera y tener un cuidado razonable cuando utilice los frenos.

iii) Usted se sentará en el simulador, y se le dará una simulación de práctica para familiarizarse con el simulador de conducción. Una vez usted se sienta cómodo con el simulador, usted maneja a través de un trayecto que tomará cerca de 2 a 5 minutos para cada escenario virtual en que conducirá. Si en algún momento del trayecto siente molestia o cinetosis/mareo, informe al investigador de inmediato para que se detenga la simulación. No habrá ningún tipo de penalidad, o efecto adverso al estudio porque su participación no pueda ser completada.

7. ¿EXISTE ALGÚN RIESGO O BENEFICIO ASOCIADO CON LA PARTICIPACIÓN?

En términos de la operación del simulador de conducción, existe un leve riesgo de cinetosis (mareos). Un pequeño porciento de los participantes que manejan el simulador podrían experimentar sensación de náuseas o náusea actual. El experimento ha sido trabajado para minimizar el riesgo. Se recomienda que <u>si usted ha experimentado cinetosis (mareos) anteriormente mientras viaja o maneja un vehículo real, usted no debería participar en este experimento.</u>

Si durante el trayecto de la simulación, usted siente malestar o náuseas, debería de informar al investigador inmediatamente para que la simulación pueda ser detenida. La interrupción de la simulación debería reducir la molestia rápidamente. Si usted no se siente mejor tan pronto la simulación es interrumpida, los investigadores pueden gestionar para que alguien los guíe a su hogar o a buscar atención médica si es necesario.

Los beneficios de participar en este estudio incluyen aprender potencialmente como ser un conductor más precavido/seguro y a familiarizarse con los cambios de configuración de plazas de peaje.

8. ¿QUIÉN VERÁ LOS RESULTADOS Y/O MI DESEMPEÑO EN ESTE ESTUDIO?

Los resultados de esta investigación serán publicados en revistas de investigación científica y serán presentados en conferencias y simposios de entidades científicas profesionales. Los resultados podrían ser utilizados por los investigadores aprobados para propósitos internos. Ningún participante será identificable en los reportes o publicaciones ya que ni el nombre ni las iniciales de ningún participante serán utilizados. Para mantener la confidencialidad de los archivos, los investigadores utilizarán códigos para identificar a cada sujeto, en vez de nombres, para toda la data colectada mediante cuestionarios y la data colectada durante su utilización del simulador. La data será asegurada en el Laboratorio de Ingeniería de Transportación de la Universidad de Puerto Rico en Mayagüez y solo será accesible por el investigador principal, y cualquier otro investigador aprobado para el estudio.

Es posible que su archivo de investigación, incluyendo información sensitiva y/o información de identificación, pueda ser inspeccionado y/o copiado por agencias federales o del gobierno estatal, en el curso del desempeño de sus funciones. Si su archivo es inspeccionado por alguna de estas agencias, su confidencialidad será mantenida en la medida permitida por la ley.

9. ¿RECIBIRÉ ALGÚN TIPO DE COMPENSACIÓN MONETARIA POR PARTICIPAR DE ESTE ESTUDIO?

No. Su participación en este estudio es completamente voluntaria.

10. ¿QUÉ PASA SI TENGO UNA PREGUNTA?

Si tiene alguna pregunta sobre el experimento o cualquier otro asunto relativo a su participación en este experimento, o si sufre de alguna lesión relacionada a la investigación como resultado del estudio, puede llamar al investigador, Edgardo Concepcion Carrasco, al (787) 248-9634 o vía correo electrónico a edgardo.concepcion2@upr.edu o al Dr. Didier Valdés, al (787) 832-4040 ext. 2179 o didier.valdes@upr.edu. Si, durante el estudio o después de, usted desea discutir su participación o preocupaciones en cuanto al mismo con una persona que no participe directamente en la investigación puede comunicarse con el Comité para la Protección de los Seres Humanos en la Investigación del Recinto Universitario de Mayagüez al (787) 832-4040 ext. 6277 ó 6347 o cpshirum@uprm.edu. En caso de que el participante lo desee, una copia de este formulario de consentimiento informado será proveída para que la guarde en sus archivos.

11. ¿QUÉ PASA SI ME NIEGO A PROVEER MI CONSENTIMIENTO?

Su participación es voluntaria, por lo tanto, usted puede negarse a participar o puede retirar su consentimiento y dejar de participar en el estudio en cualquier momento y sin penalidad alguna.

***12.* ¿QUÉ SI ME LESIONO?**

Como usted es parte de la comunidad del Recinto Universitario de Mayagüez (ya sea empleado o estudiante) el seguro médico del Recinto le cubre en caso de tener algún riesgo o incomodidad.

13. DECLARACIÓN DE CONSENTIMIENTO VOLUNTARIO DEL SUJETO

Al firmar abajo, yo, el participante, confirmó que el investigador me ha explicado el propósito de la investigación, los procedimientos del estudio a los que voy a someterme y los beneficios, así como los posibles riesgos que puede experimentar. También se han discutido alternativas a mi participación en el estudio. He leído y entiendo este formulario de consentimiento.

____ _____________

Nombre en letra de molde del participante Fecha

____

Firma del participante

14. DECLARACIÓN DEL EXPERIMENTADOR

Al firmar abajo, yo, el investigador, indicó que el participante ha leído este Formulario de Consentimiento Informado y yo le he explicado a él/ella el propósito de la investigación, los procedimientos del estudio a los que él/ella va a someterse y los beneficios, así como los posibles riesgos que él/ ella puede experimentar en este estudio, y que él/ella ha firmado este formulario de consentimiento informado.

____ _____________

Firma de la persona que obtiene el consentimiento informado Fecha

Appendix B. Pre-Test Questionnaire

CUESTIONARIO ANTES DEL ESTUDIO

El cuestionario es confidencial, lo que usted provea no será utilizado para conseguir su identidad. Usted será identificado con un número asignado por el investigador, De esta manera se podrá validar la información obtenida durante la simulación. De sentirse incomodo/a contestando una o más preguntas tiene el derecho de no contestar la pregunta.
*Obligatorio

1. # asignado: *

___

Seccion 1: Datos demograficos

2. Apellidos:

___

3. Nombre:

___

4. Correo Electrónico:

___

5. Sexo:

Marca solo un óvalo.

- Mujer
- Hombre

6. Edad:

Marca solo un óvalo.

- 18
- 19
- 20
- 21
- 22
- 23
- 24
- 25
- 26
- 27
- 28
- 29
- 30
- 31
- 32
- 33
- 34
- 35
- 36
- 37
- 38
- 39

- 65
- 66
- 67
- 68
- 69
- 70

7. Fecha de Nacimiento:

Seccion 2: Historial de conduccion

8. Edad aproximada a la cual obtuvo la licencia de conducir:

9. País donde obtuvo la licencia de conducir:

10. País donde aprendió a conducir:

11. País donde a conducido la mayor parte de su vida:

12. Restricciones en su licencia de conducir:

Marca solo un óvalo.

- Ninguna
- Espejuelos
- Lentes de contacto
- Otra

13. Si su respuesta fue otra, indique:

Appendix C. Post-Test Questionnaire

CUESTIONARIO LUEGO DEL ESTUDIO

El cuestionario es confidencial, lo que usted provea no será utilizado para conseguir su identidad. Usted será identificado con un número asignado por el investigador, De esta manera se podrá validar la información obtenida durante la simulación. De sentirse incomodo/a contestando una o más preguntas tiene el derecho de no contestar la pregunta.
*Obligatorio

1. *

____

Seleccione la opción que mejor describa su experiencia.
Siendo 5 excelente y 0 deficiente.

2. Proyección de la simulación

Marca solo un óvalo.

- 5
- 4
- 3
- 2
- 1
- 0

3. Se siente como si fuera un vehículo real

Marca solo un óvalo.

- 5
- 4
- 3
- 2
- 1
- 0

4. Aceleración

Marca solo un óvalo.

- 5
- 4
- 3
- 2
- 1
- 0

5. Freno

Marca solo un óvalo.

- 5
- 4
- 3
- 2
- 1
- 0

6. Audio

Marca solo un óvalo.

- 5
- 4
- 3
- 2
- 1
- 0

7. Simulación en general

Marca solo un óvalo.

- 5
- 4
- 3
- 2
- 1
- 0

Gracias por participar de este estudio! Nos ayuda a mejorar la seguridad en la carretera.