Phase II: Operational and Safety-Based Analyses of Varied Toll Lane Configurations

SAFETY RESEARCH USING SIMULATION

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A Report on Research Sponsored by SAFER-SIM

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
BRT	Bus Rapid Transit
CATTS	Center of Advanced Transportation Systems Simulations
CBD	Central Business District
CSL	Cognitive Systems Laboratory
DOT	Department of Transportation
DTL	Dynamic Toll Lane
EB	Eastbound
ETC	Electronic Toll Collection
FHWA	Federal Highway Administration
HCM	Highway Capacity Manual
HSM	Highway Safety Manual
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
ITS	Intelligent Transportation Systems
LLC	Limited Liability Company
LOS	Level of Service
LW	Lane Width

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
PSL	Posted Speed Limit
RDG	Road Design Guide
RITA	Research and Innovative Technology Administration
RLS	Reversible Lane System
RTI	RealTime Technology Incorporation
SAFER-SIM	Safety Research Using Simulation
SDRP	Standard Deviation of Roadway Position
TCD	Traffic Control Devices
ToD	Time of Day
UPRM	University of Puerto Rico at Mayagüez
UTC	University Transportation Center
VMS	Variable Messages Signs
VPD	Vehicles Per Day
WB	Westbound

SPONSORSHIP

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 research, 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 on transportation with the objective of promoting and addressing transportation safety issues in the United States of America. The educational institutions comprising 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 a major educational institution that has over 30,000 students within 11 college campuses. This university was founded in 1847 and provides education at both undergraduate and graduate levels for Engineering, Medicine, Pharmacy, Public Health, and Liberal Arts. Furthermore, the UI has a transportation research center named 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 is 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 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 is dedicated to investigations related to 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 1980. The HPL is a research center that is dedicated to driving behavior and safety by performing transportation-related studies such as novice and older drivers, effects of Traffic Control Devices (TCDs), improved vehicle technologies and other ITS. This laboratory has a desktop simulator, a full-sized vehicle driving simulator, an 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 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 on 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 a motion base that has the simulation projected on a 240 degree arc screen.

University of Puerto Rico – Mayagüez, PR (UPRM)

The University of Puerto Rico at Mayagüez was founded in 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 is dedicated 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 RTI driving simulator, which includes the basic components of a vehicle, screens, projects, and computer software.

ABSTRACT

A transportation issue that has affected metropolitan regions around the world is traffic congestion. Due to the increase in traffic congestion, many transportation agencies are focusing on the development of new technologies that address this issue. One of the technologies used to mitigate the effect of traffic congestion and improve the level of service in transportation facilities is a managed lanes system. This system utilizes different lane management strategies and techniques to improve roadway efficiency, capacity and other characteristics.

The Puerto Rico Dynamic Toll Lane (DTL) is a 6.44 mi (10.4 km) reversible facility within a stretch of freeway PR-22 that operates a congestion pricing system; the first of its kind in the Commonwealth of Puerto Rico. This managed lane system is shared by private vehicles and the Bus Rapid Transit (BRT) system and is located at the median of PR-22, between the freeway lanes. However, the DTL has conflict/decision points at the entrance, as well as in the diverging lanes before the bridge piers segment, during the bridge segment and after the bridge separation, and in the exits of the DTL, for both eastbound and westbound directions. This has generated safety concerns for administrators and road users as well.

This research project presents the study of the PR-22 DTL using the UPRM driving simulator, which is located in the Transportation Laboratory of the University of Puerto Rico at Mayaguez (UPRM). The main goal of this research was to evaluate the DTL facility's safety and driver behavior on this system. In order to complete this goal, a Full Factorial Design of 3^3 was used. Three factors of interest were selected at three levels, where each level represented a treatment, namely, lane width (i.e. 12, 11 and 10 feet), posted speed limit (i.e. 65, 55 and 45 mph), and time of day (i.e. morning, evening, and night). A total of 27 scenarios were developed for this designed experiment that used a block design to replicate the base scenarios between three representative groups. To evaluate the performance of subject drivers and the road safety

associated with the DTL, three dependent variables were used as a surrogate measure, namely, average speed, acceleration noise and standard deviation of roadway position (SDRP). Moreover, these performance measures were evaluated in five zones of interest.

The results from the analysis of variance realized for this research project indicates that lane width variable had a statistical difference in all zones for average speed, whereas narrow lanes resulted in a reduction of average speed. Likewise, the time of day negatively affected the acceleration noise of drivers, increasing the variations of acceleration in Zones 2, 3, 4 and 5. As a result of this increment, a higher crash frequency inside the DTL can be expected. Furthermore, for the SDRP variable the result indicated that significant differences were found between the morning and night and morning and evening, before and after the bridge piers separation (Zone 2 and 4). Additionally, subject drivers used the incorrect DTL exit lane in approximately 26% of all simulated scenarios, with the 57% of them happening in the morning scenarios.

In conclusion, this research study provides the first-ever freeway safety evaluation of a managed lane system that combines reversible lane operations with a congestion pricing system in a highway facility that is shared by private vehicles and a Bus Rapid Transit (BRT) system.
The statistical analysis indicated that the optimum scenario for the average speed in PR-22 DTL is a posted speed limit of 55 mph with 11 ft lane width. However, further research is needed to provide feasible countermeasures that improve road safety and efficient operations of the reversible DTL in both the short and long term.

CHAPTER 1 INTRODUCTION

This chapter describes several safety issues that generated the need to study the Puerto Rico Dynamic Toll Lane. The identified safety problems included driver speed profiles higher than the posted speed limit and drivers passing through the exclusive lane of the "Metro Urbano" bus. Therefore, three hypotheses were analyzed using a driving simulator to understand how different lane widths and posted speed limits influence driving behavior in managed lanes during different times of day.

1.1 Background

Transportation issues that are related to traffic congestion are affecting metropolitan regions around the world. The increase of traffic not only affects vehicle mobility and the environment (e.g., noise and air pollution) but also influences negatively the economic development of a city. For this reason, different transportation agencies around the world are focused on the development of new technologies that can be used to address traffic congestion without the need for huge investments and major changes in the existing roadways.

One of the recent techniques that have been widely implemented in many roadways to counteract the effects caused by traffic congestion is the application of managed lanes. A managed lane can be defined as a facility that uses lane management strategies and techniques to improve roadway efficiency, capacity and any other objective established by the operating agency (Collier and Goodin, 2004). These management strategies consist of congestion pricing, vehicle eligibility (e.g., High Occupancy Vehicle (HOV) lanes or exclusive truck lanes), and access control (e.g., reversible lane operations) (Kuhn et al., 2005). Furthermore, the complexity of managed lanes increases when two or more of these strategies are combined. An example of a complex managed lane used to reduce traffic congestion is the reversible Dynamic Toll Lane (DTL) located in the metropolitan area of Puerto Rico. This multifaceted facility not only integrates congestion pricing technologies with reversible lane operations, but also shares the right-of-way with a Bus Rapid Transit (BRT) system.

However, there is no documented research related to freeway operations and its effects on road safety in a corridor segment where is implemented a managed lane that combines a reversible lane operation with congestion pricing and an exclusive BRT. This research project evaluates the effect of time of day, posted speed limit, and lane width on driver behavior in a reversible DTL that is shared with an exclusive bus lane. Driving simulation technology was employed as a research tool to address the impacts on drivers' operating speed and road safety throughout different virtual scenarios of the managed lane system implemented in the Commonwealth of Puerto Rico.

1.2 Puerto Rico Reversible Dynamic Toll Lane (DTL)

Traffic congestion is an increasing issue that concerns transportation agencies in the island. This is probably due to the fact that the metropolitan area of Puerto Rico ranks as the 22nd largest metropolitan area in the United States by population with approximately 2.3 million residents (Colucci, 2015). As result of traffic congestion issues, a Public Private Partnership (PPP) was created to design, build, and operate the first-ever reversible DTL system in Puerto Rico. The partnership, between the Puerto Rico Highway and Transportation Authority (PRHTA) and the *Autopistas Metropolitanas de Puerto Rico* (Metropistas) LLC, was created on June 27, 2011, for a 40 year period, to develop the DTL, which mitigates high volumes during morning and evening peak hours connecting the municipalities of Toa Baja and Bayamón, and also improve the PR-22 freeway safety. The traffic flow and Level of Service (LOS) inside the DTL is guaranteed by 22 cameras distributed throughout the 6.46 mi (10.4 km) roadway that adjusts in real-time, the price of the toll using congestion pricing techniques. As illustrated in Figure 1.1, this managed lane facility has two lanes, both 12 ft (3.65 m) wide, with a posted speed limit of 45 mph in eastbound direction toward Bayamón and 45 mph in westbound direction toward Toa Baja with a reduction to 40 mph in the exit.

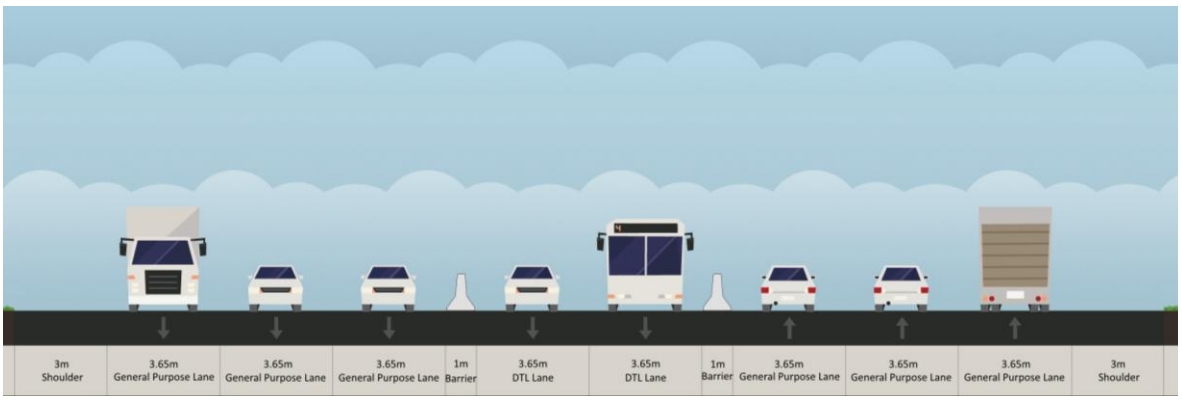

Figure 1.1 Cross-Section View of PR-22 with Lane Configurations and Widths

The DTL is located in the median of PR-22 (as illustrated in Figure 1.2), where a barrier system separates the exclusive lanes from general-purpose lanes. The PR-22 freeway is a principal corridor that provides mobility into the metropolitan area using three travel lanes per direction, which has an Annual Average Daily Traffic (AADT) of 110,923 vehicles per day (vpd) for the year 2007; meanwhile an AADT of 6,000 vpd was recorded inside the DTL for the year 2015. The DTL operates between three traffic schemes, namely during the AM peak EB, PM peak WB, and holidays and weekends. This managed lane system is shared between private vehicles and the Bus Rapid Transit (BRT), while heavy vehicles aren’t allowed to travel through this exclusive lane. This multifaceted managed lane facility is the first of its kind in Puerto Rico.

Figure 1.2 Reversible Dynamic Toll Lane System in PR-22

1.3 Problem Description

The Puerto Rico reversible Dynamic Toll Lane is a new and unique concept introduced to Puertorican drivers. Although this multifaceted managed lane system has decreased traffic congestion in freeway PR-22 and reduced vehicle emissions, several safety issues have arisen as a consequence of driver behavior. First, as illustrated in Figure 1.3, the posted speed limits inside the express lane (40 mph EB and 45 mph WB) are lower than the posted speed limit in PR-22 (55 mph). Lower posted speed limits could contribute to the fact that a vast majority of drivers that use the DTL have the tendency to travel at higher operating speeds inside the managed lane. In addition, it could affect drivers' decision on whether to use the DTL during off-peak periods and pay a higher toll when they would be forced to drive at a lower operating speed than those motorists who stayed in freeway PR-22.

(a)

(b)

Figure 1.3 Posted Speed Limits in PR-22
(a) PR-22 Mainline
(b) PR-22 DTL

Second, driving confusion occurs at divergent segments such as prior bridge separations (Figure 1.4) and the DTL exit, where drivers have high variations in acceleration and operating speed that influence lane- changing movements and unexpected braking. Additionally, there is a considerable number of drivers that exits the DTL through the wrong gate by using the BRT exit lane. Therefore, the existing signage configuration may not meet the requirements established by the Manual Uniform Traffic Control Devices (MUTCD), 2009 edition, which states that an effective traffic control device (TCD) should command attention, convey a clear simple meaning, and provide an adequate time for proper response (MUTCD, 2009).

Figure 1.4 PR-22 DTL Bridge Segment in WB Direction

These principles could be compromised since a considerable number of drivers uses the BRT exit as the DTL exit lane, where either motorists may be confusing the terms “express lane” with “exclusive lane” (Figure 1.5) or drivers are not understanding the message provided by the TCDs.

Figure 1.5 Overhead Signage at the DTL Exit for the EB Direction

Potentially hazardous situations are generated prior to bridge piers and each time a driver chooses the wrong exit and starts driving in reverse to get into the express lane exit. As illustrated in Figure 1.6, drivers that exit through the BRT lane must stop and maneuver in reverse until they can change into the exclusive lane exit or wait until the operating agency gives access to the vehicle and continue driving through the BRT lane. This issue not only influences the safety of all managed lane users but also decreases travel time, reliability, and other operational characteristics of the BRT system.

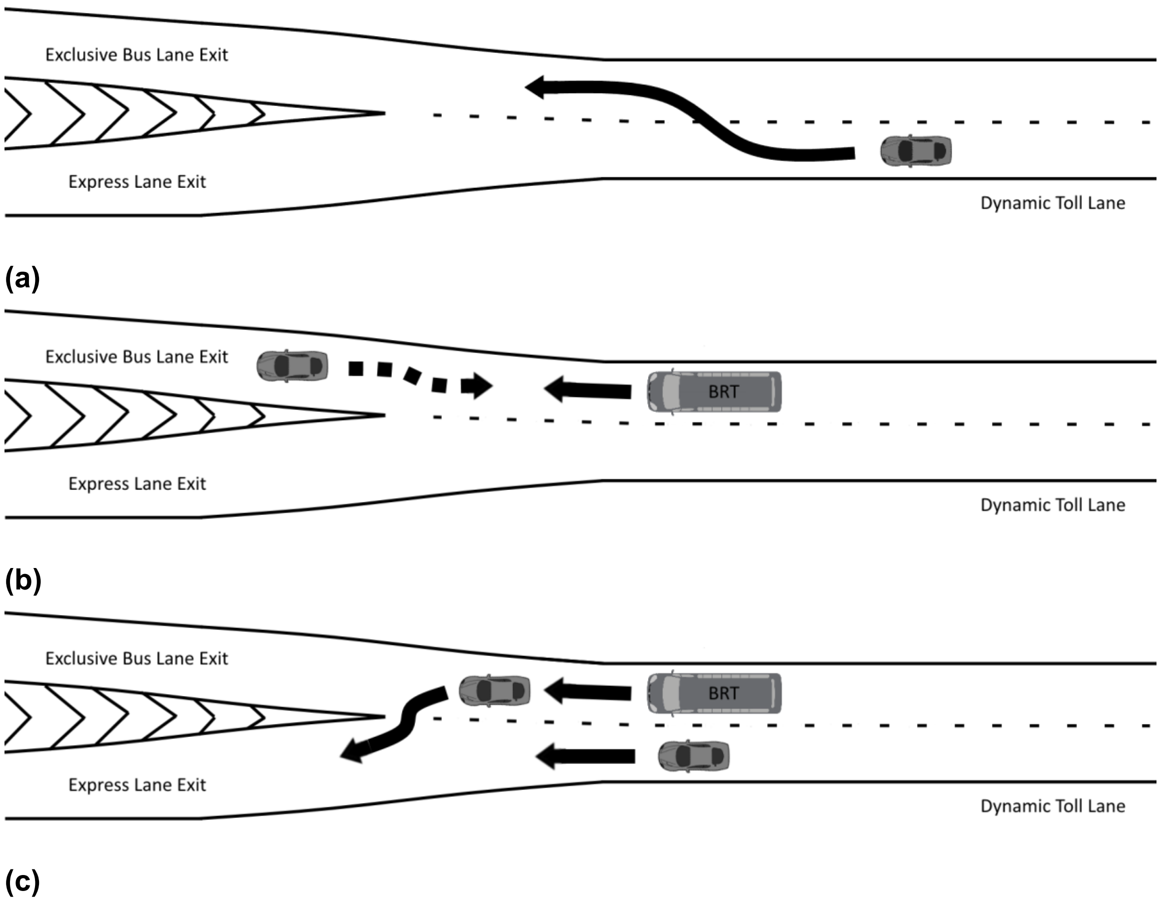

Figure 1.6 Driving Maneuvers when Exiting through the BRT Lane:
(a) Vehicle Exits through the Wrong Lane and Stops
(b) Vehicle Starts to Maneuver in Reverse
(c) Vehicle Changes into the Express Lane Exit

Lastly, concrete barriers and narrow shoulders could influence vehicle lateral position inside the DTL, where less experienced drivers may tend to drive closer to other vehicles located in the adjacent lane. Therefore, the Puerto Rico express lane facility has a great research potential for evaluating driving behavior and managed lane safety issues.

1.4 Hypotheses

The hypotheses established for this research project were in accordance with a full factorial 3^3 experimental design, in which 27 subject drivers drove through three different scenarios where the independent variables time of day, posted speed limit, and lane width were controlled. The three general hypotheses used in this research study are described below:

1. *The subject drivers in scenarios with narrow lanes will have lower speed limits and acceleration noise than those exposed to scenarios with wider lanes.*
2. *Subject drivers will tend to have higher speed profiles than the posted speed limit.*
3. *At the diverging segments (e.g., prior to the bridge and exits of the reversible lane) for both directions the subject driver will experience higher variability in the lane position than in the normal lanes.*

To substantiate the established hypotheses, three performance measures were selected to evaluate the driving behavior of subject participants, namely standard deviation of roadway position (SDRP), average speed, and acceleration noise.

1.5 Organization of Report

This report is composed of the following chapters. Chapter 2 summarizes the literature used to understand managed lanes operation and safety and driving simulators. Chapter 3 explains the methodology used to develop this investigation, including the description of the UPRM driving simulator, the development process of virtual scenarios, variables used as performance measurements for the evaluation of driving behavior, and definition of the locator references used to analyze the data. Chapter 4 describes the results of the integrated data analysis of this research project, for the independent and dependent variables established for the study, and the discusses the results. Chapter 5 provides conclusions, recommendations, and acknowledgements. Lastly, references and appendixes are included at the end of the report.

Chapter 2 LITERATURE REVIEW

This chapter consists of a review of published research studies that are related to managed lanes operation and safety, and the use of driving simulators as an efficient tool for transportation related studies. Managed lanes are a concept that has been implemented over the past 20 years to reduce traffic congestion. However, the design and operation of this system and its effects on road safety have not been widely studied since roadway design and signage configurations inside these types of facilities vary among operating agencies. Therefore, these topics were reviewed to understand how driving simulation equipment serves as a research tool to evaluate driving behavior and road safety inside the reversible DTL system that is located in the Commonwealth of Puerto Rico.

2.1 Managed Lanes

2.1.1 Overview

One of the major challenges that transportation agencies are constantly dealing with in many metropolitan and suburban regions is traffic congestion. This issue not only affects travel delay, the environment, and society but also influences the movement of freight vehicles inside metropolitan zones (Collier and Goodin, 2004). Common practices used to improve road capacity usually involve high construction costs and considerable changes of the roadway, which is generally a constraint among other transportation facilities or structures. Consequently, traffic operators are adapting a new concept, known as managed lanes, as a countermeasure to efficiently improve traffic operations in metropolitan areas where roadway expansion and construction costs are limited.

Managed lanes systems have been widely used over the past decades all around the world. Although the definition and design of managed lanes varies among transportation agencies, the term is generally defined as a highway facility where different operational strategies are implemented and managed in response to changing conditions (FHWA, 2008). In other words, this type of facility consists of any roadway lane that can be modified with the purpose of reducing traffic congestion while increasing freeway efficiency utilizing different operational strategies, such as congestion pricing, vehicle eligibility, and access control (Turnbull, 2003). Additionally, lane management strategies can be combined to form complex managed lanes such as HOT lanes, reversible HOV lanes, busways, and truck-only lanes, among others (Figure 2.1). Managed lanes applications provide several benefits such as additional travel options for drivers, enhancement of travel time reliability, improved freight movement, and the integration of transit systems (Neudorff et al., 2011). However, there are few published studies that address managed lane design and safety of all road users.

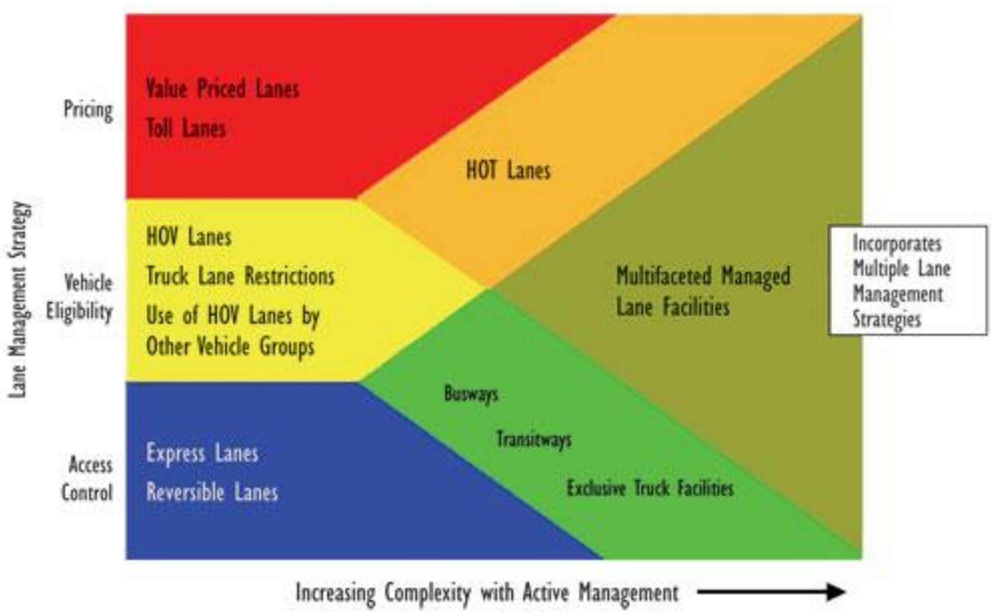

Figure 2.1 Managed Lane Applications (Reference: FHWA, 2008)

2.1.2 Congestion Pricing

A common managed lane application used in many highway facilities that are affected by vehicle congestion is lane pricing. This type of management strategy takes advantage of underutilized capacity (i.e., travel lane, median, shoulder, or other roadway component) in which pricing schemes vary according to the level of congestion (Collier and Gooding, 2004). A priced lanes facility provides more traveling options for those drivers that are willing to pay an amount of money during peak hours or drive in a roadway that has significantly less traffic than the main road during off-peak periods. Congestion pricing is generally divided into two categories: fixed pricing schemes, in which the price is set for a given period time and users adapt their behavior accordingly, and dynamic pricing schemes, in which the toll price is set in reaction to or in anticipation of roadway conditions (Verhoef et al., 1996; Yang and Huang, 2004; Dong et al., 2011). High-occupancy toll lanes and dynamic toll lanes are application examples of fixed and dynamic pricing schemes. The effectiveness of congestion pricing operations depends on a crucial element, the method in which drivers perform the transaction in order to use the managed lane facility. The payment process used in congestion pricing facilities is based on electronic toll collection (ETC) accounts, which are usually used in combination with open road tolling (ORT). ETC is an efficient intelligent transportation system (ITS) application that has several benefits (i.e., reducing transaction time, environmental effects, and fuel consumption) since vehicles are not required to stop at the toll station (Coelho et al., 2005; Venigalla and Krimmer, 2006). Similarly, ORT is high-speed ETC lanes in which road users perform the toll transaction in an electronic and instantaneous process without a significant reduction in the operating speed (Yang et al., 2012). Although there are has been an increase in studies related to congestion pricing, the majority of road pricing studies are focused on deriving toll prices to manage congestion with the goal of maintaining a good system-wide level of service (LOS) (Hearm and Ramana, 1998; De Palma and Lindsey, 2011).

2.2 Reversible Lane Systems

Another frequent operational strategy used in managed lanes is reversible lane systems (RLS). This management strategy is described by the Institute of Transportation Engineers (ITE) as one of the most efficient methods of improving road capacity during rush-hour periods (ITE, 1999). Reversible lane systems improve the overall capacity of a particular roadway by employing underutilized lanes or shoulders in the less-congested direction and reorienting traffic flow in the opposite direction for a given period time period (Wolshon and Lambert, 2006a). This type of managed lane is regularly utilized to increase directional capacity during peak-hour periods, planned events, and emergency events. However, RLS must be designed and operated with extreme caution because it could generate potential conflict points that affect road safety for all users (NCHRP, 2004).

2.3 Safety

Driving is a task that most people must execute to achieve their daily goals. Drivers should be able to perform different and sometimes simultaneous decisions that involve several skills. Drivers have the responsibility of processing a vast amount of data with a quick response time, where approximately 90% of the information is visually absorbed by the motorist (HCM, 2010). According to the Highway Safety Manual, the driving task is categorized into three main components, namely, control, guidance, and navigation (HSM, 2010). Control refers to the drivers' ability to maintain a proper travel speed and direction inside the lane. Guidance is associated with the driver's capability of understanding traffic control devices and performing safe maneuvers when near other vehicles. Navigation is related to the driver's ability in performing a safe origin-to-destination trip by observing and understanding every road element and guidance object.

Two important parameters that must be taken into consideration to design safer roadways are the perception-reaction time of drivers and the sight distance. The perception-reaction time, also known as perception-response time, refers to the time that is required for drivers to detect a situation, process the information, make a decision, and perform an action (HSM, 2010). Similarly, sight distance is the minimum length of roadway required for drivers to perceive and observe an object in the road and perform an action or maneuver to avoid a collision while traveling at the designed travel speed (Garber and Hoel, 2008).

The three factors that contribute to crashes are human factors, vehicles, and the roadway or environment (HSM, 2010). Driving errors, which are associated with human factors, are the most contributing factor and the main cause of over 90% of all crashes. Road safety and operational aspects are affected by driving behavior, which includes factors such as time of day, driver age and health, and the effects of alcohol and other drugs, among other things (HCM, 2010). Therefore, researchers have encountered the need to study how drivers behave under different conditions while exposed to different types of transportation facilities.

One of the transportation infrastructures that is being affected by crashes is freeways. According to the HCM, a freeway is defined as a divided highway facility that has two or more lanes per direction for exclusive use of a particular traffic (HCM, 2010). Generally, there are three types of freeway segments, namely, merging and diverging segments, weaving segments, and basic segments (Figure 2.2). A merge occurs when two or more traffic lanes converge into a single lane, whereas a diverge take place when a single traffic lane splits into two or more separate lanes. These types of freeway segments are associated with ramp junctions that give access onto or off the freeway mainline. According to AASHTO A Policy on Geometric Design of Highways and Streets (AASHTO Green

Book, 2011), ramps comprise all types of designs that connect two or more legs in an interchange, where its components are the terminal and the road that is being connected.

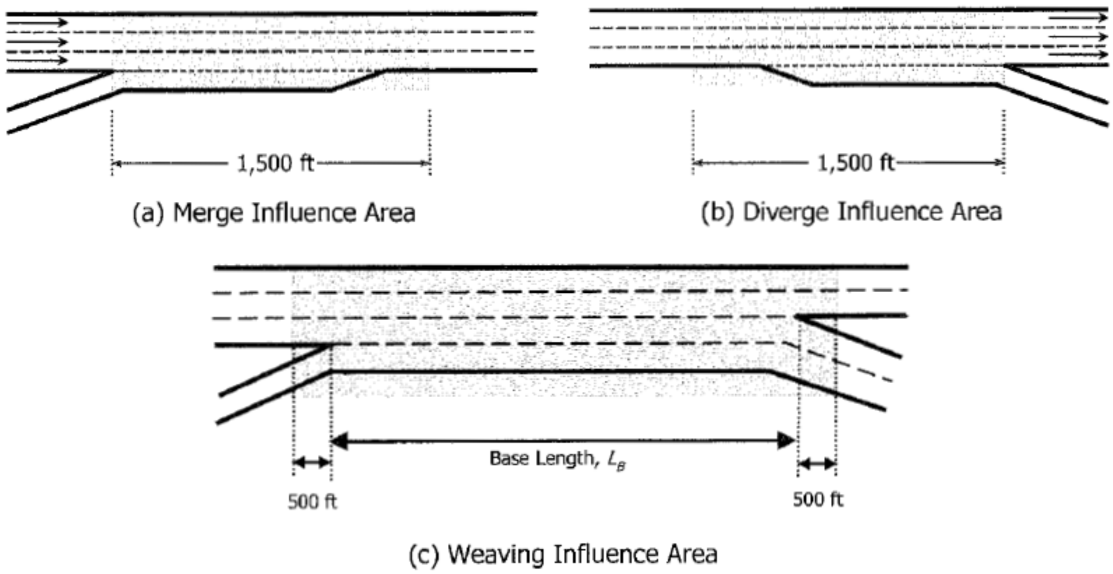

Figure 2.2 Influence Areas of Merge, Diverge, and Weaving Segments in Freeways (Reference: HCM, 2010)

Ramp terminals are defined as the area in the traveled way where traffic merges or diverges from the freeway mainline; this includes speed-change lanes, tapers, and islands. The design of exit ramp terminals, which includes the geometric layout of gores and TCDs (Figure 2.3), should provide a safe and understandable path for road users.

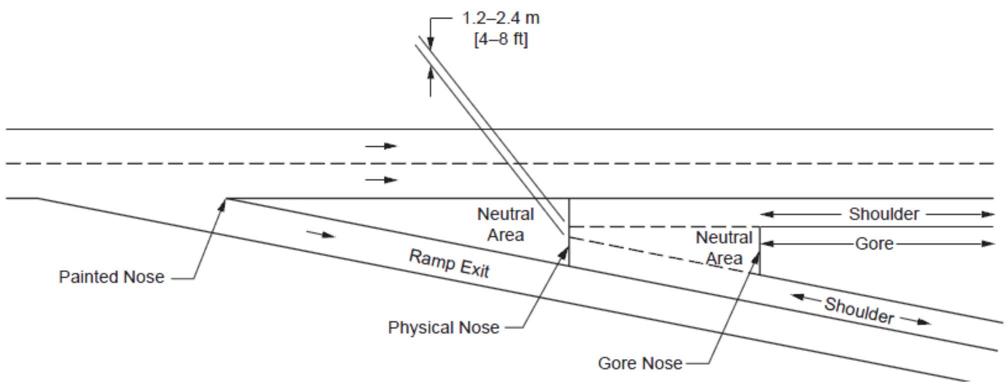

Figure 2.3 Characteristics of a Typical Exit Gore (Reference: HCM, 2010)

On the other hand, a weave occurs when there is a close gap between a merging and diverging segment or between two consecutive on-off ramps within the same traffic lane. In this case, drivers must perform complex movements in which vehicles entering the freeway mainline through an on-ramp (vehicles going from B to C in Figure 2.4) and have to cross the path of those drivers that are attempting to exit the freeway mainline throughout the off-ramp (vehicles going from A to D in Figure 2.4). Lastly, a basic freeway segment is described as a freeway segment in which no merging, diverging, or weaving movements take place.

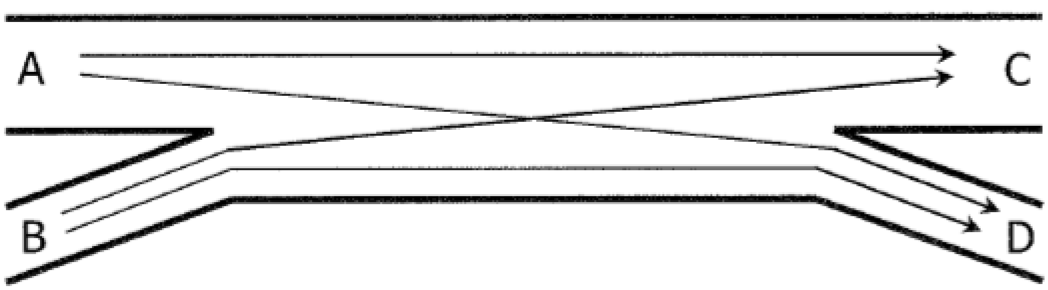

Figure 2.4 Weaving Movements Example in a Freeway Between an On-Ramp and Off-Ramp (Reference: HCM, 2010)

Merging, diverging, and weaving segments are areas that have high potential for crash frequency as a consequence of the conflict points generated. For this reason, freeway design must take into consideration several human factors considerations in order to maintain a safe transportation facility for all road users.

However, the lack of uniformity in managed lane systems, in terms of roadway design and safety features, could generate even more conflict points for drivers. Therefore, it is important to understand how different design elements could affect road safety in managed lanes and which treatments may be applied to improve safety for all road users.

One major aspect that could affect managed lanes safety is the vast variety of designs, including the combination of operational strategies, roadway geometry, signage configurations, and other TCDs. For example, RLS have safety issues that are associated with speed differential between the contraflow lane and the adjacent general-purpose lanes, opposing vehicle traveling at higher speeds when reinforced barrier systems are not available, and emergency services in segments where shoulder widths are limited due to roadway width constraints (Neudorff et al., 2011). According to Lathrop, conflict points in road segments that have contraflow operations may lead to a hazardous situation, particularly in decision-making zones where drivers have to perform an immediate maneuver (Lathrop, 1972). Although there are several conflict points, the reversible lane entrance and exit zones are considered the most hazardous as a consequence of merging, diverging, and weaving movements that occur and the number of travel lanes that are reversed. In order to improve road safety in managed lanes, it is essential to have a design and operation that takes into consideration all possible hazardous situations for both travel directions. Furthermore, the installation of appropriate traffic control devices such as crash cushions, delineators, and other TCDs can improve road safety and reduce the frequency of crashes associated with RLS (Wolshon and Lambert, 2006b). In addition to efficient TCDs, road barrier systems serve as a reliable countermeasure to separate managed lanes facilities from general-purpose lanes. Cothron et al. (2004) concluded that barrier systems used to divide managed lanes from general-purpose lanes in freeway corridors did not have a significant effect on injury crash rates, whereas managed lane facilities that were not physically separated generated an increase in injury crash rates inside and outside the freeway corridor.

Signage configurations inside managed lane facilities should comply with the MUTCD by providing a clear and simple message at an appropriate distance where drivers have adequate time to understand its meaning for a proper response. Signage design and configuration is essential for managed lane facilities, especially when several operational strategies are combined. Each road sign should be located at a longer distance than the minimum decision sight distance established by AASHTO Green Book. Despite the fact that several transportation agencies have indicated that managed lanes improve road safety when appropriate planning and design are implemented with pertinent TCDs (NCHRP, 2004; Neudorff et al., 2011), none of the existing literature studies safety aspects of a managed lane that operates reversible lanes in combination with congestion pricing and BRT express lanes. Although many of the existing managed facilities are separated from general-purpose lanes by TCDs, there are few research studies related to the driving behavior and safety of all road users.

2.4 Speed and Lane Width

In terms of roadway design, lane width and posted speed limit are essential elements of managed lanes design that could greatly influence the safety of drivers inside and outside the facility. Even though there is no published literature regarding the effects of lane widths and posted speed limits inside managed lanes, there are other investigations that have addressed this issue in other types of facilities. Rosey et al. used a driving simulator to investigate the effect of lane width on drivers' operating speed and the lateral position of the vehicle on rural roads (Rosey et al., 2009). They stated that narrow lanes affected drivers' lateral position. Still, it had no significant effect on drivers' speed even though subjects drove at higher speeds than they usually operate in real-life conditions. Likewise, vehicle speed may be influenced by different geometric components of the roadway since narrower lanes and shoulder widths increase the discomfort of drivers (Stamatiadis et al., 2010). Although transportation officials have tried to influence drivers' speed by reducing posted speed limits, a considerable amount of drivers do not notice or ignore the posted speed limit (Fitzpatrick et al., 2000; Stamatiadis et al., 2007). Visual indicators as well as posted speed limits are essential to force drivers to travel at lower speeds (Stamatiadis et al., 2007). Still, there is no published study that addresses the relation of lane width and posted speed limit on drivers' operating speed inside managed lane facilities. This creates a big opportunity, to investigate, utilizing driving simulation technology, the effects of lane width variations and different posted speed limits in managed lanes.

2.4.1 Summary

In conclusion, managed lane systems are efficient and relatively economical operational strategies that can be implemented in urban and suburban regions that have severe traffic congestion. Although these facilities have different configurations according to the operating agency's goals and objectives, they provide similar benefits for all road users as well as societal and environmental aspects. For this reason, further research is needed in order to generate a unified guideline or manual for transportation officials to use in those regions where managed lanes have potential for improving traffic operations.

2.5 Driving Simulators

One of the research technologies that has been of great benefit for many transportation-related studies is driving simulators. Simulation can be used to explore the field of human factors, road safety, and other matters under different circumstances without exposing subject drivers to any physical damage. In addition, this efficient research tool provides the opportunity to investigate existing or proposed conditions in a roadway, whereas traditional investigations are based on before and after studies in which the design or treatment have the costs of implementation.

There are different types of driving simulators, where simulation fidelity and driving experience depends on several components such as vehicle parts, visual display, audio systems, and computer hardware and software. For example, desktop simulators are usually composed of a set of monitors, driving seat, turning signals, gearshift, and acceleration and brake pedals. On the other hand, cockpit simulators include the same features in a more realistic vehicle platform that has an arrangement of screens and projectors. The fidelity of simulation may be improved at a higher cost with additional equipment like motion systems, video recorders, and eye- tracking devices. These supplements not only enhance the reality of the simulation but also provide additional data that can be used to address other issues that standard simulators cannot acquire.

In addition to transportation engineering and human factors, driving simulation has been an effective device to attend to other matters like psychology, medicine, and computer science (Fisher et al., 2011). Many researchers have used driving simulators to address new roadway designs and safety issues with the purpose of improving existing transportation infrastructure. These transportation- related investigations include the evaluation of traffic control devices (TCD) in work zones, the effectiveness of new designs in highway safety, the effectiveness of variable message signs (VMS), the safety effect of crash cushions, and yield markings at unsignalized intersections (Watson et al., 2006; Fitzpatrick et al., 2013; Jeihani et al., 2014). Furthermore, simulation has been of great use to investigate the effect of driving distraction, impairments, fatigue, training of young drivers, and other aspects of motorists (Varkaki et al., 2014; Oron et al., 2014; Nelson et al., 2011; Gómez et al., 2011; Van der Horst et al., 2011; Papantoniou et al., 2015).

The use of this effective and innovative technology is providing many research studies to the transportation area. The amount of information on driving behavior, road safety, and related transportation performance measures in real time is the most essential utility of the driving simulators. Therefore, this emerging technology is an ideal instrument to gather important transportation aspects on freeways that have managed lanes systems like the current PR-22 Dynamic Toll Lane with congestion pricing and an exclusive BRT system.

Chapter 3 METHODOLOGY

The following chapter describes the methodology procedure applied for this research project. The sections in this chapter include the experimental design, selection criteria of subject drivers and their characteristics, study protocol, instrument for data collection, development and description of scenarios, independent and dependent variables used to evaluate driving behavior, and zones of interest.

3.1 Methodology Description

The methodology used in this research project is illustrated in Figure 3.1 and described below. A total of twenty-seven subject drivers were studied using a block design, where nine participants were selected for each group based on their age. Each participant drove three different virtual scenarios of the reversible DTL located in freeway PR-22. Therefore, twenty-seven unique scenarios were evaluated for each block group, where the following independent variables were controlled: time of day (ToD), posted speed limit (PSL), and lane width (LW). The performance measures used for the evaluation of driving behavior were average speed, acceleration noise, and standard deviation of roadway position (SDRP) (Valdés et al., 2016). These dependent variables were analyzed in the following zones of interest: DTL entrance, before the bridge separation, bridge separation, after the bridge separation, and DTL exit.

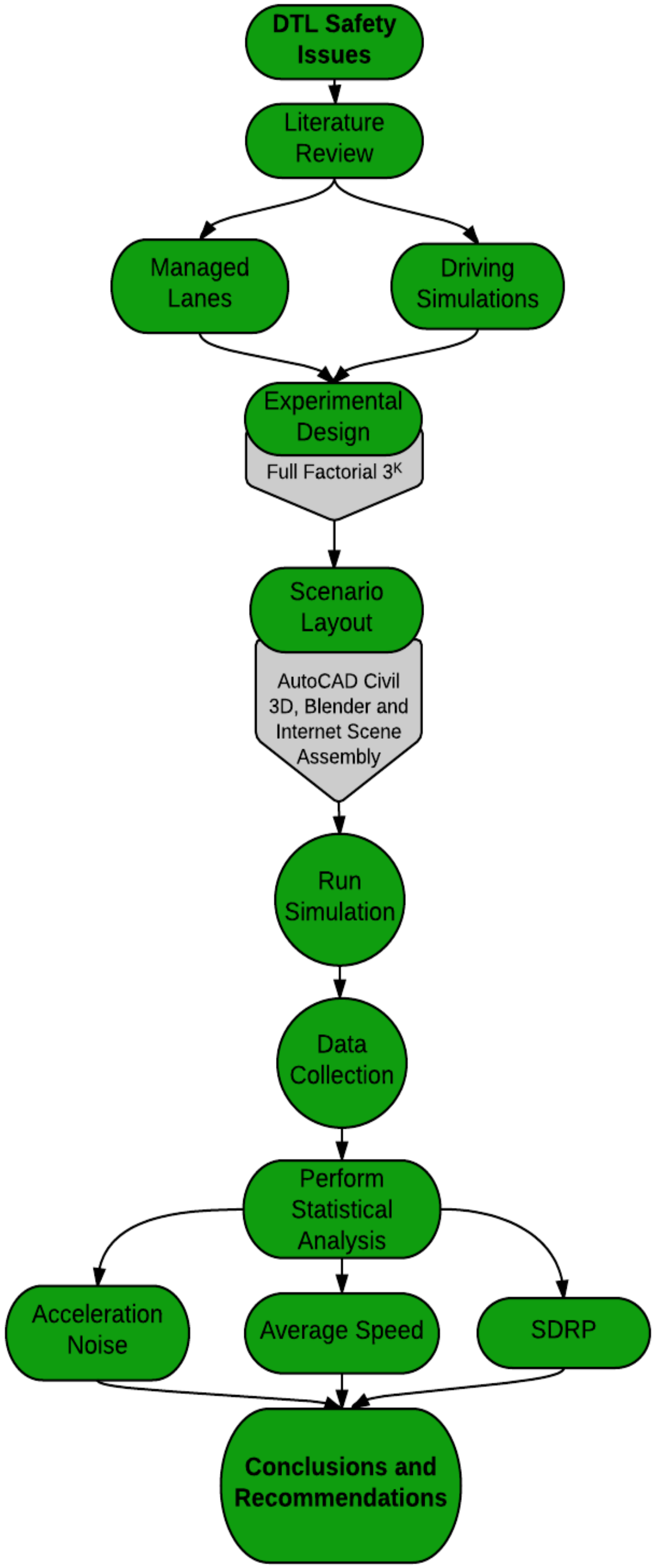

Figure 3.1 Methodology Flow Chart

3.2 Experimental Design

The experimental design applied in this research was a 3^3 full factorial design. A total of twenty-seven virtual scenarios were developed based on the independent variables time of day, posted speed limit, and lane width, and these factors were evaluated at three levels of interest. A 3^K full factorial design can be used when several quantitative factors of interest (i.e., time of day condition) have three levels of interest (i.e., morning, evening, and night condition) (Montgomery, 2013). This type of experimental design is useful to reduce the number of scenarios needed per participant while acquiring information regarding the main effects and interactions between the principal factors. In addition, a block design was applied to replicate the basic experiment using three homogenous age groups (18-25, 26-45, and 46-70 years old) to evaluate the effect of each treatment in each block.

The experimental design used in this research project was based on a full factorial to reduce the number of scenarios and the duration of experiments to which each participant was exposed, minimizing the probability of simulation sickness on participants (Kennedy et al., 2000). Even though the developed virtual scenarios had an approximate duration of five minutes, each participant was only exposed to three different scenarios. This reduced the total duration of the experiment, allowing the researchers to collect data from three subject drivers of different age groups per scenario without the effect of simulation sickness.

3.3 Subject Drivers

A total of 27 subjects formed part of this research project. Participants consisted of 14 females and 13 males, where 26 of the subjects were Hispanic and 1 was Caucasian. Subject drivers that participated in this study were distributed evenly into three age blocks. The first age block consisted of subjects from 18 to 25 years of age, the second block from

26 to 45 years of age, and the third block from 46 to 70 years of age. Subject drivers had to fulfill the established criteria in order to participate in this research project, which included having a valid driving license with a minimum driving experience of 18 months and being between 18 and 70 years old. The demographics and scenario order for each subject in the respective group is presented in Table 3.1.

Table 3.1 Subject Demographics and Scenarios Order.

Block Age 18-25					
Subject	Age	Gender	Scenarios Order		
1	23	M	20	11	2
2	25	M	14	5	23
3	25	M	18	27	9
4	23	M	1	10	19
5	23	F	4	22	13
6	23	F	3	21	12
7	23	F	15	24	6
8	25	F	26	8	17
9	23	F	7	25	16
Block Age 26-45					
Subject	Age	Gender	Scenarios Order		
1	37	F	2	11	20
2	27	F	14	23	5
3	26	M	27	18	9
4	31	F	19	10	1
5	45	M	4	13	22
6	29	M	12	3	21
7	32	M	15	6	24
8	38	F	17	26	8
9	31	F	25	16	7
Block Age 46-70					
Subject	Age	Gender	Scenarios Order		
1	60	F	11	2	20
2	53	F	23	14	5
3	51	M	27	9	18
4	63	M	10	1	19
5	49	F	13	4	22
6	48	M	3	12	21
7	51	M	6	15	24
8	48	F	26	17	8
9	63	M	16	25	7

3.4 Study Protocol

The study protocol consisted of a two-step procedure. During the first step, participants had to sign an informed consent form and fill out a pre-study questionnaire. The informed consent form contained an overall explanation of this research project, which included the investigators and sponsors in charge, the requirements that determine the qualification of participants, what subjects are asked to do, and the risks and benefits of the investigation. On the other hand, the pre-study questionnaire was used to obtain demographic information, driving history, and previous simulation exposure and vision issues of participants. 55% of subject participants drove between 100 and 300 miles the week before the study. In addition, 59% didn't have restrictions on their driver's license, while 41% had eyeglasses or contact lens restrictions. Of the 27 subject drivers, 16 had not been exposed to the driving simulator before. In terms of the research study, 88% of the participants acknowledged the DTL system, but only 30% of them had been accustomed users of the system. The second step consisted of the description of the driving simulator equipment, which included an explanation of how to use the acceleration and brake pedals, gearshift, steering wheel, turn signals, and the location of the rearview mirror and speedometer in the projected simulation.

Before starting with the experimental scenarios, every subject was exposed to a generic simulation in order to become familiarized with the simulator equipment and clarify any doubts or questions that may have arisen. Additionally, subject drivers were told to imagine that they were using a rental vehicle in which the performance and feeling of the vehicle were different from the car they own. This was done with the purpose of ensuring that all subjects began the experiment with the same vehicle expectations. In addition, the research assistants encouraged participants to drive as they ordinarily do in their own vehicles when driving. Finally, they were instructed to enter the DTL express lane.

3.5 Instrument for Data Collection: UPRM Driving Simulator

The UPRM Driving Simulator is divided into three main elements: a driving cockpit, a system of projectors and screens, and the computer software. The driving cockpit consists of a driving wheel, accelerator and brake pedals, gearshift, turn signals, and the driving seat placed in a wooden frame with six wheels for mobile applications (Figure 3.2). A steering wheel with turn signal controls was installed in front of the car seat, which rests on a wooden countertop that serves as a dashboard for the simulator. The brake and throttle pedals are located on top of the wooden floor, while the gear shift is situated on the right side of the car seat with three configurations: drive, neutral, and reverse. The visual display of the driving simulator is composed of a set of three projectors that are fixed on the ceiling of the laboratory, where each projector is aimed at a different screen. This set of screens is placed in front of the cockpit, creating a virtual driving environment that has perspective visibility of 120 degrees of roadway. The audio for the simulation is provided through a sound bar system that is located above the simulator pedals. The hardware and software system of the simulation consists of a desktop and a laptop computer that has an Nvidia graphic card and Realtime Technologies Inc. (RTI) simulation software, which includes SimCreator/SimVista and Internet Scene Assembler (ISA) (SimVista,2013).

(a)

(b)

Figure 3.2 UPRM Driving Simulator:
(a) Fixed Version (b) Mobile Version

3.6 Scenario Development Process

The DTL scenarios were developed using a step-by-step procedure because the driving simulation software provided by RTI did not have an integrated managed lane scenario. In order to develop the required scenarios for this investigation, four commercial software programs were used: AutoCAD Civil 3D, Blender 2.49b, Microsoft PowerPoint, and Internet Scene Assembler (ISA). The As-Built plans of the PR-22 DTL were used in combination with videos taken from a dashboard car camera while traveling throughout the express lane to recreate the pertinent scenarios. These scenarios included existing road elements such as geometric design of lane, shoulder, and pavement markings; concrete barriers; the bridge piers protector; crash cushions; and traffic control devices and sign details and locations.

Four tasks were performed to generate the DTL scenarios. The first task consisted of modeling the PR-22 and DTL corridor in AutoCAD Civil 3D. The freeway and DTL roadway was created and then exported as a .dxf file. The pavement marking as well as concrete barriers were also created in AutoCAD and exported as a .dxf file. The second task consisted of importing the .dxf files created in AutoCAD into Blender 2.49b. The computer software Blender was used to create materials and textures utilized to add color and other visual features to each roadway element. These generated materials and textures included the grass located on the roadside and the median, the concrete barrier system of the DTL, the sign supports, and the asphalt texture for both PR-22 and the DTL. In addition, this program was used in order to export each element in .vrml format, which is the file extension utilized in the simulator software SimCreator/SimVista that was used for this research. The third task consisted of generating the existing signage configuration in PR-22 and the DTL. All the signs were created based on the existing conditions that are in compliance with the MUTCD (2009) and the Manual of Traffic Signage for Puerto Rico Roadways. In the fourth task, the vrml files were imported into the Internet Scene Assembler software library. The design objects that were generated through the different software programs were added to the object library that had the simulation. The simulation scenarios were completed using the traffic control device objects available in ISA and the corresponding overhead and roadside signage created, which are based on information provided by design plans and videos collected with the dashboard car camera.

3.7 Scenarios Description

Two basic scenario layouts were modeled in this research. The scenario layout consisted of the PR-22 with the DTL, where the first layout is in the eastbound direction (Toa Baja to Bayamón) and the second layout is westbound (Bayamón to Toa Baja). The first layout has total length of 4.85 mi (7.8 km) divided as so: 0.37 mi (0.6 km) before the entrance of the DTL, 1.24 mi (2.0 km) of entrance, 0.87 mi (1.4 km) of pocket lane in the right, 0.37 mi (0.6 km) of bridge separation, 0.87 mi (1.4 km) of pocket lane in the left, approximately 1.00 mi (1.6 km) of exit section, and 0.12 mi (0.2 km) after the exit of the DTL. The second layout, from Bayamón to Toa Baja, has total length of 4.97 mi (8.0 km) divided as follows: 0.25 mi (0.4 km) before the entrance of the DTL, approximately 1.00 mi (1.6 km) length of entrance, 0.87 mi (1.4 km) of pocket lane in the left, 0.37 mi (0.6 km) of bridge separation, 0.87 mi (1.4 km) of pocket lane in the right, 1.24 mi (2.0 km) of exit section, and 0.37 mi (0.6 km) after the exit of the DTL.

A total of twenty-seven virtual scenarios were developed by controlling three independent variables: time of day, lane width, and posted speed limit. Time of day was evaluated during three different configurations, namely, morning, evening, and night. The DTL reversible operation occurs in the eastbound direction toward Bayamón during the morning, whereas evening and night traffic operates in the westbound direction toward Toa Baja. Therefore, the directional flow was taken into consideration for the development of scenarios to maintain the reversible DTL, which included the orientation of the ambient traffic in accordance with the existing environment and operation. In terms of lane width, three different configurations were evaluated, namely, 10, 11, and 12 ft (3.05, 3.35, and 3.65 meters). Lastly, three different posted speed limits (45, 55, and 65 mph) were evaluated inside the DTL. Table 3.2 describes all evaluated scenarios for this research study.

Table 3.2 Description of the Scenarios.

Scenario	Time of day			Lane width (ft)			Speed limit (mph)		
	Morning (EB)	Evening (WB)	Night (WB)	10	11	12	45	55	65
1	x			x			x		
2	x			x				x	
3	x			x					x
4	x				x		x		
5	x				x			x	
6	x				x				x
7	x					x	x		
8	x					x		x	
9	x					x			x
10		x		x			x		
11		x		x				x	
12		x		x					x
13		x			x		x		
14		x			x			x	
15		x			x				x
16		x				x	x		
17		x				x		x	
18		x				x			x
19			x	x			x		
20			x	x				x	
21			x	x					x
22			x		x		x		
23			x		x			x	
24			x		x				x
25			x			x	x		
26			x			x		x	
27			x			x			x

3.8 Variables Evaluated

The following variables were used for this research project.

3.8.1 Independent Variables

Three independent variables were controlled, namely, time of day conditions, lane width, and posted speed limit. Three times of day were evaluated: morning, evening, and night. Morning operations of the DTL are in the direction toward Bayamón, while evening and nighttime operations are in the other direction. Therefore, daytime scenarios were created for the eastbound direction, whereas the rest of the scenarios were in the westbound direction towards Toa Baja. Also, three lane widths were evaluated at 10, 11, and 12 ft. Finally, three posted speed limits inside the DTL were analyzed at 45, 55, and 65 mph.

3.8.2 Dependent Variables

Three dependent variables were evaluated in the experiment, namely, average speed, acceleration noise, and standard deviation of roadway position (SDRP) (Valdés, 2016). The acceleration noise variable, standard deviation of the acceleration, has been used as a surrogate measure for crash frequency and a potential indicator of traffic flow quality that can be experienced by individual drivers (Boonsiripant, 2009).

3.9 Zones of Interest

Five zones of interest were selected for this research project. These zones (Figure 3.3) were selected after reviewing the trajectory of all subject drivers and were defined as: DTL entrance, before the bridge mainline separation, bridge separation segment, bridge mainline connection, and the DTL exit.

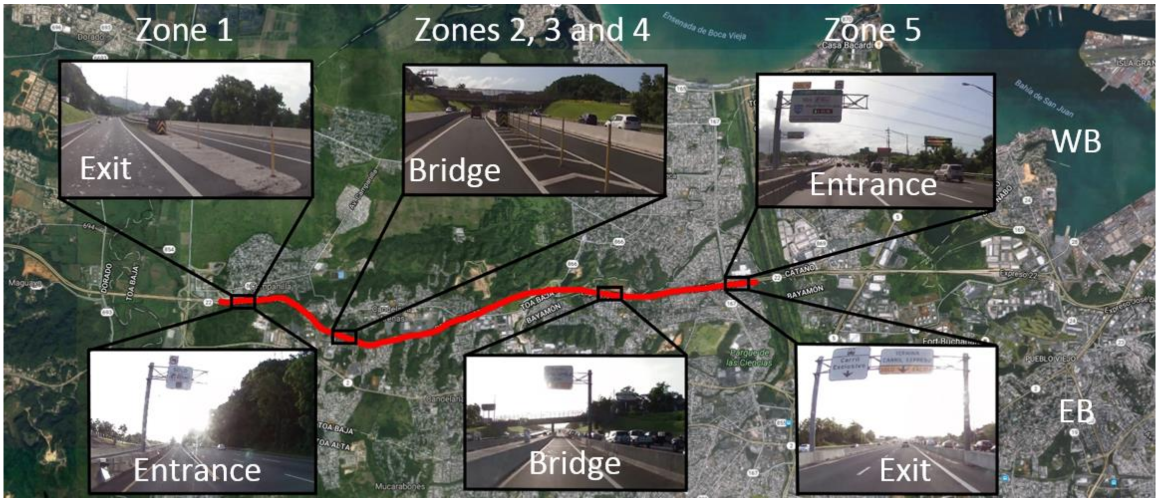

Figure 3.3 Zones of Interest Inside PR-22 DTL

Driving behaviors of subject drivers were studied in these zones of interest because of their potential for generating hazardous situations as a consequence of merging and diverging movements when passing through the DTL entrance, bridge segment, and exit. The data collection area was selected using the decision sight distances described in the AASHTO A Policy on Geometric Design of Highways and Streets (AASHTO Green Book, 2011 Edition). Decision sight distance is the measure needed for a driver to detect an unexpected or otherwise difficult-to-perceive information source or condition in a roadway environment that may be visually cluttered, recognize the condition or its potential threat, select an appropriate speed and path, and initiate and complete complex maneuvers (Alexander et al., 1975).

Table 3.3 shows the study area selected for each of the zones of interest used in this research study. For both directions, Zone 1 represented the DTL entrance, Zone 2 before the bridge mainline separation, Zone 3 bridge segment, Zone 4 bridge mainline connection, and Zone 5 DTL exit.

Table 3.3 Study Area for Each Zone of Interest.

Zone	Description	Study Area (m)
1	DTL Entrance	742
2	Before Bridge Separation	210
3	Bridge Segment	210
4	After Bridge Connection	210
5	DTL Exit	580

Chapter 4 ANALYSIS AND RESULTS

The following chapter explains the procedure used to perform the integrated data analysis of this research study. This includes the description of each dependent variable (standard deviation of roadway position, average speed, and acceleration noise), the statistical tests applied for the analysis of each performance measure, and the discussion of results. Statistical information, such as tables and graphs, is provided to demonstrate which variables had significant differences and how the independent variables interacted with each dependent variable.

4.1 Statistical Test Description

The integrated data analysis was applied for each of the twenty-seven scenarios in five zones of interest that were defined after analyzing all the trajectories of subject drivers. The standard deviation of roadway position (SDRP) comparison was performed using the F-test (Equation 1) at a 95% confidence level, which compares each zone of interest with respect to the time of day. As illustrated in Equation 1, the F-test compared the variance of the data in each configuration between the locator references, where significant differences are founded when the p-value is less than 0.05. However, to eliminate the effect of the “family wise error,” a Bonferroni correction was used for each of the analyzed zones. The Bonferroni correction uses a p-value less than 0.00341 to identify significant differences in the data. The comparison of average speed and acceleration noise variable was performed using an ANOVA analysis, which compares the variance of the sample data. Statistical differences were determined at a 95% confidence level for each independent variable, where the p-value needed to be less than 0.05 to be significant.

$$F - Test = \frac{S_X^2}{S_Y^2} \qquad \text{(Eq.1)}$$

where:

S_X^2 = Variance of group 1

S_Y^2 = Variance of group 2

4.2 Standard Deviation of Roadway Position Analysis

The standard deviation of roadway position (SDRP) was used to compare the longitudinal and lateral position of subject drivers throughout the DTL scenarios evaluated. The effect of time of the day in each of the five zones of interest was made to compare driver's position with respect to the time of day. A significant difference in any of the five zones evaluated means that the driver's lateral position is affected with respect to the time of day. From the integrated data analysis of the dependent variable SDRP, two of the five zones evaluated resulted in a significant difference at a 95% confidence level. Twenty-six percent of the overall scenarios were significant on the SDRP variable, while 44% of those scenarios were significant at the bridge segment as seen in Table 4.1. The comparison between evening and morning was significant in Zone 2 (entrance of the bridge) and Zone 4 (exit of the bridge). Likewise, the comparison between night and morning condition was also significant in Zones 2 and 4. However, there was no significant difference when comparing night and evening, which could be associated with the fact that the travel direction was westbound with the same TCDs. These results suggest that the road segment prior to the bridge could be a potentially hazardous location since the variability in data was significant. This indicates that drivers may become confused about which travel lane to choose when approaching the divergent movement before the bridge. In addition, the variability in vehicle position after the bridge may have resulted as a consequence of immediate lane changing movements performed by subject drivers during the convergence of lanes. Driving confusion in these decision zones could be caused by TCDs that do not satisfy all criteria established by the MUTCD. Therefore, the lack of a sign providing a short, efficient, and understandable message affects subject drivers' lane changing movements before and after the bridge located inside the DTL.

Table 4.1 Standard Deviation of Roadway Position Comparison Results.

Comparison	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Evening vs Morning	0.301	<0.001*	0.110	0.002*	0.016
Night vs Evening	0.729	0.955	0.542	0.411	0.996
Night vs Morning	0.490	<0.001*	0.317	<0.001*	0.016

*P-value with Bonferroni Correction <0.00341

On the other hand, Zone 1 (DTL entrance), Zone 3 (Bridge separation), and Zone 5 (DTL exit) were not statistically significant. This could be due to the fact that these zones of interest only have one lane where drivers are confined between two continuous concrete traffic barriers inside a facility that has a reversible lane operation with varying shoulder width on each side. Therefore, one should expect no significant variation in the SDRP of subject drivers. In addition, there is a possibility that the shy line (described in the AASHTO Roadside Design Guide, 2011) does not comply with the required minimum distance for the design velocity for both directions of the reversible DTL. For this reason, one should consider the shoulder width for further research studies.

The lateral and longitudinal position of all subject drivers is illustrated in Figure 4.1 for the time of day variable, where (a) is the morning configuration (eastbound direction), (b) is the evening condition (westbound direction), and (c) is the night condition (westbound direction). Additionally, participants exit the DTL through the exclusive BRT lane in 26% of all virtual scenarios evaluated.

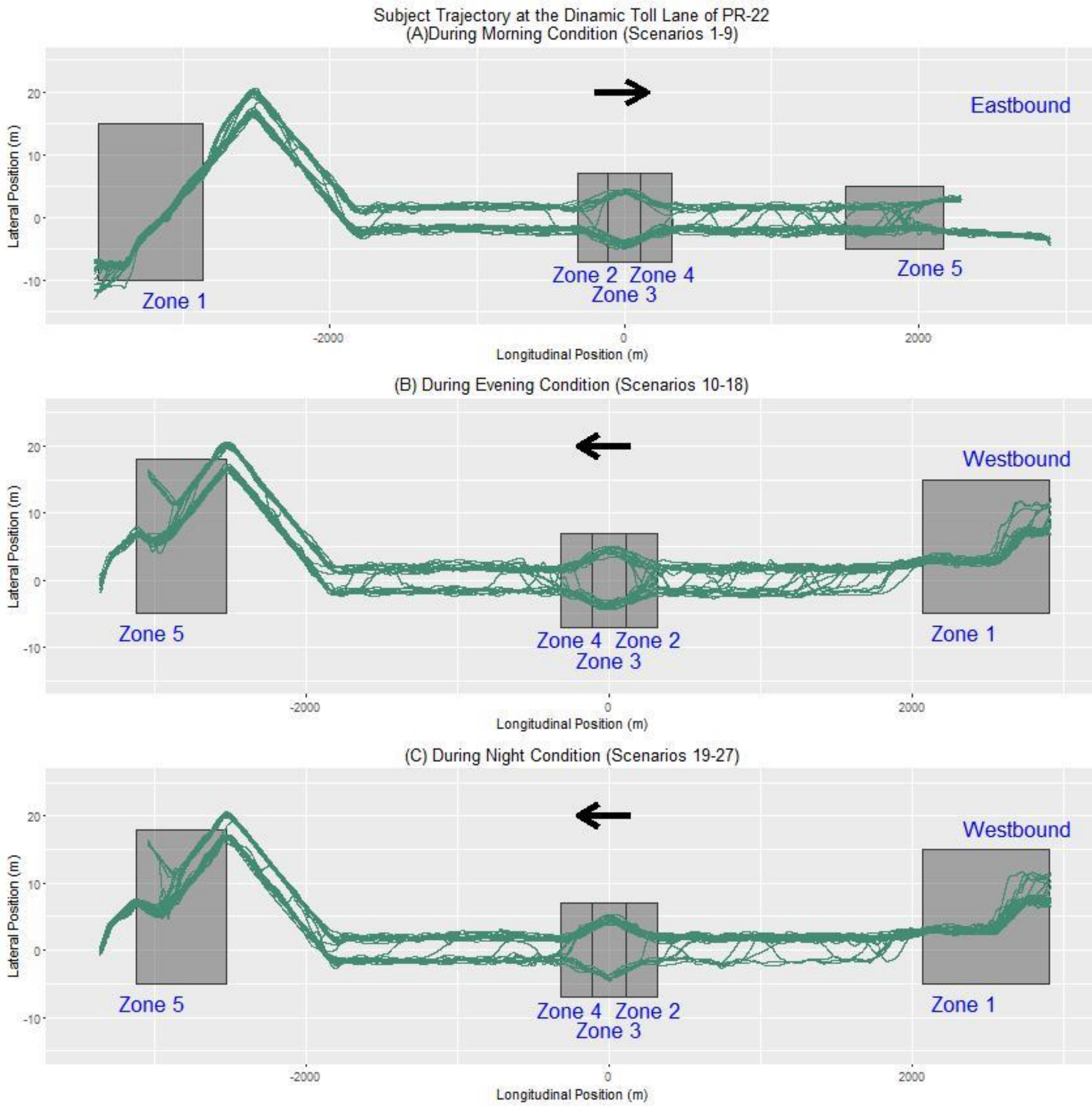

Figure 4.1 The Lateral and Longitudinal Position for the Time of Day and Direction Evaluated

The number of subject drivers that departed the DTL using the incorrect exit lane for each of the independent variables is shown in Table 4.2. Forty-four percent of subject drivers exited through the incorrect lane during morning scenarios. Likewise, 33% of all participants used the exclusive bus lane exit in scenarios with lane widths of 11 ft, whereas 37% used the incorrect exit while traveling scenarios with 65 mph posted speed limit.

Table 4.2 Subject Drivers that Used the Incorrect DTL Exit (BRT Exit) by Independent Variable.

Variable	Time of Day			Lane Width (ft)			Posted Speed Limit (mph)		
Level	**Morning**	**Evening**	**Night**	**10**	**11**	**12**	**45**	**55**	**65**
Total	12	4	5	7	9	3	6	5	10
%	44	15	19	26	33	11	22	19	37

Driving confusion related to DTL users exiting through the BRT exclusive lane could be related to the existing configuration of roadside and overhead signage, which may not comply with one of the basic requirements of TCDs cited in the MUTCD Part 1 Section 1A.02 (MUTCD, 2009):

> "*To be effective, a traffic control device should meet five basic requirements:*
>
> *A. Fulfill a need;*
>
> *B. Command attention;*
>
> *C. Convey a clear, simple meaning;*
>
> *D. Command respect from road users; and*
>
> *E. Give adequate time for proper response*
>
> *Design, placement, operation, maintenance, and uniformity are aspects that should be carefully considered in order to maximize the ability of a traffic control device to meet the five requirements listed in the previous*

> *paragraph. Vehicle speed should be carefully considered as an element that governs the design, operation, placement, and location of various traffic control devices."*

It is our understanding that point C of the basic requirements of MUTCD (convey a clear, simple meaning) is not satisfied. Most of the subject drivers were confused by the terminology in the TCDs, using the exclusive BRT lane exit as the express lane exit. It was hypothesized that the number of subject drivers using the incorrect exit was higher in the westbound direction because the managed lane exit is in the left lane, which is a non-common practice. However, the most incorrect actions by scenario were found to be in the eastbound direction where the exit was in the right lane.

4.3 Average Speed Analysis

The statistical analysis done for the dependent variable average speed was an ANOVA test at a 95% confidence level. This statistical test, based on the full factorial design, was used to determine significant differences between the three independent variables (time of day, posted speed limit, and lane width) when the p-value is less than 0.05. Therefore, the differences in subjects' average speed were compared between scenarios as well as the effect of each dependent variable in the five zones of interest. The statistical analysis of the full factorial design of the average speed of the subject in each zone of interest is summarized below.

For Zone 1, the main effects PSL and LW presented statistical significant differences, which are presented in Table 4.3. The average speed in the entrance changes significantly between the 65 mph posted speed limit scenarios and its counterparts of 45 and 55 mph. The average speed in the 65 mph scenarios was 7 mph lower than the 45 and 55 mph scenarios. In the same way, the average speed was nearly 7 mph lower for the 10 ft lane width as compared with the 11 and 12 ft scenarios. The average speed in Zone 1 for each independent variable is illustrated in Figure 4.2.

Table 4.3 Analysis of Variance for the Full Factorial for Average Speed Zone 1.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	2	106.300	53.200	1.173	0.317
ToD	2	3.500	1.800	0.039	0.962
PSL	2	2348.900	1174.400	25.921	<0.001*
LW	2	988.200	494.100	10.905	<0.001*
Double Interaction					
ToD*PSL	4	288.800	72.200	1.594	0.190
ToD*LW	4	89.600	22.400	0.495	0.740
PSL*LW	4	155.000	38.800	0.855	0.497
Triple Interaction					
ToD*PSL*LW	8	159.500	19.900	0.440	0.891
Residuals	52	2356.100	45.300		

*Statistical Significant Differences <0.05.

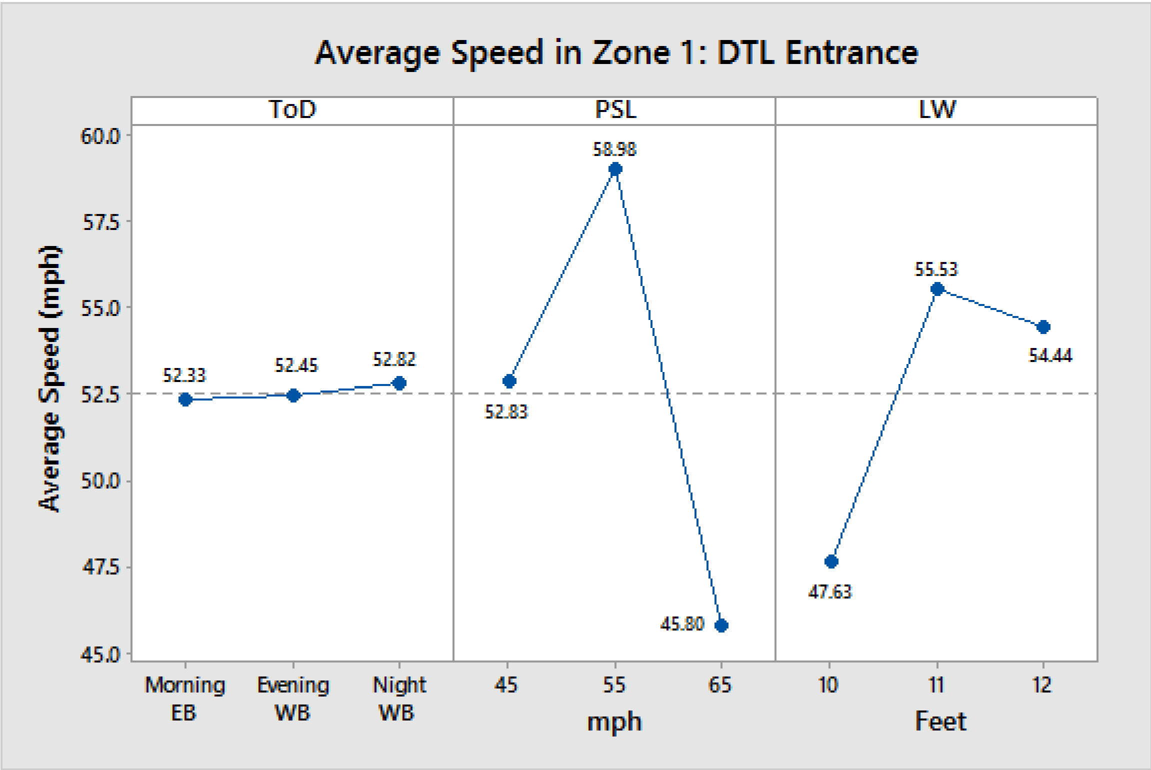

Figure 4.2 Average Speed on each Variable Evaluated in Zone 1

In Zone 2, the main effects PSL, LW, and the double interaction LW*PSL presented statistically significant differences. The statistical analysis of the full factorial for average speed in Zone 2 is presented in Table 4.4. The posted speed limits presented a differential of 3 to 4 mph for all levels taken in consideration. Variable lane width increased average speed by 9 mph in areas between 10 and 11 ft wide, whereas a 7 mph increment was observed for areas 11 to 12 ft wide. Also, the age differential was significant, meaning that the subject driver's age affected the behavior in the zone before the mainline separation. The average speeds of each variable evaluated in Zone 2 are illustrated in Figure 4.3.

Table 4.4 Analysis of Variance for the Full Factorial for Average Speed Zone 2.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	2	347	173.5	4.262	0.0193*
ToD	2	3	1.5	0.038	0.963
PSL	2	319	159.4	3.916	0.026*
LW	2	3871	1935.7	47.552	<0.01*
Double Interaction					
ToD*PSL	4	426	106.6	2.619	0.0454
ToD*LW	4	116	28.9	0.71	0.5888
PSL*LW	4	55	13.7	0.338	0.8513
Triple Interaction					
ToD*PSL*LW	8	134	16.7	0.41	0.9095
Residuals	52	2117	40.7		

*Statistical Significant Differences <0.05.

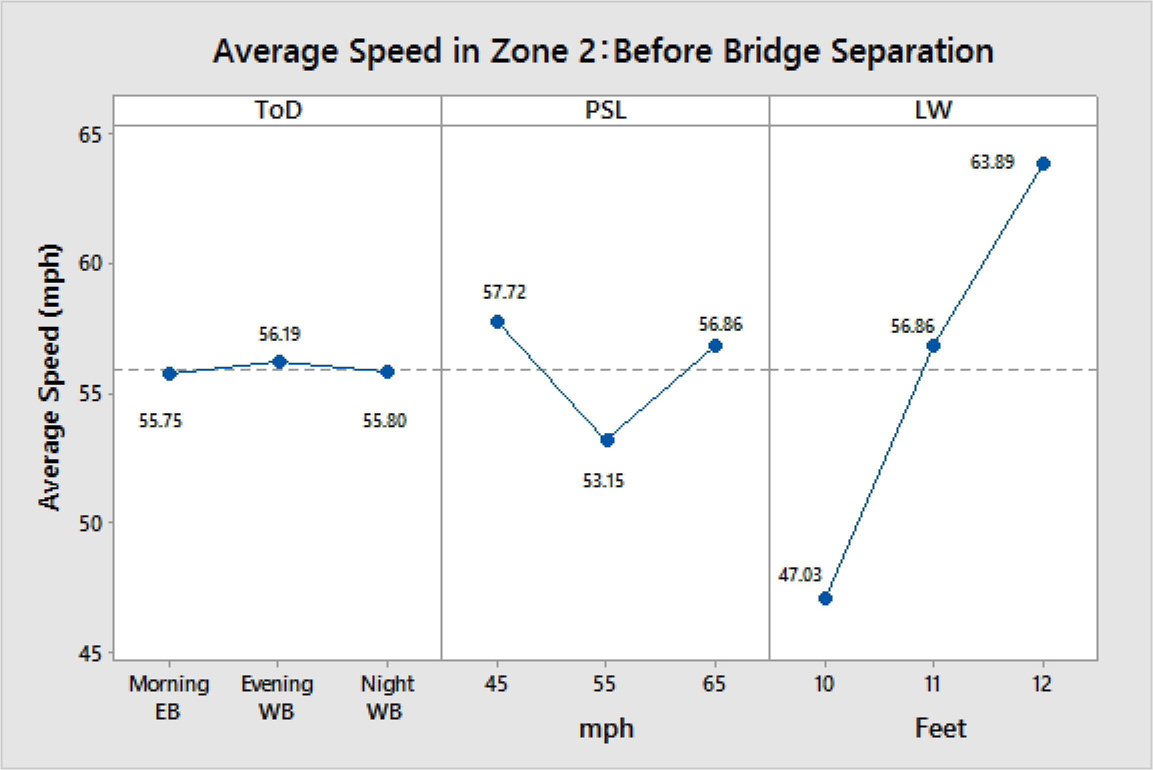

Figure 4.3 Average Speed on each Variable Evaluated in Zone 2

For Zone 3, the main effect LW resulted in statistically significant differences since p-values were less than 0.05 as illustrated in Table 4.5. Lane width represented an average speed that was an increment of 9 mph between 10 and 11 ft and approximately 7 mph for 11 to 12 ft. In addition, the age difference affected the performance of the subject participants in this zone of interest. The average speed for each variable in Zone 3 is presented in Figure 4.4.

Table 4.5 Analysis of Variance for the Full Factorial for Average Speed Zone 3.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	2	548	274.2	7.891	<0.001*
ToD	2	17	8.5	0.245	0.783
PSL	2	91	45.7	1.315	0.277
LW	2	3746	1872.9	53.903	<0.001*
Double Interaction					
ToD*PSL	4	293	73.3	2.109	0.093
ToD*LW	4	63	15.6	0.45	0.772
PSL*LW	4	41	10.3	0.296	0.879
Triple Interaction					
ToD*PSL*LW	8	123	15.3	0.441	0.891
Residuals	52	1807	34.7		

*Statistical Significant Differences <0.05.

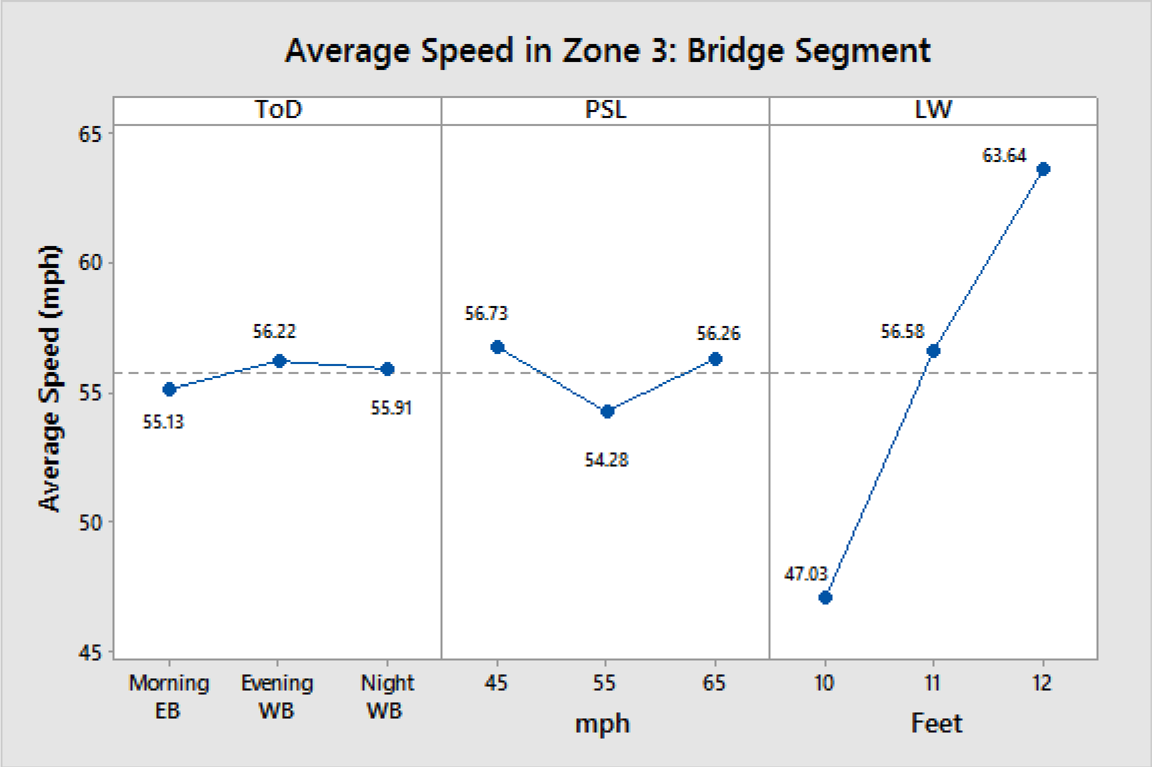

Figure 4.4 Average Speed on each Variable Evaluated in Zone 3

For Zone 4, the main effects of LW resulted in statistically significant differences with p-values less than 0.05 as illustrated in Table 4.6. The lane width represents an average speed that was an increment of 10 mph between 10 and 11 ft and approximately 9 mph for 11 to 12 ft. The age difference in this locator reference had a significant effect, which means that the difference in subject drivers' age influences the driving performance of the drivers. The average speed for each variable in Zone 4 is presented in Figure 4.5.

Table 4.6 Analysis of Variance for the Full Factorial for Average Speed Zone 4.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	2	612	306.1	9.54	<0.001*
ToD	2	33	16.3	0.507	0.605
PSL	2	28	13.8	0.43	0.653
LW	2	3770	1884.9	58.745	<0.001*
Double Interaction					
ToD*PSL	4	294	73.4	2.288	0.072
ToD*LW	4	44	11.1	0.345	0.846
PSL*LW	4	50	12.4	0.387	0.817
Triple Interaction					
ToD*PSL*LW	8	148	18.5	0.578	0.791
Residuals	52	1668	32.1		

*Statistical Significant Differences <0.05.

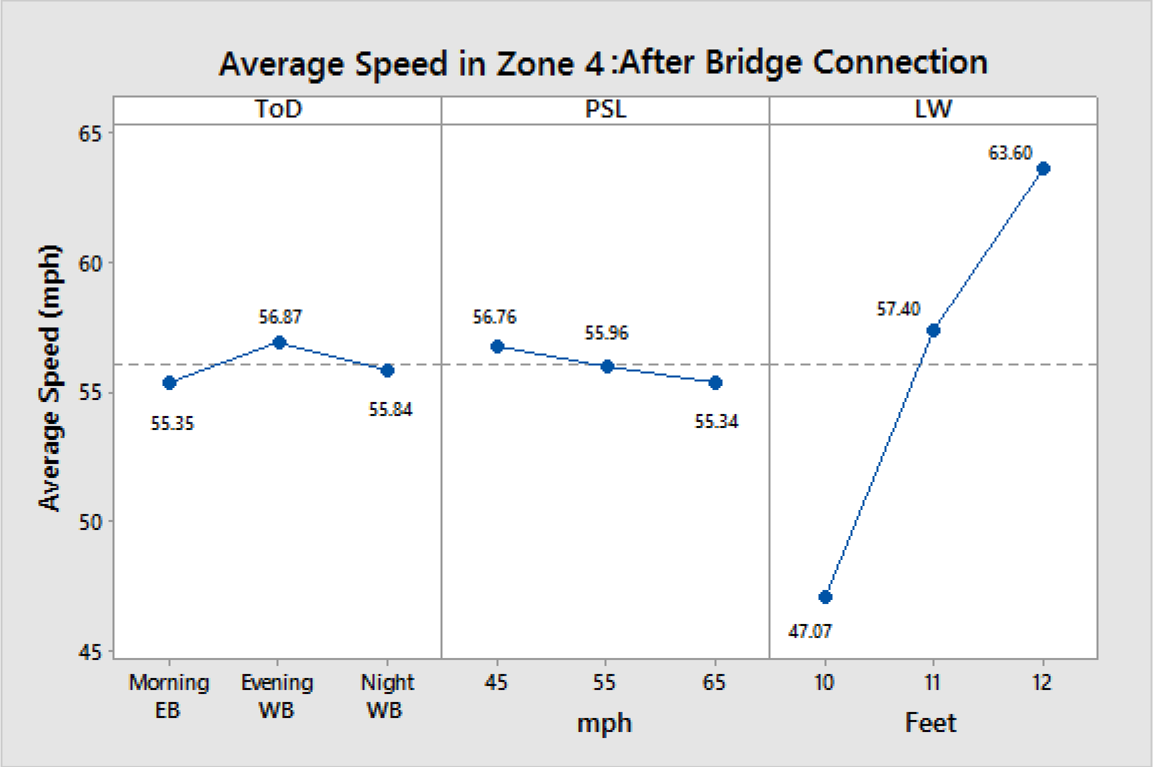

Figure 4.5 Average Speed on each Variable Evaluated in Zone 4

For Zone 5, the main effects of LW resulted in statistically significant differences as illustrated in Table 4.7. The lane width represented an average speed that was an increment of 8 mph between 10 and 11 ft and approximately 6 mph for 11 to 12 ft. The average speed for each variable in Zone 5 is presented in Figure 4.6.

Table 4.7 Analysis of Variance for the Full Factorial for Average Speed Zone 5.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	2	138	69	1.852	0.167
ToD	2	11.1	5.5	0.148	0.862
PSL	2	215.5	107.8	2.892	0.064
LW	2	2645	1322.6	35.5	<0.001*
Double Interaction					
ToD*PSL	4	158.5	39.6	1.064	0.384
ToD*LW	4	36.7	9.2	0.247	0.911
PSL*LW	4	304.2	76	2.041	0.102
Triple Interaction					
ToD*PSL*LW	8	125	15.6	0.419	0.9042
Residuals	52	1937	37.3		

*Statistical Significant Differences <0.05.

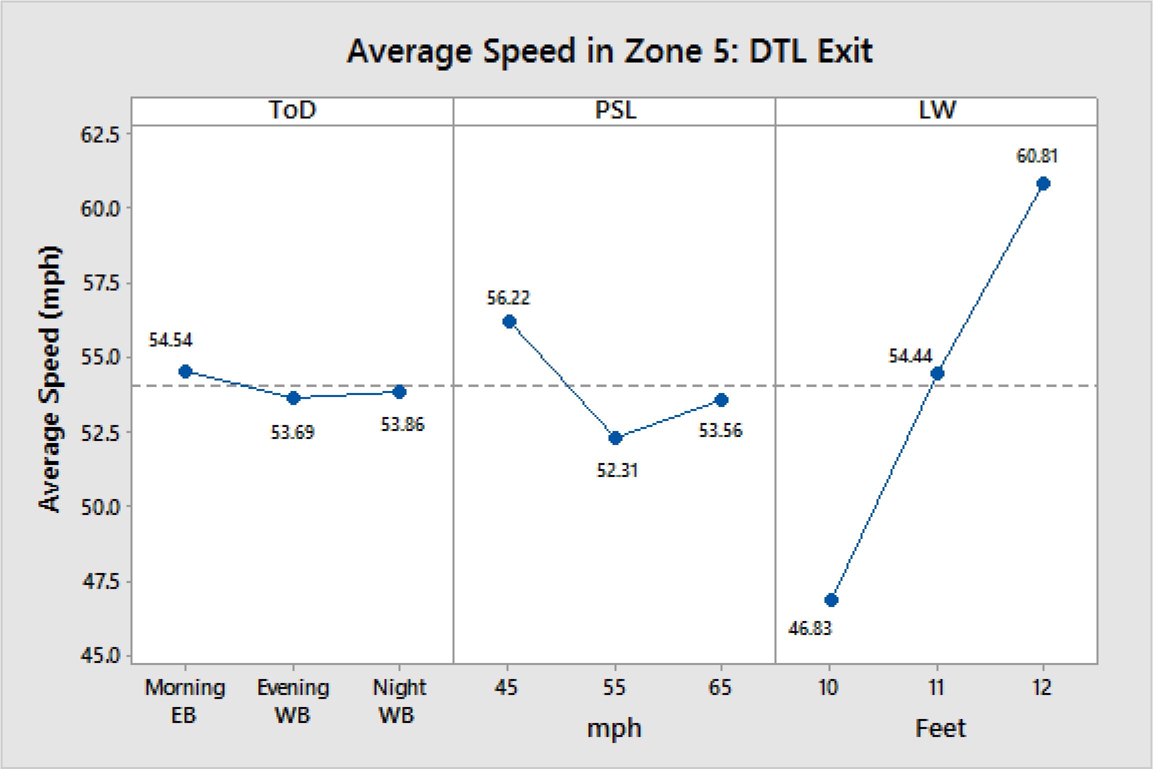

Figure 4.6 Average Speed on each Variable Evaluated in Zone 5

The average speed variable was compared between the 27 scenarios in five zones of interest. This dependent variable resulted in a significant difference in all the zones evaluated, where the lane width (significant differences in all the scenarios) and posted speed limit (significant difference in the first two scenarios) were the independent variables with significant differences for the average speed variables. Also, after the integrated analysis it can be inferred that the optimum lane width and posted speed limit for the managed lane system in Puerto Rico are 55 mph and 11 feet wide, respectively.

4.4 Acceleration Noise Analysis

The analysis of the acceleration noise was also based on the ANOVA test of the full factorial design at a 95% confidence level. The results of the statistical analysis for the acceleration noise of the subject matters in each zone of interest are summarized in this section. In addition, the main effects of each independent variable (time of day conditions, lane width, and posted speed limit) and their interactions are analyzed with respect to subject matter acceleration noise.

As seen in Table 4.8, the main effect PSL in Zone 1 was statistically significant. The 55 mph condition presented the lowest acceleration noise with 0.152, while the 45 mph and 65 mph presented 0.205 and 0.425, respectively. This means that the 55 mph can represent a lower crash frequency since a lower acceleration noise represents less speed change. The average acceleration noise for each variable in Zone 1 is presented in Figure 4.7.

Table 4.8 Analysis of Variance for the Full Factorial for Acceleration Noise Zone 1.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	2	0.006	0.003	0.552	0.579
ToD	2	0.004	0.002	0.358	0.701
PSL	2	0.123	0.062	11.144	<0.001*
LW	2	0.014	0.007	1.234	0.3
Double Interaction					
ToD*PSL	4	0.014	0.003	0.628	0.644
ToD*LW	4	0.022	0.005	0.986	0.423
PSL*LW	4	0.006	0.001	0.27	0.896
Triple Interaction					
ToD*PSL*LW	8	0.020	0.002	0.442	0.89
Residuals	52	0.287	0.006		

*Statistical Significant Differences <0.05.

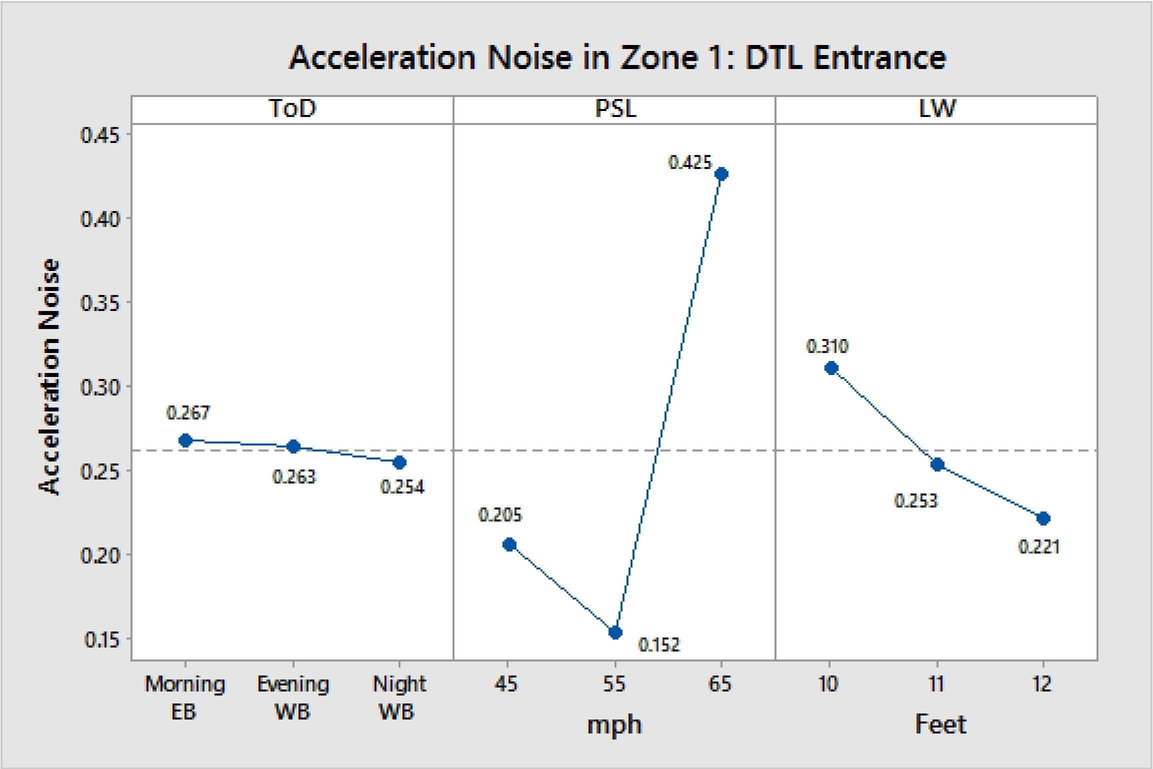

Figure 4.7 Acceleration Noise on each Variable Evaluated in Zone 1

For Zone 2 and Zone 3, the main effect PSL showed a statistically significant difference (Table 4.9 and Table 4.10). Both zones have a lower acceleration noise in the 45 mph scenario. Zone 2 had an acceleration noise of 0.029, while Zone 3 had 0.036 in the 45 mph scenario. On the other hand, the 65 mph resulted in the highest acceleration noise for

Zones 2 and 3 with 0.208 and 0.118, respectively. The average acceleration noise for each variable in Zones 2 and 3 are illustrated in Figure 4.8 and Figure 4.9.

Table 4.9 Analysis of Variance for the Full Factorial for Acceleration Noise Zone 2.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	2	0.069	0.035	2.877	0.065
ToD	2	0.049	0.025	2.056	0.138
PSL	2	0.217	0.109	9.032	<0.001*
LW	2	0.004	0.002	0.144	0.866
Double Interaction					
ToD*PSL	4	0.064	0.016	1.339	0.268
ToD*LW	4	0.025	0.006	0.519	0.722
PSL*LW	4	0.046	0.011	0.952	0.442
Triple Interaction					
ToD*PSL*LW	8	0.108	0.014	1.127	0.361
Residuals	52	0.625	0.012		

*Statistical Significant Differences <0.05.

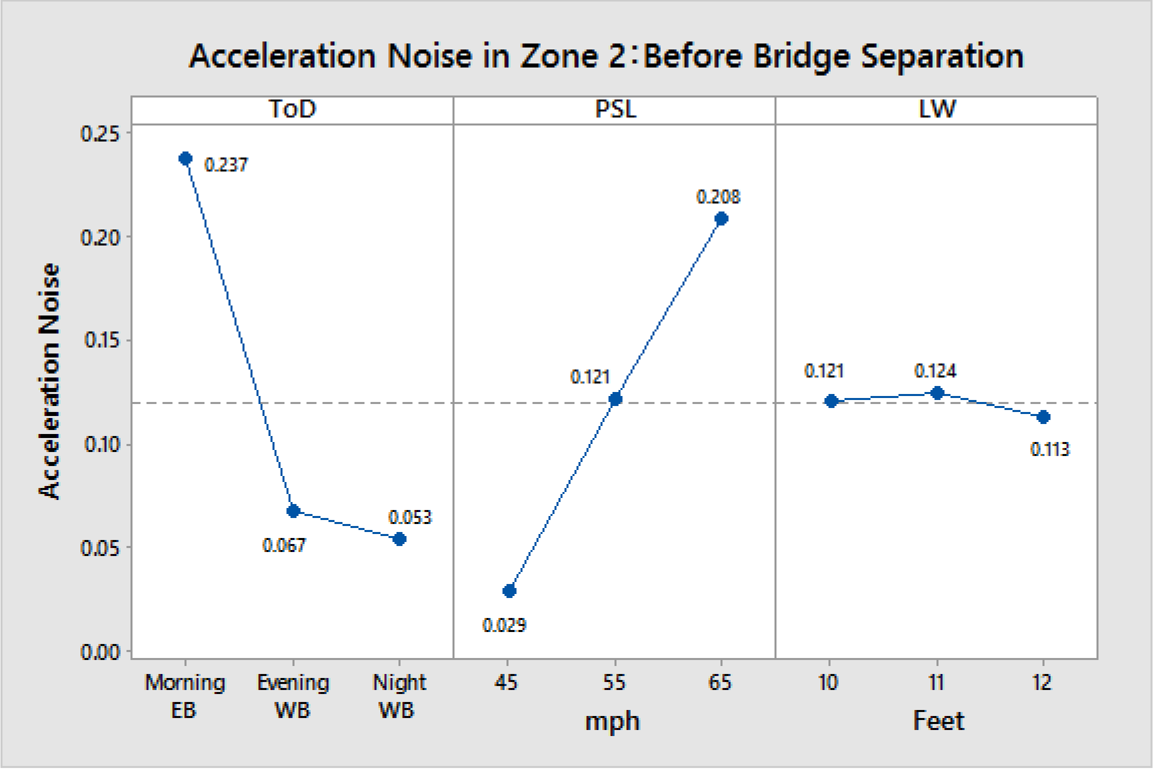

Figure 4.8 Acceleration Noise on each Variable Evaluated in Zone 2

Table 4.10 Analysis of Variance for the Full Factorial for Acceleration Noise Zone 3.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	2	0.039	0.020	1.435	0.248
ToD	2	0.001	0.001	0.042	0.959
PSL	2	0.118	0.059	4.325	0.018
LW	2	0.006	0.003	0.223	0.801
Double Interaction					
ToD*PSL	4	0.0349	0.009	0.641	0.636
ToD*LW	4	0.033	0.008	0.607	0.659
PSL*LW	4	0.0533	0.013	0.978	0.428
Triple Interaction					
ToD*PSL*LW	8	0.049	0.006	0.45	0.885
Residuals	52	0.708	0.014		

*Statistical Significant Differences <0.05.

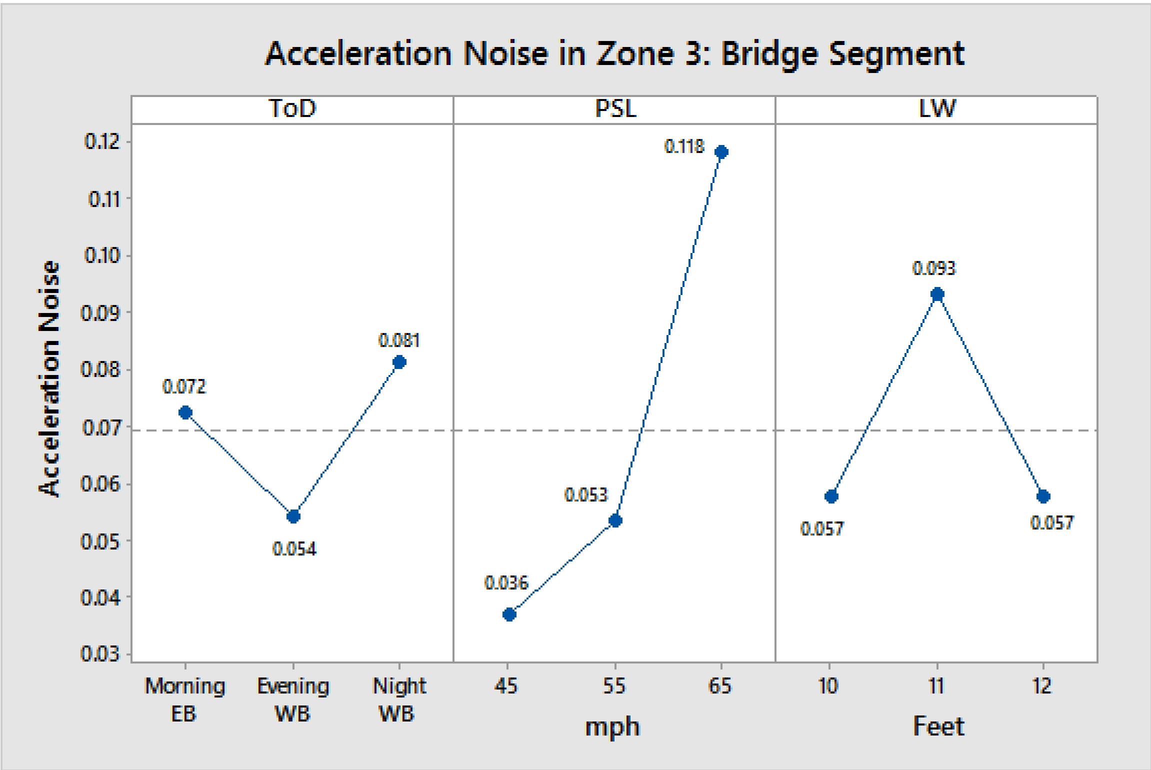

Figure 4.9 Acceleration Noise on each variable evaluated in Zone 3.

The integrated data analysis for the acceleration noise in Zone 4 didn't reflect any significant differences for the variables evaluated as shown in Table 4.11. However, it can be seen in Figure 4.10 that the acceleration noise changed in the time of day condition variable by 0.023 for the evening and 0.065 in the night in comparison with the morning condition. Also, the posted speed limit variable demonstrated an increase of 0.07 in the 65 mph scenarios in comparison with the 45 and 55 scenarios. In addition, the 11 lane width scenarios show an increased significance of 0.05.

Table 4.11 Analysis of Variance for the Full Factorial for Acceleration Noise Zone 4.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	2	0.018	0.009	0.829	0.442
ToD	2	0.050	0.025	2.262	0.114
PSL	2	0.064	0.032	2.868	0.066
LW	2	0.009	0.004	0.393	0.677
Double Interaction					
ToD*PSL	4	0.011	0.003	0.239	0.915
ToD*LW	4	0.019	0.005	0.439	0.780
PSL*LW	4	0.060	0.015	1.358	0.261
Triple Interaction					
ToD*PSL*LW	8	0.095	0.012	1.067	0.400
Residuals	52	0.576	0.011		

*Statistical Significant Differences <0.05.

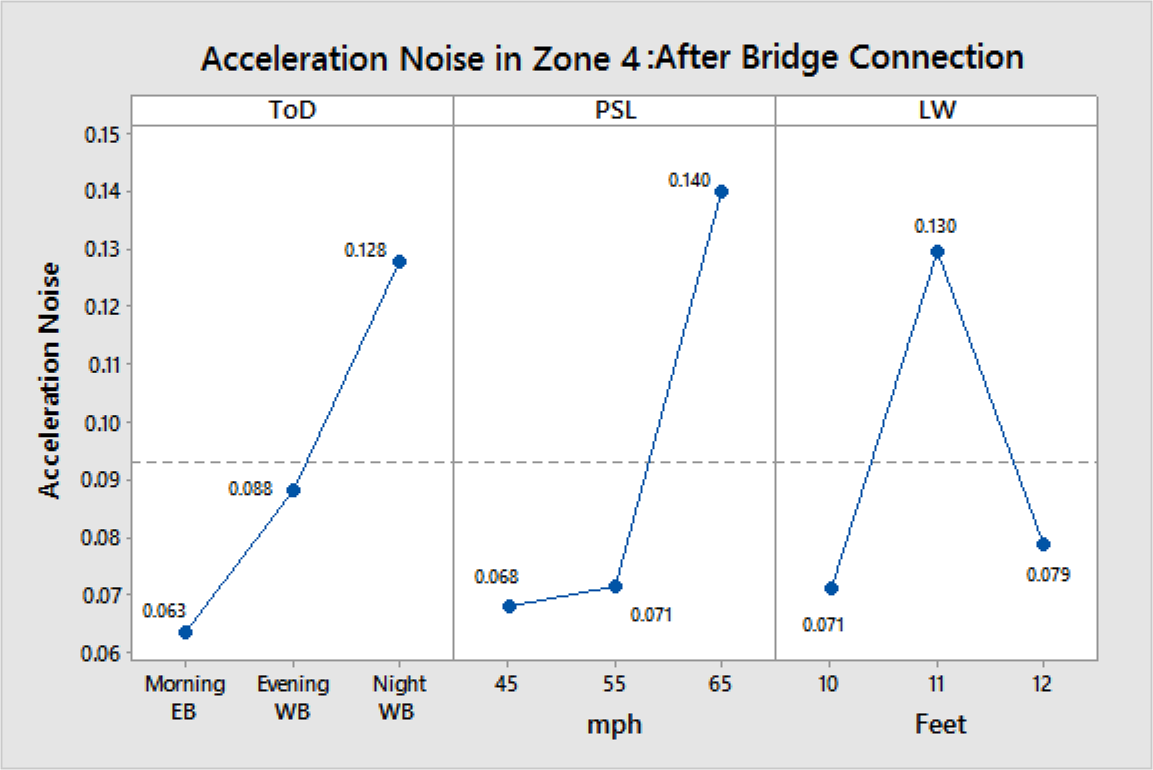

Figure 4.10 Acceleration Noise on each Variable Evaluated in Zone 4

In Zone 5, the main effects Blocks, ToD, and ToD*PSL resulted in a statistically significant difference, as seen in Table 4.12. The exit of the DTL, evening condition, lane width of 11 ft, and 55 mph posted speed limit presented approximately a 0.5 acceleration noise increase in comparison with the equivalent variations. Additionally, an increment of approximately 95% and 77% is observed between the 10 ft and 11 and 12 ft, respectively. The average acceleration noise for each variable in Zone 5 is illustrated in Figure 4.11.

Table 4.12 Analysis of Variance for the Full Factorial for Acceleration Noise Zone 5.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	2	0.154	0.077	4.143	0.021*
ToD	2	0.143	0.072	3.851	0.028*
PSL	2	0.101	0.051	2.726	0.075
LW	2	0.072	0.036	1.938	0.154
Double Interaction					
ToD*PSL	4	0.254	0.063	3.408	0.015*
ToD*LW	4	0.036	0.009	0.486	0.746
PSL*LW	4	0.074	0.019	0.995	0.419
Triple Interaction					
ToD*PSL*LW	8	0.127	0.016	0.851	0.563
Residuals	52	0.967	0.019		

*Statistical Significant Differences <0.05.

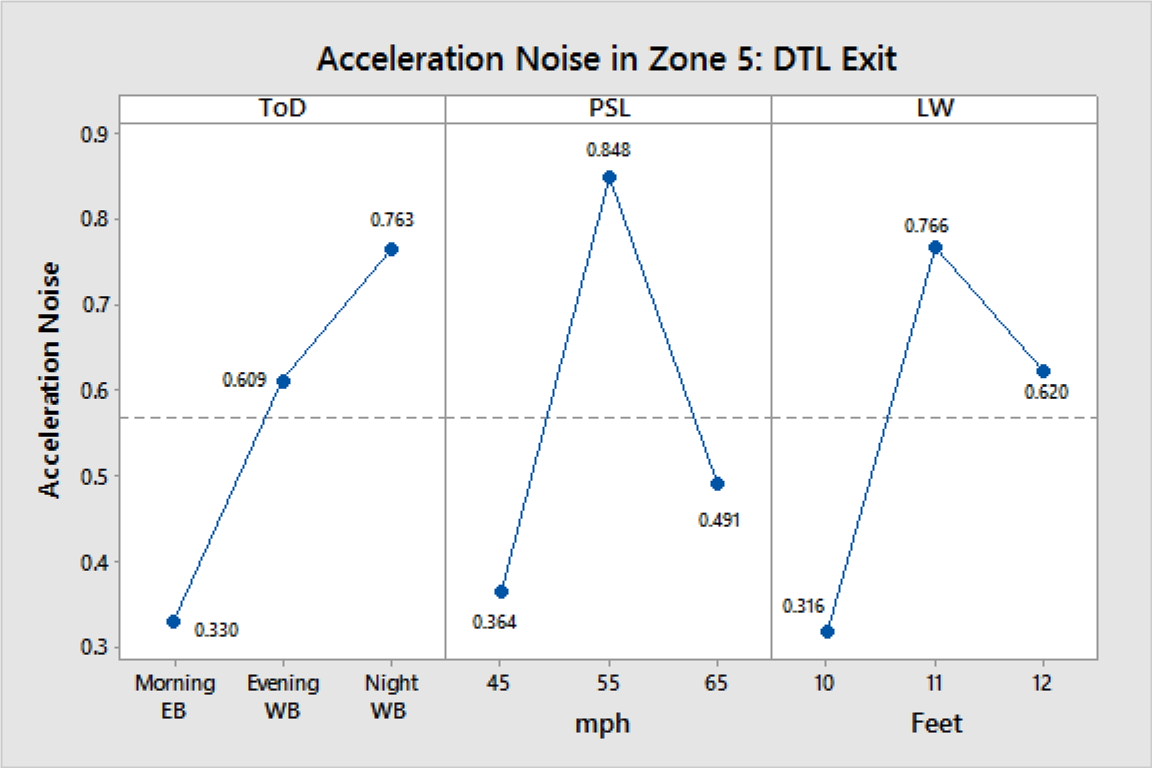

Figure 4.11 Acceleration Noise on each Variable Evaluated in Zone 5

Chapter 5 CONCLUSIONS

This research project consisted of understanding the behavior of subject drivers who were exposed to virtual scenarios of a multifaceted managed lane system using a cockpit driving simulator. A total of twenty-seven subject drivers, of different age groups, traveled three scenarios of the reversible DTL located in PR-22 with the purpose of evaluating operational and safety characteristics of the facility under study.

5.1 Research Findings

Based on the integrated analysis of Puerto Rico managed lanes, the following conclusions were achieved:

- Safety hazard points were confirmed as a higher variation in the acceleration noise variable since they were detected in four out of the five evaluated zones, namely DTL entrance (Zone 1), before the mainline bridge separation (Zone 2), in the bridge segment (Zone 3), and DTL exit (Zone 5). The only zone that did not reflect a significant difference was Zone 4, which is after the bridge segment separation.
- The variable *time of day conditions* affected negatively the acceleration noise of drivers, increasing the variations of the acceleration for Zones 2, 3, 4, and 5 to 0.017, 0.027, 0.04 ,and 0.16, respectively. As result of this increase, a higher crash frequency can be expected.
- The first hypothesis, which stated that subject drivers in scenarios with narrow lanes will have lower speed limits on managed lanes, was accepted. Drivers presented a lower speed on 10 ft lanes as compared with 11 and 12 ft lanes for the five zones of interest evaluated.

- Participants in scenarios with lane width of 10 ft present an operating speed reduction of approximately 7 to 10 mph with respect to the 11 ft lane width. Meanwhile, operating speed on lane widths of 11 ft were between 6 to 7 mph lower than 12 ft wide lanes (except from the Zone 1, DTL entrance, where the average speeds in 12 ft wide lanes were lower than those in 11 ft wide lanes).
- It was found from the statistical analysis that the optimum scenarios for the average speed in PR-22 DTL is a posted speed limit of 55 mph with 11 ft lane width.
- The second hypothesis, which is that subject drivers will tend to have higher speed profiles than the posted speed limit, was only accepted for a posted speed limit of 45 mph. Participants on scenarios with a 45 mph posted speed limit drove at higher speeds than the posted speed limit in all zones of interest. However, scenarios with a 55 mph posted speed limit resulted in higher operational speed only for Zones 1 and 4, whereas the operational speed of the subject drivers exposed to the 65 mph posted speed limit were lower than the posted speed limit in all the evaluated zones.
- Subject drivers with posted speed limits of 45 drove above 56.05 mph. Nevertheless, drivers' operational speeds in the 55 and 65 mph posted speed limit scenarios were lower, with an average speed of 54.94 and 53.56 mph, respectively.
- Zones 2 and 5 showed significant differences in the interaction between the time of day conditions and posted speed limit for the variables average speed and acceleration noise, respectively.
- For the Standard Deviation of Roadway Position (SDRP) variable, Zones 2 and 4 show a significant difference when comparing the evening vs morning and night vs morning condition scenarios. This could be due to the fact that these zones of

interest are before and after the bridge separation segment, when the subject driver made a decision on which lane should be taken. The other three zones of interest evaluated only have one lane where drivers are confined between two continuous concrete traffic barriers inside a facility that has a reversible lane operation with varying shoulder width on each side. Therefore, one should expect no significant variation in the SDRP of subject drivers.

- In this driving simulator research study, in 26% of the scenarios evaluated (44% EB-AM toward CBD; 56% WB-PM) the subject driver used the incorrect exit, exiting through the exclusive BRT lane. Moreover, 48% (10 out of 21) of these scenarios were in the 65 mph posted speed limit scenarios. This is probably due to the fact that the TDCs in the DTL exit didn't satisfy the recommended practice and fundamental principle for an effective TCD, namely, "give adequate time for proper response" (MUTCD 2009).

5.2 Future Tasks

In the short term, the researchers will emphasize developing different efficient solutions that address safety issues encountered in PR-22 DTL. These include feasible design changes and effective countermeasures that have a high potential for enhancing the existing managed lane facility. The outcome of this research will help provide recommendations that not only improve the express lane infrastructure, but also enrich driving behavior and the decision-making process in hazardous locations of the DTL. However, in the long term, a procedure will be followed to evaluate other potential countermeasures and design improvements that are not feasible in the short term.

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APPENDIX

A. Graphical Representation of Subjects' Driving Speed at Each Zone of Interest

B. Forms and Questionnaires Used in This Research Study

C. Poster Presented at Safer-Sim Symposium

A. Graphical Representation of Subjects' Driving Speed at Each Zone of Interest

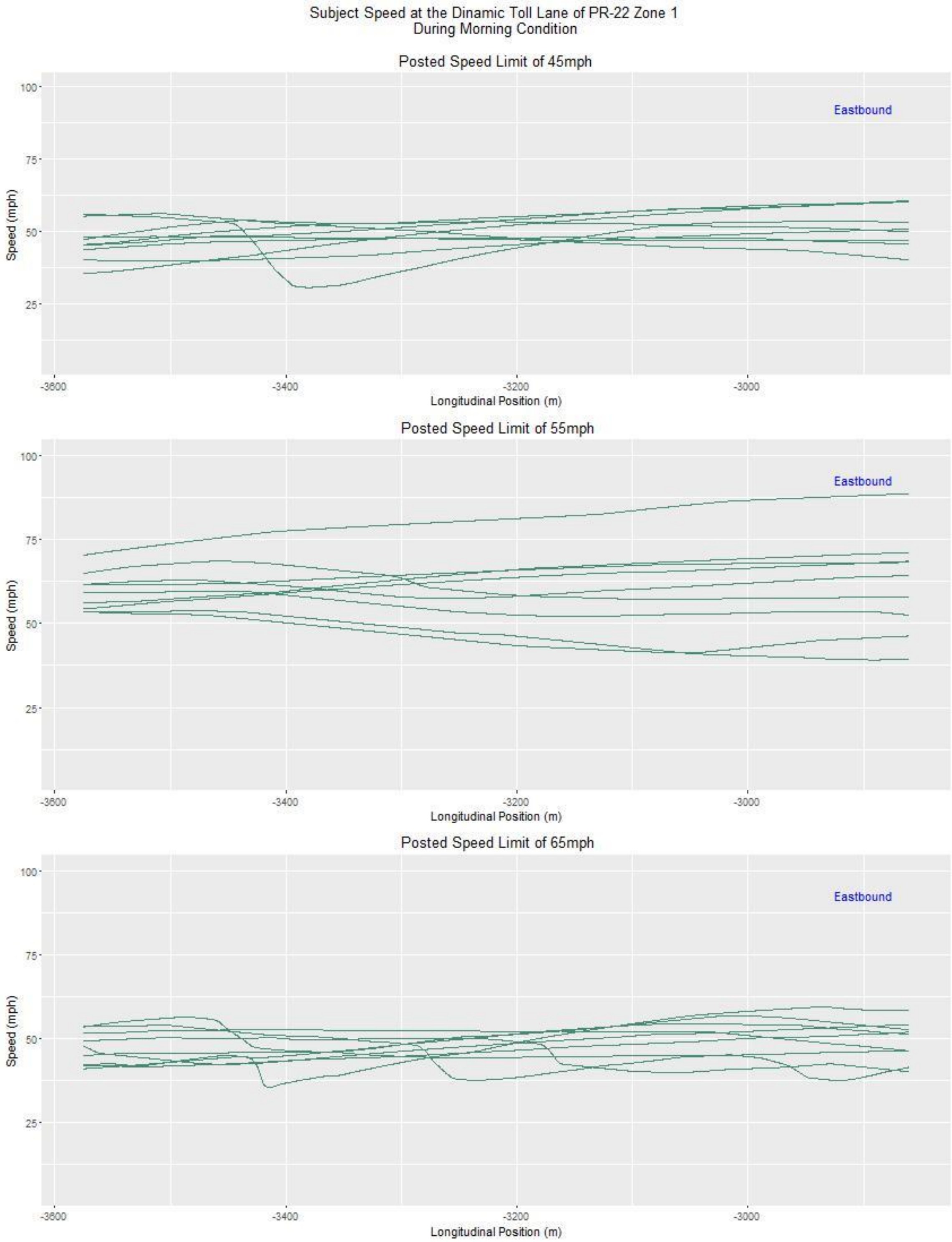


Figure A.1 Subject Speed at the DTL in Zone 1 During Morning Condition for 45, 55 and 65 mph Posted Speed Limit

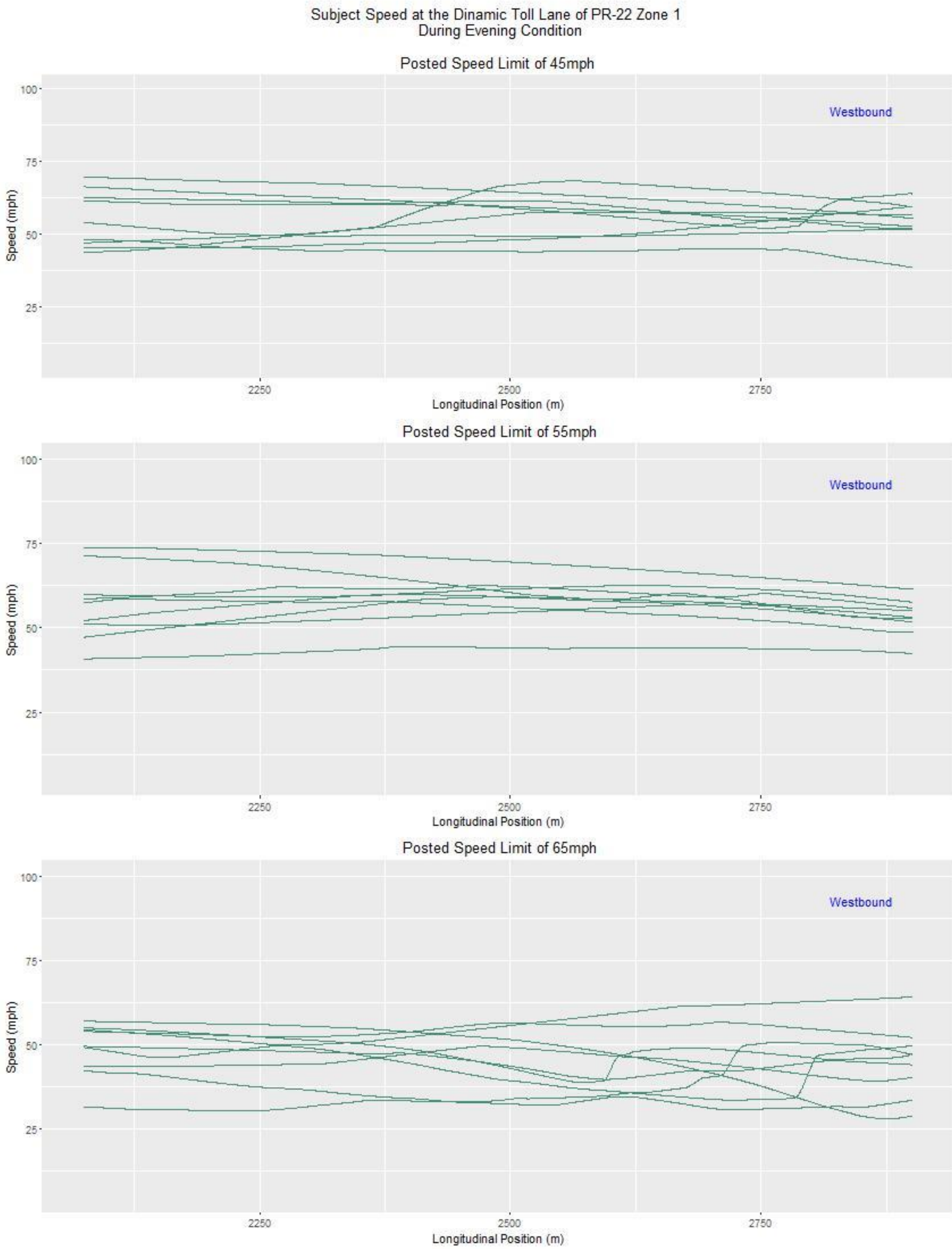


Figure A.2 Subject Speed at the DTL in Zone 1 During Evening Condition for 45, 55 and 65 mph Posted Speed Limit

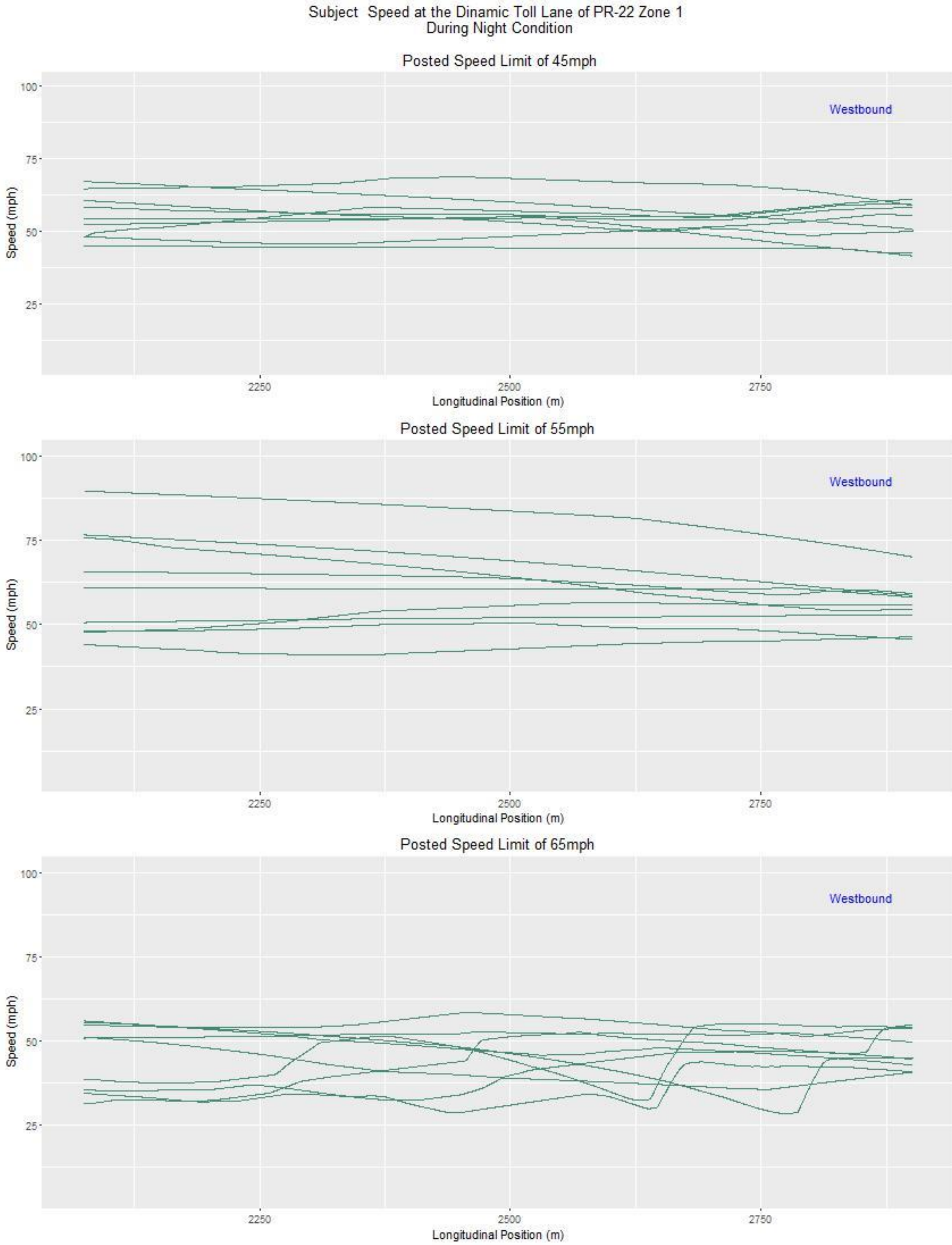


Figure A.3 Subject Speed at the DTL in Zone 1 During Night Condition for 45, 55 and 65 mph Posted Speed Limit

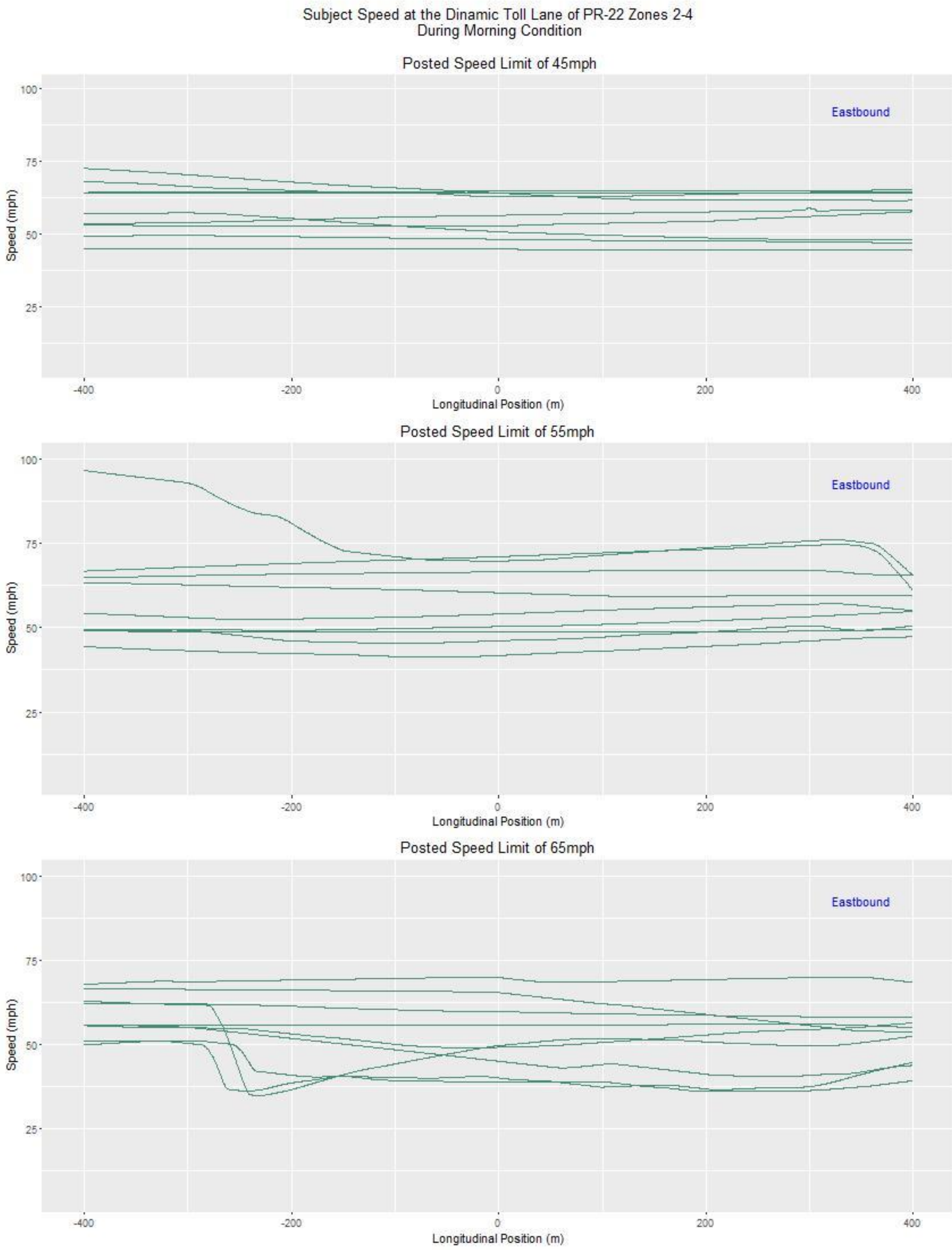


Figure A.4 Subject Speed at the DTL in Zones 2, 3 and 4 During Morning Condition for 45, 55 and 65 mph Posted Speed Limit

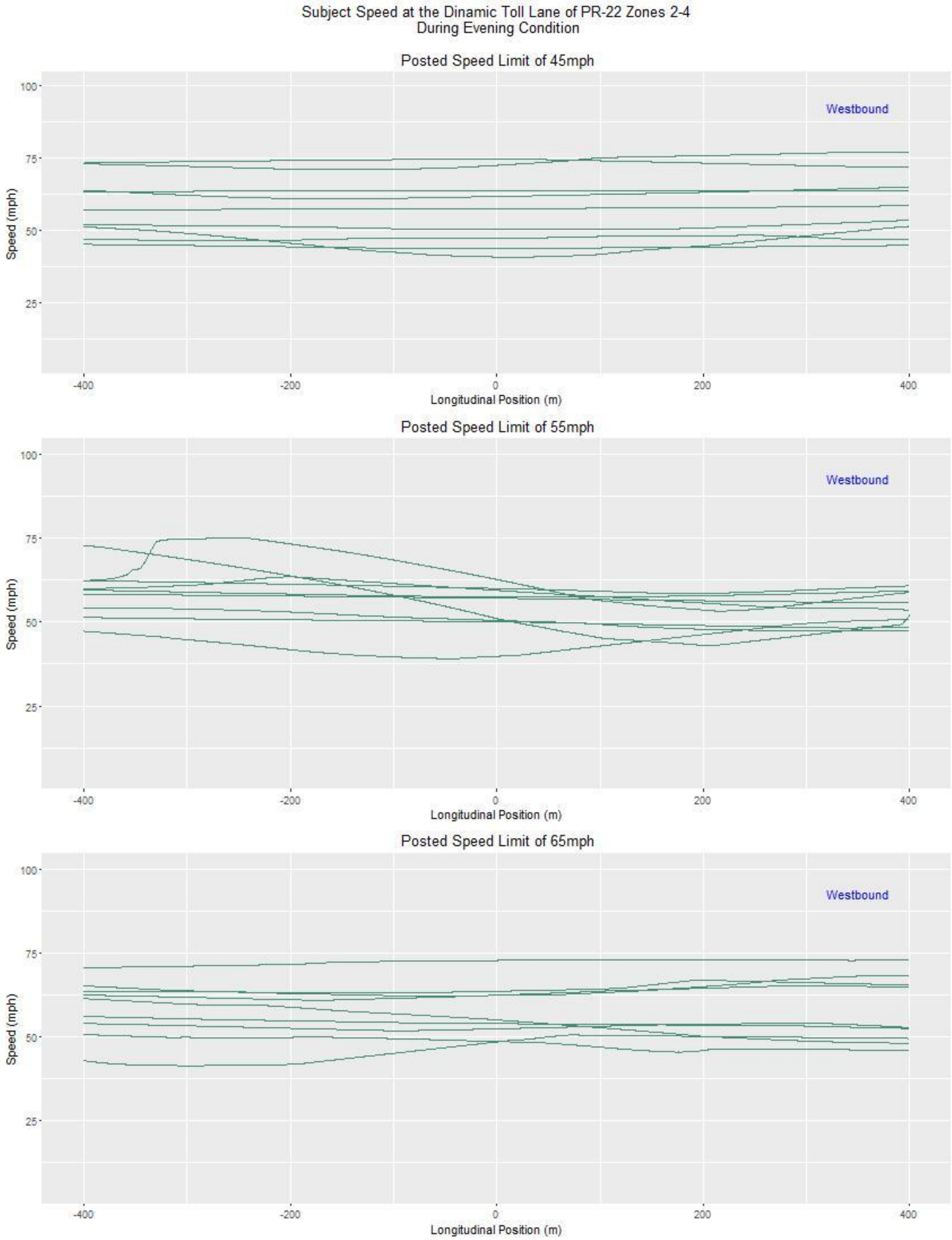


Figure A.5 Subject Speed at the DTL in Zones 2, 3 and 4 During Evening Condition for 45, 55 and 65 mph Posted Speed Limit

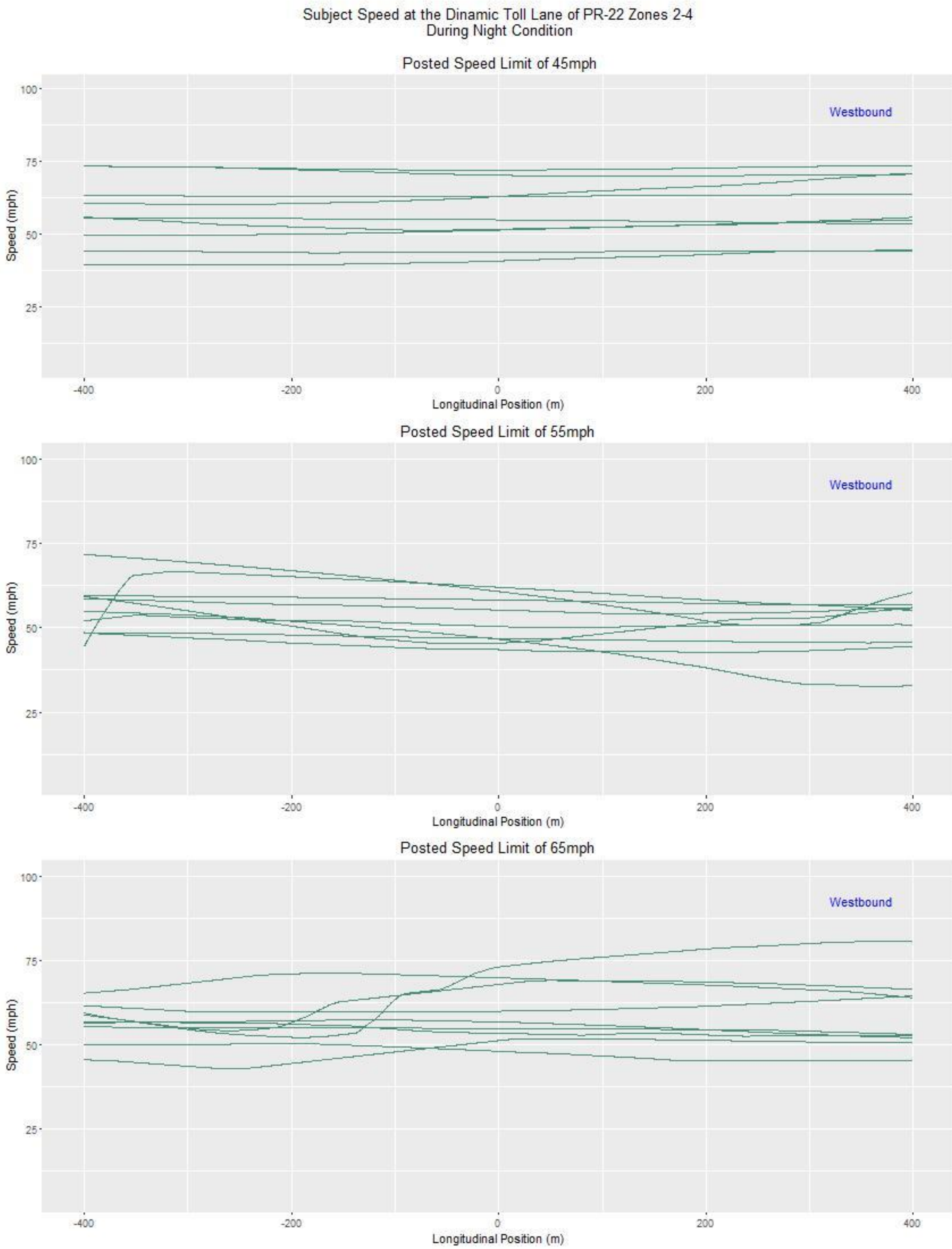


Figure A.6 Subject Speed at the DTL in Zones 2, 3 and 4 During Night Condition for 45, 55 and 65 mph Posted Speed Limit

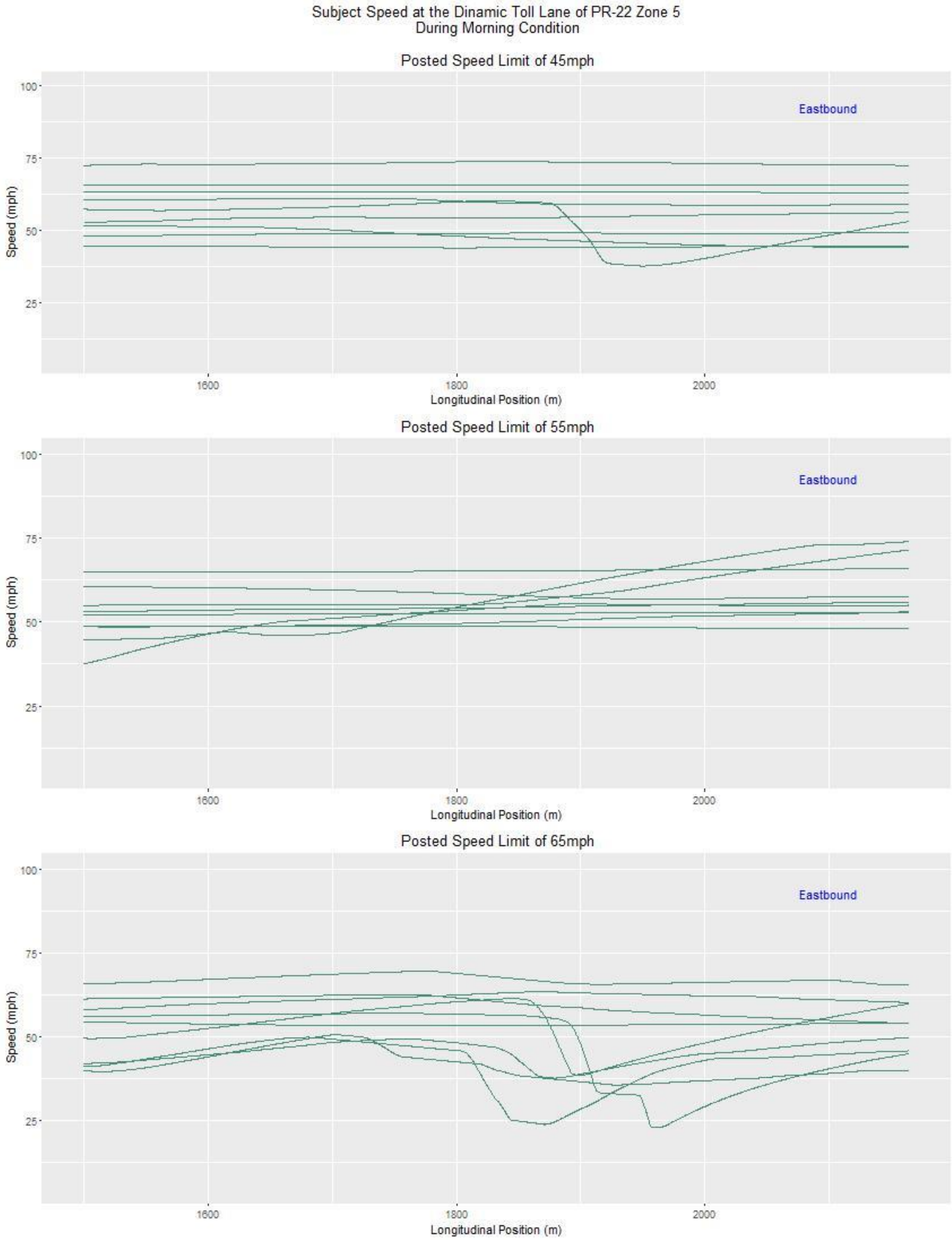


Figure A.7 Subject Speed at the DTL in Zone 5 During Morning Condition for 45, 55 and 65 mph Posted Speed Limit

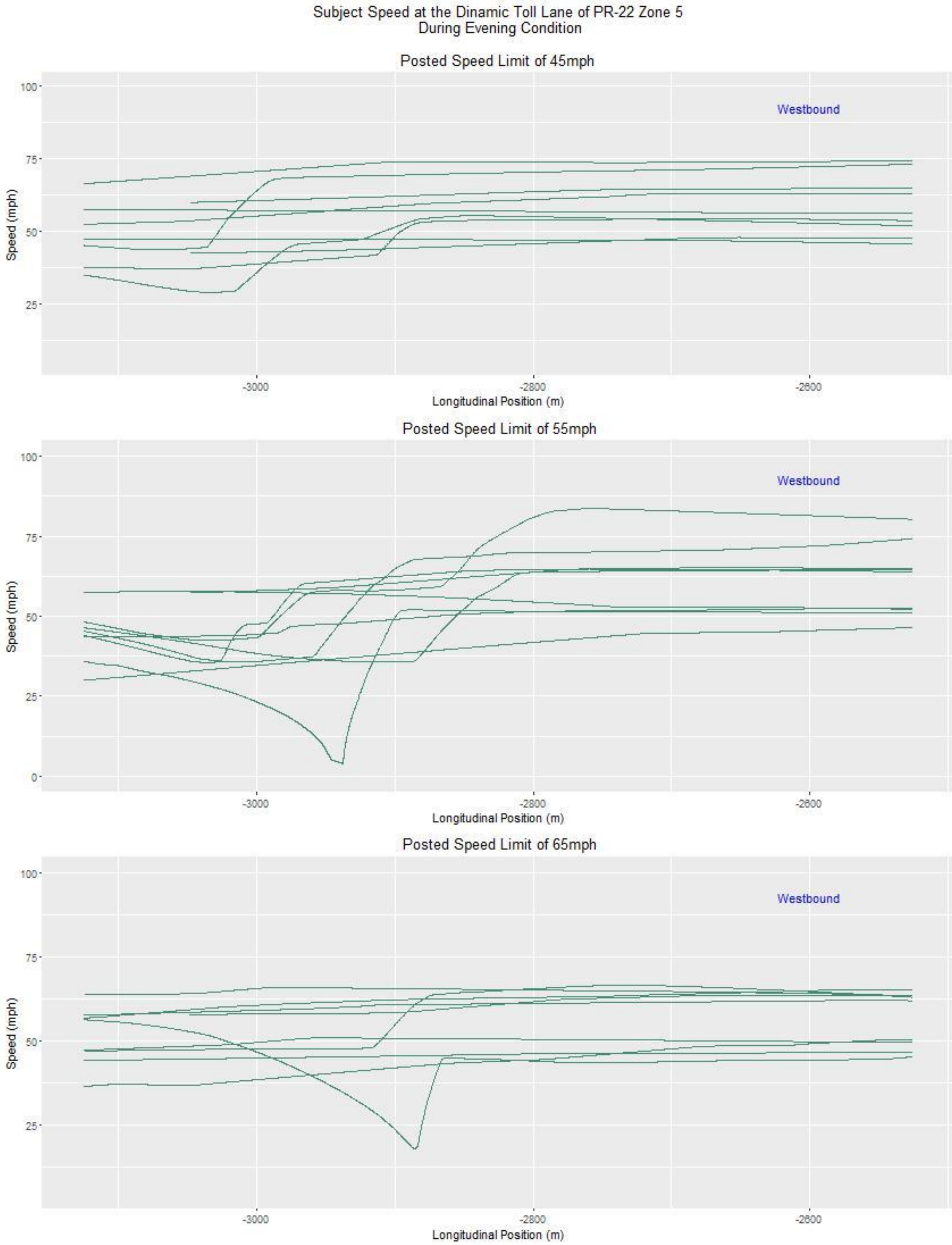


Figure A.8 Subject Speed at the DTL in Zone 5 During Evening Condition for 45, 55 and 65 mph Posted Speed Limit

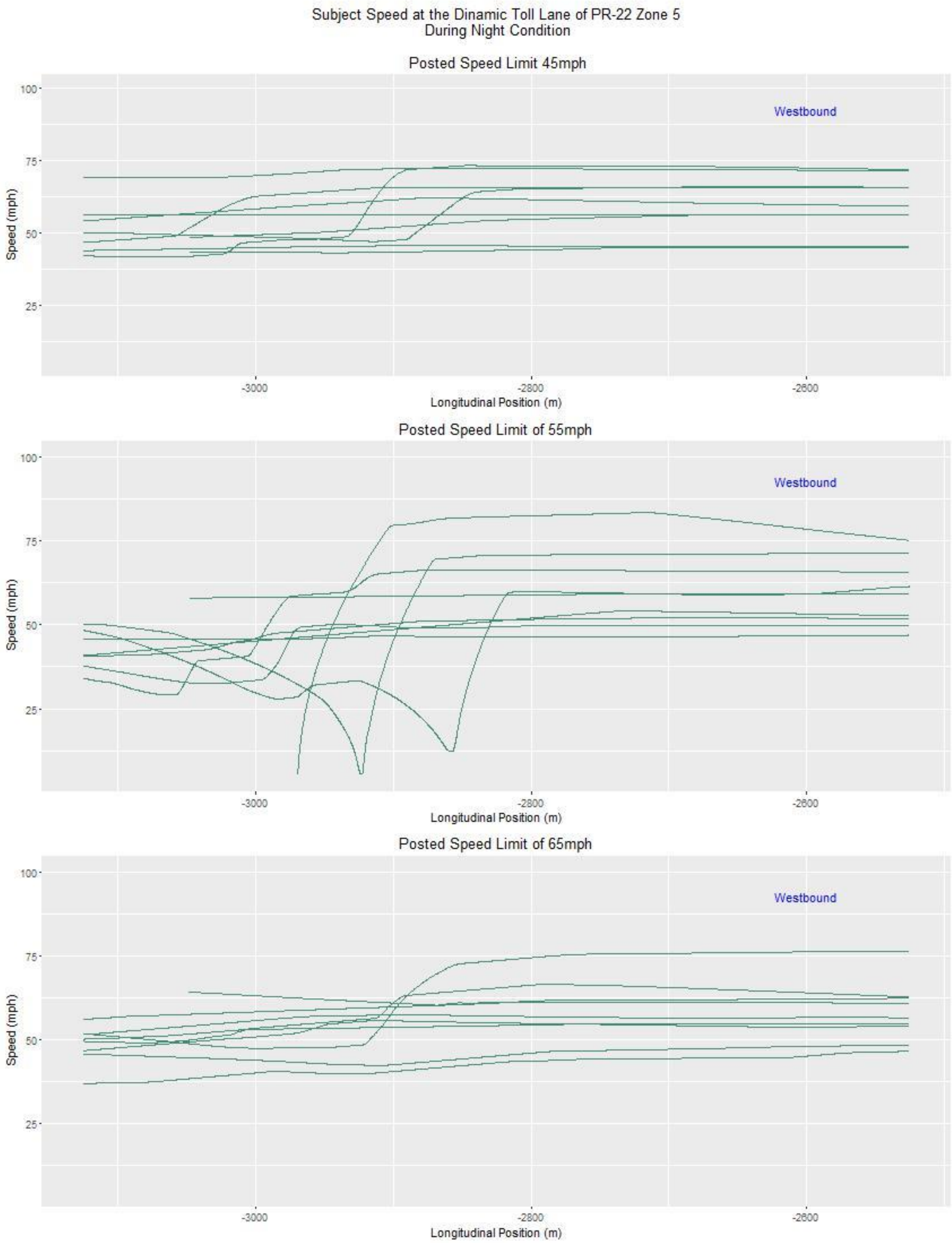


Figure A.9 Subject Speed at the DTL in Zone 5 During Night Condition for 45, 55 and 65 mph Posted Speed Limit

B. Forms and Questionnaires Used in This Research Study

ESTUDIO DE SIMULACIÓN DE PLAZA DE PEAJE

FORMULARIO DE CONSENTIMIENTO INFORMADO

Investigador Principal: Dr. Didier Valdés Díaz

Co-Investigador Principal: Johnathan J. Ruiz González, Ricardo García Rosario, Bryan Ruiz Cruz y Enid Colón Torres.

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

Título de Proyecto: Operational and Safety-Based Analyses of High Occupancy Toll Lane Configurations

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 Administración de Investigación e Innovación en Tecnología (RITA, por sus siglas en inglés).

4. ¿CUÁL ES EL PROPÓSITO DE ESTE ESTUDIO?

El propósito de este estudio es evaluar el comportamiento del conductor bajo varias condiciones de tráfico en configuraciones específicas de una plaza de peaje.

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 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 manejará a través de un trayecto que tomará cerca de 4 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 si usted ha experimentado cinetosis (mareos) anteriormente mientras viaja o maneja un vehículo real, usted no debería participar en este experimento.

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 de 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.

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 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 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 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, Profesor Didier Valdés, al (787) 832-4040 ext. 3809 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 cpshi@uprm.edu. Una copia de este formulario de consentimiento será proveída a usted 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 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, 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

Fecha: _______________
Número de participante: _______________

LABORATORIO DE SIMULACIÓN DE TRANSPORTACIÓN

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 dado 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.

Sección 1: Datos demográficos

Sexo: ☐ Hombre ☐ Mujer

Fecha de nacimiento: Mes____ / Día____ /Año____ Edad: ___

Raza/Etnicidad: ☐ Afroamericano ☐ Asiático
(marque todas las que apliquen) ☐ Caucásico ☐ Hindú
☐ Hispano ☐ Otra

¿Usted ha participado en un estudio en este laboratorio en el pasado? ☐ Sí ☐ No

Sección 2: Historial de Manejo

¿Aproximadamente que edad tenía cuando obtuvo su licencia de conducir? ____Años___ Meses

¿Aproximadamente cuantas millas manejó la semana pasada?

☐ Menos de 50 ☐ Menos de 100 ☐ 100 a 200 ☐ 200 a 300 ☐ 300 a 500 ☐ Más de 500

Restricciones en su licencia de conducir:

☐ Ninguna ☐ Espejuelos ☐ Lentes de contacto ☐ Otra: __________

¿Experimenta síntomas de mareo al manejar o al ir de pasajero en un vehículo? ☐ Sí ☐ No
(Si su respuesta fue Sí, informe de inmediato al investigador)

¿Hay algún otro factor relacionado a su historial de manejo o su salud, incluyendo algún medicamento, que pueda causar que usted maneje mejor o peor que otros conductores?

☐ Sí ☐ No

Si su respuesta fue Sí, indique:____

Comentarios del Participante:

Selecciona la opción que mejor describa su experiencia, siendo 5 excelente y 0 deficiente.

	5	4	3	2	1	0
Sensación de que el Vehículo Fuese Real						
Aceleración						
Frenos						
Sonido						
Imagen						

Comentarios adicionales:

____

____

____

C. Poster Presented in Safer-Sim Symposium

Operational and Safety-Based Analysis of PR-22 Dynamic Toll Lane (DTL) Using UPRM Driving Simulator

Johnathan J. Ruiz-González[1], Ricardo E. García-Rosario[2], Bryan Ruiz-Cruz[1] and Enid M. Colón-Torres[2]
Dr. Didier Valdés-Díaz, Dr. Benjamín Colucci-Ríos; Co-PI's
University of Puerto Rico at Mayagüez
[1] Graduate Students, [2] Undergraduate Students

SAFETY RESEARCH USING SIMULATION
UNIVERSITY TRANSPORTATION CENTER

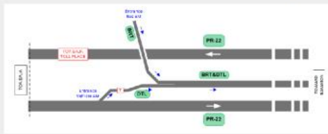
ABSTRACT

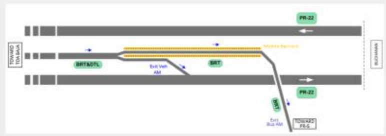
- PR-22 Dynamic Toll Lane (DTL) is a 6.44 mile (10.4 km) reversible facility in the median within a stretch of freeway PR-22.
- Conflict points have been identified in the DTL system at the entrance, transition of freeway, bridge piers approaches and freeway exit at both eastbound and westbound direction.
- Full Factorial Design of 3^K with 27 scenarios will be used to evaluate the safety performance of the DTL.
- This research project explains the process of generating the representative driving scenarios using the UPRM driving simulator, the rationale of variables selected and the assembly of the DTL base scenario.

INTRODUCTION

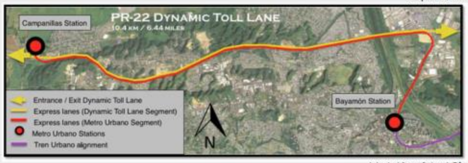
- The DTL, administered through a Public Private Partnership (PPP) between the Puerto Rico Highway and Transportation Authority (PRHTA) and Autopistas Metropolitanas de Puerto Rico (Metropistas) LLC, is located at the median of the PR-22 that connect the municipalities of Toa Baja and Bayamón.
- An Annual Average Daily Traffic (AADT) of 6,000 vpd was recorded inside the DTL for year 2015.
- DTL traffic is shared by private vehicles and Bus Rapid Transit (BRT) system that travel from the Tren Urbano Bayamón Station to the BRT Campanilla Station.
- Three (3) traffic schemes:
  - AM peak: inbound towards Bayamón
  - PM peak: outbound towards Toa Baja
  - Holidays and weekends

DTL CONFLICT POINTS: PR-22 EASTBOUND AND WESTBOUND

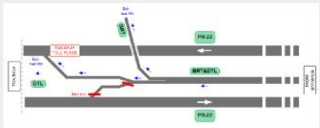


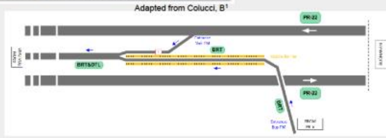


Adapted from http://metropistas.com/pages/DTL.apsx [2]



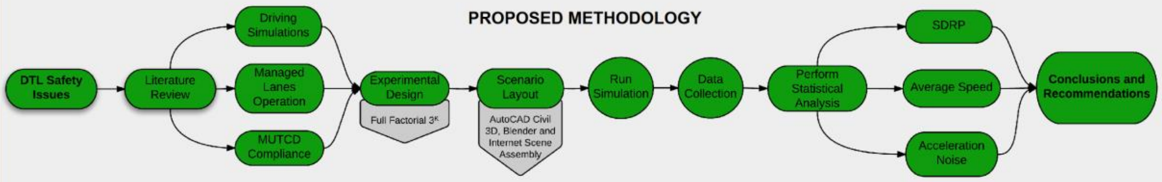
Adapted from Colucci, B[1]





Adapted from http://metropistas.com/pages/DTL.apsx [2]

PROPOSED METHODOLOGY



OBJECTIVES

- Evaluate the difference in the subject driver's behavior with respect to lane width, speed limit and time of day conditions.
- Identify highway safety hazards points inside the DTL.
- Evaluate a potential relationship between lane width and speed limit on managed lanes.

DTL EXPERIMENTAL DESIGN

- A Full Factorial Design of 3^K with twenty seven (27) scenarios.
- Three independent variables:
  - Lane width (12, 11 and 10 feet)
  - Speed limit (65, 55 and 45 mph)
  - Time of day condition (morning, evening and night)
- A Block Design will be used to replicate the basic experiment with a homogenous group to quantify the effect of each treatment.

DTL ON-GOING RESEARCH TASKS

- **BRIDGE PIERS (~km 15.0):**
  - Separation of the mainline within the DTL which creates a merging and diverging scenario.
- **SIGNAGE CONFIGURATION:**
  - Combination of overhead and roadside sign
  - Regulatory BRT exclusive lane sign
- **DTL EXITS (km 12 and 22):**
  - Eastbound exit is on the left
  - Westbound exit is on the right

EXISTING PR-22 CONDITION — UPRM DEVELOPED SCENARIOS

DTL SIMULATED SCENARIOS

	AGE GROUP	DIRECTION	SUBJECT MATTERS								
			1	2	3	4	5	6	7	8	9
BLOCK 1	18-25	EASTBOUND	65-10*	55-11	45-12	45-10	65-12	55-10	55-12	65-11	45-11
		WESTBOUND	65-10	55-11	45-12	45-10	65-12	55-10	55-12	65-11	45-11
		WESTBOUND NIGHT	65-10	55-11	45-12	45-10	65-12	55-10	55-12	65-11	45-11
BLOCK 2	AGE GROUP	DIRECTION	1	2	3	4	5	6	7	8	9
	26-45	EASTBOUND	55-12	65-11	45-11	65-10	55-11	45-12	45-10	65-12	55-10
		WESTBOUND	55-12	65-11	45-11	65-10	55-11	45-12	45-10	65-12	55-10
		WESTBOUND NIGHT	55-12	65-11	45-11	65-10	55-11	45-12	45-10	65-12	55-10
BLOCK 3	AGE GROUP	DIRECTION	1	2	3	4	5	6	7	8	9
	46-70	EASTBOUND	45-10	65-12	55-10	55-12	65-11	45-11	65-10	55-11	45-12
		WESTBOUND	45-10	65-12	55-10	55-12	65-11	45-11	65-10	55-11	45-12
		WESTBOUND NIGHT	45-10	65-12	55-10	55-12	65-11	45-11	65-10	55-11	45-12

LEGEND: *Each cell corresponds to a combination of speed limit and leght width for a particular age group, direction, and subject matter (65 mph speed limit with lane width of 10 feet for subject matters number, age group 18-25 and eastbound direction).

FUTURE TASKS

SHORT TERM:
- Design a configuration with safety countermeasures to improve the existing As-Build in-service conditions.
- Recruitment and trainning of subject matters participant of the different age group.
- Perform statistical analysis of the recorded data.
- Present recommendations of potential highway safety countermeasure based on research findings.

LONG TERM:
- Collaborate with others UTC participanting universities to improve the research study.
- Evaluate proposed safety countermeasure in the DTL mainline.

REFERENCES

1. Colucci, B. Dynamic Toll Lane: A Success Story as Part of the Public Private Partnerships in the Commonwealth of Puerto Rico. (2015). Proceedings of the 2nd International Conference on Public-Private Partnerships. Austin, Texas, U.S.A.
2. Autopistas Metropolitanas de Puerto Rico, LLC. (2015). Dynamic Toll Lane (DTL) Access. Retrives May 27 from: http://metropistas.com/pages/DTL.apsx

ACKNOWLEDGMENTS

- Autopistas Metropolitanas de Puerto Rico, LLC, Puerto Rico Highway and Transportation Authority (PRHTA) and CMA Architects and Engineers, LLC for providing the PR-22 Design Drawings to develop the DTL simulated scenarios.
- Research and Innovative Technology Administration (RITA) for supporting this collaborative research project as part of the UTC SaferSim.