Phase III: Operational and Safety-Based Analyses of Varied Toll Lanes

SAFETY RESEARCH USING SIMULATION

UNIVERSITY TRANSPORTATION CENTER

Didier Valdés, PhD,
University of Puerto Rico at Mayagüez
Department of Civil Engineering and Surveying
University of Puerto Rico at Mayagüez

Benjamín Colucci, PhD,
University of Puerto Rico at Mayagüez
Department of Civil Engineering and Surveying
University of Puerto Rico at Mayagüez

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Didier M. Valdés Díaz, PhD
Principal Investigator
Department of Civil and Surveying
University of Puerto Rico at Mayagüez

Benjamín Colucci Ríos, PhD
Principal Investigator
Department of Civil and Surveying
University of Puerto Rico at Mayagüez

Johnathan Ruiz González, BSCE
Graduate Research Assistant
Department of Civil and Surveying
University of Puerto Rico at Mayagüez

Bryan Ruiz Cruz, BSCE, BSST
Graduate Research Assistant
Department of Civil and Surveying
University of Puerto Rico at Mayagüez

Ricardo García Rosario, BSCE
Graduate Research Assistant
Department of Civil and Surveying
University of Puerto Rico at Mayagüez

Enid Colón Torres
Graduate Research Assistant
Department of Civil and Surveying
University of Puerto Rico at Mayagüez

A Research Report Sponsored by SAFER-SIM

November 2017

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Acronyms

ADT	Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
BRT	Bus Rapid Transit
CATSS	Center of Advanced Transportation Systems Simulations
CSL	Cognitive Systems Laboratory
DOT	Department of Transportation
DTL	Dynamic Toll Lane
EB	Eastbound
ETC	Electronic Toll Collection
FHWA	Federal Highway Administration
HOT	High Occupancy Toll
HOV	High Occupancy Vehicle
HPL	Human Performance Laboratory
IRB	Institutional Review Board
ISA	Internet Scene Assembler
ITE	Institute of Transportation Engineers
LLC	Limited Liability Company
LOS	Level of Service
MPH	Miles Per Hour
MUTCD	Manual on Uniform Traffic Control Devices
NADS	National Advanced Driving Simulator
ORT	Open Road Tolling
OST	Office of the Secretary of Transportation
OST-R	Office of the Assistant Secretary for Research and Technology
PPP	Public Private Partnership
PRHTA	Puerto Rico Highway and Transportation Authority
PRT	Perception-Response Time
RITA	Research and Innovative Technology Administration
RLS	Reversible Lane System
ROW	Right-of-Way
RTI	Real-Time Technology Incorporation
SAFER-SIM	Safety Research Using Simulation
TCD	Traffic Control Device
UCF	University of Central Florida
UI	University of Iowa
UMass	University of Massachusetts - Amherst
UPRM	University of Puerto Rico at Mayagüez
UTC	University Transportation Center
UW	University of Madison Wisconsin
VPD	Vehicles Per Day
WB	Westbound

Abstract

Managed lanes facilities are providing an opportunity to reduce travel time as well as pollution worldwide. In 2013, Puerto Rico built their first ever two lane reversible Dynamic Toll Lane (DTL) facility. The 10.4-kilometer managed lane, located at the median of the PR-22 freeway, is shared by Bus Rapid Transit (BRT) and passenger cars. Safety issues have been found associated to sudden lane changing and incorrect use of the designated DTL exit. An online survey was developed to gather information and knowledge of drivers in managed lanes facilities. A driving simulator was used to study the safety aspects of driving behavior along the PR-22 DTL. The University of Puerto Rico at Mayagüez cockpit simulator was used to compare the driving behavior between two configurations of signage and pavement markings. Configuration 1 corresponds to the existing condition of signage and Configuration 2 consists of a proposed treatment of signage and in-lane pavement markings. The information gathered in the online survey was used to develop the proposed treatment. A total of 24 participants drove 6 representative scenarios based on the independent variables traffic flow and time of the day. The performance measurement used to evaluate driving behavior was the vehicle Average Lane Position. The results indicate that Configuration 2 improved the Average Lane Position variable in at least 67% of the zones evaluated, when compared to Configuration 1.

1 Introduction

This chapter provides an overview of managed lanes and safety issues related to the reversible dynamic toll lane of freeway PR-22 in Puerto Rico. A description of this managed facility is provided along with the problem statement. Also, the research objectives, scope, and hypothesis are described, as is the outline of the report.

1.1 Background

Traffic congestion is a major issue in metropolitan areas, raising safety and environmental concerns among transportation agencies. The construction and expansion of the transportation infrastructure have not been able to keep up with the increase of traffic over the past years [1]. Traffic congestion impacts the capacity and mobility of transportation systems and the economic development of the metropolis. Since many of the available treatments (e.g., the addition of a travel lane or corridor) used to minimize congestion and its negative effects are expensive or are limited by the available right-of-way (ROW), transportation agencies have searched for an economical and feasible solution that could minimize traffic congestion in urban corridors. One alternative that has been implemented over the past decades is the use of managed lanes.

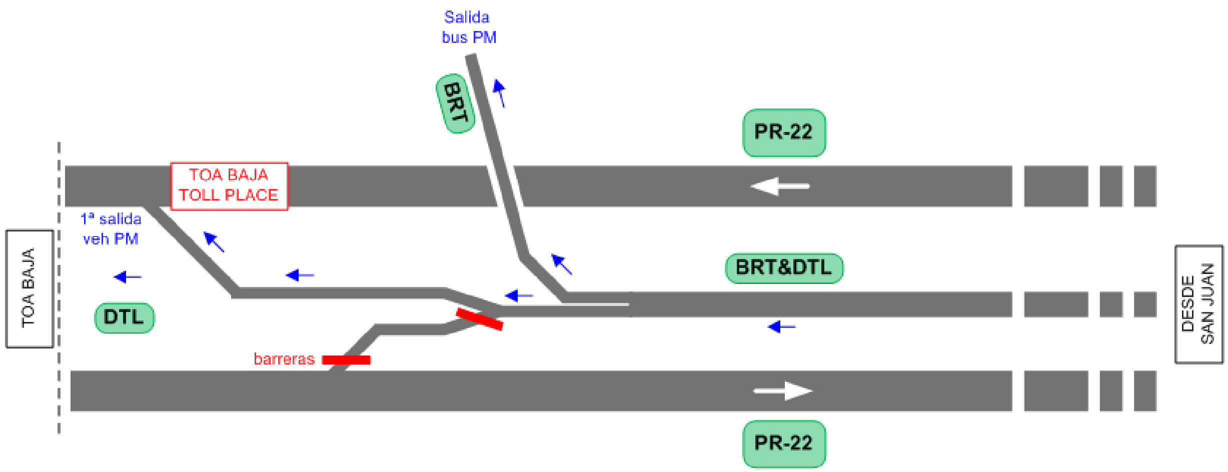
Managed lanes are transportation facilities in which operational strategies are implemented to reduce the negative effects of traffic congestion, such as longer travel times and pollution, in major cities [2]. The Federal Highway Administration (FHWA) defines managed lanes as highway facilities or a set of lanes in which operational strategies are implemented and managed in response to real-time conditions [3]. The most commonly implemented operational strategies are pricing, vehicle eligibility, and access control. Representative examples of these technologies include high-occupancy vehicle (HOV) lanes, dynamic toll lanes (DTL), and reversible lane systems (RLS). In addition, these operational strategies can be combined to create multifaceted managed lanes such as high-occupancy toll (HOT) lanes and reversible DTLs.

The design and operation of managed lanes vary among transportation agencies in accordance with their goals and objectives. Although the Manual on Uniform Traffic Control Devices (MUTCD) [4] includes a section dedicated to preferential and managed lanes, there are no guidelines that address the uniformity and consistency of traffic control devices (TCDs) in complex managed-lane systems that combine different operational strategies. Furthermore, there is little published literature regarding driver behavior in managed lanes and how safety issues could affect the users of these facilities. One particular managed-lane system that has safety issues associated with driver behavior is the reversible DTL of freeway PR-22, located in the Commonwealth of Puerto Rico. This managed lane combines congestion pricing and reversible lane operation along with a BRT system.

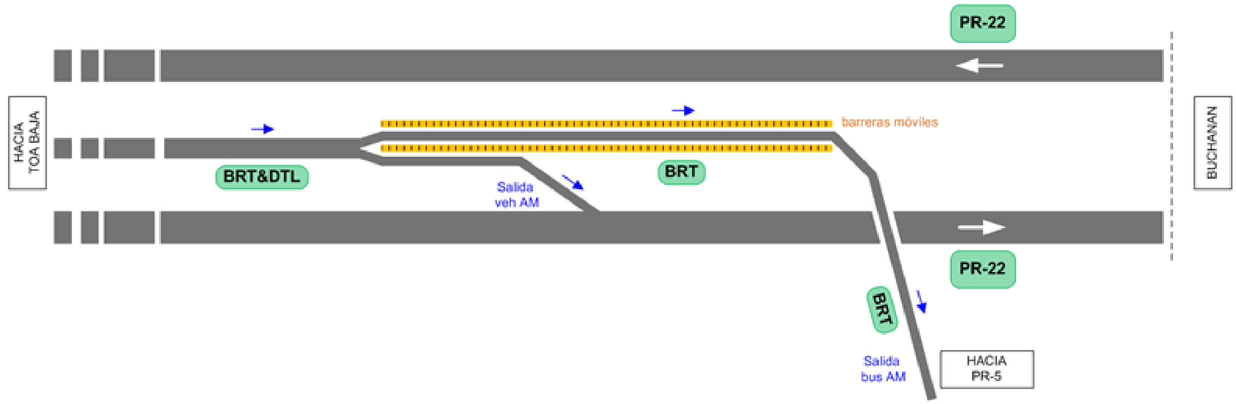
1.2 Puerto Rico Dynamic Toll Lane

This 10.4 kilometer (6.5 mile) multifaceted managed-lane facility was designed and constructed in 2013 under a Public Private Partnership (PPP) between the Puerto Rico Highway and

Transportation Authority (PRHTA) and Autopistas Metropolitanas de Puerto Rico (Metropistas, LLC) [5]. This managed facility is located in the median of freeway PR-22, which is one of the most used corridors in Puerto Rico with an average daily traffic (ADT) of 110,923 vehicles per day (vpd) for 2007. The PR-22 DTL has two travel lanes 12 ft (3.65 m) wide with a posted speed limit of 45 mph in the direction to Bayamón (eastbound) and 45 mph in the direction to Toa Baja (westbound) with a limit of 40 mph in the exit gate. The DTL, also known as an express lane, is separated from the general-purpose lanes by a barrier system. In addition, the express lane is shared between private vehicles and the Metro Urbano BRT system, which has exclusive exit ramps. The DTL exit is located in the right lane for the eastbound (EB) direction and the left lane for the westbound (WB) direction, whereas the BRT exit lane is located in the left lane for the EB direction and the right lane for the WB direction (Figure 1.1). In addition, heavy vehicles are not allowed to travel through this exclusive lane. The DTL operates under three traffic schemes: AM peak inbound towards Bayamón, PM peak outbound towards Toa Baja, and holidays and weekends. The ADT of PR-22 DTL was 6,000 vpd for the year 2015.



(a) EB - BRT exit on the left and passenger cars on the right



(a) WB - BRT exit on the right and passenger cars on the left

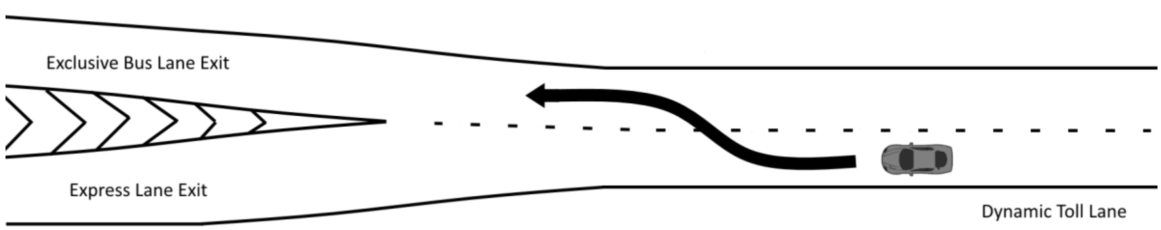
Figure 1.1 PR-22 DTL eastbound and westbound exits.

(Source: Metropistas LLC [6]).

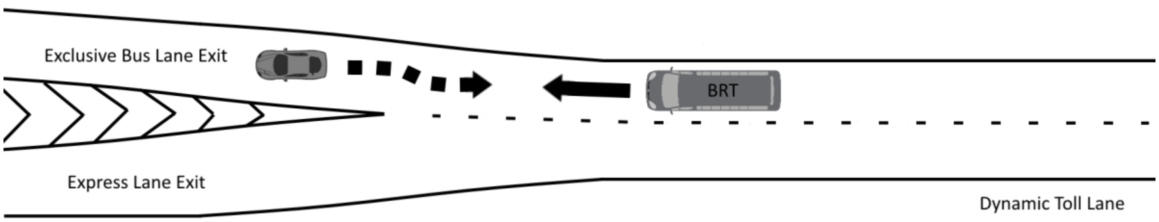
1.3 Problem Statement

A major issue that has raised concerns related to the operation and safety of this new and unique managed-lane facility is the exit lanes for both the EB and WB directions. PR-22 DTL is shared between light traffic and a BRT system that has an exclusive exit lane. Driving confusion may affect road users since a considerable number of drivers exit wrongly through the BRT exit lane. Results from a previous driving simulator study showed that subject drivers exited the express lane wrongly through the BRT exit lane in 26% of the evaluated scenarios [7]. Therefore, driving confusion may influence the variation in traveling speed, acceleration, and braking, as well as sudden lane changes when approaching the exit of the DTL, creating conflict points that affect the safety aspects of the managed lanes.

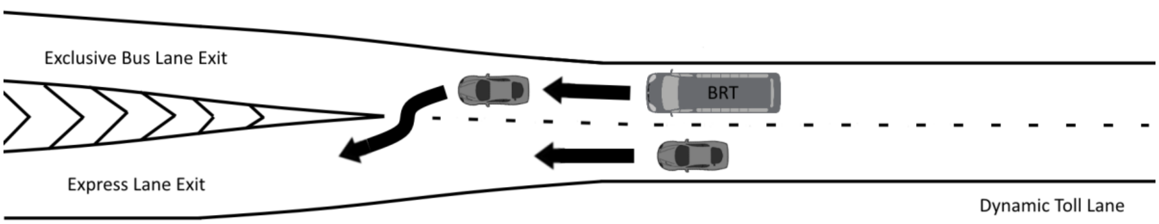
Drivers who wrongly exit through the BRT lane stop and drive in reverse until they can reincorporate into the DTL exit, as illustrated in Figure 1.2. This issue generates potential hazardous situations since another vehicle or a bus can approach the exit lane while the driver is moving in reverse. However, if drivers stay and wait in the exit lane, the operating agency must open the exit gate to provide access before the bus arrives, thereby affecting the safety, reliability, travel time, and other operational characteristics of the BRT system.



(a) Driver exits through the BRT exit lane



(b) Driver stops the vehicle and maneuvers in reverse



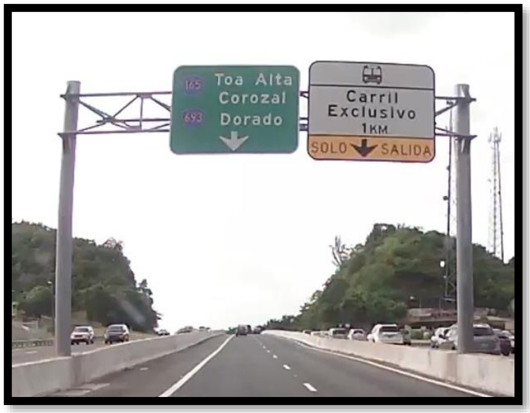
(c) Driver changes into the DTL exit lane

Figure 1.2 Driving maneuvers when exiting westbound through the BRT lane

(Source: Valdés et al. [7]).

This safety issue could be influenced by the fact that the BRT exit is in the left lane for the EB direction inbound toward the metropolitan region, while it is in the right lane for the WB direction outbound toward Toa Baja. Drivers are familiar with ramp exits in the right lane, so having the DTL exit in the left lane (as happens when traveling in the WB direction) could generate confusion among drivers. Consequently, the TCDs implemented in PR-22 DTL should be evaluated to understand if they fulfill the requirements established by the MUTCD. This manual stipulates that an effective TCD should command attention and convey a simple and clear message that road users can understand at a proper response time [4]. However, as illustrated in Figure 1.3, there is a lack of uniformity in signs along PR-22 DTL. For instance, the EB exit signs have the words EXIT ONLY with an arrow on a yellow background for the express lane, while the WB exit signs have the same sign for the BRT-exclusive lane. Furthermore, the fact that the exits for the express and the exclusive lanes are in the opposite WB direction could influence drivers' understanding of which lane should be taken.

(a) EB – BRT exit at the left



(b) WB – BRT exit at the right

Figure 1.3 PR-22 DTL eastbound and westbound exit signage configurations 1 km before the exit.

Hence, the case of PR-22 DTL provides a research opportunity to evaluate potential treatments that could improve driving performance using driving simulation. The addition of modified signs and in-lane pavement markings for preferential lanes could reduce driving confusion and assist drivers to change lanes into the express lane exit with anticipation. Furthermore, driving simulation provides a cost-effective approach to evaluate the effects of signage and pavement markings on the driving behavior of representative subject drivers in Puerto Rico without incurring the costs and safety aspects of a field investigation.

1.4 Research Objectives and Scope

The main objective of this research is to evaluate the driving performance of participants who drove through scenarios representing the existing conditions of the PR-22 DTL and compare them to the results of participants who drove scenarios with the proposed treatments. The specific objectives of this research are the following:

1. Perform an online survey to gather demographic information about Puerto Rican drivers and their understanding of managed lane signs.
2. Develop new signs and pavement markings for both the exclusive lane and express lane exits based on driver understanding gathered through the online survey.
3. Evaluate driving behavior when approaching the exit lane of PR-22 DTL in the EB and WB directions and compare the results between the scenarios representing the existing conditions and the proposed treatments using the UPRM Driving Simulator.

4. Provide conclusions and recommendations based on survey and driving simulation study results to provide feasible treatments that improve the safety and the operation of the PR-22 reversible DTL.

The scope of this research project is to evaluate driving behavior on both the EB and WB exits of PR-22 DTL for the existing and proposed treatments. The proposed treatment consists only of the modification of the current exit signs of the express lane and the exclusive lane with the addition of in-lane pavement markings that do not include raised or textured pavement markers. Lastly, the performance measure used to evaluate driving behavior is the vehicle average lane position. The research hypothesis tested in this research project is the following:

> *"Subject drivers exposed to scenarios with the proposed treatments will have a better average lane position at the exit of the DTL than those drivers exposed to the existing conditions."*

1.5 Report Organization

The organizational structure of this report consists of six chapters. Chapter 2 contains a review of published literature related to managed lanes, signs, pavement markings, and driving simulators, while Chapter 3 explains the methods used in this investigation. Chapter 4 provides the results of the online survey, and Chapter 5 includes the results of the statistical analysis of the driving simulator. Lastly, Chapter 6 provides conclusions and research recommendations. References, acknowledgments, and appendices are included at the end of the report.

2 Literature Review

This chapter contains a summary of published research studies related to managed lanes, signs, pavement markings, and driving simulators. These topics were reviewed to understand the design and operation of managed lanes and how potential treatments could be evaluated using a driving simulator study. This literature consists of published articles, journals, books, reports, and other technical documents.

2.1 Managed Lanes

According to Obenger, managed lanes are defined by the FHWA as highway facilities or a set of lanes in which operational strategies are implemented and managed in response to real-time conditions [3]. The main operational strategies utilized in managed lane systems are pricing, vehicle eligibility, and access control, as illustrated in Figure 2.1. Pricing is a demand management strategy used to provide an alternative lane in which a driver is willing to pay a fare to travel because it offers less traffic volume and travel time. A common example of this strategy is congestion pricing, where the toll charge varies according to real-time traffic congestion and the desired level of service (LOS) for the managed facility. Representative examples of managed lanes with congestion pricing include HOT lanes and DTL. In addition, congestion pricing usually utilizes electronic toll collection (ETC) accounts to perform toll payments in combination with open road tolling (ORT), permitting drivers to operate at normal travel speeds. Vehicle eligibility is another operational strategy utilized to control which types of vehicles are allowed in the facility (e.g., HOV, only buses, or no trucks). Lastly, access control is an operational strategy used to maintain mobility along the managed facility using express lanes or reversible lanes.

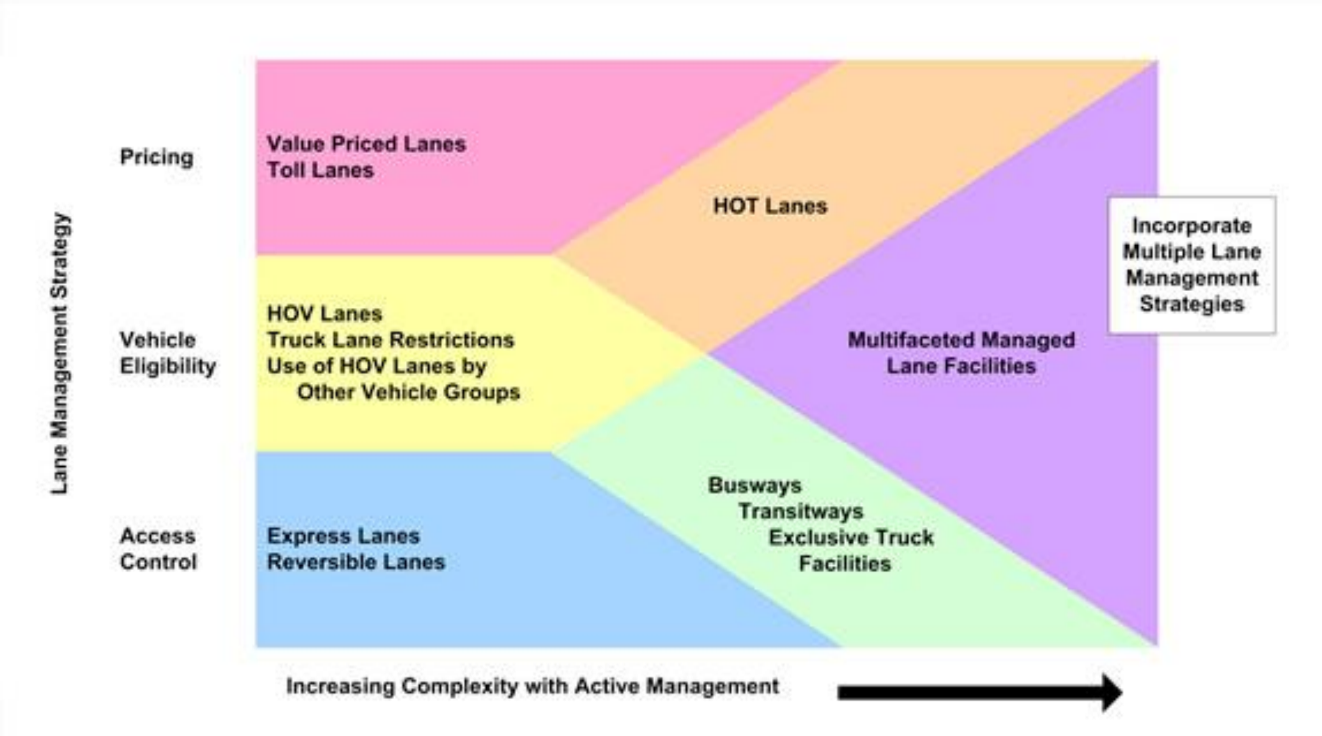


Figure 2.1 Management strategies of managed lane facilities.

(Source: FHWA, 2010 [8]).

According to the Institute of Transportation Engineers (ITE), RLS are one of the most effective management strategies that improve road capacity during peak-hour periods [9]. Reversible lanes, also known as contraflow or tidal lanes, have been utilized to increase directional capacity during planned events and emergency evacuation events [10]. This type of access control increases roadway capacity by utilizing shoulders or opposing adjacent traffic lanes as travel lanes in the direction of congestion for a given period of time [11]. Even though reversible lanes have been used since the late 1930s, their design and operation are substantial for safety, since conflict points may affect all road users [10, 12].

Managed-lane strategies can also be combined to create complex managed lanes, as illustrated in Figure 2.1. Although there are plenty of managed lanes in service, there is limited literature regarding the safety aspects and configurations of the required TCDs. According to the American Association of State Highway and Transportation Officials (AASHTO) in *A Policy on Geometric Design of Highways and Streets*, it is essential to have uniformity in highway design and TCDs since they help reduce the number of conflict points by making drivers aware of what is ahead in the roadway [13]. A wide variety of signage configurations is present in highways that have managed lanes, since each operating agency designs the facility and TCDs according to their work experience. Furthermore, pavement markings that are included by the MUTCD for preferential lanes are the diamond shape symbol for HOV lanes or busways and word markings to indicate vehicle eligibility (e.g. Busways, EZpass lane or HOV lane). Therefore, this generates an opportunity for research regarding the use of new signage configuration and pavement markings that could be uniformly implemented in managed facilities to ensure drivers' understanding of how managed lanes should be utilized.

2.2 Signs and Pavement Markings

The MUTCD stipulates that signs are used in transportation facilities to provide information to all road users. Signs are classified into three groups: regulation, warning, and guidance [4]. Regulatory signs are utilized to inform drivers of laws and regulations that are applicable to the road. Warning signs are implemented to advise drivers of a situation that needs attention ahead in the road. Guidance signs, on the other hand, are installed to provide information on routes, destinations, distance, and other things that may be required for drivers to maneuver from their origin to destination. Regulatory, warning, and guidance signs combine the use of words, symbols, and arrows to convey a message. Moreover, urban and rural conditions have their respective signage configurations since road characteristics differ. One factor that is essential to maintaining safety and efficiency and minimizing the potential of road crashes in roadway facilities is the uniformity of TCDs among transportation facilities [14]. Therefore, the design of TCDs shall take into consideration the perception-response time (PRT) of drivers, which includes the time required to detect, recognize, make a decision, and perform an action [4]. However, signs should be incorporated at a reasonable distance from the situation that is providing information because signs that are placed too far ahead might be forgotten by the driver as a result of roadway distractions, whereas those placed too closely may not provide sufficient time for drivers to detect and respond in a safe manner.

A specific shape shall be used for a specific type of sign; for example, warning signs use a diamond shape, whereas regulatory, guidance, and certain warning signs are shaped as rectangles or squares as indicated in the MUTCD. Furthermore, the color code established for TCDs is identified for each type of sign, as shown in Table 2.1; black and white is used for regulation, green for guidance, and yellow for warning. All signage characteristics are provided in the supplementary book of the MUTCD, "Standard Highway Signs and Markings" [15]. The MUTCD indicates that word messages should be as short as possible, and the message should not contain periods, apostrophes, question marks, or any other characters that are not letters, numbers, or hyphens, which may lead to confusion among drivers [4]. In addition, signs that serve different purposes shall have a sufficient spacing distance taking into consideration the posted speed limit or the 85th percentile speed, thereby providing sufficient time for drivers to think and decide. Additionally, signs should be placed at a determined height and lateral distance, as illustrated in Figure 2.2, providing roadside safety to drivers. However, overhead signage should be installed in freeways if no roadside space is available or in locations where a specific lane use is desired [4]. Additionally, several research studies have found that overhead sign configurations reduce the variability in drivers' speed and lane position, making it easier for motorists to visualize information and navigate through the road, thereby improving the safety of all road users [14, 16].

Table 2.1 Sign colors according to the MUTCD (Source: MUTCD [4]).

Type of Sign	Legend								Background										
	Black	Green	Red	White	Yellow	Orange	Fluorescent Yellow-Green	Fluorescent Pink	Black	Blue	Brown	Green	Orange*	Red*	White	Yellow*	Purple	Fluorescent Yellow-Green	Fluorescent Pink
Regulatory	X		X	X					X					X	X				
Prohibitive			X	X										X	X				
Permissive		X													X				
Warning	X															X			
Pedestrian	X															X		X	
Bicycle	X															X		X	
Guide				X								X							
Interstate Route				X						X				X					
State Route	X														X				
U.S. Route	X														X				
County Route					X					X									
Forest Route				X							X								
Street Name				X								X							
Destination				X								X							
Reference Location				X								X							
Information				X						X		X							
Evacuation Route				X						X									
Road User Service				X						X									
Recreational				X							X	X							
Temporary Traffic Control	X												X						
Incident Management	X												X						X
School	X																	X	
ETC-Account Only	X																X****		
Changeable Message Signs																			
Regulatory			X***	X					X										
Warning					X				X										
Temporary Traffic Control					X	X			X										
Guide				X					X			X**							
Motorist Services				X					X	X**									
Incident Management					X			X	X										
School, Pedestrian, Bicycle					X		X		X										

* Fluorescent versions of these background colors may also be used.

** These alternative background colors would be provided by blue or green lighted pixels such that the entire CMS would be lighted, not just the legend.

*** Red is used only for the circle and slash or other red elements of a similar static regulatory sign.

**** The use of the color purple on signs is restricted per the provisions of Paragraph 1 of Section 2F.03.

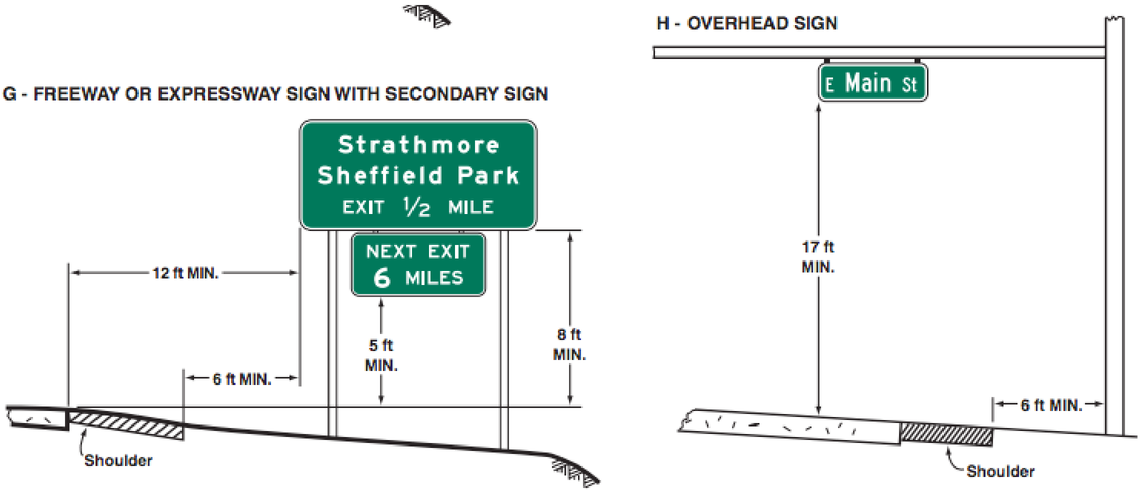


Figure 2.2 Examples of heights and lateral distance of roadside and overhead signs (Source: MUTCD [4]).

Pavement markings provide additional information to road users while exerting minimal driver distraction and are commonly used to supplement other TCDs such as signs and signals [4]. Markings are used to inform road users of regulations, guidance, or warnings along the road. Nevertheless, it is important to take into consideration the visibility and durability of the marking treatment when selecting a proposer type of marking and material. The visibility of pavement markings could be affected by snow, debris, water, and adjacent markings, while their durability depends on material characteristics, traffic volumes, weather, location, and other road conditions [4]. Therefore, it is important to select an appropriate type of marking and materials (e.g., paints and thermoplastics), as well as to provide constant maintenance for an efficient and durable marking treatment.

Furthermore, several research studies have evaluated the use of different pavement marking treatments and have encountered safety improvements. For example, Brown et al. concluded that the use of signals, signage, and pavement markings at toll plazas with different lane purposes reduced lane changes and potential crashes near toll stations and guided drivers to choose the desired lane with anticipation [17]. Other researchers investigated the effect of word, symbol, and arrow markings at freeway interchanges and concluded that in-lane pavement markings should be used for guidance and warning purposes in highway exit lanes, since drivers' lane selection was enhanced when combining route shields and arrows [18]. Likewise, Finley and Ullman performed a before-and-after study using symbols and arrow markings as treatment, and found a reduction in drivers' lane-changing maneuvers prior to the exit, when compared with data from the original conditions [19]. In conclusion, the implementation of word, symbol, and arrow markings has successfully reduced lane changes and oriented drivers to perform driving maneuvers with much anticipation when approaching freeway exits or preferential lane access points.

According to the MUTCD, transverse marking, which includes word, symbol, and arrow markings, shall be white unless provided in the Manual. In addition, letters and numbers should have a height equal or greater than 6 ft. Moreover, the word or message should not exceed three lines and shall be read in the direction of travel, where the first word of the message should be nearest to the driver [4]. Lastly, pavement markings representing official highway route shield signs may be used to provide guidance to drivers of destinations ahead on the road, where elongated route shield dimensions should be 6 ft wide and 15 ft long [4].

Furthermore, in-lane pavement markings can also be used to distinguish preferential lanes such as HOV lanes, ETC lanes, and busways [4]. For example, a bus lane should have the word marking BUS ONLY in the preferential lane as exhibited in Figure 2.3. The MUTCD recommends at least 1000 ft (300 m) of spacing between a set of markings at freeways that have preferential lanes. However, there is a lack of literature regarding the benefits of pavement markings in multifaceted managed-lane facilities and their effects on driving behavior. Additionally, no design standards are available for pavement markings in managed-lane facilities that operate reversible lanes that integrate a BRT system. Therefore, an opportunity was present to investigate how symbol and word pavement markings influence driver behavior and decision making in reversible lanes that have an exclusive bus exit lane.

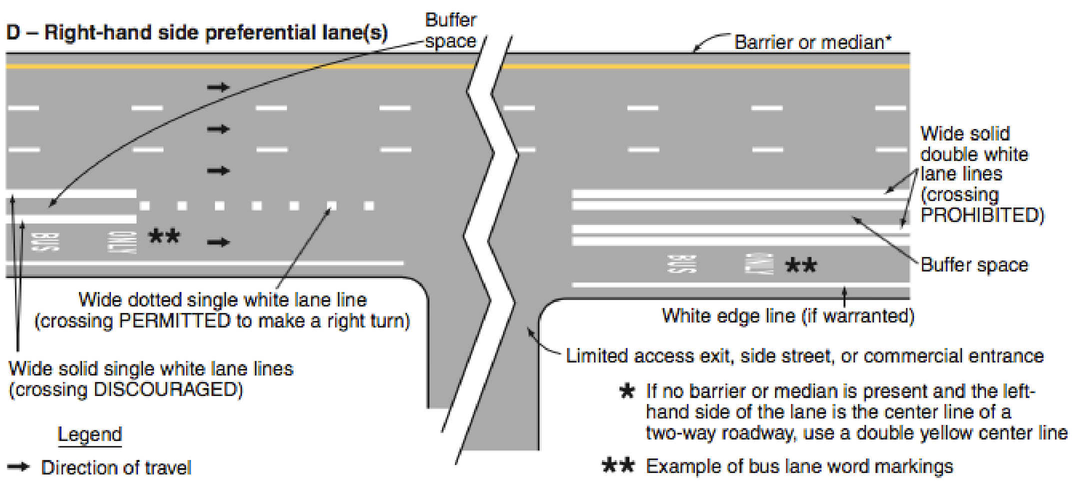


Figure 2.3 Word pavement marking example for a preferential bus lane

(Source: MUTCD [4]).

2.3 Driving Simulators

Driving simulators are some of the most-used equipment in transportation studies that include human factors, road safety, signage, pavement markings, traffic control devices, response and reaction time, work zones, and roadway geometrics, amongst other research topics [20-25]. There are several types of driving simulators whose cost and fidelity influence the driving performance felt by participants. For instance, desktop simulators usually have a driver seat, steering wheel, turn signals, gearshift, and acceleration and braking pedals, as well as a visual display composed of a set of monitors. Likewise, cockpit and full-size vehicle simulators provide similar features with a more realistic experience, where a set of projectors and screens displays the simulation. Additionally, the driving experience of cockpit and full-sized simulators may be improved using a 360-degree display with surrounding audio systems and a motion system that permit a certain degree of movement, generating a more realistic driving motion. However, the addition of vehicle motion, sudden braking, sharp curves, and the amount of time and exposure to the simulation may increase the possibility of simulator sickness [26-28]. The symptoms of simulator sickness may include headache, fatigue, eyestrain, nausea, sweating, vertigo, and vomiting [29]. Therefore, simulation exposure should be conducted in short sessions to reduce the possibility of simulator sickness in research studies. The complexity of the simulation system should depend on the research goals and objectives, and not entirely on the available budget, meaning that a simple driving simulator could be sufficient to evaluate a potential treatment for a roadway.

Driving simulators have successfully served as an innovative research instrument for evaluating driving behavior in transportation-related studies. Although simulation has its limitations, there is a potential for evaluating transportation issues related to infrastructure design and management, human factors, and safety. Therefore, driving simulation provides a cost-effective and efficient alternative to evaluate the operational and safety aspects of the PR-22 reversible DTL system. For instance, Valdés et al. studied how drivers in the real world and in the UPRM driving simulator used the designed westbound BRT exit at the PR-22 DTL [30]. It was found that this segment generates a lot of confusion for some drivers, who then take the wrong exit and generate hazardous conditions in the traffic exiting the DTL. Therefore, a proposed signage treatment including in-lane pavement markings (complying with the MUTCD) was evaluated to improve drivers' decision-making, choices, and maneuvers at the PR-22 DTLs exit [31]. However, the results indicated that the proposed combination did not significantly improve the vehicle average position and speed. For this reason, new signs and pavement marking treatments are evaluated for PR-22 DTL through this research project.

The University of Puerto Rico at Mayagüez (UPRM) driving simulator equipment is divided into three principal components: driving cockpit, visual display, and computer system. The simulator cockpit consists of a steering wheel, gearshift, acceleration and braking pedals, turn signals, and a driving seat. These elements are mounted on a wooden base that has six wheels, making the driving simulator compatible with portable applications. The visual display is composed of three projectors fixed to the ceiling of the laboratory and a set of three screens that are placed in front of the simulator (Figure 2.4). The projection system creates a perspective visibility of 120 degrees. Lastly, the computer system includes a laptop and a desktop computer with a NVidia GTX 980 graphics card and Realtime Technologies Inc. (RTI) simulation software, which includes SimCreator/SimVista and Internet Scene Assembler (ISA).

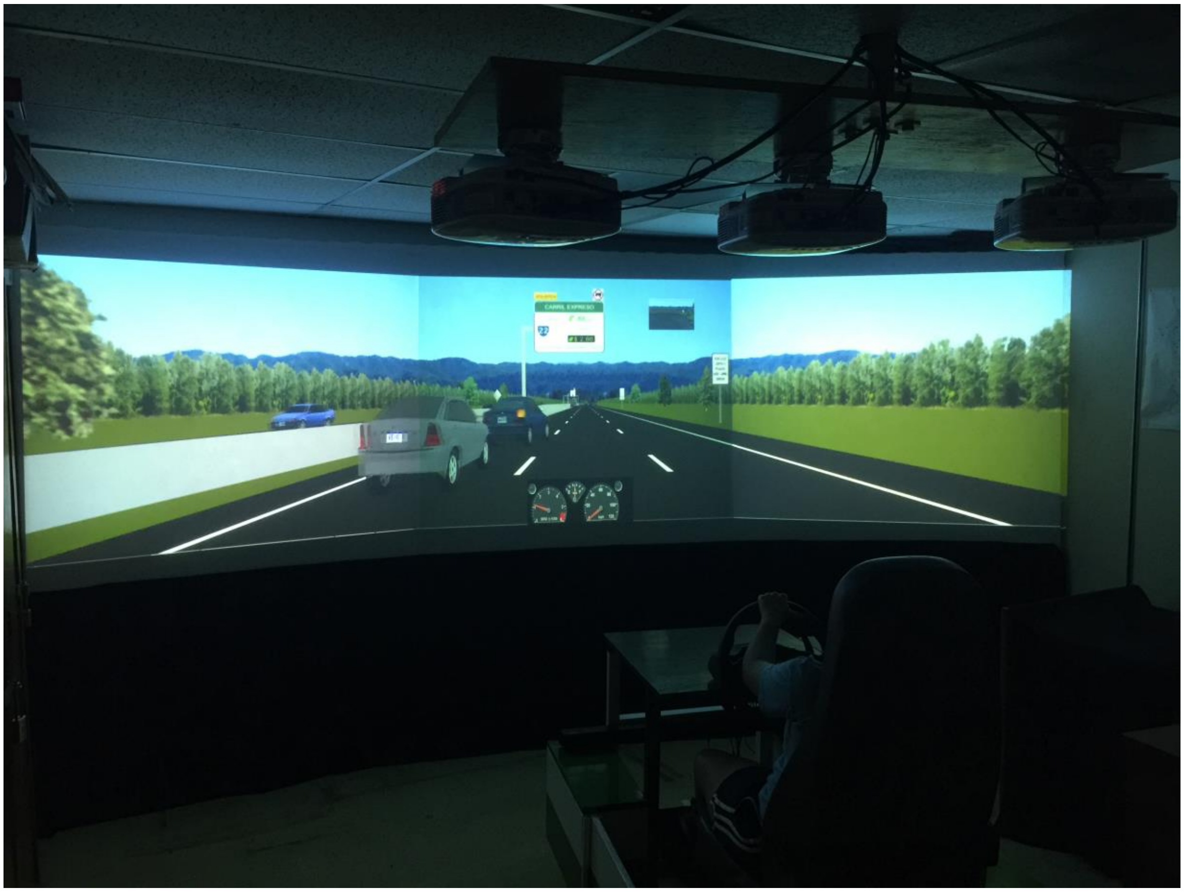


Figure 2.4 Fixed version setup of UPRM cockpit driving simulator.

3 Methodology

This chapter describes the applied methodological procedure for this study. The methodology of this research includes the experimental design, online survey, and development of scenarios. The research methodology flowchart is illustrated in Figure 3.1.

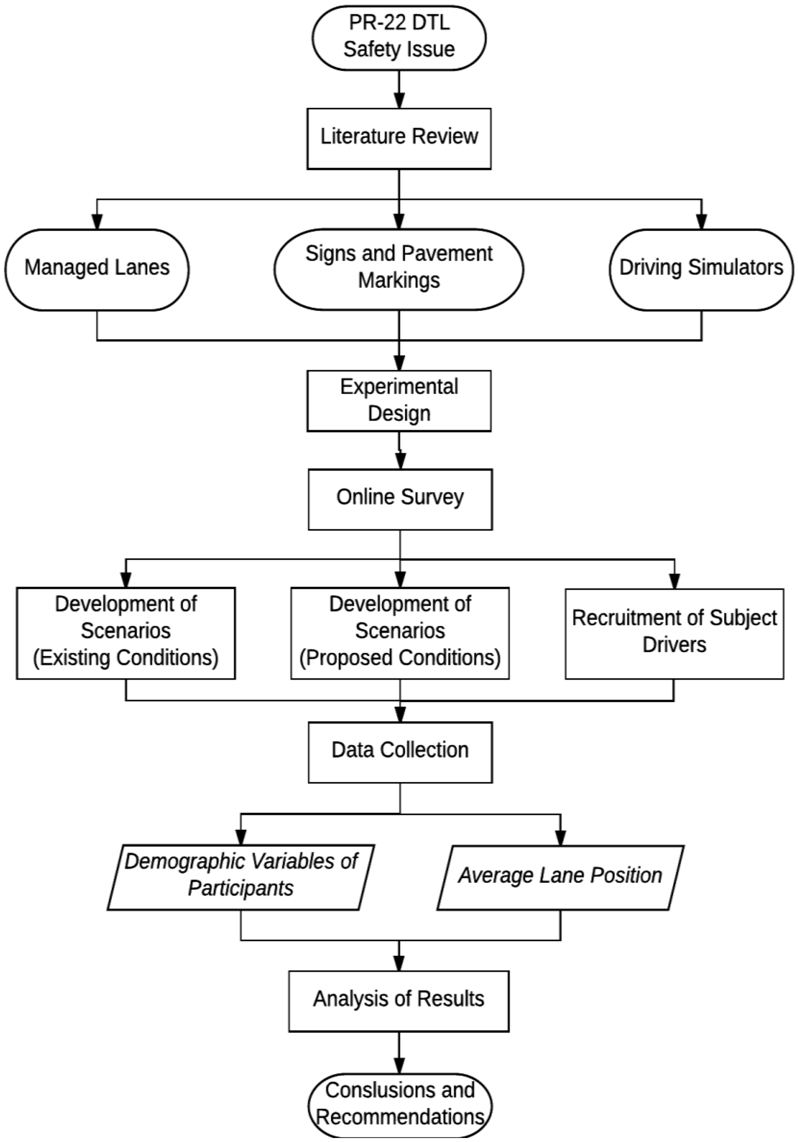


Figure 3.1 Research methodology flowchart.

3.1 Task 1: Experimental Design

The experimental design consisted of 12 scenarios divided into two configurations. Configuration 1 was based on the existing signs of PR-22 DTL, whereas Configuration 2 was based on a proposed treatment (based on survey performed to understand drivers' perception of signs and markings in managed lanes) using modified signs and pavement markings. The pavement marking treatment of Configuration 2 consisted of in-lane pavement marking using the PR-22 route shield and the word message BUS ONLY (Table 3.1). The design and dimensions of both symbols and word markings were based on Part 3 (Markings) of the MUTCD and guidelines that apply for signs and pavement markings in the Commonwealth of Puerto Rico [32]. Furthermore, the independent variables considered for the development of all scenarios were time of day (ToD) and traffic flow (TF). The scenarios developed for both configurations are presented in Table 3.2, where ToD consists of three levels, namely, morning, afternoon, or nighttime, and the TF consists of two levels, low or no traffic.

Table 3.1 Configurations considered for this research study.

<table>
<tr><th>Configuration</th><th>Description</th><th>Marking Treatment</th></tr>
<tr><td>1</td><td>Existing conditions</td><td>None</td></tr>
<tr><td rowspan="2">2</td><td>a) Signage configuration using a bus symbol, PR-22 route shield and a proposed no vehicle allowed symbol.</td><td>
PR-22 Route Shield</td></tr>
<tr><td>b) In-lane pavement markings using PR-22 route shield and words BUS ONLY.</td><td>
Bus Only Lane</td></tr>
</table>

Table 3.2 Description of scenarios of each configuration.

Scenario	Time of Day (*ToD*)	Traffic Flow (*TF*)
1	Morning	None
2	Morning	Low
3	Afternoon	None
4	Afternoon	Low
5	Nighttime	None

6	Nighttime	Low

In addition, one replication of the basic experiment was included to increase the sample size of participants. Therefore, a total of 25 participants drove six scenarios of the same configuration. The order in which scenarios were presented to subject drivers was based on the Latin Square design. This would counterbalance the order in which subject drivers are exposed to each scenario, thereby reducing the influence of scenario order on participants (Valdés et al., 2016).

3.2 Task 2: Online Survey

An online survey was performed to gather driver understanding of managed-lane signs and pavement markings in the Commonwealth of Puerto Rico. The results of this survey were considered to develop the proposed treatment that was evaluated with the existing conditions using the UPRM driving simulator. This survey consisted of five sections:

1. Demographic Information
2. Driving History
3. Concepts of Managed Lanes
4. Signage
5. Pavement Markings

The results of the online survey are presented and discussed in Chapter 4.

3.3 Task 3: Scenario Development

The development of the six scenarios associated with the existing conditions of TCDs along the PR-22 DTL (Configuration 1) was based on the "as built" plans provided by Metropistas LLC, and video data that was recorded to identify and verify the location and type of TCDs. These TCDs included signs, longitudinal pavement markings, chevron markings, crash cushions, pylons, and barriers. The six scenarios for the proposed treatment (Configuration 2) were developed based on the online survey results and in accordance with the MUTCD and the supplementary Manual of TCDs for Spanish text, signs, and symbols used by the Puerto Rico Highway and Transportation Authority (PRHTA).

3.3.1 Description of Signs in Configuration 1

Configuration 1 consists of a set of three overhead guide and regulatory signs located over the last two kilometers of PR-22 DTL, where the first set of signs was placed at 2 km, the second set of signs at 1 km, and the third at the start of the exit lane. The DTL exit (for passenger cars) in the EB direction is located in the right lane, whereas the BRT-exclusive exit is located in the left lane. As illustrated in Figure 3.2, the overhead regulatory sign for the DTL exit in the EB direction has a white background with black letters and an additional yellow warning plaque (according to the MUTCD E11-1 sign) with the words SOLO SALIDA (EXIT ONLY) and a downward lane arrow in black. Similarly, the BRT exit sign has a white background with the words CARRIL EXCLUSIVO

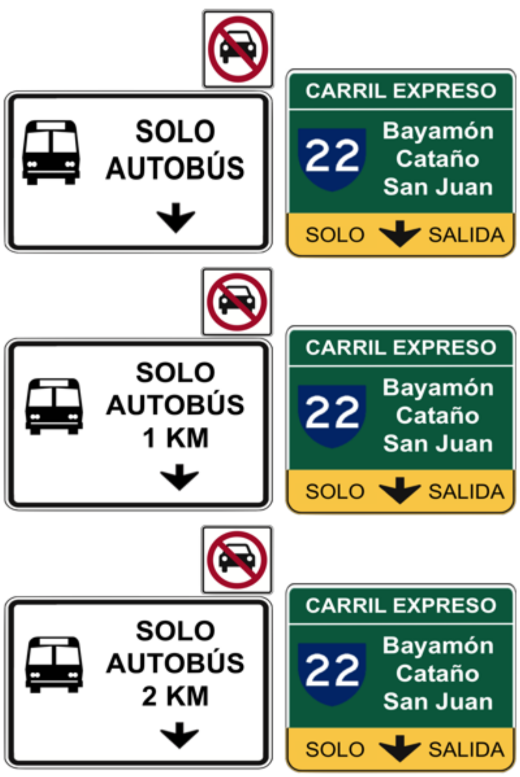
(EXCLUSIVE LANE), a bus symbol, and a downward lane arrow in black (Figure 3.2). On the contrary, the DTL exit sign in the WB direction consists of a guidance sign with destinations in white and a downward lane arrow. This sign is organized according to MUTCD designation D1-3a with a green background and the location of Toa Alta, Corozal, and Dorado highway number. In addition, the BRT sign has a white background with the words CARRIL EXCLUSIVO (EXCLUSIVE LANE), a bus symbol in black, an additional yellow warning plaque with the words SOLO SALIDA (EXIT ONLY), and a downward lane arrow in black.

3.3.2 Description of Signs in Configuration 2

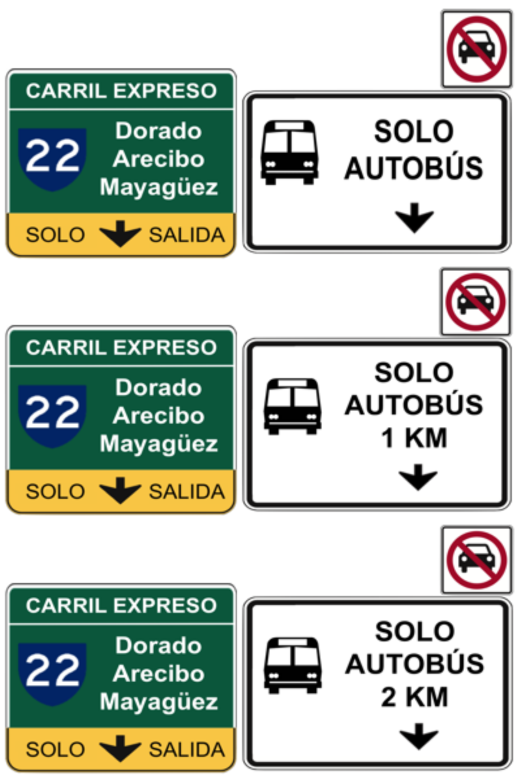
Configuration 2 consists of the proposed treatment of three overhead guide and regulatory signs and in-lane pavement markings at the DTL exit. The set of signs is located at the same points of the existing signage location and maintains a consistent overhead signage configuration for both travel directions. The passenger car exit signs include the route shield designated for freeway PR-22, which has a blue background and number 22 in white, and the nearest municipalities in each travel direction (in the EB direction: Bayamón, Cataño, and San Juan; and in the WB direction: Dorado, Arecibo, and Mayagüez). In addition, the Spanish text CARRIL EXPRESO (EXPRESS LANE) is located at the top of the sign and a yellow warning plaque that indicates SOLO SALIDA (EXIT ONLY) is located at the bottom. Furthermore, the BRT exit sign contains the words SOLO AUTOBÚS (ONLY BUS), a bus symbol, and an additional plaque with a no vehicles allowed symbol (proposed signage), which is located at the top-right of the sign. Also, in-lane pavement markings start 1 km prior to the exit ramp and finish after the separation of the two exit ramp lanes. The designed lane exit of the BRT has SOLO BUS (ONLY BUS) written on it, and the passenger cars lane exit has the PR-22 symbol, as shown in Figure 3.3.

Configuration 1 in EB Direction

Configuration 1 in WB Direction



Configuration 2 in EB Direction



Configuration 2 in WB Direction

Figure 3.2 Configuration 1 and Configuration 2 signs in each direction.

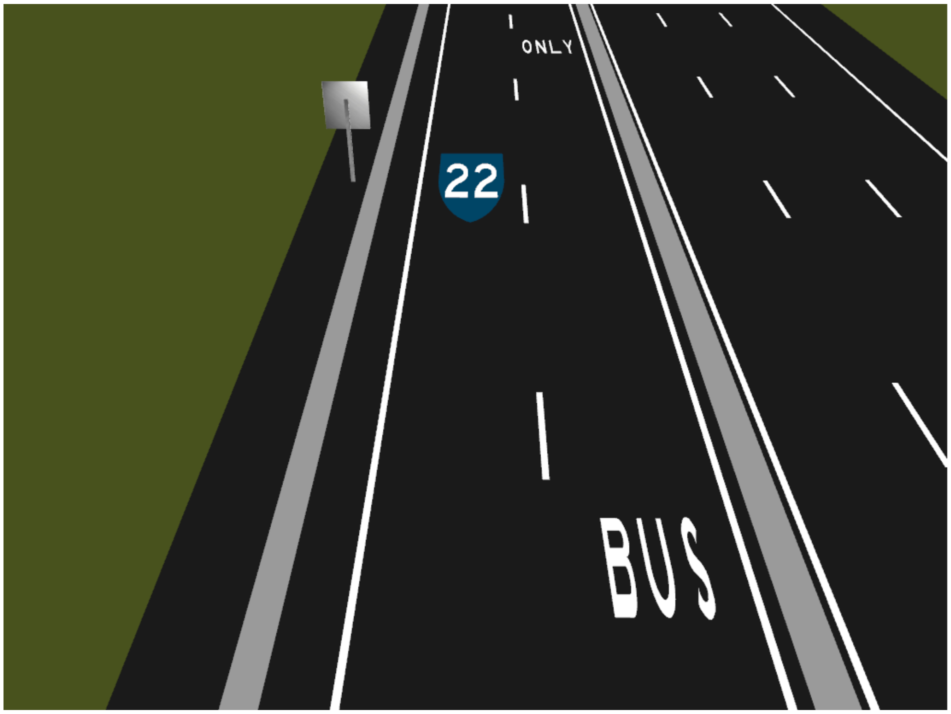


Figure 3.3 Proposed in-lane pavement marking treatment.

4 Online Survey

This chapter provides the results obtained through an online survey. This data was used to understand drivers' perception of managed lane signs and markings. These results were used to develop a treatment that could improve the driving performance of PR-22 DTL users. A total of 312 representative drivers of Puerto Rico participated in the online survey, which was approved by UPRM's Institutional Review Board (IRB) committee. The results of this survey study, which consisted of four sections, provided participants with an understanding of managed-lane signs, and inquired as to which treatment for signs and pavement markings they preferred, according to their knowledge.

The first section contained demographic information. This part included the gender and age of the participants. As illustrated in Figure 4.1, more than half of the participants were female.

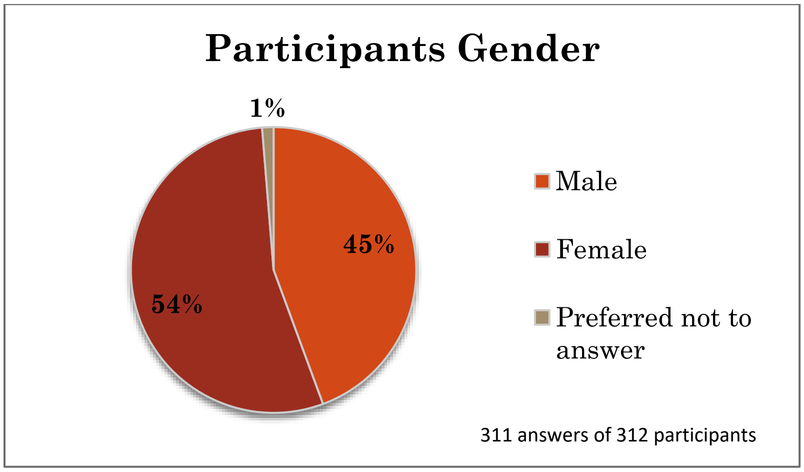


Figure 4.1 Gender distribution of participants.

In terms of participants' age distribution, 49% of participants were between 25 and 54 years of age, while 42% were between 18 to 24 years of age. Still, 9% had an age of 55 years or more.

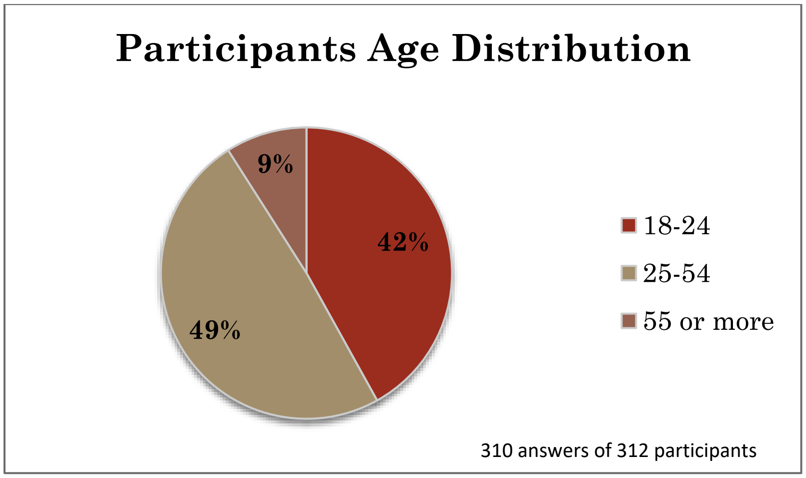


Figure 4.2 Age distribution of participants.

The second section was driving history, where participants answered questions regarding their knowledge of PR-22 DTL and the frequency with which they used the system. As depicted in Figure 4.3, almost 90% of participants acknowledged that a DTL was located within a segment of freeway PR-22. However, at least half of the participants had never used this managed-lane system, while 33% had used it fewer than three times (Figure 4.4). This suggests that more than 83% of the surveyed drivers were not familiar users of this unique and complex managed facility.

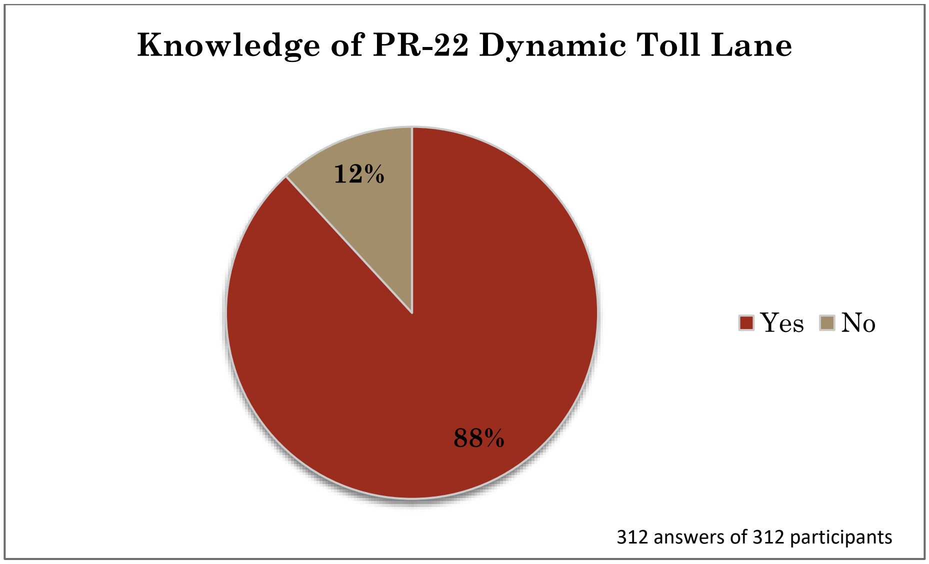


Figure 4.3 participants' knowledge of PR-22 dynamic toll lane.

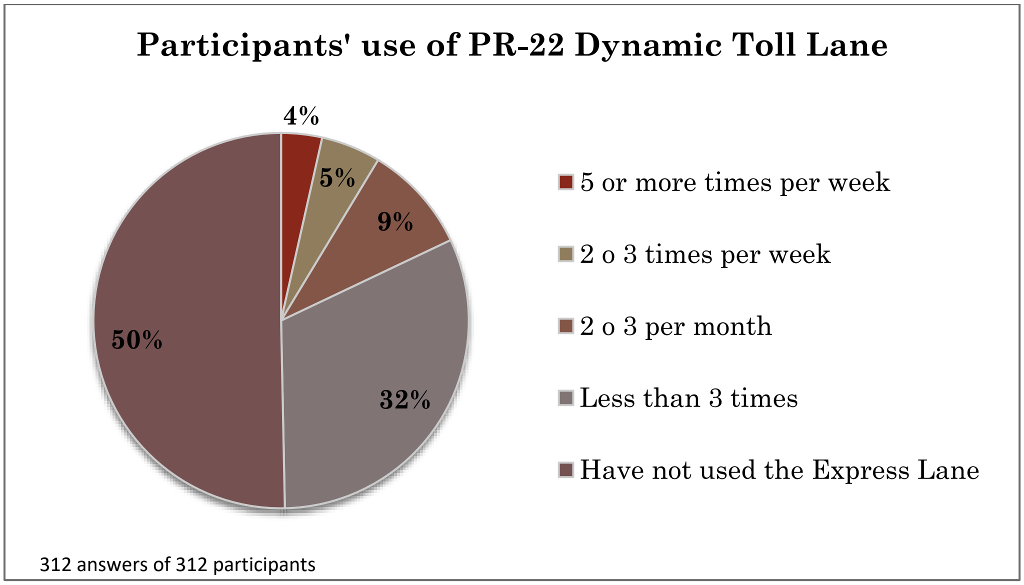


Figure 4.4 Participants' use of PR-22 dynamic toll lane.

The third section of the survey pertained to concepts of managed lanes, which included the participants' interpretation of the HOV diamond-shaped symbol, the bus symbol, and a proposed "no vehicles allowed" symbol. Survey results suggest that at least 65% of participants (Figure 4.5) do not understand the meaning of the diamond-shaped symbol, since their selection was not related to HOV, carpooling, or bus lanes. On the contrary, participants had a better understanding of the bus symbol and the no vehicles allowed symbol since their correct response rates were 82% and 99%, respectively, as illustrated in Figure 4.7.

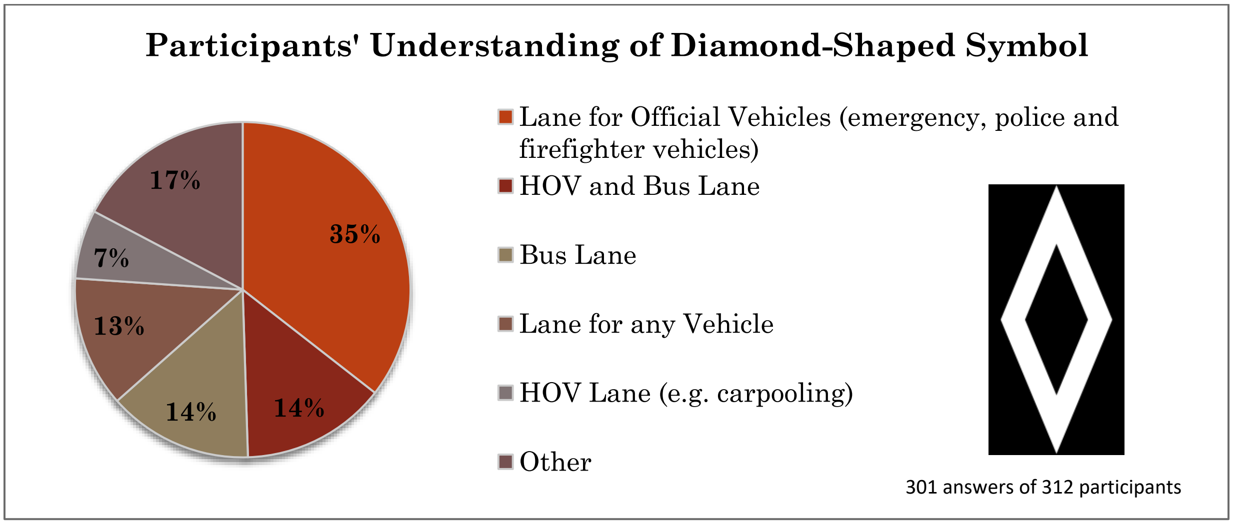


Figure 4.5 Participants' understanding of diamond-shaped symbol.

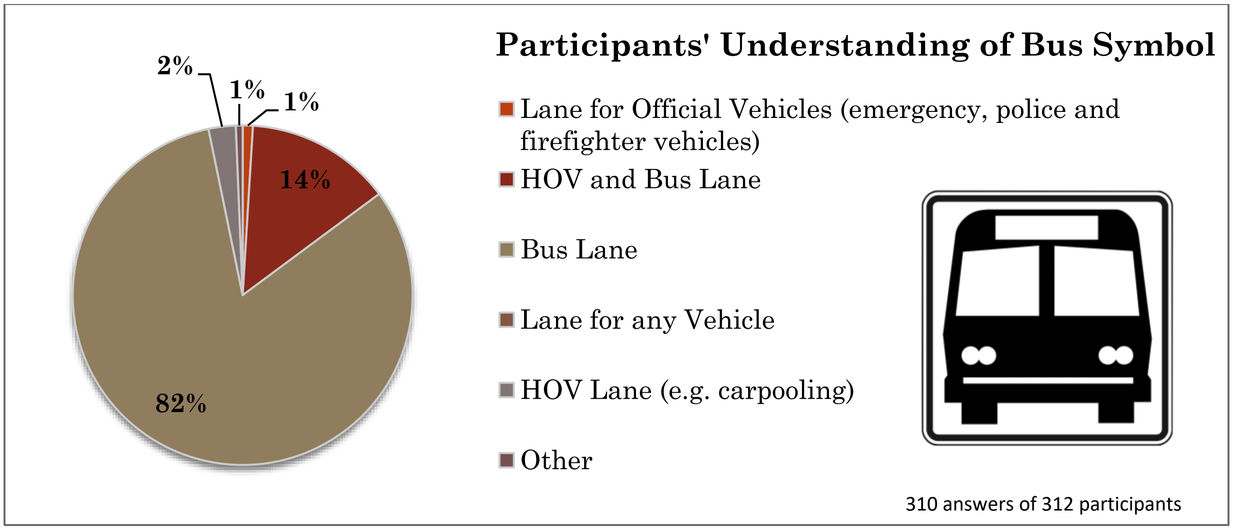


Figure 4.6 Participants' understanding of bus symbol.

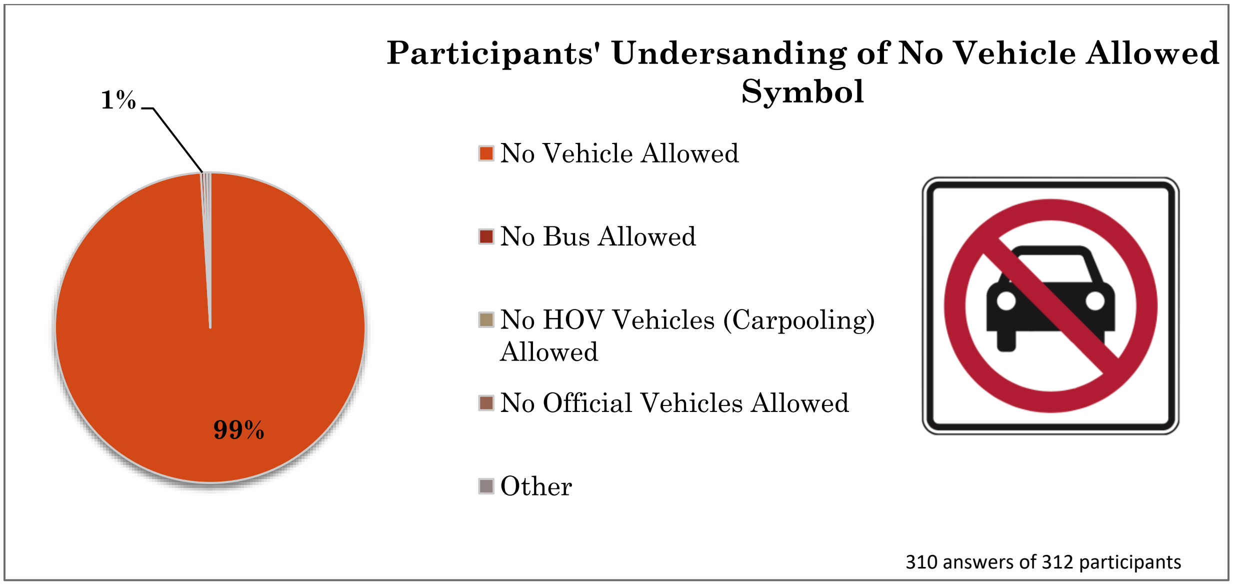


Figure 4.7 Participants' understanding of no vehicle allowed symbol.

The fourth section of the survey was signage, where participants selected the sign that was more appropriate for the DTL lane and the exclusive BRT lane. Survey results indicated that 63% (Figure 4.8) of participants preferred the DTL (also known as the express lane) sign that had a green background with destinations, the freeway PR-22 route shield, and the additional yellow plaque SOLO SALIDA (ONLY EXIT) with a downward arrow in black, to indicate the lane.

However, for the exclusive BRT exit lane sign, participants' selections were mainly between three sign configurations. As illustrated in Figure 4.11, alternative e was selected by 29% of participants, alternative c by 27% of participants, and alternative d by 23% of participants. Therefore, a combination of these three proposed signs was used to generate a proposed BRT exit lane sign, which includes a white background with the words SOLO AUTOBÚS (ONLY BUS) with a downward black arrow and a bus symbol. In addition, the no vehicle allowed symbol was included as an additional plaque in the top-right side of the sign. This proposed BRT exit sign is illustrated in Figure 4.10.

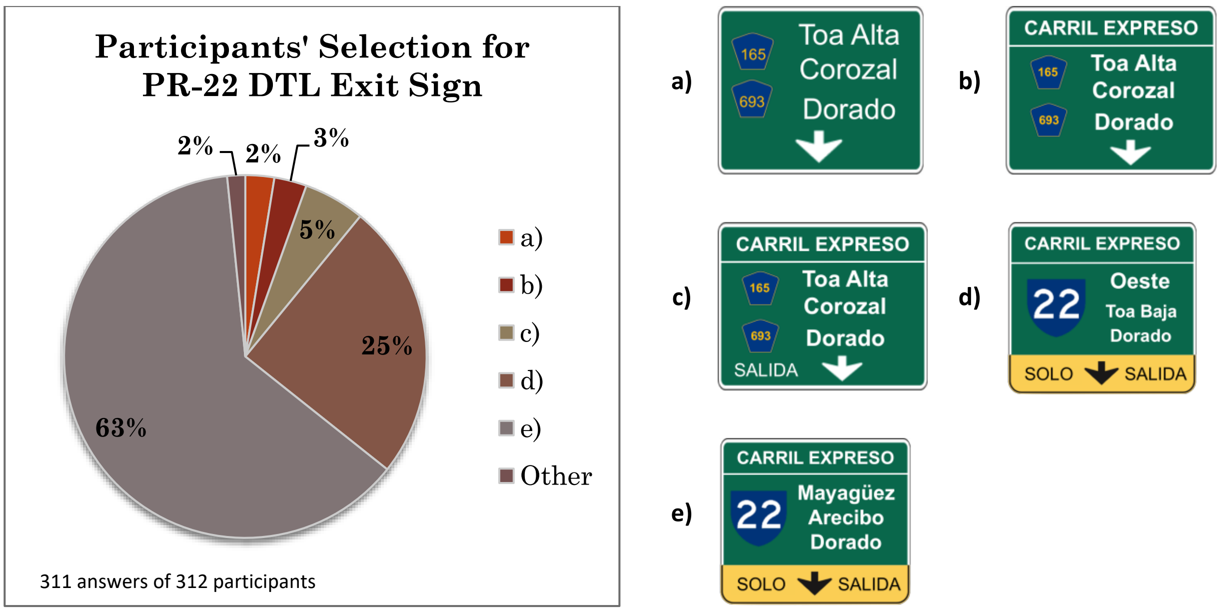


Figure 4.8 Participants' selection for PR-22 DTL exit sign.

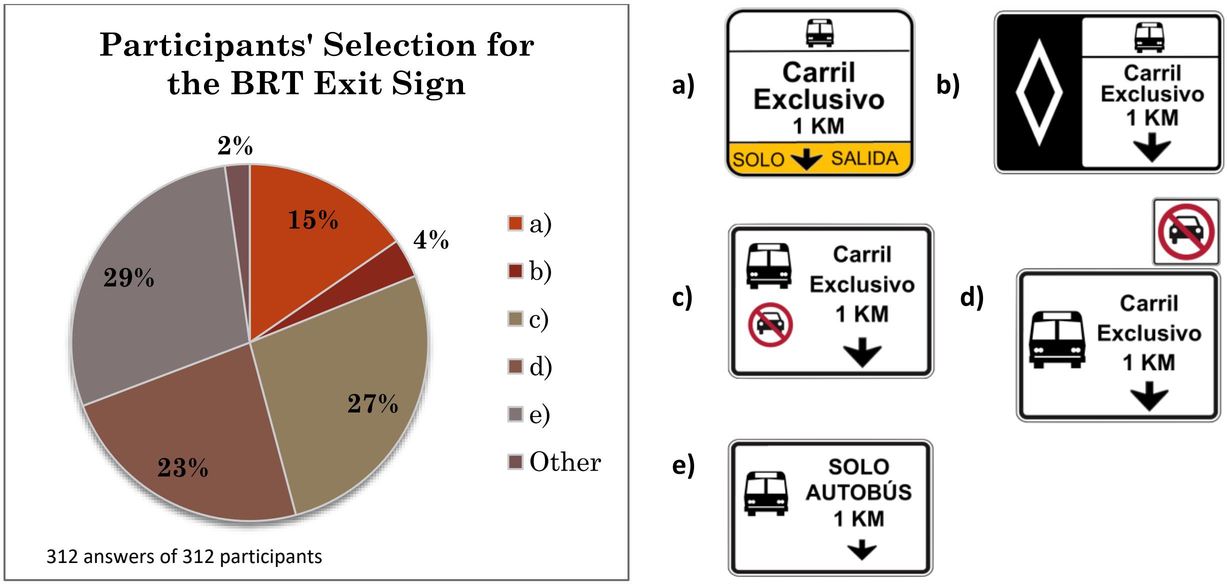


Figure 4.9 Participants' selection for the BRT exit sign.

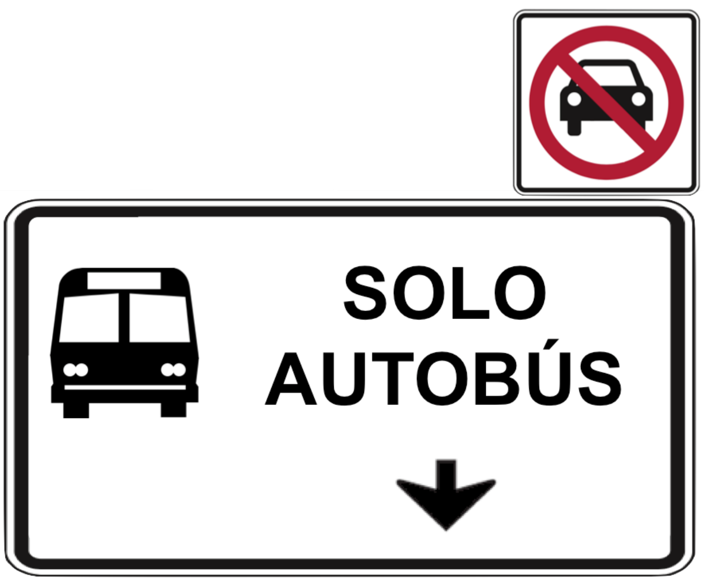


Figure 4.10 Proposed BRT exit sign based on survey response.

Lastly, the fourth survey section was pavement markings, which included the participants' selection of pavement marking treatments. According to the survey results presented in Figure 4.11, 65% of participants understood that words and symbols should be used to designate lanes when approaching the DTL exit. In terms of which type of treatment, 33% of participants chose the alternative that included words BUS ONLY, the HOV diamond-shaped symbol, and the PR-22 route shield, while 27% selected the alternative that combined words BUS ONLY with the diamond-shaped symbol. However, the HOV diamond-shaped symbol was not included in the final design since 65% of surveyed drivers did not understand its meaning. The final design of movement markings for both DTL and exclusive BRT exit lanes is illustrated in Figure 3.3.

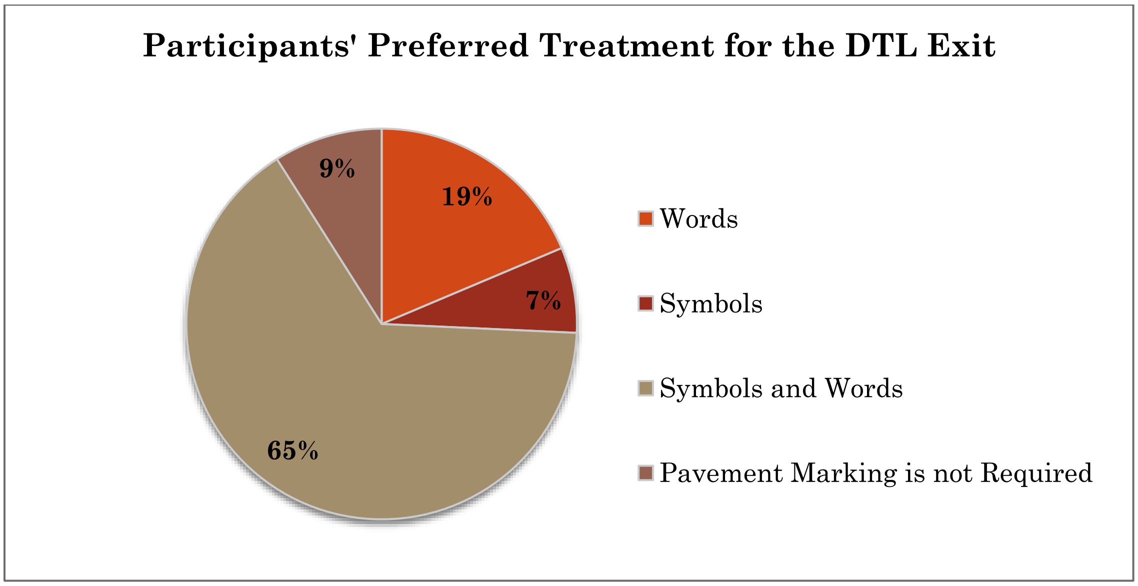


Figure 4.11 Participants' preferred treatment for the DTL exit.

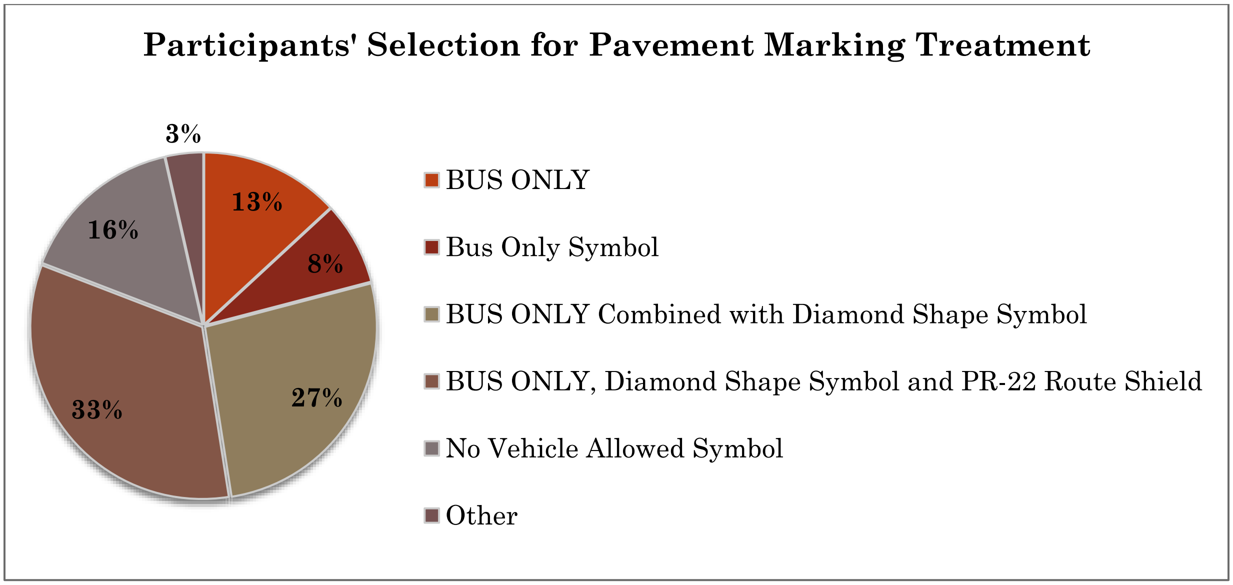


Figure 4.12 Participants' Selection for Pavement Marking Treatment.

5 Driving Simulator Study

The following chapter discusses the results of the statistical analysis applied to this research study. Graphs and tables are provided to summarize and illustrate the results. The performance measurement used to evaluate driving behavior was the vehicle average lane position.

An F-Test analysis was performed to evaluate the average lane position (ALP) of vehicles and make comparisons between Configuration 1 (existing signs) and Configuration 2 (proposed signs and pavement markings). This statistical analysis was used to compare the variance of ALP obtained from the sample data within the two configurations with a p-value less than 0.05. The F-Test equation is the following:

$$F - Test = \frac{S_1^2}{S_2^2} \qquad \text{(Eq. 5.1)}$$

where:

S_1^2 = Variance of group 1

S_2^2 = Variance of group 2

In addition, a Bonferroni correction was applied to eliminate the Type I error and reduce the possibility of occurrence of the family-wise error (also known as false positive values) due to the multiple hypotheses analysis. The Bonferroni correction changes the p-value from 0.05 to 0.0020833. Therefore, statistical differences are encountered when p-values are less than 0.0020833.

A total of four zones of interest were defined for this research, as illustrated in Figure 5.1. Zone 1 starts at the second guidance sign of the DTL exit and ends approximately 2200 ft before the PR-22 DTL exit. Zone 2 is located after the guidance sign, illustrating the distance from the exit ramp (approximately from 2200 ft to 1100 ft before the PR-22 DTL exit). Zone 3 covers the 1100 ft before the divergences of the DTL exit gore area where the last guidance signs are located. Lastly, Zone 4 covers the area after the passenger car exit ramps of the BRT.

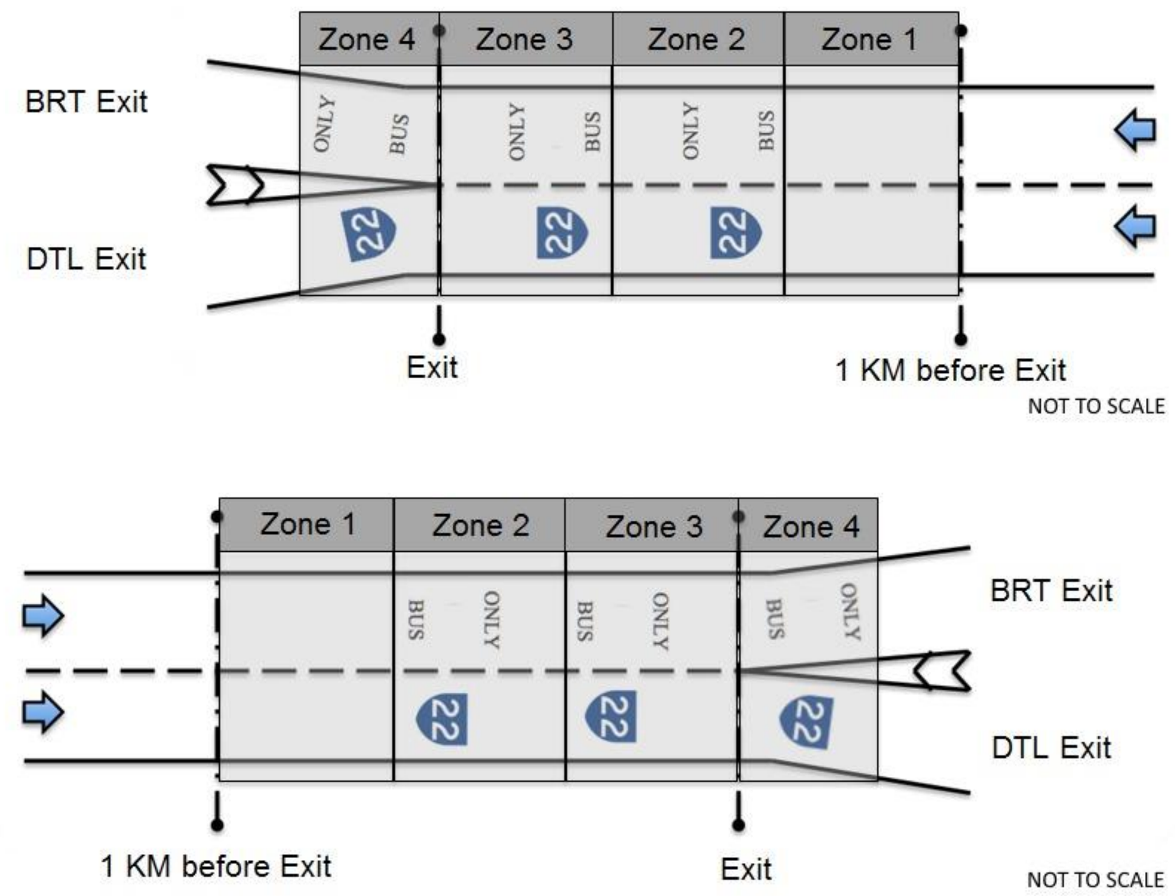


Figure 5.1 Evaluated zones of PR-22 DTL exit for both travel directions.

The results of the two statistical analyses, normal F-Test and with Bonferroni correction, for the performance measurement ALP are illustrated in Table 5.1.

Table 5.1 F-test for the four zones evaluated for each of the six scenarios.

F-Test with P-Value Set to <0.05				
Scenario	Zone			
	1	2	1	4
1	<0.001*	<0.001*	<0.001*	<0.001*
2	<0.001*	<0.001*	<0.001*	<0.001*
3	<0.001*	<0.001*	<0.001*	0.190
4	0.735	0.787	0.054	0.015*
5	<0.001*	<0.001*	<0.001*	<0.001*
6	<0.001*	<0.001*	<0.001*	0.514
F-Test with Bonferroni Correction with 24 Test P-Value Set to 0.0020833				
Scenario	Zone			
	1	2	3	4
1	<0.001**	<0.001**	<0.001**	<0.001**
2	<0.001**	<0.001**	<0.001**	<0.001**
3	<0.001**	<0.001**	<0.001**	0.190
4	0.735	0.787	0.054	0.015
5	<0.001**	<0.001**	<0.001**	<0.001**
6	<0.001**	0.045	<0.001**	0.514

*Significant Difference, P-value<0.05

**Significant Difference, P-value<0.0020833

The results of the F-Test analyses at an 85% confidence level shown in Table 5.1 reveal that subject drivers exposed to scenarios with the proposed treatment (Configuration 2) had less variation in the ALP variable when compared to existing condition scenarios (Configuration 1). For instance, Configuration 2 p-values show significant differences among drivers' ALP in 67% of the evaluated zones (24 zones in total). Nevertheless, significant differences were obtained in 40% of the evaluated zones after applying the Bonferroni correction for ALP comparisons between configurations.

Results from the F-Test analysis without the Bonferroni correction show that Zones 1, 2, and 3 have a significant difference in 83% of the scenarios evaluated, while Zone 4 has a significant difference in 67% of the scenarios. However, the analysis can also be interpreted in terms of driving performance by scenario, where Scenarios 1, 2, and 5 show significant differences in all zones of interest. Similarly, Scenarios 3 and 6 show a significant difference in 75% of the zones evaluated, while Scenario 4 shows statistical difference in the last zone evaluated.

Likewise, when applying the Bonferroni correction for the F-Test analysis, Zones 1 and 3 have a higher significant difference in 83% of the evaluated scenarios. Nevertheless, when interpreting the results by scenario, it is seen that Scenarios 1, 2, and 5 show significant difference in the all zones of interest. In addition, Scenario 3 and Scenario 6 have significant difference in 75% and 50% of the evaluated zones, respectively. However, Scenario 4 did not show significant difference in ALP inside the DTL. Nonetheless, research results demonstrate that Configuration 2 in Zone 1 (after seeing the guidance sign) and in Zone 3 (1100 ft before the exit) improve the participants' vehicle position.

Subject drivers' lane choice was improved when exposed to Configuration 2 scenarios. Results from participants exposed to the first scenario (Figure 5.2) illustrates that 33.33% of participants used the BRT exit lane incorrectly in Configuration 1, while all participants in Configuration 2 passed through the DTL exit lane. In addition, it is seen that participants changed into the correct exit lane with much anticipation when driving through Scenario 1 of Configuration 2.

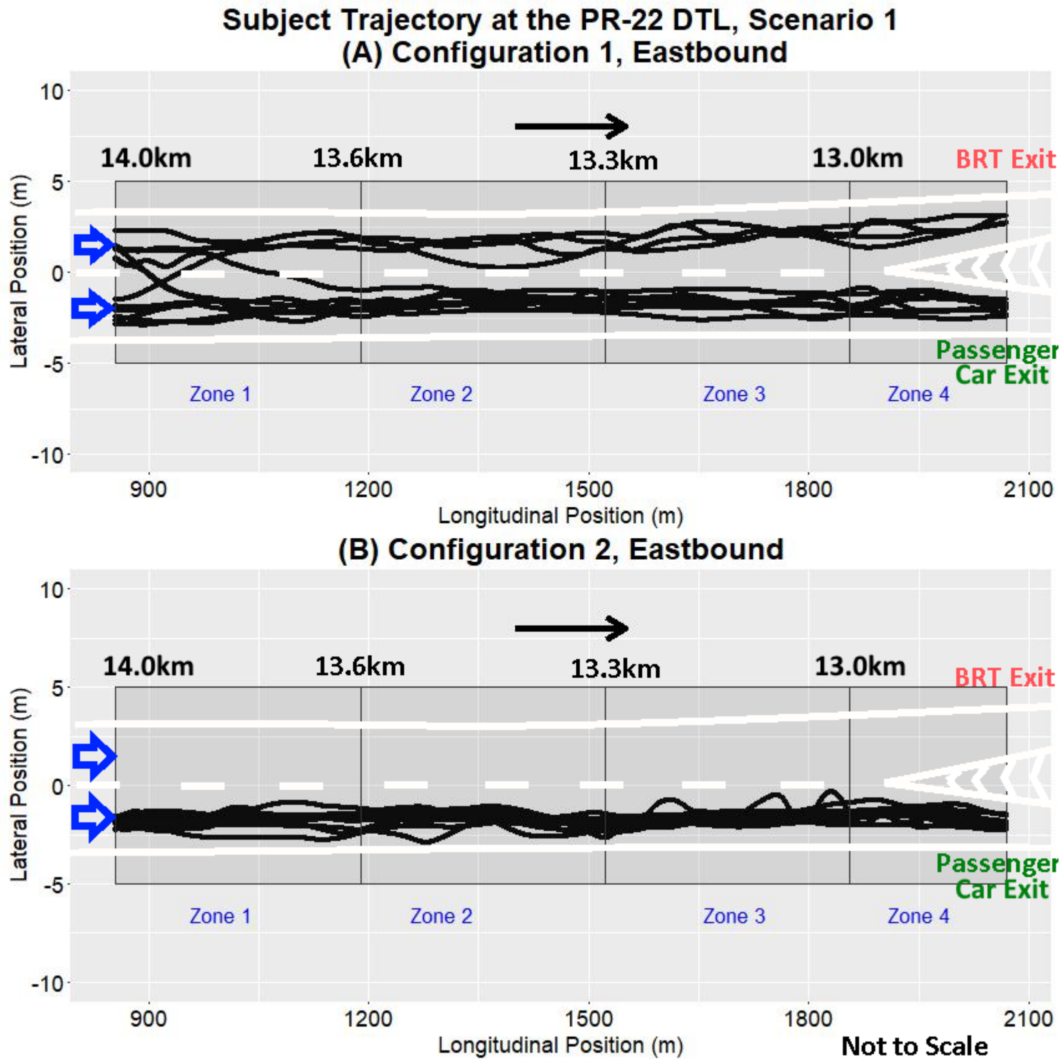


Figure 5.2 Subject trajectory at the PR-22 DTL exit for Scenario 1 in both configurations.

Similarly, as illustrated in Figure 5.3, 41.67% of participants in Scenario 2 of Configuration 1 used the incorrect exit lane, while all subject drivers exposed to Configuration 2 changed into the DTL lane before the last kilometer. In addition, one participant in Configuration 1 had a last-moment lane change into the DTL exit, passing over the chevron markings.

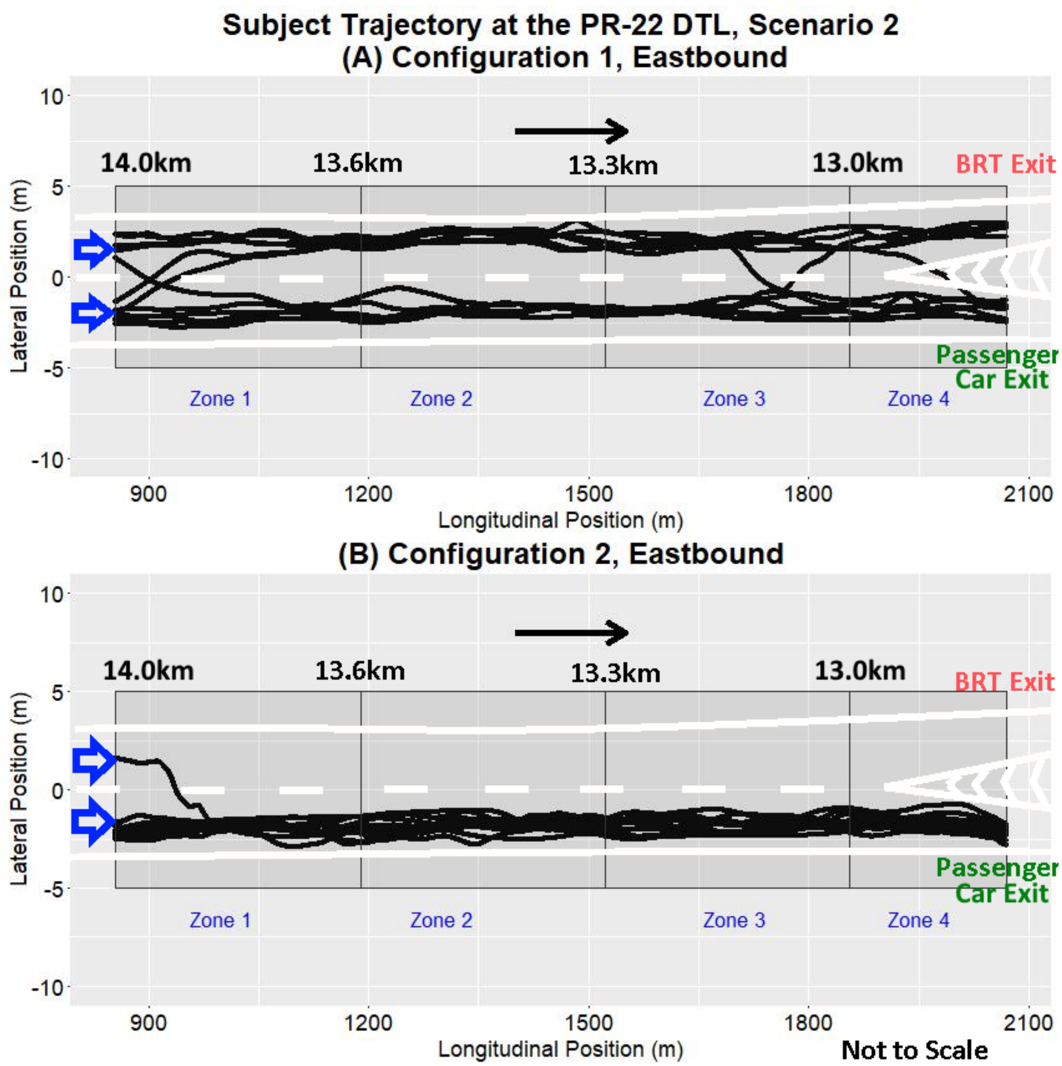


Figure 5.3 Subject trajectory at the PR-22 DTL exit for Scenario 2 in both configurations.

However, participants exposed to Scenario 3 used the correct DTL exit in both configurations. Figure 5.4 illustrates that 33.33% of participants in Configuration 1 changed lane when approaching the DTL exit, whereas all participants of Configuration 2 changed into the correct exit lane before the first zone of interest.

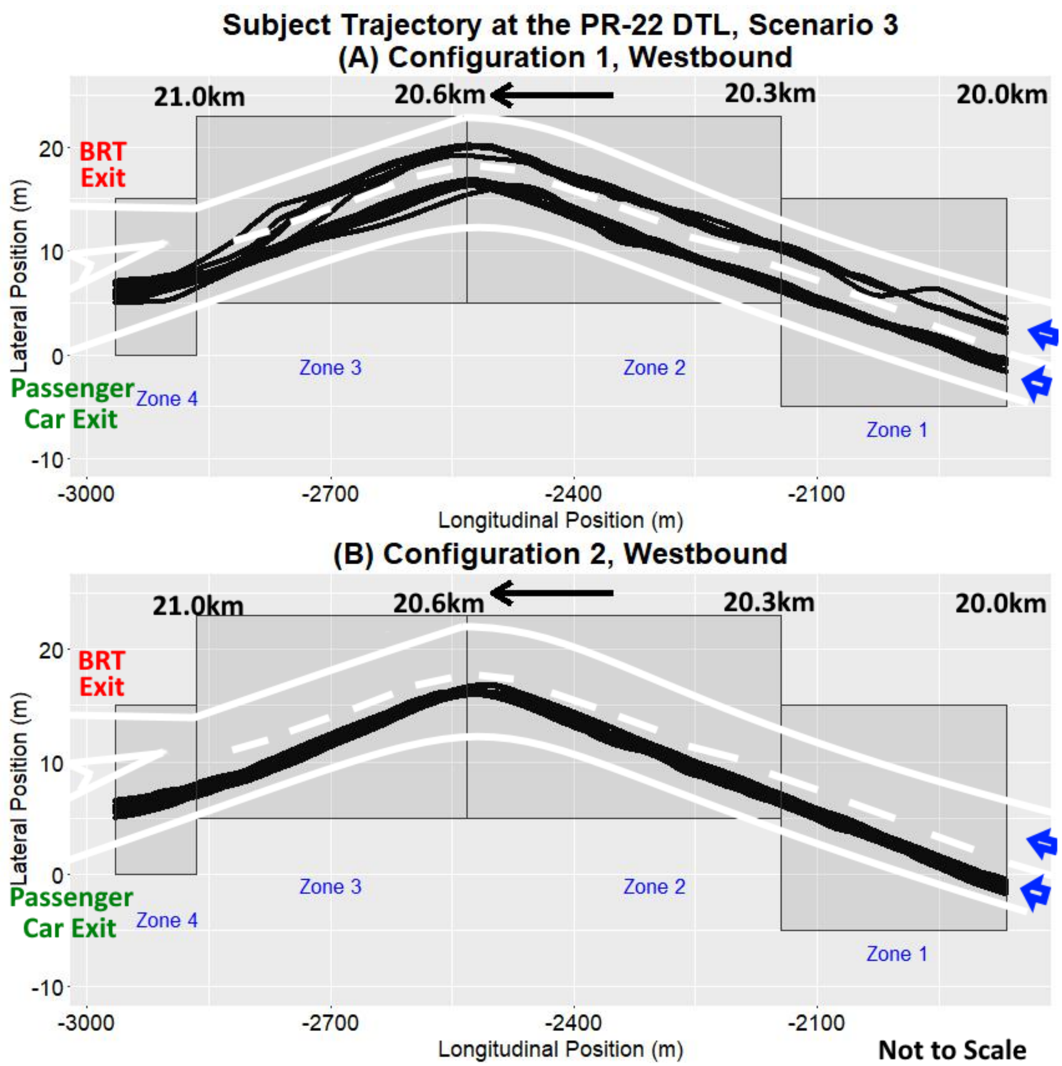


Figure 5.4 Subject trajectory at the PR-22 DTL exit for Scenario 3 in both configurations.

As exhibited in Figure 5.5, driving performance in Scenario 4 was similar between participants of both configurations, where drivers used the correct exit lane and performed lane movements before the divergent gore area.

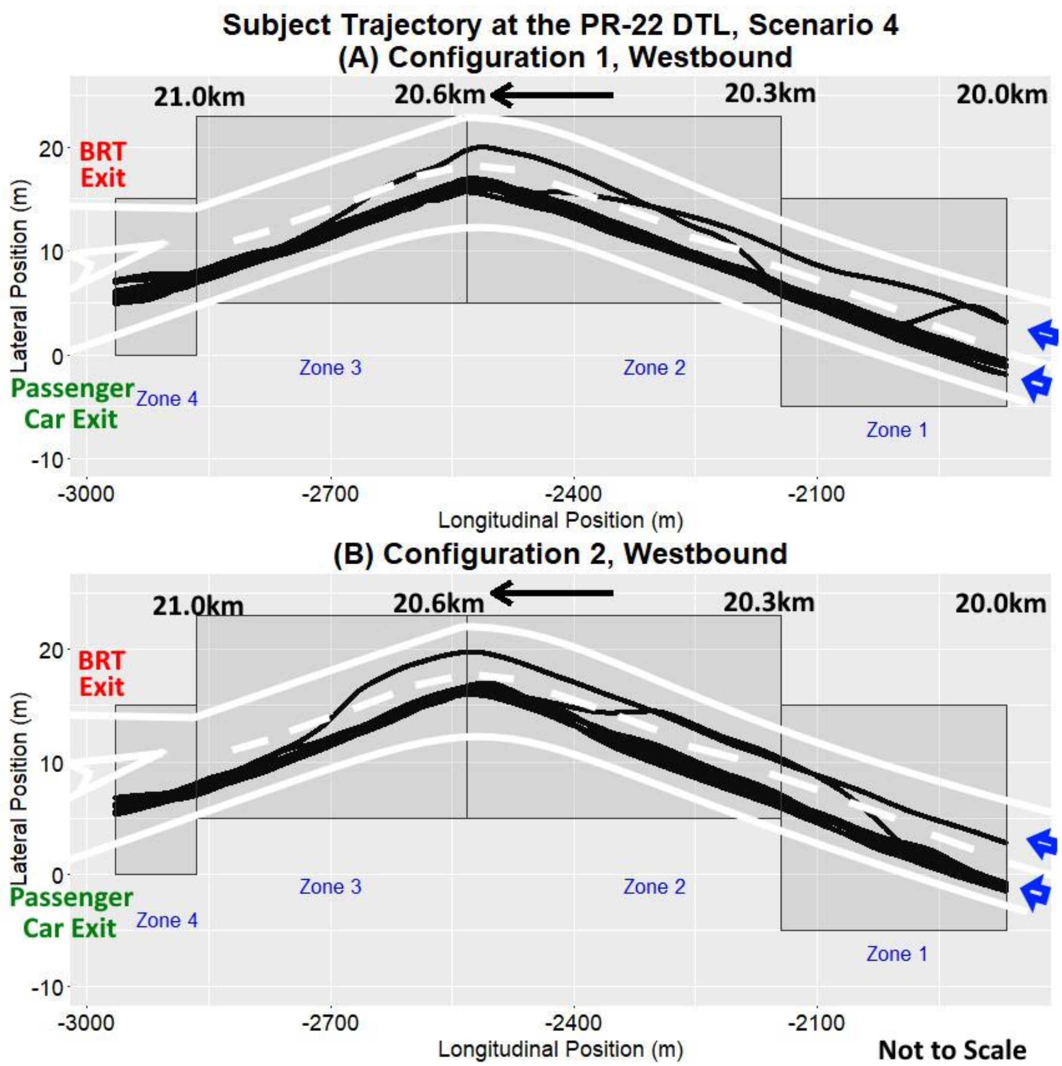


Figure 5.5 Subject trajectory at the PR-22 DTL exit for Scenario 4 in both configurations.

Subject drivers exposed to Scenario 5 of Configuration 2 had a better driving performance than those exposed to Configuration 1, since they made lane changes with anticipation. Additionally, Figure 5.6 shows that two participants of Configuration 1 changed into the BRT exit lane at the last moment. This suggests that both drivers had trouble when choosing the exit that they were supposed to use, thereby changing into the incorrect exit lane.

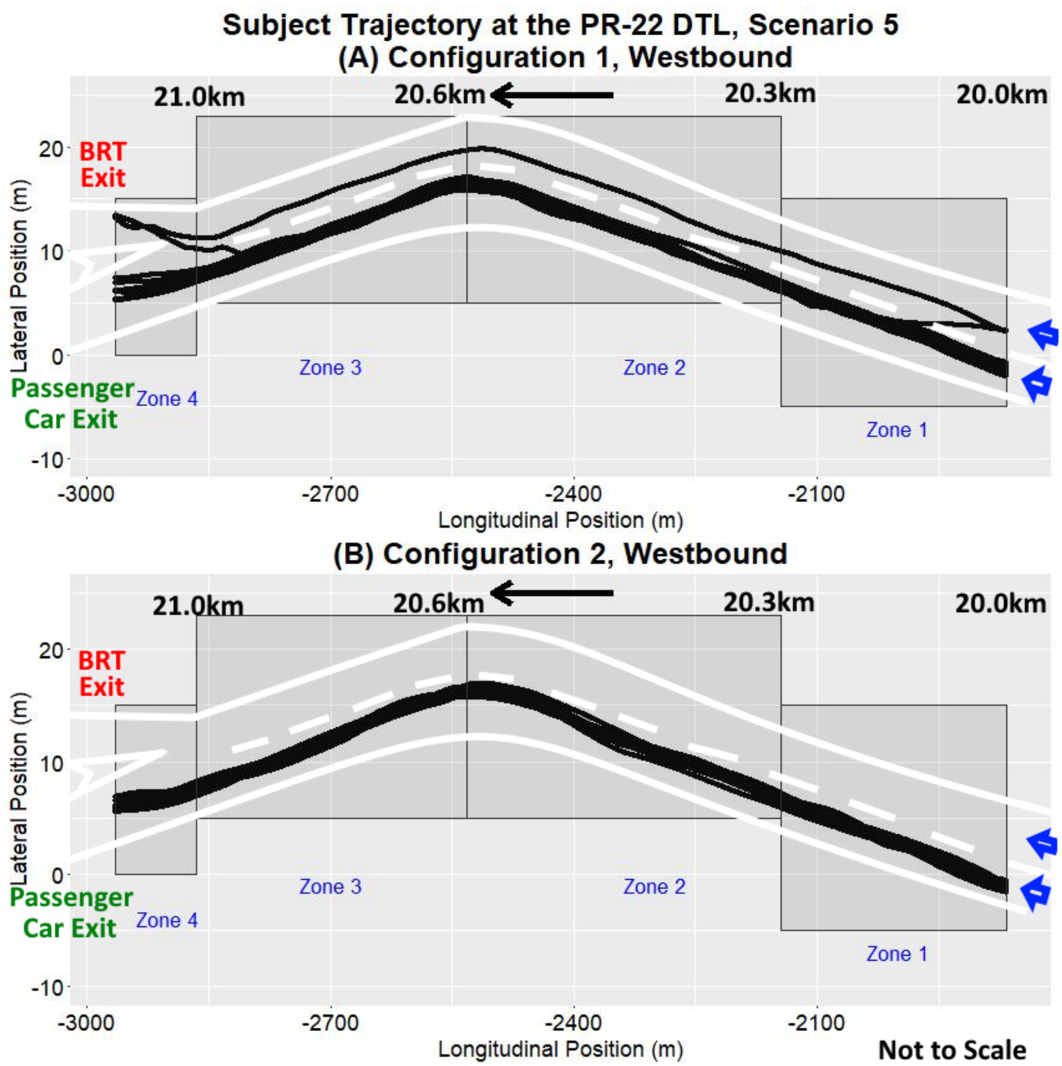


Figure 5.6 Subject trajectory at the PR-22 DTL exit for Scenario 5 in both Configurations.

Lastly, Figure 5.7 illustrates that participants exposed to Scenario 6 of Configuration 2 had a better driving performance than those exposed to Configuration 1. Although one participant managed to use the BRT exit lane incorrectly, there were several last-moment lane changes. This could result in safety issues since these participants performed sudden lane changes that could result in an unexpected brake of a driver that is approaching the DTL exit.

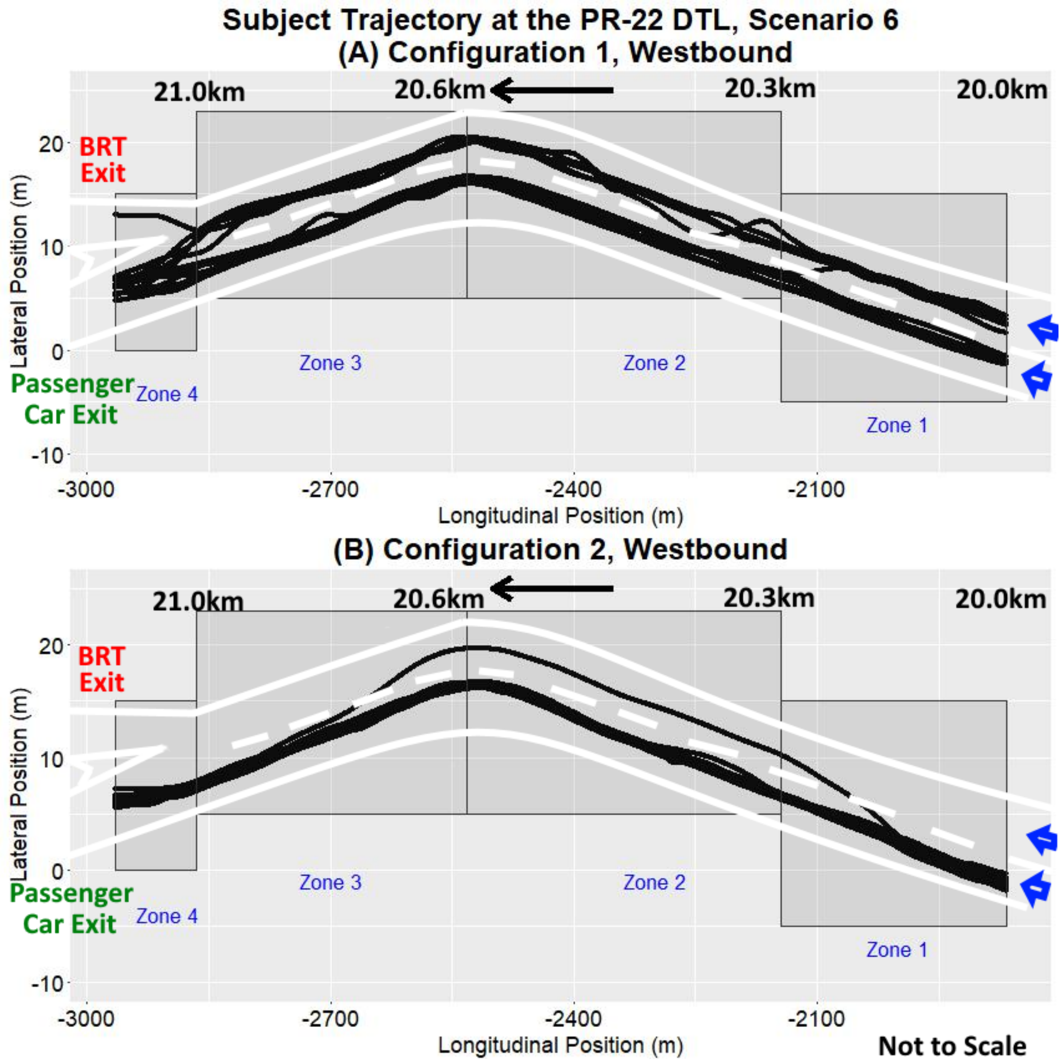


Figure 5.7 Subject trajectory at the PR-22 DTL exit for Scenario 6 in both configurations.

In summary, subject drivers exposed to Configuration 2 (proposed treatment using new signs and pavement markings) had a better driving performance when comparing participants' trajectory and lane movements for each scenario with Configuration 1 (existing conditions). Participants exposed to Configuration 1 tended to change lanes just before the divergence of the road, generating a dangerous situation, while participants of Configuration 2 changed lanes with much anticipation (before Zone 1). This indicates that the information provided in the signs and pavement markings gave the subjects enough information to complete the expected maneuvers correctly and with anticipation, eliminating the dangerous maneuver of changing lanes before the divergence of the road.

6 Conclusions

The following chapter includes major research findings and recommendations that could be implemented to improve the driving performance of PR-22 DTL users. In addition, research limitations are provided with the purpose of enhancing future studies that involve driving simulators. Lastly, other performance measures and statistical analyses are suggested for further research that could benefit driving simulator studies.

6.1 Major Findings

This research consisted of the evaluation of two configurations of PR-22 DTL: existing conditions (Configuration 1) and a proposed treatment using new signs and pavement markings (Configuration 2). A total of 24 subject drivers were exposed to six scenarios per configuration, where the vehicles' average lane position was analyzed and compared between configurations. Additionally, drivers' lane choice (DTL exit or the incorrect BRT exit lane) was compared, as well as the moment in which drivers performed lane changes (last-moment maneuvers or with anticipation). Based on the hypothesis tested in this research study and the integrated analysis of the six scenarios in the two different configurations, the following concluding remarks are presented.

- Results from the online survey showed that 65% of participants misunderstood the significance of the HOV diamond-shaped symbol. Similarly, 75% of participants of the driving simulator study did not know or misunderstood the meaning of this symbol.
- Participants in the online survey and driving simulator study correctly understood the meaning of the bus and "no vehicles allowed" symbols.
- Based on the results of the driving simulator study, it can be inferred that Configuration 2 (proposed treatment) improved subject drivers' decision making as well as driving maneuvers before the PR-22 DTL exit as compared to Configuration 1 (existing signage configuration).
- Statistically significant differences were observed between the evaluated configurations for the performance measure ALP inside the simulated PR-22 DTL.
- Subject drivers exposed to Configuration 2 used the DTL exit lane correctly, while 37.5% and 12.5% of participants of Configuration 1 wrongly used the BRT exit lane in the EB and WB direction.

The use of uniform signage configurations and the addition of in-lane pavement markings using the words BUS ONLY for the BRT exit lane and the PR-22 route shield in the DTL exit (proposed treatment in Configuration 2) improved drivers' decision-making processes. Safety improvements were achieved since a reduction in lane maneuvers, last-moment lane changes, and the incorrect use of the BRT exit lane was observed when drivers were exposed to scenarios of the proposed treatment for PR-22 DTL. Therefore, it is important to maintain uniformity in the installation of signs and other TCDs, especially when operating complex managed facilities that have multiple lanes and operational strategies (e.g., PR-22 DTL).

6.2 Recommendations and Future Research

Although the results of the driving simulator study show improvements in driving performance, there are several research limitations when performing studies with driving simulators. For instance, the total number of participants can be increased, from 24, to provide more data and an enriched statistical analysis. In addition, simulation fidelity is difficult to measure since each participant perceives the reality of the simulation differently. For example, 8.3% of participants mentioned that simulator acceleration and brake pedals felt different from a real vehicle, while 12.5% of participants indicated the sensation of driving speed was different than that shown by the simulator speedometer. Therefore, driving simulator equipment should be evaluated to determine if its components could be adjusted or upgraded to simulate a more realistic driving system.

In terms of the driving simulator study, further research should include the evaluation of variables such as average speed, standard deviation of roadway position, and acceleration noise, in order to perform an integrated analysis that supports the performance measurement ALP. In addition, the age of participants could be considered as a blocking factor that can influence driving performance in driving simulators. Furthermore, a different statistical analysis (e.g., multi-factor ANOVA, regression models) could be developed to understand the relation between the independent variables and their interactions.

Acknowledgments

The authors would like to express their gratitude to the University Transportation Centers (UTC) Program for providing funding the SAFER-SIM program that supported this research project.

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Appendices

A. Sponsorship

B. Consent Informed Form of Driving Simulator

C. Online Survey

A. SAFER-SIM Research Team

This research project is administered under the Office of the Assistant Secretary for Research and Technology (OST-R), which forms part of the Office of the Secretary of Transportation (OST). Since 2014, the OST-R acquired all programs, statistics and researches, including the Safety Research using Simulation (SAFER-SIM) University Transportation Center, that were managed by the Research and Innovative Technology Administration (RITA). This program integrates several educational institutions that focus in transportation with the objective of promoting and addressing transportation safety issues in the United States of America. The educational institutions comprise the SAFER-SIM program are: University of Iowa, University of Central Florida, University of Massachusetts, University of Wisconsin and University of Puerto Rico at Mayagüez.

University of Iowa – Iowa City, IA (UI)

The University of Iowa, located in Iowa City, is one of the major educational institutions that has over 30,000 students within 11 college campuses. This university was founded in 1847 and provides education at both undergraduate and graduate level for Engineering, Medicine, Pharmacy, Public Health, and Liberal Arts. Furthermore, the UI has a transportation research center named as the National Advanced Driving Simulator (NADS). This research facility specializes in transportation safety that involves human factors, driver impairment and distraction, simulation, and data collection technologies among other things. NADS research equipment's are mostly composed of an instrumented vehicle and three driving simulators, including a full size vehicle inside a dome that provides motion and projects visuals at 360 degrees.

University of Central Florida – Orlando, FL (UCF)

The University of Central Florida was founded in Orlando in year 1963. This college institution has more than 60,000 students and over 200 bachelor and graduate programs. UCF has a research facility known as Center for Advanced Transportation Systems Simulation (CATSS) that dedicates to investigations related with transportation safety and human factors. This research center has an Intelligence Transportation System (ITS) Laboratory in which a MiniSim driving simulator is available for virtual scenario development and data collection.

University of Massachusetts – Amherst, MA (UMass)

The University of Massachusetts Amherst was founded in the year 1863. UMass Amherst is one of the top public research universities with a total student population of 28,000. This college institution established the Arbella Insurance Human Performance Laboratory (HPL) in year 1980. The HPL is a research center that dedicates to driving behavior and safety by performing transportation related studies such as novice and older drivers, effects of Traffic Control Devices (TCD's), improved vehicle technologies and other ITS. This laboratory has a desktop simulator, a full-sized vehicle driving simulator, eye tracker device and other research equipment available for transportation safety studies.

University of Wisconsin – Madison, WI (UW)

The University of Wisconsin was founded in year 1848 and has more than 43,000 total students enrolled under different undergraduate and graduate programs. This college institution has a Cognitive Systems Laboratory (CSL) established in the Department of Industrial and Systems Engineering that focuses in understanding and improving technology systems that are related to human factors and driving behavior. Researchers of the CSL perform experiments in real and simulated environments using video analytics to analyze naturalistic driving data and a full-sized vehicle with motion based that has the simulation projected in a 240 degree arc screen.

University of Puerto Rico – Mayagüez, PR (UPRM)

The University of Puerto Rico at Mayagüez was founded in year 1911 and is one of the major bilingual institutions in the island. This minority college institution has over 13,000 undergraduate and graduate students under different departmental programs, including Agriculture, Arts, Science, Business Administration, Engineering, and other professional studies. UPRM has a Transportation Engineering Laboratory established in the Department of Civil Engineering and Surveying that dedicates to the understanding of traffic operations, road safety, human factors, and other transportation related issues. One of the recent investigation equipment used for studying driving behavior and transportation safety issues is the custom made RealTime Technology Incorporation (RTI) driving simulator, which includes the basic components of a vehicle, screens, projects, and computer software.

B. Informed Consent Form for Driving Simulator

Comité para la Protección de los Seres Humanos en la Investigación
CPSHI/IRB 00002053
Universidad de Puerto Rico – Recinto Universitario de Mayagüez
Decanato de Asuntos Académicos
Call Box 9000
Mayagüez, PR 00681-9000

8 de febrero de 2017

Bryan Ruiz Cruz
Ingeniería Civil y Agrimensura
RUM

Estimado estudiante:

El Comité para la Protección de los Seres Humanos en la Investigación (CPSHI) ha considerado su Solicitud de Revisión y demás documentos sometidos para el estudio titulado ***Use of driving simulator for the operational and safety evaluation of signage and pavement markings:a case study of PR-22 dynamic toll lane*** *(#Protocolo 20170112).*

Su proyecto cualifica para un proceso expedito de aprobación bajo la categoría 7 del 45 CFR 46.110. Luego de evaluarlo, el comité determinó que este estudio no supera el nivel mínimo de riesgo y cumple con todos los requisitos de protección de seres humanos según definidos por la reglamentación federal 45 CFR 46. Igualmente, luego de evaluar su solicitud de dispensa de los requisitos del consentimiento informado se le aprueban las siguientes dispensas:

- Dispensa de hoja de consentimiento de adulto para investigación con menores

Por tanto, aprobamos su investigación con las anteriores dispensas. La aprobación tiene vigencia de un año a partir de hoy; esto es, desde el 8 de febrero de 2017 hasta el 7 de febrero de 2018. Le recordamos que la aprobación emitida por nuestro comité no lo exime de cumplir con cualquier otro requisito institucional o gubernamental relacionado al tema o fuente de financiamiento de su proyecto.

La reglamentación federal exige que nuestro comité supervise toda investigación mientras continúe activa. Se consideran activos aquellos proyectos que aún estén reclutando participantes o haya terminado el reclutamiento pero aún se estén recopilando o analizando datos. Si vislumbra que su proyecto seguirá activo al momento de vencerse la fecha de aprobación, le pedimos que someta una solicitud de extensión a más tardar un mes antes del vencimiento de su vigencia.

Le adjuntamos la hoja de consentimiento y hoja de reclutamiento con el sello de aprobación del Comité. Le agradeceremos utilice estos documentos para los trámites correspondientes de su investigación. Le recordamos que debe entregarle una copia de la hoja de consentimiento informado a todos/as los/as participantes que acepten ser parte de su estudio.

Cualquier cambio al protocolo o a la metodología deberá ser revisado y aprobado por el CPSHI antes de su implantación, excepto en casos en que el cambio sea necesario para eliminar algún riesgo inmediato para los/as participantes. El CPSHI deberá ser notificado de dichos cambios tan pronto le sea posible al/a la investigador/a. El CPSHI deberá ser informado de inmediato de cualquier efecto adverso o problema inesperado que surgiera con relación al riesgo de los seres humanos, de cualquier queja sobre esta investigación y de cualquier violación a la confidencialidad de los participantes.

Cordialmente,

Dr. Rafael A. Boglio Martínez
Presidente
CPSHI/IRB

Teléfono: (787) 832 - 4040 x 6277, 3807, 3808 – **Fax:** (787) 831-2085 – **Página Web:** www.uprm.edu/cpshi
Email: cpshi@uprm.edu

CPSHI / IRB - RUM
No. 00002053
8 feb 17 / 7 feb 18
APROBADO

ESTUDIO DE SIMULACION DE PLAZA DE PEAJE

FORMULARIO DE CONSENTIMIENTO INFORMADO

Investigador Principal: Bryan Ruiz Cruz

Patrocinador: Centro de Investigación en Transporte (UTC) SaferSim (Safety Research Using Simulation)

Título de Proyecto: USE OF DRIVING SIMULATOR FOR THE OPERATIONAL AND SAFETY EVALUATION OF SIGNAGE AND PAVEMENT MARKINGS: A CASE STUDY OF PR-22 DYNAMIC TOLL LANE

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 comportamiento del conductor utilizando diversos escenarios y configuraciones que representan el "Dynamic Toll Lane" (DTL, por sus siglas en inglés) localizado en la PR-22.

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 60 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 seguir los límites de velocidad y las reglas estándares de la carretera y tener un cuidado razonable cuando utilice los frenos. Por favor guíe en la forma que usted lo hace típicamente.

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 manejará 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 PARTICIPACION?

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 nauseas o nausea real. El experimento ha sido trabajado para minimizar el riesgo. Se recomienda que usted no participe en este experimento si ha tenido cinetosis (mareos) anteriormente mientras viaja o maneja un vehículo real.

Si durante el trayecto de la simulación, usted siente molestia o nauseas, debería 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 guie a su hogar o a buscar atención medica si es necesario.

Beneficios de participar en este estudio incluyen aprender potencialmente como ser un conductor más precavido/seguro y familiarizarse con carriles de peaje dinámicos en la mediana de una autopista.

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 de esta investigación también serán publicados en la tesis de maestría del investigador principal, Bryan Ruiz Cruz. 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 confidencialidad de los archivos, los investigadores utilizarán códigos para identificar a cada sujeto, en vez de nombres, para todos los datos recolectados mediante cuestionarios y los datos recolectados durante su utilización del simulador. Los datos serán asegurados en el Laboratorio de Transportación de la UPR Mayagüez y solo serán accesibles 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 de 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 ALGUN TIPO DE COMPENSACION 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 alguna lesión relacionada a la investigación como resultado del estudio, puede llamar al investigador, Bryan Ruiz Cruz, al (787) 366-6349 o via correo electrónico a bryan.ruiz@upr.edu o el Dr. Didier Valdés, al (787) 832-4040 ext. 2179 o didier.valdes@upr.edu. Si, durante el estudio o después de el, 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 provista 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 si tiene algún riesgo o incomodidad.

13. DECLARACIÓN DE CONSENTIMIENTO VOLUNTARIO DEL SUJETO

Al firmar abajo, yo, el participante, confirmo 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 puedo 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, indico 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

CPSHI / IRB - RUM
No. 00002053
8/feb/17 , 7feb 18
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UNIVERSIDAD DE PUERTO RICO
RECINTO UNIVERSITARIO DE MAYAGUEZ
DEPARTAMENTO DE INGENIERIA CIVIL Y AGRIMENSURA

¡Reciba un cordial saludo!

Estamos reclutando personas para participar de un estudio de simulación, donde tendrá la oportunidad de utilizar el simulador de conducción de la UPRM. La participación, el cual es de forma voluntaria, tiene como propósito evaluar el comportamiento del conducto al conducir diversos escenarios que representan un segmento de carretera localizado en la PR-22. Para poder participar del estudio debe cumplir con los siguientes requisitos:

Requisitos para participar del estudio

- Edad: mayor de 18 años
- Licencia de conducir vigente con al menos 18 meses de experiencia conduciendo
- No padecer de alguna condición visual que pueda afectar su desempeño como conductor
- No padecer de vértigo y/o epilepsia

Información adicional

- Fecha: 1 de febrero al 1 de marzo de 2017
    - Horario: lunes a viernes 8:00 am a 5:00 pm
    - Tiempo de duración aproximada: 1 hora
- Lugar: Laboratorio de Transportación (CI 102-F) del Departamento de Ingeniería Civil y Agrimensura

De estar interesado en participar en el estudio, favor de llenar la información y que se encuentra en el siguiente enlace:

https://goo.gl/forms/mKrFtz4Srd9KsYfD3

De tener algún comentario, duda o pregunta referente al estudio, puede comunicarse con el estudiante graduado Bryan Ruiz Cruz al correo electrónico **bryan.ruiz@upr.edu** o por teléfono al **(787) 366-6349**.

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Cordialmente,

Bryan Ruiz Cruz

Estudiante Graduado del Departamento de Ingeniería Civil y Agrimensura

C. Online Survey

Estudio Sobre el Carril Expreso de la Autopista PR-22

Consentimiento Informado

Su ayuda es bien importante para poder realizar mi tesis de maestría. Por esta razón agradezco su colaboración en esta encuesta, el cual es parte de mi investigación de tesis en la Universidad de Puerto Rico Recinto Universitario de Mayagüez (RUM). El propósito de esta encuesta es evaluar la percepción de varias alternativas de rotulación y marcado en el pavimento para determinar qué conjunto de rotulación lleva un mensaje claro al conductor.

Para participar en esta encuesta debe tener al menos 18 años de edad y una licencia de conducir vigente. Su participación es de manera voluntaria, donde podrá terminar de participar en el momento que considere necesario. La información recopilada es totalmente confidencial. El tiempo de duración de esta encuesta es de aproximadamente 10 minutos.

De tener algún comentario o pregunta acerca del estudio se puede comunicar con Bryan Ruiz Cruz, estudiante graduado del Departamento de Ingeniería Civil y Agrimensura del RUM, mediante el correo electrónico bryan.ruiz@upr.edu.

Favor de indicar si acepta participar en esta encuesta.

a) Sí
b) No

Sección 3: Conceptos de Carriles Exclusivos

1. **¿Qué significa para usted el siguiente símbolo cuando aparece en un letrero del carril exclusivo?**

a) Carril para vehículos oficiales (e.g. vehículos de emergencia, policías, bomberos, etc.)
b) Carril de autobuses
c) Carril para vehículos de alta ocupación de pasajeros (e.g. carpooling)
d) Carril para cualquier automóvil
e) Carril para vehículos de alta ocupación de pasajeros y autobuses
f) Otro: ___________________________

Sección 1: Datos Demográficos

1. **Sexo:**
   a) Hombre
   b) Mujer
   c) Prefiero no contestar

2. **Edad: ____**

Sección 2: Historial de Conducir

1. **Edad en la cuál obtuvo su licencia de conducir: ________**

2. **¿Conoce el carril expreso (donde el usuario realiza un pago por utilizarlo) localizado en la autopista PR-22 entre Toa Baja y Bayamón?**
   a) Sí
   b) No

3. **¿En los pasados seis (6) meses, ha conducido por el carril expreso de la autopista PR-22?**
   a) 5 o mas veces a la semana
   b) 2 o 3 veces a la semana
   c) 2 o 3 veces al mes
   d) No he utilizado el carril expreso

2. **¿Qué significa para usted el siguiente símbolo cuando aparece en un letrero del carril exclusivo?**

a) Carril para vehículos oficiales (e.g. vehículos de emergencia, policías, bomberos, etc.)
b) Carril de autobuses
c) Carril para vehículos de alta ocupación de pasajeros (e.g. carpooling)
d) Carril para cualquier automóvil
e) Carril para vehículos de alta ocupación de pasajeros y autobuses
f) Otro: ______________________________

3. **¿Qué significa para usted el siguiente símbolo cuando aparece en un letrero del carril exclusivo?**

a) Prohibido el acceso a automóviles
b) Prohibido el acceso a autobuses
c) Prohibido el acceso a vehículos de alta ocupación (e.g. carpooling)
d) Prohibido el acceso a vehículos oficiales (e.g. vehículos de emergencia, policías, bomberos, etc.)
e) Otro: ______________________________

<u>Sección 4: Señalizaciones</u>

1. ¿Cuál de las siguientes señalizaciones es mas clara para indicar la salida del carril expreso hacia la autopista PR-22?

a)

b)

c)

d)

e)

2. ¿ Cual de las siguientes señalizaciones es mas clara para indicar que la salida del carril exclusivo es solamente para autobuses y no para otro tipo de vehículo?

a)

b)

c)

d)

e)

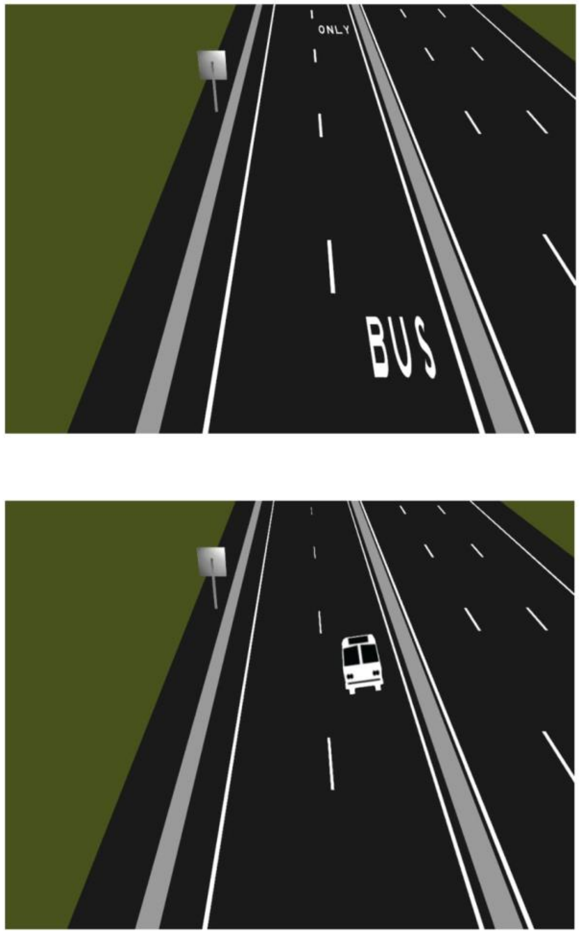
Sección 5: Marcados en el Pavimento

1. **¿Cuál de las siguientes alternativas de marcado en el pavimento usted prefiere para reforzar las rotulaciones del carril expreso?**

a) Símbolos
b) Palabras
c) Símbolos y Palabras
d) Entiendo que no es necesario añadir algún marcado en el pavimento para reforzar el mensaje de los rótulos.

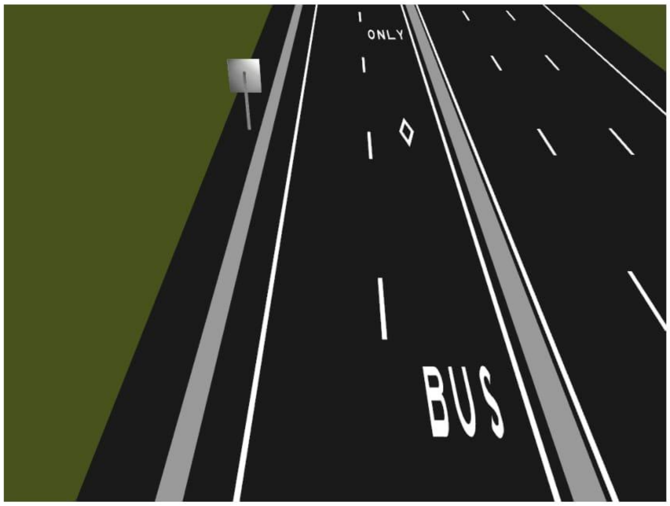
2. **¿Cuál de las siguientes alternativas complementan mejor las señalizaciones?**

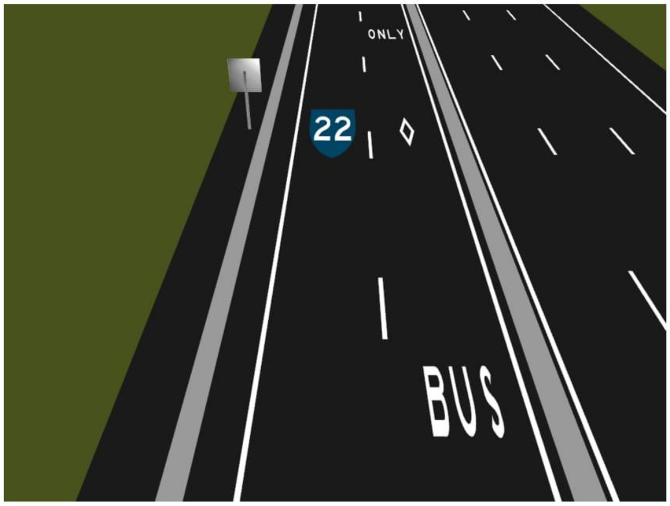
a) El uso de las palabras BUS ONLY, el cuál es representativo para autobuses para la salida del carril exclusivo.
b) El uso del símbolo del autobús para la salida del carril exclusivo.
c) El uso de las palabras BUS ONLY en combinación con el símbolo diamante, el cuál es representativo para autobuses en la salida del carril exclusivo.
d) El uso del número y símbolo representativo de la autopista PR-22, en combinación con la alternativa (c).
e) El uso del símbolo de prohibido vehículos en el carril exclusivo para autobuses.
f) Otro: ______________________________

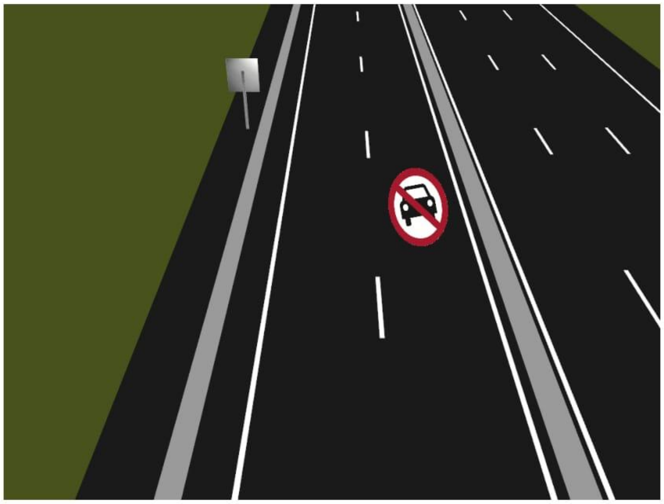


a)

b)

c) 

d) 

e) 

¡Gracias por Participar!

De tener algún comentario o pregunta acerca del estudio se puede comunicar con Bryan Ruiz Cruz, estudiante graduado del Departamento de Ingeniería Civil y Agrimensura del RUM, mediante el correo electrónico bryan.ruiz@upr.edu.