Operation and Safety Evaluation of Roadway Geometrics and Posted Speed Limit in the PR-22 Dynamic Toll Lane Using a Driving Simulator

By

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ABSTRACT

This research presents the initial in-depth study of the PR-22 Dynamic Toll Lane (DTL) using the University of Puerto Rico at Mayagüez (UPRM) driving simulator, the first of its kind in Puerto Rico. The PR-22 DTL is a managed lane facility implemented in Puerto Rico in 2011 and operated by Autopistas Metropolitanas de Puerto Rico, LLC (METROPISTAS - an ABERTIS Company). This system is used to improve the level of service and mitigate the effect of traffic congestion in the Metropolitan area. The managed lane system combines reversible lane operations shared by private vehicles, as well as a Bus Rapid Transit (BRT).

Driving behavior and potential safety hazards associated with this type of facility were evaluated using fifty-four (54) subject drivers across three independent variables that represented each 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 Condition (i.e. morning, evening, and night). These treatment combinations were measured through three dependent variables as part of the study, namely, Operational Speed, Acceleration Noise and Lateral Position. Furthermore, simulation data of these variables were collected in seven zones of interest that represented safety hazard points inside the PR-22 DTL, specifically the DTL entrance, pocket lanes at the left side, before, during and after the bridge separation, pocket lanes at the right side and at the DTL Exit. The integrated statistical data analysis consisted of two methods, General Linear Model (linear model) and Random Forest Model (non-linear model).

Research findings showed that subject drivers have a higher operational speed in narrow lanes (less than 12 feet) and used the incorrect DTL exit in 22% of all the scenarios. In addition, an

increase in the variable acceleration noise was detected at the DTL exit for the Time of Day Condition variable, where nighttime condition resulted with the highest acceleration noise. The most important variable in the Random Forrest Model for the Operational Speed variable is the Posted Speed Limit variable that records the highest Increase in Mean Square Error Percentage (IncMSE%) in six of the seven zones evaluated. The Lane Width variable was the most important variable in the Random Forest Model for the Acceleration Noise variable. Lastly, as it was expected the Time of Day Condition is the most important variable that affects the Lateral Position variable. The findings demonstrated that the non-linear model validates the results of the linear model evaluated.

Based on the findings of this research, a new configuration of geometric elements, as well as a new posted speed limit in the PR-22 DTL is proposed. This recommendation can be adapted in the future by the administrators of the PR-22 DTL, METROPISTAS, to contribute to improve the safety and operation of the facility.

Resumen

Esta investigación presenta el primer estudio a profundidad del Carril de Peaje Dinámico (DTL, por sus siglas en inglés) utilizando el simulador de conducción de la Universidad de Puerto Rico en Mayagüez (UPRM), el primero de su tipo en Puerto Rico. El DTL de la PR-22 es una instalación de carriles administrados implementada en Puerto Rico en 2011 y operada por Autopistas Metropolitanas de Puerto Rico, LLC (METROPISTAS – una Compañía de ABERTIS). Este sistema se utiliza para mejorar el nivel de servicio y mitigar el efecto de la congestión del tráfico en el área metropolitana. El sistema de carriles administrados combina operaciones de carriles reversibles compartidos por vehículos privados, así como un Autobuses de Tránsito Rápido (BRT, por sus siglas en inglés).

El comportamiento del conductor y los posibles riesgos de seguridad asociados con este tipo de instalación se evaluaron utilizando cincuenta y cuatro (54) conductores y tres variables independientes que representaban cada tratamiento, Ancho de Carril (p.e. 12, 11 y 10 pies), Límite de Velocidad Rotulado (p.e. 65, 55 y 45 mph) y la Condición del Día (mañana, tarde y noche). Se recopilaron tres variables dependientes como parte del estudio, Velocidad Operacional, Ruido de la Aceleración y la Posición Lateral. Además, los datos de simulación de estas variables se recolectaron en siete zonas de interés que representaban puntos peligrosos de seguridad dentro del DTL de la PR-22, específicamente la entrada del DTL, carriles de bolsillo en el lado izquierdo, antes, durante y después de la separación del puente, carriles de bolsillo en el lado derecho y en la salida del DTL. El análisis integrado de los datos estadísticos consistió en dos métodos, a saber, el Modelo Lineal General (modelo lineal) y el Modelo *Random Forest* (modelo no-lineal).

Los resultados de la investigación mostraron que los sujetos tienen una Velocidad Operacional más alta en carriles con ancho menor al de 12 pies y usaron la salida DTL incorrecta en el 22% de todos los escenarios. Además, se detectó un aumento en la variable Ruido de la Aceleración en la salida de DTL para la variable de Condición del Día, donde la condición nocturna resultó con el ruido de la aceleración más alto. El modelo de *Random Forest* mostró que la variable de Velocidad Limite Rotulada resultó con el mayor incremento porcentual del Error Cuadrado Medio (MSE, por sus siglas en inglés) en la variable Velocidad Operacional en seis de las siete zonas evaluadas. La variable Ancho de Carril resultó ser la variable más influyente en el Modelo de *Random Forest* para la variable Ruido de la Aceleración. Por último, como fue esperado la variable de Condición del Día resultó ser la que más afecta la variable de Posición Lateral. Los hallazgos encontrados demostraron que el modelo no-lineal valida los resultados obtenido en el modelo lineal evaluado.

Con base en los hallazgos de esta investigación, se propone una nueva configuración de elementos geométricos, así como un nuevo límite de velocidad en el DTL de la PR-22. Esta recomendación puede ser adaptada en el futuro por los administradores del DTL, METROPISTAS, para contribuir a la seguridad y la operación dentro de la facilidad.

Dedication

To my future wife Melissa Valentín Millán

To my brother Marcus Ruiz González

To my parents, Mayra González Rivera and Hector Ruiz Figueroa

For their support and efforts over the past years that motivated me to achieve my goal and became a productive person in the society.

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LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
BRT	Bus Rapid Transit
DTL	Dynamic Toll Lane
EB	Eastbound
ETC	Electronic Toll Collection
FHWA	Federal Highway Administration
HOT	High Occupancy Toll
HOV	High Occupancy Vehicle
HSM	Highway Safety Manual
ISA	Internet Scene Assembler
ITE	Institute of Transportation Engineers
LLC	Liability Company
LOS	Level of Service
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
ORT	Open Road Tolling
PPP	Public Private Partnership
PRHTA	Puerto Rico Highway and Transportation Authority
RDG	Roadside Design Guide
RLS	Reversible Lane System
RTI	RealTime Technology Inc.
TCD	Traffic Control Devices
TOT	Truck Only Toll
UCF	University of Central Florida
UI	University of Iowa at Iowa City
UMass	University of Massachusetts at Amherst
UPRM	University of Puerto Rico at Mayagüez
UTC	University Transportation Center
UW	University of Wisconsin at Madison
VPD	Vehicles per Day
WB	Westbound

CHAPTER 1. INTRODUCTION

The American Association of State Highway and Transportation Officials (AASHTO) in 2011, refer to the term geometrics to the physicals aspect of the roadway that include horizontal and vertical alignment as well as road curvatures, road and lanes width, amongst others (AASHTO, 2011). The response performed by the drivers are related with the stimulus created by physical component of the road. In 2011, Fisher et al., stated that a particular geometric design, such as the lane width or curvature, implicitly provide information to the driver on how fast to drive, when to slow down and where the curves are approaching (Fisher, 2011). Therefore, the selection of a good design or redesign of the roadway geometric is important since a poor design can result in crashes and/or fatalities. Moreover, it is imperative to understand the effects of the geometric designs in the driver's response specially in freeway facilities. Hence, the driving simulation has been an important technology used to evaluate the effects of the different geometric roadway designs without spending a significant amount of money or harming any driver.

Driving simulators is a well-known technology used by researchers in engineering, medicine, computer science, amongst others, to study pertinent aspects of their respective discipline (Fisher et al, 2011). The use of this technology has reduced the time needed to perform research studies as well as the cost in the development of environments and situations. In transportation engineering, this cost-effective tool provides the opportunity to investigate existing or proposed conditions in a roadway whereas traditional investigations are based in before and after studies. Transportation researchers have used driving simulators to study several aspects such as: human factors, road safety, signage, pavement markings, traffic control devices, response and reaction time, potential countermeasures, and roadway geometrics. However, driving simulation has not been used to study the geometrical aspects and its effect on safety and operational on managed lanes facilities.

Managed lanes are highway lanes or sets of lanes for which variable operational strategies such as direction of travel, tolling, pricing, and/or vehicle type or occupancy requirements are implemented and managed in real-time in response to changing conditions (MUTCD, 2009). The most used strategies in managed lanes facilities are: the vehicle eligibility, pricing (fixed or dynamic) and restriction of access points. Over the last two decades, the increase of these facilities has served to reduce the travel time and traffic congestion on high occupancy lanes specially in urban roadways during morning and afternoon peak hours.

1.1 PUERTO RICO DYNAMIC TOLL LANE

As result of traffic congestion issues, a Public Private Partnership (PPP) was created to design, build, and operate the first ever reversible Dynamic Toll Lane (DTL) system in Puerto Rico. The partnership between the Puerto Rico Highway and Transportation Authority (PRHTA) and the Autopistas Metropolitanas de Puerto Rico, LLC (METROPISTAS) was created in June 27, 2011 for a 40-year period as part of Act No. 29 of June 8, 2009, known as the PPP Act (PPPA, 2009). In 2016, the partnership was renegotiated and now is a 50 year-contract. As part of the partnership, PRHTA delegated to METROPISTAS the rehabilitation, conservation, improvement of the freeway infrastructure and enhancement of safety to all road users of two of the most used corridors in Puerto Rico, PR-22 and PR-5. The PR-22 is one of the most traveled freeway corridors in Puerto Rico and provides mobility to thousands of drivers every day to the metropolitan area with an

Annual Average Daily Traffic (AADT) of 110,923 vehicles per day (vpd) for the year 2007 (PRHTA, 2016).

The PPP agreement states that METROPISTAS will design, operate and manage the PR-22 (DTL). The PR-22 DTL is a managed lane system connecting the municipalities of Toa Baja and Bayamón, using a two-lane express freeway facility that incorporates variable operational strategies such as: reversible lane, congestion pricing and an exclusive system throughout the 6.46 miles (10.4 km) of the roadway. Therefore, heavy vehicles are not allowed to travel throughout this facility; only passenger cars as well a Bus Rapid Transit (BRT) systems, knows as Metro Urbano, are allowed in this express lane, as illustrated in Figure 1-1. As it is built, the system is designed to mitigate high volumes during morning and evening peak-hours and to improve freeway safety. As mentioned before, the DTL is a reversible facility and its operation variates between three traffic schemes, namely during the morning peak (EB direction), afternoon peak (WB direction), and holidays and weekends, which depends on the traffic flow and the direction in which it is needed. In addition, using congestion pricing techniques, the DTL adjusts, in real-time, the price of the toll, improving the traffic flow and Level of Service (LOS) that is guaranteed by 13 cameras located on specific points throughout the DTL.

Figure 1-1 Passenger Cars and BRT exit lanes inside the DTL in the EB Direction.

An extension of 2 km of the PR-22 DTL in the EB direction was opened to vehicular traffic in April of 2017. This extension reduced peak-hour congestion queue in the EB direction using one lane of the PR-22 in the WB direction. This research project only considers the original 10.4 km, therefore the evaluation of the extended segment was beyond the scope of this study.

1.2 RESEARCH PROBLEM

DTL potential safety and operational related issues have appeared due to driver behavior. This managed lane served as an express lane to the PR-22 under peak hours, however the posted speed limit inside the DTL (45 mph in the EB and 40 mph in the WB directions) are lower than the posted speed limit in PR-22 (55 mph). Commuters inside the DTL have a tendency of traveling at higher speeds than the current posted speed limit in both directions. Possible reasons for this tendency could be associated with the fact that outside the DTL, the posted speed limit is higher, and the commuters continue at a higher operating speed. The information gathered by the administrator of the PR-22 DTL between December 2016 and February 2017, demonstrated a higher speed in both direction inside the DTL. An operating speed from 47 to 55 mph is observed in the DTL. Nevertheless, the range of the average speed in the entrance is between 47 and 49 mph. However, inside the DTL, the range increased between 53 and 55 mph. Table 1-1 presents the average operating speed of the drivers inside the PR-22 DTL. Law enforcement has been applied to reduce the operating speeds inside the DTL, however this affects the drivers' decision on whether to use the DTL, since they are paying a higher toll, but are forced to travel at a lower speed than other motorists outside the DTL.

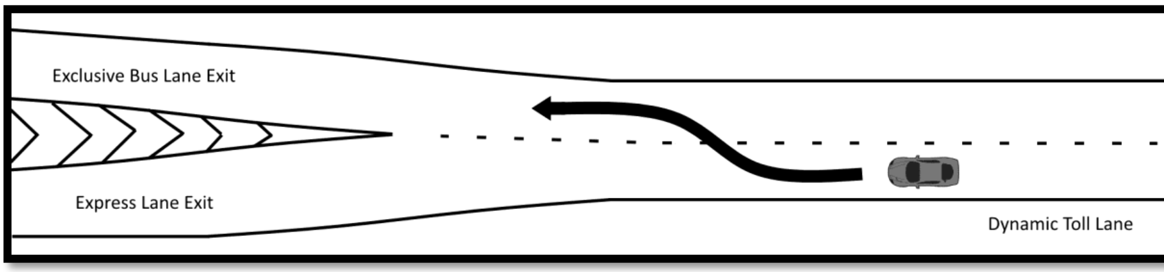
Table 1-1 Average Running Speed of drivers in the PR-22 DTL.

Location	**Direction**	**Average Running Speed (mph)**
DTL Entrance	EB	47.2
DTL Exit	EB	53.2
DTL Entrance	WB	49.2
DTL Exit	WB	54.8
Before Bridge Separation	Both	54.8
After Bridge Separation	Both	54.8

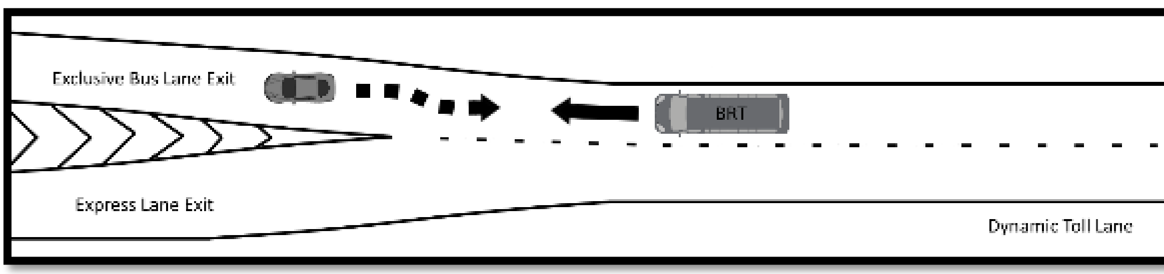
The incorrect use of the BRT system exit gate is a safety aspect that is under consideration by administrators as well as researchers (Valdés et al., 2016). A considerable number of drivers using the DTL use the incorrect exits, either because they want to take advantage of the BRT system exclusive lane or the driver is confused by the current signage configuration. Therefore, the current signage configuration may not meet one of the principle requirements for an effective signage established by the Manual Uniform Traffic Control Devices (MUTCD), 2009 edition and revised in May 2012, 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). Inconsistencies in signage configuration can affect the driver expectancy inside the DTL. Driver expectancy is the ability driver to react to respond situations, events and information in predictable and successful ways (Campbell et al. 2012). The inconsistencies of signage may lead to erratic movement at the DTL exits, that may influence in crashes, as well as decreased used of the DTL because the driver does not understand how it work. A common maneuver used by the drivers that get confused, using the BRT system exit, is illustrated in Figure 1-2. Once the driver acknowledges they are in the BRT system exit, they get to a complete stop and maneuver in reverse until they can change into the exclusive lane exit. This issue affects the safety of motorists as well as the operation of the BRT system inside the DTL. In an observation study conducted by METROPISTAS during February 9 and 10 of 2017, it was observed that drivers, deliberately or not, used the BRT exit especially in the westbound direction with a 1.33% of commuters using the incorrect exit. Table 1-2 presents the data collected by METROPISTAS during the observation study.

(a) Driver of private motor vehicle gets confused and chooses the wrong exit

(i.e. Exclusive Bus Lane Exit)



(b) Driver of private motor vehicle acknowledges the mistake and starts to maneuver in reverse with potential conflict with incoming BRT or other private motor vehicles



(c) Driver private motor vehicle perform a lane change manuever into the correct exit lane

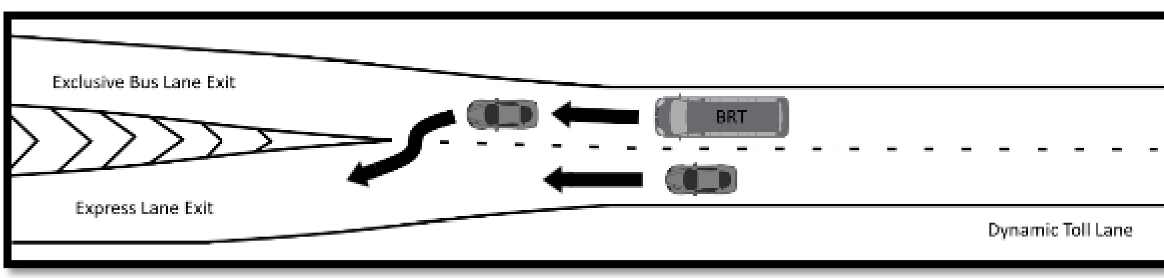


Figure 1-2. Driving Maneuvers when Exiting through the BRT Lane: (Courtesy of:UPRM SAFER-SIM Phase 2 Final Report).

Table 1-2 Incorrect Used of DTL Exit Gate.

Date	Direction	Vehicle	Used of Incorrect DTL Exit	Vehicles that Changes into Correct Lane
Thursday February 9, 2017	Westbound	3,575	22	2
Friday February 10, 2017	Eastbound	4,644	5	0
Friday February 10, 2017	Westbound	4,565	87	2

1.3 JUSTIFICATION

The research comprises the first ever development of virtual scenarios of the PR-22 DTL using the driving simulator of the University of Puerto Rico at Mayagüez (UPRM). This driving simulator is the first of his kind in Puerto Rico used to develop research with in-service toll plazas facilities. The research is part of the Phase II: *Operational and Safety-Based Analysis of Variable Toll Lane Configuration*, as proposed to the United States Department of Transportation (USDOT) in the SAFER-SIM proposal under *Theme Areas: Traffic Operations and Safety Evaluations.* Safety Research Using Simulation (SAFER-SIM), funded by the University Transportation Center (UTC), is a consortium between five universities namely, University of Iowa (UI) (Lead Institution), University of Wisconsin at Madison (UW), University of Central Florida (UCF), University of Massachusetts – Amherst (UMass) and University of Puerto Rico at Mayaguez (UPRM). The main focus of this consortium is to promote safety by doing research in how the road users, roadway infrastructure, and new vehicle technologies, interact with each other using simulations.

The driving simulation is a great tool to study the driving behaviors and decision making since the simulation can variate traffic flow, time of day condition, environmental conditions, hazardous driving situations, geometric designs, amongst other conditions on a short period of time. This innovative technique has reduced the cost and the time of doing safety research projects since the time of creation and development of scenarios in driving simulation studies is lower than the creation and development of real world scenarios.

Although managed lanes have been in operation during the past two decades, there is not sufficient studies that focus on safety and operations of these facilities (NHCRP 2016). This research analyzes the driving behavior of subject drivers in the first in-service DTL study in Puerto Rico. Higher operational speed profiles than the posted speed limit in the DTL have driven this study to evaluate the driving behavior of subject under different geometric and posted speed limits conditions. The incorrect use of the DTL exit will also be evaluated as part of the driving behavior inside of the facility.

The findings of this research will certainly contribute to the safety and operational conditions of the PR-22 DTL by providing a mechanism to evaluated changes to the existing geometric design and posted speed limit without exposing motor vehicles drivers to any physical damage or hazardous situations by using the UPRM driving simulator. Based on the findings of this research thesis, a new configuration of geometric elements as well as a new posted speed limit in the PR-22 DTL, are proposed. These recommendations can be considered in the future by the administrators of the PR-22 DTL, Autopistas Metropolitanas de Puerto Rico, LLC, (METROPISTAS) with the potential to improve the safety and operation of the facility, for private motor vehicle and BRT that used the DTL during different time of the day, in the EB and WB direction.

1.4 THESIS OBJECTIVES

This research study evaluated the stimulus created by the changing of lane width and posted speed limits on the driving behaviors of subject drivers using three surrogate measures, operating speed, acceleration noise, and lateral position. The four principal objectives of this research study are presented below:

- Generate the first ever PR-22 DTL virtual scenario to be used to evaluate the driving behavior of subject drivers in the UPRM driving simulator.
- Gather information of the driving behaviors, inside the PR-22 DTL, from subject drivers in Puerto Rico using the UPRM driving simulator.
- Determine which lane width and posted speed limit levels presents the less variability in driving behavior in terms of Operating Speed, Acceleration Noise and Lateral Position therefore contribute to improve safety and operation.
- Compared and validate the results of a linear model and non-linear model.
- Provide recommendations of improvement to the PR-22 DTL.

1.5 RESEARCH SCOPE

The scope of the research project is to improve the safety and operation aspects on segments with different geometric designs at a managed lanes facility. The study focusses on evaluating the driving behavior of subject drivers in specific points in which the geometric aspects of the managed lane mainline variates (e.g. DTL entrance, shoulders, mainline separation and exits) within the median of the freeway separated with concreted barriers and shared with a BRT system.

A series of simplifications were performed in order to develop the simulation environment. Since the UPRM Driving Simulator did not have motion axis, the scenarios were developed with tangent segments and leveled terrain. The BRT that uses the PR-22 DTL (Metro Urbano), and the rainstorm outlets were not developed, since they were not going to be evaluated in this research.

1.6 THESIS HYPOTHESES

The hypotheses established for this research project were in accordance with the twenty-seven (27) scenarios under study, in which fifty-four (54) subject drivers drove through three different scenarios, where the independent variables the Time of Day Condition, Posted Speed Limit and Lane Width were evaluated. Three dependent variable, Operating Speed, Acceleration Noise and Lateral Position, were evaluated to identify the driving behavior in the driving simulation study.

The general hypotheses used in this research study are described below:

1) The subject drivers with narrow lane scenarios will have lower operational speed and lower acceleration noise but higher variance in lateral positioning than those exposed to scenarios with wider lanes.
2) Subject drivers will tend to have higher speed profiles than the posted speed limit.
3) On average, subject drivers will use the incorrect exit gate in the westbound direction, due to that the exit lane is at the left side of the facility.
4) Segments with merging or diverging will present higher variation in Operating Speed, Acceleration Noise and Lateral Position variables in compare with basic segments. Therefore, this would be known as safety hazard point.

1.7 ORGANIZATION OF THESIS

The thesis will be composed by six chapters. Chapter 1 will be the introduction, in which the description of the managed lane facility, problem statement and procedure realized to complete the research will be summarized. Chapter 2 will be the literature review used to understand the pertinent aspects of this research project (e.g. managed lanes, human factor, driving simulators, geometric design, safety). Chapter 3 will explain the research methodology used to develop the experimental design as well as the generation of virtual scenarios, the study protocol, the subject drivers, the selection of zones of interest and the variables evaluated. Chapter 4 will describe the importance of the driving simulation, provide an overview of the PR-22 and DTL, and the generation of virtual scenarios. Chapter 5 will describe the results of the pre- and post-study questionnaire, the validation procedure, and the results of the integrated data analysis of the dependent variables study. Chapter 6 will provide the conclusions and recommendations of the research project as well as future research topics to be considered by UTC and METROPISTAS. Finally, the thesis will conclude with the list of references cited and the appendixes.

CHAPTER 2. LITERATURE REVIEW

The literature review consists of several topics to be studied in this research project. The topics to be covered in this section include managed lanes and its operations, geometric designs focused on managed lanes and freeways, driving simulators and safety. Pertinent definitions, section of manuals, handbooks and technical publication associated with safety, traffic operation, driving and simulators published by FHWA, ITE, and TRB are also incorporated in this chapter.

2.1 OPERATIONS OF MANAGED LANE SYSTEM

The Manual on Uniform Traffic Control Devices (MUTCD) in the 2009 edition stated that *"Managed Lane is a highway lane or set of lanes, or a highway facility, for which variable operational strategies such as direction of travel, tolling, pricing, and/or vehicle type or occupancy requirements are implemented and managed in real-time in response to changing conditions. Managed lanes are typically buffer- or barrier-separated lanes parallel to the general-purpose lanes of a highway in which access is restricted to designated locations"* (MUTCD, 2009). Therefore, a managed lane is a specific lane facility, within a highway, that separates these lanes from the general purpose-lanes.

The first managed lane design was constructed in the United States in the 1960's and was an exclusive busway (FHWA, 2008). However, over the last two decades, the term "Managed Lane" has been used to identify a variety of special-use highways lanes that included high-occupancy vehicle (HOV) lanes, high-occupancy toll (HOT) lanes, express toll lanes (ETL), and truck-only toll (TOT) lanes (Collier et al., 2002). The special-use highways mentioned before used two specific strategies to maintain the traffic flow and level of service: the vehicle eligibility and the pricing.

These managed lanes systems have been allocated in areas where the traffic congestion is present with limited space to improve the current infrastructure. Under this condition, the managed lane applications had provided several benefits to these areas 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). The three pertinent aspects of the managed lanes, managed lane strategies, reversible lanes and concreted barrier separation, are described below.

2.1.1 Managed Lane Strategies

The managed lanes operate under different strategies to manage the traffic flows and maintain a specific level of service (LOS). The most used strategies are the vehicle eligibility, pricing and access to the system. The vehicle eligibility strategy intends to restrict the use of the specific lanes to a specific vehicle type. This strategy serves as a mechanism to limiting the demand and separate a specific vehicle type of the general-purpose lane, such as trucks, buses or high-occupancy lanes. The most used eligibility strategy is the vehicle occupancy as it is illustrated in the Figure 2-1 (FHWA, 2008). This strategy required a minimum occupancy of more than two persons inside the vehicle. This strategy combined with a toll facility ensures that a vehicle with a specific occupancy rate is using the designed lane. The toll facility can be dynamic, using a higher occupancy rate at peak hours and a lower occupancy rate at off-peak hours. Typically, these lanes allow mass transit system to use the lanes without paying the toll. The truck and bus lanes are not used as much as the high occupancy lanes. The purpose of truck or bus-only lanes is to separate these vehicles from traffic flow to enhance safety, improve capacity and service of the highway.

Figure 2-1. Vehicle Eligibility Strategy (FHWA, 2008).

Several managed lanes used a strategy named congestion pricing (Collier and Gooding, 2002). This type of management strategy takes advantage of underutilized capacity (i.e. travel lane, median, shoulder or other roadway component) in which pricing schemes varies according to the time of the day (peak/off-peak), day of the week and level of congestion inside and outside the managed lane (FHWA, 2008). There are two categories of congestion pricing, fixed and dynamic pricing schemes. Fixed pricing refers to a fixed toll price, in which the price is set for a given period time. Meanwhile, the dynamic pricing refers to a variate toll price that changed in real time based on the actual roadway condition (Verhoef et al., 1996; Yang and Huang, 2004; and Dong et al., 2011). Therefore, a higher toll is charged when congestion and the travel time is at the worst, while lower toll is charged during periods of lowest traffic congestion. Figure 2-2 illustrated an example of a managed lane with dynamic pricing system.

Figure 2-2. Dynamic Pricing Scheme Example. (Freeway Management and Operations Handbook, 2011)

Finally, the access points separating the managed lanes from the general-purpose lanes serves as a mechanism to control the use of managed lanes. The use of separated barriers in managed lanes facilities limit the access to road users to a specific point. Generally, these points are at the beginning or the end of the managed lane in which it is common to see a toll plaza facility. However, extended managed lane provided mid-block entrance and exit points for road user. The separation of managed lanes and general-purpose lanes typically are accomplished with fixed physical barriers or with traffic control devices (TDC's) such as tubular markers (pylons) or painted buffers (Figure 2-3).

Figure 2-3. Pylon Separated (Freeway Management and Operations Handbook, 2011)

2.1.2 Reversible Lanes Systems (RLS)

Reversible lanes systems (RLS) 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 time period (Wolshon and Lambert, 2006). RLS is considered cost-effective and strategy to increase the overall capacity of a facility, particularly during peak hour periods (ITE, 1999). This traffic flow treatment is better than adding a new lane to a current roadway with traffic congestion. Moreover, the RLS also serves to increase the direction capacity during planned events as well as emergency events.

RLS must be designed and operated with caution because it could generate potential conflict points that affect road safety for all users (NCHRP Synthesis 340, 2004). A combination of signage and safety in access points should be used. Prevention of traffic flow from the off-peak direction into the opposite direction should be made with the inclusion of gates and barriers. The signage configuration and information should, without a doubt, establish the hours of operations of the reversible facility.

2.2 MANAGED LANES GEOMETRIC DESIGN

Roadway geometric is an important element in the driving behavior and road safety. AASHTO states that geometrics refer to the physical aspects of the roadway that include, but are not limited to, horizontal and vertical alignments, road curvatures, road and lane width (AASHTO, 2011). The physical component of the road, such as the lane width or curvature, implicitly provide information to the driver on how fast to drive, when to slow down and when the curves are approaching (Fisher et al., 2011). Poor roadway geometric designs can result in a variety of crashes and the possibility of fatalities. For that reason, it is extremely important to select a good design that provides safety to all road users.

The designs of managed lanes are similar to general-purpose lanes. Roadway elements, namely sight distances, taper lengths and lane width in managed lanes, have similar standard and policies set by AASHTO and in the MUTCD as compared with the general-purpose lanes (NCHRP Synthesis 340, 2004). Generally, these facilities are located at the medians of the freeway. Hence, the design of a managed lane may require reconstructing the roadway to fit within the existing conditions or reduce the design to meet the required standards. This section will focus on three important roadway geometric aspects, cross section, design vehicle, design speed and barrier separated.

2.2.1 Managed Lanes Cross Sections

The design of cross section in managed lanes is not different from standard cross section design. However, cross section designs of managed lanes need special consideration since the direction of travel can change during peak hours. Safety features associated with managed lanes (e.g. crash cushions, TCD's, guardrails, and physical barriers) should be applied in both directions. However, lane width is the most varied element in managed lanes cross section. AASHTO standard highway lane width is 12 ft but allows variation in lane widths. Lane width of 9.5 ft have been reported for a mass transit system in managed lanes (Link, 1975). Table 2-1, present the geometric elements in managed lanes and their typical dimension.

Table 2-1. Managed Lane Geometric Elements (AASHTO Guide for High Occupancy Vehicle (HOV) Facilities)

Geometric Element	**Typical dimensions**
Lane Width	12 feet
Shoulder Width	10 feet (preferable) 2 feet (minimum, depending on the number of lanes, operations and sight distance)
Buffer Width (for non-barrier-separated operation)	Between 2 to 4 feet

The geometric of the managed lane will depend on the configuration and operation of the system. Usually, managed lanes use one or more lanes that work in the same direction as the traffic flow (known as concurrent operation) or depending on the direction of traffic condition (known as reversible operation). Concurrent operation provides one or more lanes in the direction without taking in consideration the traffic peaking. Meanwhile, reversible operations may provide one or more lanes but are required to be physically separated. Figure 2-4 illustrates the desired and reduced cross sections dimensions for managed lanes systems (that used RLS) in accordance with multiple reports that represent the current practice for managed lanes design. (NCHRP Report 414 HOV System Manual, 1998 and AASHTO HOV Design Guide, 2004). Desired design cross section refers to the dimension that typically meet all AASHTO design standards. Reduced design cross section refers to the typical dimension of managed lanes where constraints of limited space are presented. The major concern with restricted width is the inability to provide suitable shoulders areas. These areas are important to provide space for emergency stopping areas, incident responders and in some cases, enforcement patrol vehicles. Table 2-2, adapted from the NCHRP Report 835, illustrates the advantages and disadvantages of cross-sections design elements.

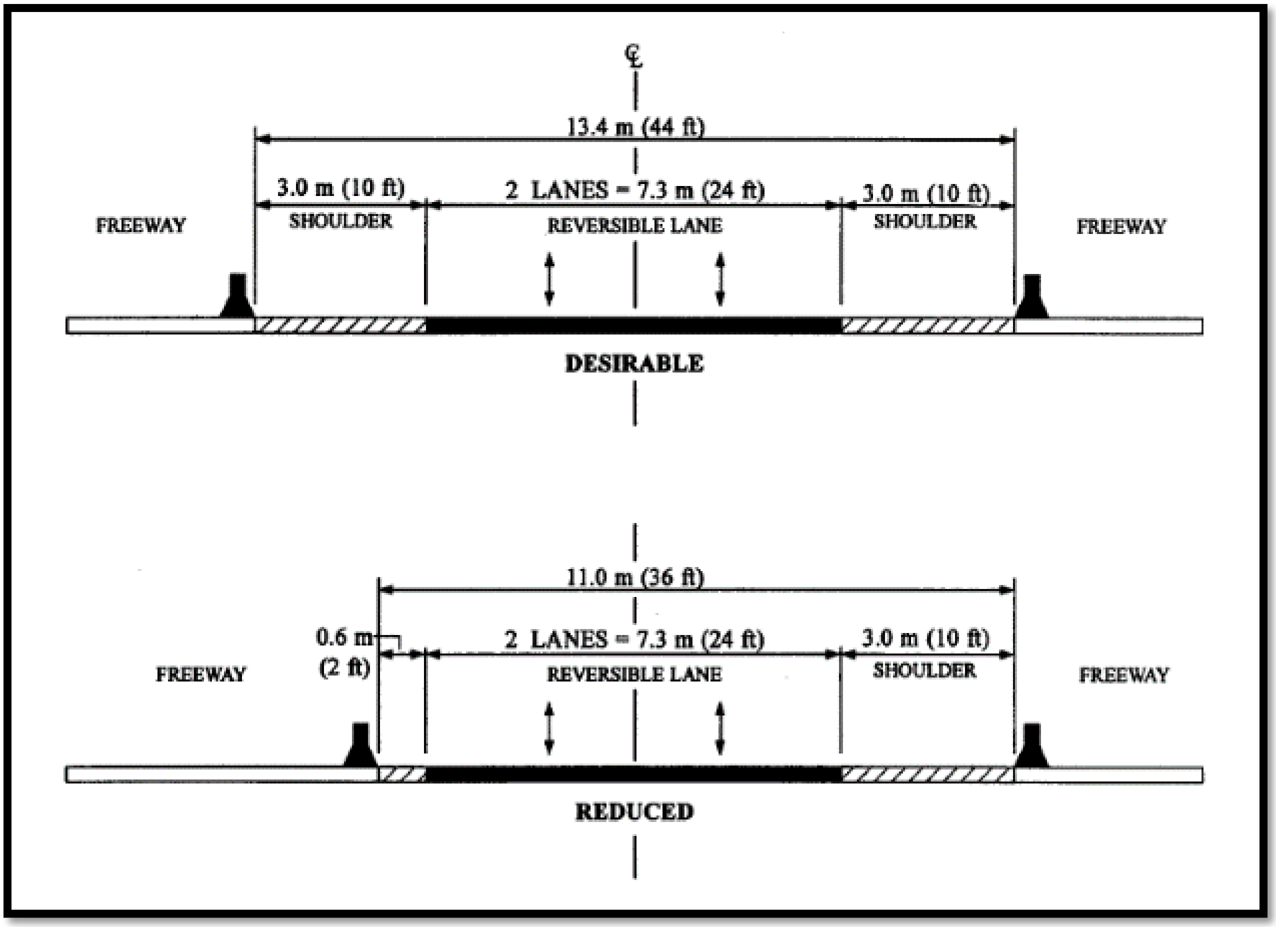


Figure 2-4. Desire and Reduced Managed Lane Cross Section. (NCHRP Report 414, 1998)

Table 2-2. Advantages and Disadvantages of Cross-sections Design Elements (Adapted from NCHRP Report 835, 2016)

Design Elements	Dimension (feet)	Advantages	Disadvantages
Travel Lane	12	Accommodation of buses and trucks. Maintain typical geometric of general-purpose travel lanes on freeways	May need the reduction of width from other elements in the managed lane or general-purpose facilities.
Shoulder	12	Maintain typical geometric of general-purpose travel lanes on freeways. Provide space for disable vehicles, enforcement activities, and an alternative lane in case of an incidents in the managed lane mainline.	May need the reduction of width from other elements in the managed lane or general-purpose facilities.
Travel Lane	11	Easy to provide in comparison with the 12-ft lane. May implicated a safety trade-off in comparison with the 12-ft lane. May be acceptable if associated with wider buffer.	Narrower than typical freeway lane. Less-than-minimum width in some guidelines.
Shoulder	10 or 11	Accommodate most passenger and heavy vehicles. Easy to provide in comparison with the 12-ft lane.	Narrower than typical freeway shoulder. May reduced and/or restricts the space for disable vehicles or enforcement activities.
Shoulder	8 to 9	Accommodate passenger cars. Easy to provide in comparison with the 12-ft lane.	Do not accommodate heavy vehicles. Restricts the space for the disable vehicles or enforcement activities.
Shoulder	Less than 8	Provides lateral clearance for drivers compared to no shoulder.	Do not provide the enough space to accommodate passengers or heavy vehicles. Not suitable for maintenance, enforcement or incident management. May Restrict the sight distance in curves. Associated with higher number of crashes (HSM, 2014).

2.2.2 Design Vehicle

The design vehicle is an essential element that influence the physical and operating characteristics of managed lanes design. (NCHRP Report 414, 1998). The dimensions of the design vehicle assist practitioners to design managed lanes projects on freeway facilities. According to AASHTO 2011, there are 20 design vehicles within four classifications, passenger cars, buses, trucks, and recreational vehicles. The passenger-car class includes passenger cars of all sizes, sport/utility vehicles, minivans, vans, and pick-up trucks. Buses include intercity (motor coaches), city transit, school, and articulated buses. The truck class includes single-unit trucks, truck tractor-semitrailer combinations, and truck tractors with semitrailers in combination with full trailers. Recreational vehicles include motor homes, cars with camper trailers, cars with boat trailers, motor homes with boat trailers, and motor homes pulling cars. The intercity bus of 40 ft. (BUS-12), the intercity bus of 45.5 ft. (BUS-14) and the articulated bus of 60 ft. (A-BUS) are the design vehicles used by practitioners to design managed lanes for freeway facilities. The typical dimensions and minimum turning path for the BUS-12 (40 ft.), BUS-14 (45 ft.) and A-BUS (60 ft.) are depicted in Figure 2-5 through Figure 2-7; respectively.

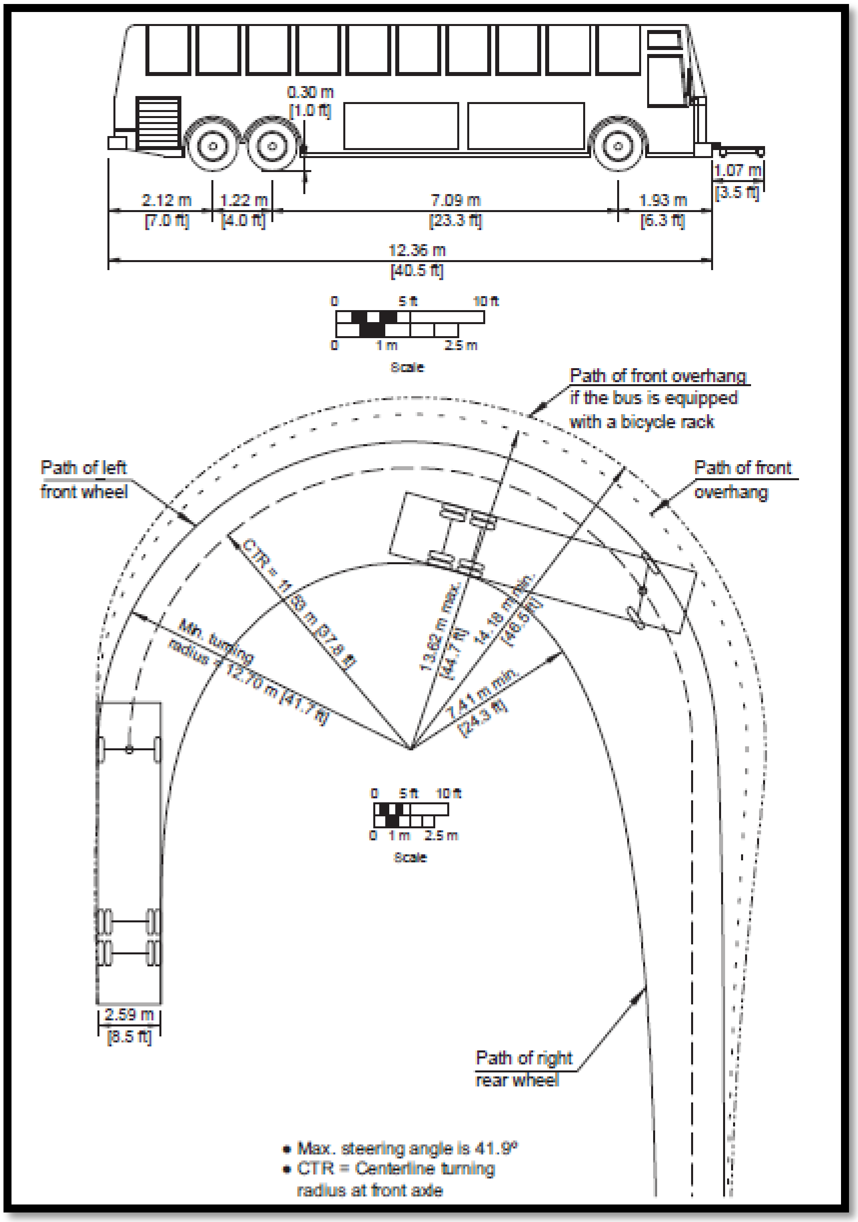


Figure 2-5. Dimension and Minimum Turning Path for Intercity Bus (Bus-12 [Bus-40]) Design Vehicle (From AASHTO, 2011)

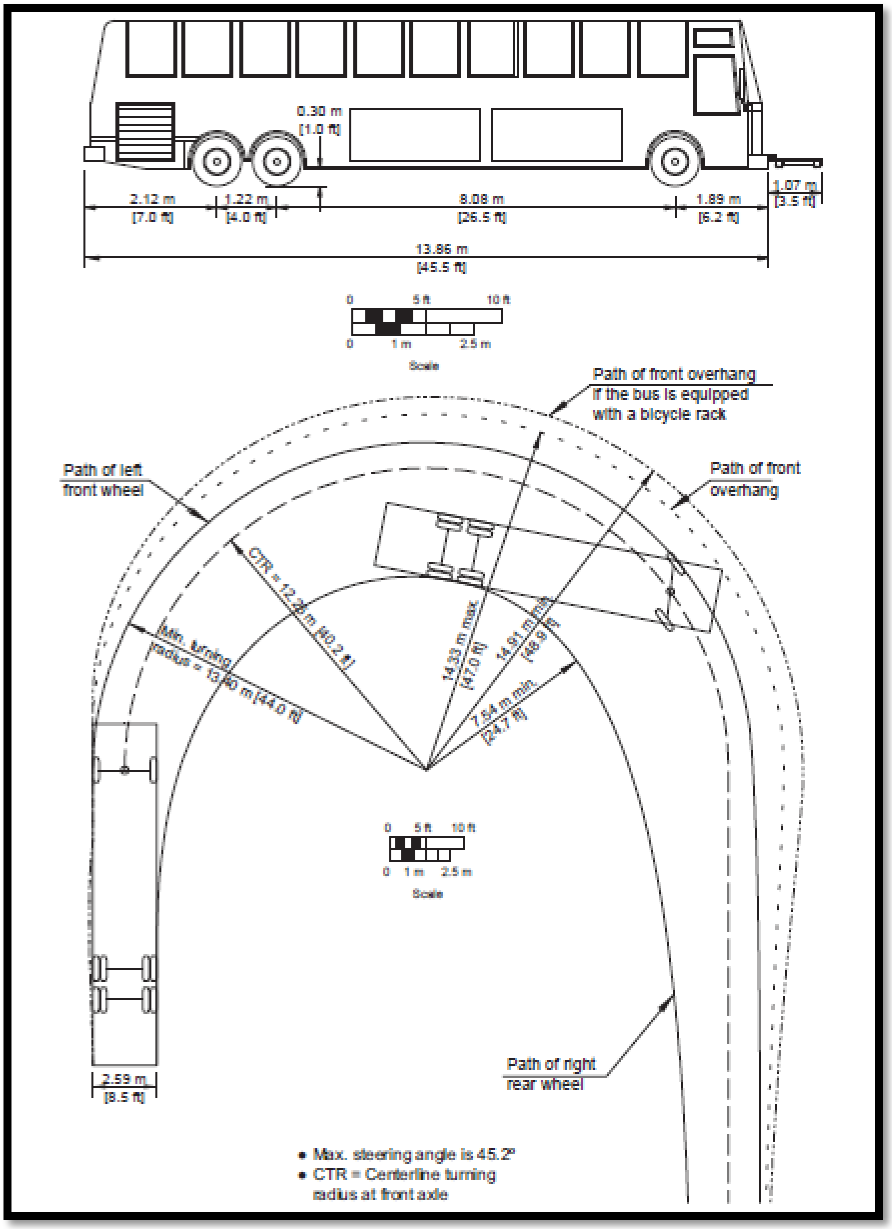


Figure 2-6. Dimension and Minimum Turning Path for Intercity Bus (Bus-14 [Bus-45]) Design Vehicle (From AASHTO, 2011)

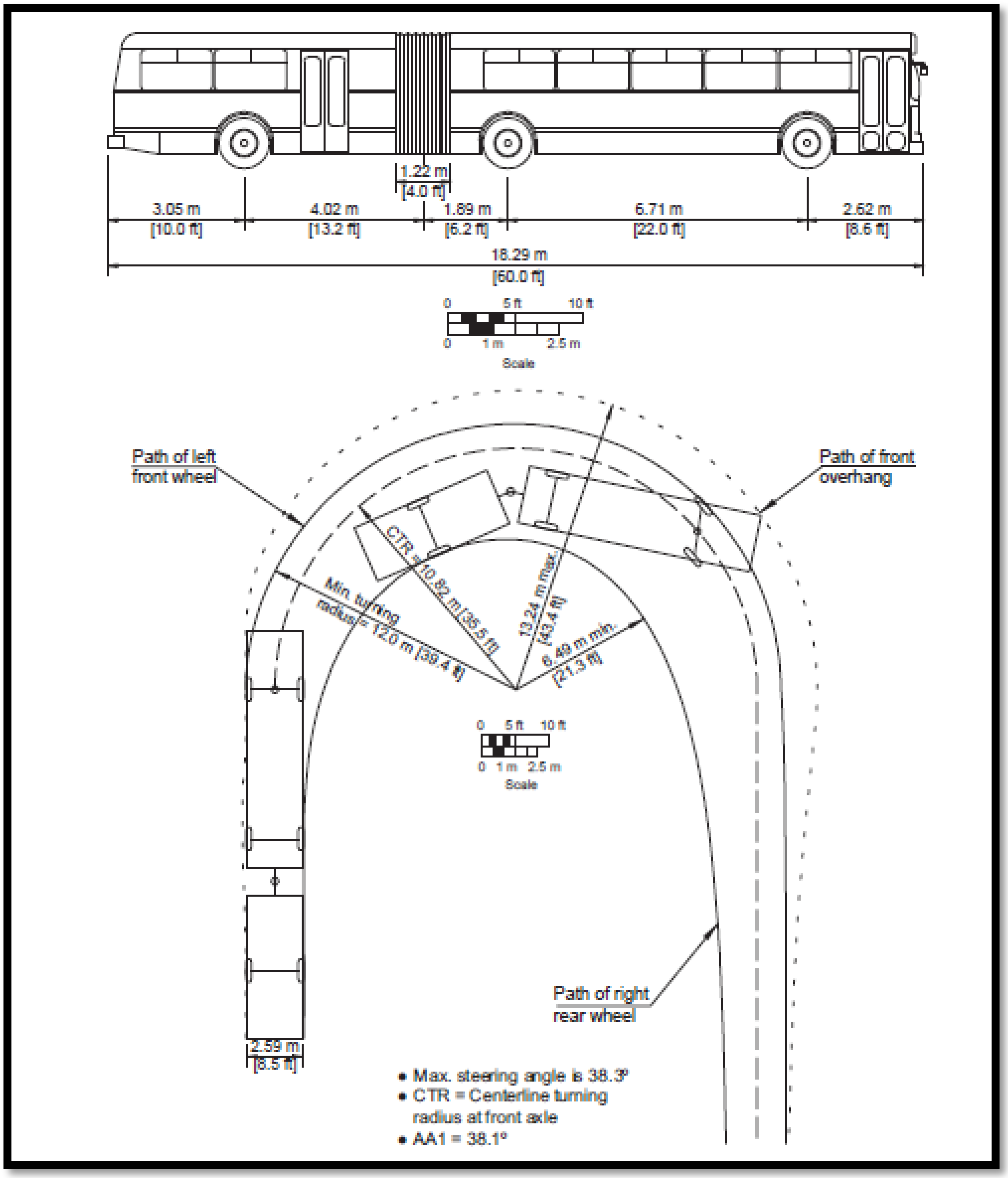


Figure 2-7. Dimension and Minimum Turning Path for Articulated Bus (A-Bus) Design Vehicle. (From AASHTO, 2011)

The dimensions of the design vehicles are shown in Table 2-3. Theses dimensions are used to determined lane and shoulders widths, lateral and vertical clearances amongst other roadway elements. WB_1 and WB_2 are the effective vehicle wheelbases, or distances between axle groups, starting at the front and working towards the back of each unit. The term *S* is the distance from the rear effective axle to the hitch point or point of articulation. The term *T* is the distance from the hitch point or point of articulation measured back to the center of the next axle or the center of the tandem axle assembly.

Table 2-3 Vehicle Design Dimensions (Adapted from AASHTO, 2011).

Design Vehicle Type	**Symbol**	**Dimensions in feet [meters]**								
		Overall			**Overhang**		**WB_1**	**WB_2**	**S**	**T**
		Height	**Width**	**Length**	**Front**	**Rear**				
Intercity Bus	BUS-12	12.00 [3.66]	8.50 [2.59]	40.55 [12.36]	6.33 [1.93]	9.00 ^ [2.73]	25.30 [7.70]	-	-	-
	BUS-14	12.00 [3.66]	8.50 [2.59]	45.57 [13.89]	6.20 [1.89]	9.00 * [2.73]	28.50 [8.69]	-	-	-
Articulated Bus	A-BUS	11.00 [3.35]	8.50 [2.59]	60.00 [18.29]	8.60 [2.62]	10.00 [3.05]	22.00 [6.71]	19.40 [5.91]	6.20 * [1.89]	13.20 * [4.02]

^ This is the length of the overhang from the back axle of the tandem axle assembly.

* Combined dimension is 19.39 feet (5.91 meters) and articulation section is 4.00 feet (1.22 meters) wide.

2.2.3 Design Speed

Design speed is the speed selected to determine the pertinent geometric design features of the roadway (AASHTO, 2011). The selected speed should take in consideration the operating speed, topography, land use, functional classification, safety, mobility, and efficiency within the constraints of environmental quality, economics, aesthetics, and social or political impacts of the designing highway. In managed lane facilities adjacent to general-purpose freeway corridor, the designing speed is typically similar to the designing speed used in the adjacent freeway (NCHRP Report 835, 2016). The design speed in managed lanes can be lower than the general-purpose design speed in certain situations due to the geometrics limitation, operational characteristics and vehicle eligibility inside of the managed lane facility. The design speed in urban freeways recommended by AASHTO is between 60 to 70 mph (NCHRP Report 835, 2016, AASHTO, 2011, and NCHRP Report 414, 1998). However, if the cross-section is reduced the design speed also decrease. Table 2-4 described the typical design speed for managed lane facility.

Table 2-4 Typical Design Speed in mph for Managed Lane Facility. (Adapted from NCHRP Report 414, 1998)

Type of Managed Lane	Typical Design Speed (mph)	
	Reduced	Desirable
Barrier separated	50	70
Concurrent flow	50	60
Bus and HOV	40	60
Contraflow	30	50

2.2.4 Barrier Separation

Depending on the design and operation of the managed lane, a physical separation may be needed. Physical barriers provide access control for road users to a specific area as well as maintaining a desired traffic condition inside the managed lane (see Figure 2-8). Also, the effect of speed differential between parallel traffic streams can be mitigated by the used of barriers. Therefore, a higher speed can be sustained in managed lanes in comparison with the general-purpose lanes, and reliability is greater than for non-separated designs (NCHRP Report 835, 2016).

Figure 2-8. Concrete Separated Barrier (Freeway Management and Operations Handbook, 2011)

The physical barrier provides safety between the general-purpose and the managed lanes, since generally the managed lane operates under different speed and vehicle eligibility than the general-purpose lane. In addition, the barriers prevent the inclusion of road users from the general-purpose lane inadvertently crossing and interrupting the traffic flow in the managed lane. Therefore, head-on crash is reduced since the vehicle cannot enter the barrier separated managed lane as it could happen in the non-barrier separated managed lane. Physically separated barriers are commonly seen in reversible lane facilities where the barrier is extremely necessary to separate the oncoming traffic flow. Also, moveable barriers are essentials in reversible facilities to allow access for both directions.

However, safety issues associated with the inclusion of physical barriers, especially in access points, is a critical element in the design of managed lanes (FHWA, 2012). The barrier at access points must be protected with the respective safety countermeasure (e.g. crash cushions) and buffered to protect road users. In addition, with the inclusion of the physicals barriers, a good drainage design should be applied to remove the storm water in order to prevent hazardous situations like hydroplaning. Other potential disadvantages of the physically separated barriers are that drivers may feel sensations of confinement that will influence the position in the lane and the operating speed. Also, if the separated managed lane didn't have removable rails or gates may produce several issues in the events of crashes or mishap (NCHRP Report 835, 2016)

2.3 SAFETY

Driving is a complex task. Drivers should be capable of performing multiple tasks in matters of seconds that include the use of several skills. As stated by the Highway Safety Manual (HSM) these tasks are associated with driver's ability and capability to maintain a proper travel speed and direction inside the lane, understand TDCs, perform safety maneuvers when other vehicles are near and perform an origin to destination trip by observing and understanding every road element and guidance (HSM, 2010). Therefore, the human factor is the number one contributing element for road crashes, with more of 90% of them is associated with driver errors (HSM, 2010). For this reason, researchers have focused their attention to understanding and evaluating the human factors that affect driving behavior in transportation facilities.

2.3.1 Freeway Safety

Freeways are one of the most used transportation infrastructures in the world. HCM defined the freeway as a "*divided highway facility that has two or more lanes per direction for exclusive use of a particular traffic*" (HCM, 2010). Freeways are comprised in three segments, namely merging and diverging segments, weaving segments and basic segments. Merging segments refer to the converges of two or more traffic lanes into a single lane, whereas the diverging segments refer to a single lane which splits into two or more traffic lanes. A weaving segment is a combination of merging and diverging segments or between two consecutive on-off ramps within the same traffic lane in a short distance of 2,500 feet or less. 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 2-9) 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 2-9). Lastly, a basic freeway segment is described as a segment in which no merging, diverging or weaving movements occur.

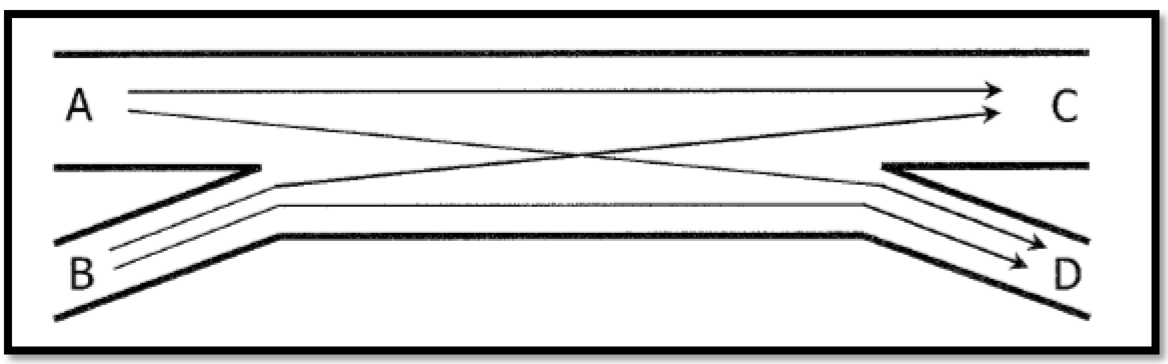


Figure 2-9 Weaving Movements Example in a Freeway Between an On-Ramp and Off-Ramp (Reference: HCM, 2010).

Generally, these segments are associated with ramp junctions that grant access or departure of drivers into the freeway facility. Ramp junctions are defined as the area where two or more highways are connected in an interchange (AASHTO A Policy on Geometric Design of Highways and Streets (AASHTO Green Book, 2011)). This element consists of two components, namely, ramp terminal and the road that is being connected.

The HCM (2010) defined the ramp terminals as the area where the traveled way in where traffic merges or diverges from the freeway mainline, which includes speed-change lanes, tapers and islands. The design of exit ramp terminals, which includes the geometric layout of gores (see Figure 2-10) and TCD's should provide a safe and understandable path for road users.

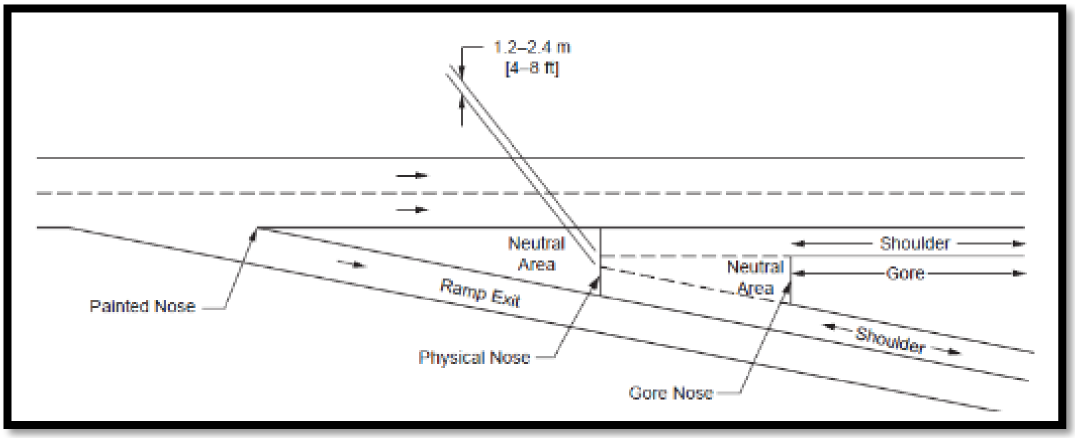


Figure 2-10 Geometric Layout Example of a Typical Exit Gore Area (Reference: HSM, 2010).

2.3.2 Crashes in Managed Lanes

The National Cooperative Highway Research Program (NCHRP) Report 835 (NCHRP Report 835, 2016) establish that crashes in managed lanes are related to three factors, namely access points, congestion and sight distance. According to the NCHRP Report 835 the typical types of crashes are the following:

- sideswipe crashes - due to passing on two-lane facilities or within access zones,
- rear-end crashes - due to congestion, and
- general crashes - causes by unexpected maneuvers of drivers in access points.

Road crashes is the most concerned safety issue in reversible facilities. These safety concerns include conflicts between opposing traffic and driver confusion associated with unfamiliarity with reversible operations, control systems and movements (NCHRP Synthesis 340, 2004). However, freeway reversible lane safety concerns are related with their use, since the access points are strictly controlled. Precisely, entry and exits points have the highest potential of conflicts and head-on crashes, because of merging, diverging and weaving movement. Therefore, it is important to install the corresponding crash cushions, pavement markers, pavement markings, signage, amongst others, to improve road safety in reversible lanes (Wolshon and Lambert, 2006). A comparison study between eight High Occupancy Vehicles (HOV) lanes with two different types of access controls (four with limited access and four with continuous access) during peak hour were evaluated to determine which type of access control may influence crashes (Jang et. al., 2013). The findings showed that the distribution as well as the frequency of the crashes are similar for both types of access however, all the crashes were concentrated at the access points.

According to Cothron et al. there is no significant differences between the injury crash rates between the managed lanes with physical concrete barriers systems and freeway corridors. However, non-physically separated managed lanes can increase the injury crash rates inside and outside the freeway corridor (Cothron et al., 2004). As stated by Lee et al., there is no evidence that crash frequency is affected by the managed-lane strategy during peak hours, AADT volumes, merging and diverging influence areas, weather, light conditions, and existence of pull-off areas (Lee et al., 2007). In 2016 Valdés et al, concluded that there is a high deviation in the acceleration at diverging segments as well as in the entry and exits points of managed lanes using a driving simulator (Valdés et al., 2016).

2.3.3 Safety Aspect of the PR-22 DTL

From the start of operation of the PR-22 DTL in 2013, a total of 27 crashes has been reported. During the four-year period, the majority of the crashes has been "Property Damage Only" (PDO) crashes with only two (2) injury crashes. Zero (0) fatal crashes have been reported inside the PR-22 DTL. Furthermore, since 2014 an increase of crashes per year has been reported inside the DTL, specially in 2015 when the crash duplicate in comparison with the previous year. The reporting crash incidents inside DTL include crashes with vehicles, lose control of the vehicle and fix objects like, crash cushions and concrete barriers. The number of crashes per year per direction inside the DTL are illustrated in Figure 2-11 where as the number of crash and crash type per year are summarized in Table 2-5.

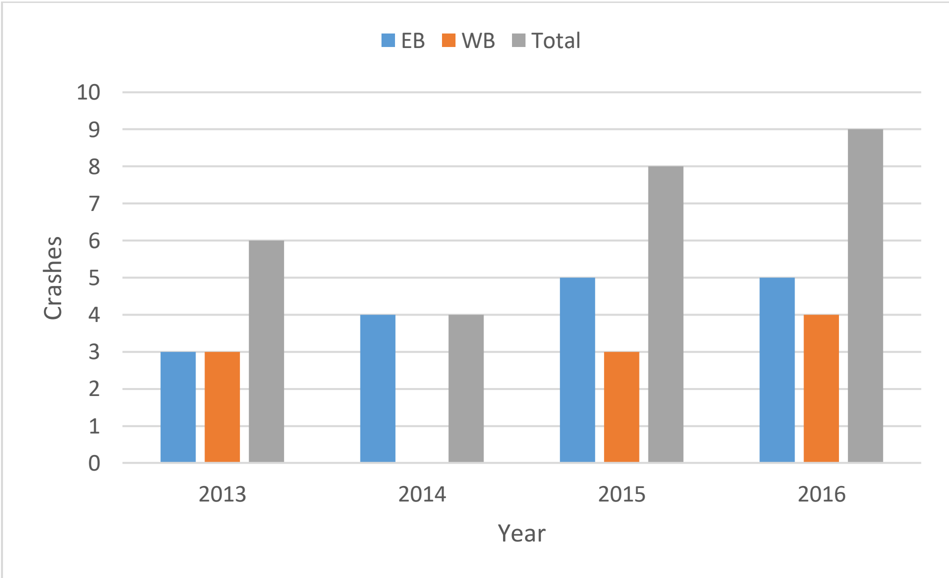


Figure 2-11 Crashes Inside PR-22 DTL per Year

Table 2-5 Crash Type Incidents Inside the PR-22 DTL per Year.

Crash Type	2013	2014	2015	2016	Total
Fix Object	5	3	2	4	14
Rear-end	1	0	4	4	9
Lose control of the vehicle	0	1	2	1	4
Total	6	4	8	9	27

The crash frequency and crash rate are the most used measures in transportation studies to evaluate the safety aspect of a specific location. The crash frequency is the number of crashes occurring at a specific location or segment in a particular time interval (Highway Safety Manual (HSM), 2010). Meanwhile, crash rate is the number of crashes that occur at a given site during a certain time period in relation to a particular measure of exposure (HSM, 2010). The arithmetic equations of the crash frequency and crash rate are illustrated in equation 1 and 2. The crash frequency at the PR-DTL is 6.75 crashes per year for the first four years of operation. Furthermore, the EB direction has 70% higher crash frequency as compared to the WB direction, (EB 4.25 crashes per year and the WB direction has 2.5 crashes per year). The reporting crash rate for the PR-22 DTL is 0.31 crashes per million vehicles per mile. Additionally, the EB direction has been found as the higher crash rate with 0.34 crashes per million vehicles per mile and the WB direction has 0.26 crashes per million vehicles per mile.

$$\text{Crash Frequency} = \frac{\text{Number of Crashes}}{\text{Time Period}}; \qquad (1)$$

$$Crash\ Rate = \frac{1{,}000{,}000}{365 * T * V * L}; \qquad (2)$$

where:

Crash Rate, Crashes per Million Vehicles per Mile,

T = Number of Years,

V = Average Daily Traffic Volume, Veh/day, and

L = Length of the Freeway Segment, Miles.

Table 2-6. Crash Frequency and Crash Rate per Direction

Parameter	**EB**	**WB**	**Total**
Crashes	17	10	27
AADT	3,321	2,490	5,811
Crash Frequency	4.25	2.5	6.75
Crash Rate	0.34	0.26	0.31

2.4 DRIVING SIMULATORS

Driving simulators are proven technologies used in different disciplines due to the benefits it brings to transportation studies. The use of this technology has reduced the time needed to perform research studies as well as the cost in the development of environments and situations. This innovation has studied several aspects such as: human factors, road safety, signage, pavement markings, traffic control devices, response and reaction time, work zones, and roadway geometrics

(Watson et al., 2006; Fitzpatrick et al., 2013; Jeihani et al., 2014, 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). In addition, this tool has been an effective device to attend other matters like psychology, medicine, and computer science (Fisher et al., 2011).

Generally, driving simulators are composed of vehicle parts such as a driving wheel with turn signals, accelerator and brake pedals, gearshift and a driving seat, visual display, audio systems, and computer hardware and software. There are different types of driving simulators, where simulation fidelity and driving experience depends of several components such as high-fidelity simulators, which include motion systems, advanced visual displays, video recorders, eye trackers, amongst other equipment. These systems allow researchers to gather multiple data on a more varied scenario than low fidelity simulators. Typically, low fidelity simulators have low or no motion systems, visual displays are lower than the high-fidelity simulation.

2.4.1 Advantages

Driving simulation has three distinctive advantages. These are: data collection, creation of dangerous conditions without physical risk, and the control and reproducibility of scenarios. Data collection in a driving simulator is particularly easy in comparison to the data collection of a real vehicle. The driving simulation can measure a variety of variables that include speed, acceleration, lateral and longitudinal positions, amongst others in a specific frequency that may not be possible to calculate in a real vehicle. The simulators have been used to expose drivers to dangerous situations without physically harming any driver. This has been used as an effective way to train drivers on complex or critical situations that may be inappropriate to practice on the road. However, the most important advantage of the driving simulators is the control and reproducibility of virtual scenarios. Driving simulators can control different traffic flows and composition, weather conditions, roadway geometrics, signage, TDC's, amongst others in a short period of time. This allows to gather feedback from the different conditions without waiting for the specific condition or having to develop real scenarios.

2.4.2 Disadvantages

Driving simulation has at least three known challenges to attend in the near future. These challenges include the fidelity, the false sense of safety, and the simulation sickness (J.C.F. de Winter et al., 2012). A low fidelity simulator can produce unrealistic driving behavior that may affect the research finding, due to the lack of visual, audio or motion systems. In addition, this may create a false sense of safety producing uncommon driving behavior since the subject knows that their actions will not harm them in any way possible. Finally, simulation sickness may be presented in driving simulation studies where demanding driving conditions or excessive use of driving simulation is present. This affects negatively the use of driving simulators. Usually, the symptoms associated with simulation sickness include discomfort, apathy, drowsiness, disorientation, fatigue, vomiting and dizziness. However, there are guidelines to reduce the possibility of the occurrence of this effect.

2.4.3 UPRM Driving Simulator

The University of Puerto Rico, at Mayagüez (UPRM) driving simulator will be used as an instrument for data collection. The simulator is located in the Transportation Engineering Laboratory in the Civil and Surveying Department in the UPRM. The simulator is comprised of three major components: a driving cockpit, system projectors and sound, and the computer software. The cockpit of the simulator includes a driving wheel with turn signals, accelerator and brake pedals, gearshift and a driving seat, and was designed in a wooden frame with six (6) wheels under the frame that served for multiple applications: it can be used as a fixed or mobile simulator as is illustrated in Figure 2-12. The driving wheel, including the turn signals, is in a wooden countertop located in the front of the car seat. The gear shift is located in the right side within the wooden frame. The accelerator and brake pedals are located over the wooden frame and under the wooden countertop. This configuration is illustrated in Figure 2-13. To keep the same conditions for all the participants, only the automatic transmission was used in the study, hence only three gear shift configurations were used, namely drive/forward, reverse and neutral/parking.

Figure 2-12. UPRM Driving Simulator Cockpit Simulator Setup.

Figure 2-13 UPRM Driving Simulator Equipment.

Three projectors, located on top of the simulator, provide the visual display of the virtual scenarios developed. Each projector is aimed to a specific screen located in front of the cockpit (see Figure 2-14) that allows the subject driver a visibility of 120 degrees of the roadway. To improve the virtual environment, a Samsung bar and subwoofer system are located in the wooden frame. Figure 2-15 illustrates the projection of the virtual scenario in the UPRM driving simulator.

Figure 2-14 Projectors Configuration of the UPRM Driving Simulator.

Figure 2-15. UPRM Driving Simulator Projection (Valdés et al., 2016).

The UPRM driving simulator used SimCreator/SimVista and Internet Scene Assembler (ISA) simulation software, property of Realtime Technologies Inc. (RTI), for the generation of virtual scenarios (SimVista, 2013). This software allows to operate the simulation throughout a laptop computer and a workstation with a Nvidia GeForce GTX 1080 and 16 GB RAM. The software gathers data of 29 set variables (e.g. acceleration, velocity, position in x, y, z coordinates, headway, lateral offset) and 21 variables defined by the researcher, for a total of 50 variables every 0.00266 seconds. Therefore, the data is collected at 60 Hz.

The UPRM Driving Simulator can be adapted to a portable version. The setup consists of the same configuration of equipment; driving wheel, gear shift, accelerator and braking pedals, three projectors, three projecting screens, a laptop and a desktop computer. The projectors and computers are located in a scaffold behind the cockpit as illustrated in Figure 2-16. This configuration is used to present and illustrate the research conducted by the UPRM research team as well as to promote highway safety.

Figure 2-16 UPRM Driving Simulator Mobile Version.

This chapter presents the literature review appraise to understand the design, operation and the safety of managed lanes facilities, and the used of driving simulators in transportation studies. Furthermore, this chapter describes the data collection instrument used in this study, the UPRM driving simulator. The next chapter will comprise of the modelling of the PR-22 Dynamic Toll Lane using the UPRM driving simulator and the processing of the data collected as part of this study.

CHAPTER 3. MODELLING OF PR-22 DYNAMIC TOLL LANE USING UPRM DRIVING SIMULATOR

This chapter describes the different stages associated with the identification, develop and modelling of the first ever PR-22 Dynamic Toll Lane (DTL) simulation using the UPRM Driving Simulator. It includes an overview of the PR-22 and DTL, field inspection and video recording of the current signage and "as built" facilities, the development of the scenarios and modelling of the DTL scenarios.

3.1 PR-22 OVERVIEW

The PR-22 corridor is an 84-kilometer divided freeway that connects 11 municipalities in the Northern part of the Commonwealth of Puerto Rico (see Figure 3-1). General travel ways variated between 4 and 10 lanes at 12 ft (3.65 m) wide and 10 feet (3.0 m) shoulders. Also, the posted speed limit variated between 55 and 65 mph. The PR-22 is one of the most traveled freeway corridors in Puerto Rico and provides mobility to thousands of drivers every day to the metropolitan area with an Annual Average Daily Traffic (AADT) of 110,923 vehicles per day (vpd) for the year 2007 (PRHTA, 2016).

Figure 3-1 PR-22 Corridor Illustration.

Due to high congestion issues, a Public Private Partnership (PPP) was created to design, build, and operate the first ever reversible Dynamic Toll Lane (DTL) system in Puerto Rico. The PPP agreement states that Autopistas Metropilitanas de Puerto Rico, LLC, (METROPISTAS) will design, operate and manage the PR-22 DTL. This managed lane system connects the municipalities of Toa Baja and Bayamón, using a two-lane express freeway facility that incorporates variable operational strategies such as: reversible lane, congestion pricing and an exclusive system throughout the 6.46 miles (10.4 km) of the roadway facility (see Figure 3-2). This varied managed lane facility is the first of its kind in Puerto Rico and the combination of the PPP, reversible lane, congestion pricing and exclusive use of BRT systems and passenger cars made the PR-22 DTL a unique system in the world. Since the implementation in 2013, the PR-22 Reversible Dynamic Toll Lane has improved the driving condition and travel time by approximated 15 minutes at the PR-22 freeway.

Figure 3-2 PR-22 DTL Corridor Illustration.

3.1.1 Puerto Rico Dynamic Toll Lane (PR-22 DTL)

The PR-22 DTL is a reversible express lane with congestion pricing located in the median of the PR-22. As built, the two lane express lanes are 11.5 ft (3.50 m) wide with a posted speed limit of 45 mph in the eastbound (EB) direction toward Bayamón and 45 mph in the westbound (WB) direction toward Toa Baja, with a reduction to 40 mph in the exit (Figure 3-3). This managed lane is separated by two concrete barriers which restrict the access to specific points in the PR-22 EB direction in km 22, and in the WB direction in km 12 and separates general-purpose lanes from the express lanes. In addition, an overpass bridge column divides the two exclusive lanes, creating diverging and merging movements.

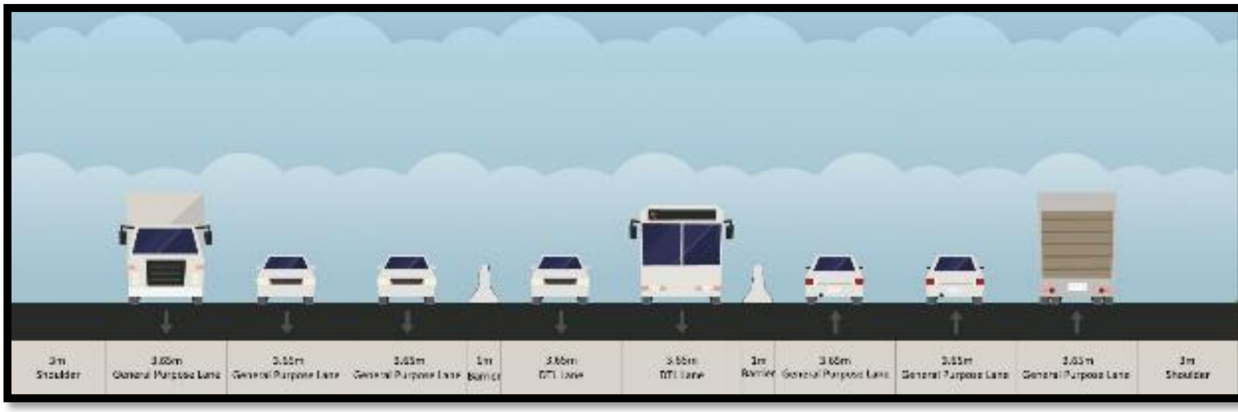


Figure 3-3. Cross-Section of the PR-22 DTL. (Courtesy of: UPRM SAFER-SIM Phase 2 Final Report).

3.1.2 PR-22 DTL Operation

The reported Annual Average Daily Traffic (AADT) of the DTL for the year 2016 was 6,197 vehicles per day (vpd) (see Figure 3-4). This volume represents an increase of 5.23% in comparison with the previous year (5,889 vpd in 2015, see Figure 3-5). Furthermore, in average daily traffic has increased each season since 2014. Nevertheless, on average the eastbound (EB) direction represent 57.14% of ADT inside the DTL (EB 3,321 vpd and WB 2,490 vpd). Over the three-year period, the highest AADT was 6,315 vpd and was reported in the month of October (see Figure 3-6). Meanwhile, as presented in Table 3-1 the lowest month with respect to AADT is July with average of 4,825 vpd.

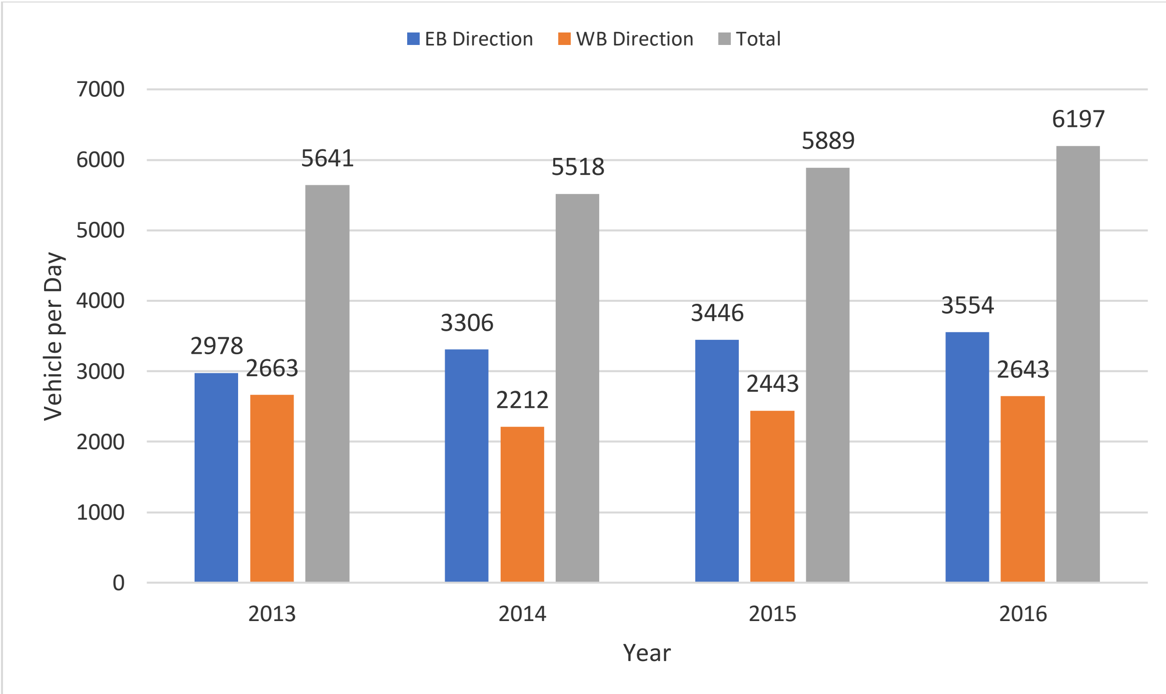


Figure 3-4. Vehicle per Day of the PR-22 DTL by Year and Direction.

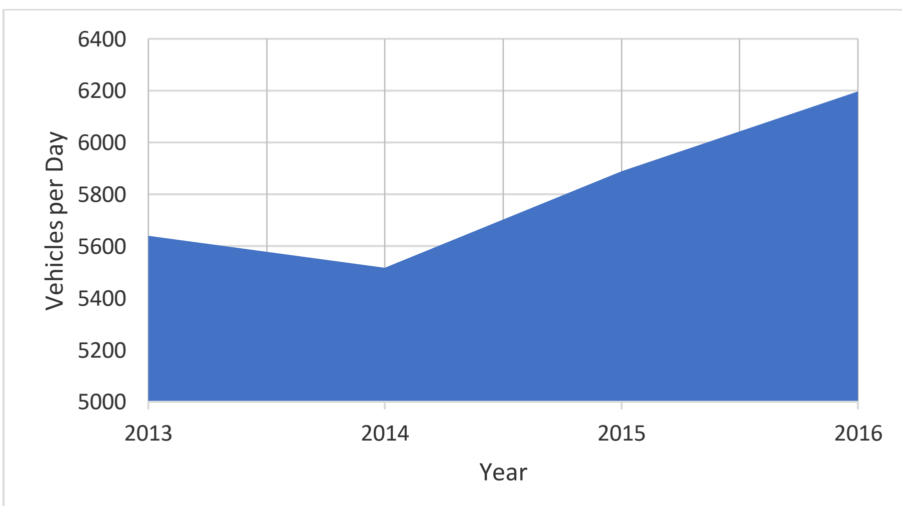


Figure 3-5. AADT of the PR-22 DTL since their opening.

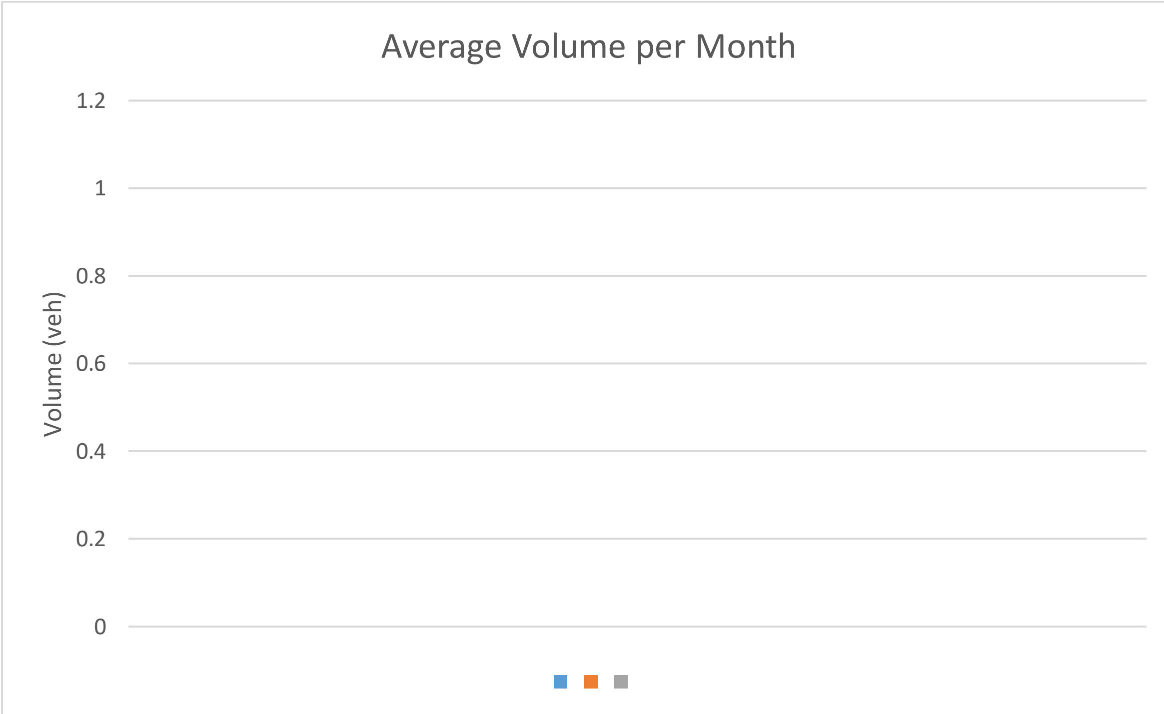


Figure 3-6 Average Traffic per Month in the PR-22 DTL.

Table 3-1 Monthly AADT per Direction Inside the DTL.

Month	EB Direction	WB Direction	Total
January	2,980	2,088^	5,068
February	3,763*	2,418	6,181
March	3,617	2,433	6,050
April	3,558	2,403	5,961
May	3,441	2,278	5,719
June	3,487	2,491	5,978
July	2,722^	2,103	4,825^
August	3,477	2,696*	6,173
September	3,470	2,585	6,055
October	3,678	2,636	6,315*
November	3,265	2,503	5,768
December	3,326	2,686	6,013

Legend:

- * Highest AADT
- ^ Lowest AADT

3.1.3 Field Inspection

A field inspection was conducted on September 18, 2015, to recreate the existing conditions of the PR-22 DTL in the virtual environment for the UPRM Driving Simulator. The objective was to identify the design and location of Traffic Control Devices (TCD's), driving behavior, the traffic flow, the "as built" design of the facilities as well as potential hazard points. A total of eight trips was conducted (two trips per direction in the DTL and two trips per direction in the PR-22). The information was recorded using a dash camera for both directions (off-peak and peak hours) in the PR-22, between the 10 km and the 25 km, as well as inside of the DTL. The dash camera used is a Garmin Dash Cam™ 10/20 (see Figure 3-7) with a frame rate of 30 fps and a 1080p video resolution.

Figure 3-7 Garmin Dash Cam 10/20.

In the eastbound (EB) direction, the video recording observed several aspects of traffic, TCD's, driving behaviors, amongst others. A higher traffic congestion in the PR-22 mainline before the DTL entrance and a safety issue related with the sun glare was observed as is illustrated in Figure 3-8. In peak-hour, the sun glare affects before, during and after the DTL segment. In terms of signage, two overhead signs advise the driver that the DTL is operating and the toll fare that will be collected. The posted speed limit at the DTL is located after the Dynamic Toll facility.

Figure 3-8 Sun Glare affecting the Visibility Inside the PR-22 DTL.

Initially, the EB direction of the DTL is confined between a new jersey barrier at the right side and a w-beam rail at the left side, which divides the BRT entrance. After approximately 1200 ft, the

DTL continues confined by new jersey barriers at both sides. Inside the DTL, four emergency gates, ArmorGuard Gate System of 16 meters (52 feet) (see Figure 3-9), are located in strategic positions to provide an alternate entrance and exit for emergency responses and to reroute the traffic.

Figure 3-9 Emergency Gate System used in the PR-22 DTL.

At gore areas, a REACT 350 (36”) crash cushion with nine cylinders (see Figure 3-10) is located to protect the concrete barriers. The ends of the concrete barrier, which protect the two overpass bridge columns that divide the exclusive lane inside the DTL, are also connected to a REACT 350 (36”) crash cushion. Both columns are covered with a concrete barrier of 9 feet wide. In terms of markings, a chevron pavement marking with an angle of approximately of 30 to 45 degrees and a spacing of 10 feet is used to advise the diverging segment of the bridge columns. In addition, ten yellow and white plastic pylons are located before the crash cushion over the chevron markings. Figure 3-11 illustrate the WB direction protection of the first bridge columns.

Figure 3-10 REACT 350 (36") Crash Cushion at the DTL Entrance.

Figure 3-11 Westbound Direction Gore Area for Bridge Columns.

In the westbound (WB) direction, the video recording observed several aspects of traffic, TCD's, driving behaviors, amongst others. The tolling of the DTL in the WB direction includes the Toa Baja Toll Plaza fare and the current fare of the DTL. For that reason, a higher DTL fare is collected at this direction. The posted speed limit is located before the dynamic toll facility in contrast to the EB direction, in which the posted speed limit is located after the dynamic toll facility. The BRT enters at the left side but exits at the right lane, similar to the EB direction.

In comparison with the EB direction, the WB peak-hour direction had a reduction in the volume traffic inside the DTL during the peak hour. The traffic volume might be lower because of several factors, which include a higher fare in comparison with the EB direction and that the commuters might not be in a rush of arriving as quickly as they can, compared to the morning condition. However, in the km 19.0 to 23 of the PR-22 mainline, a queue was observed as a consequence of the Toa Baja Toll Plaza. After the toll plaza, the traffic returned to a quasi-free flow speed. The queue length is illustrated in Figure 3-12 to Figure 3-16.

Figure 3-12 Beginning of Traffic Queue in the PR-22 Mainline Approximately at km 19.0.

Figure 3-13 Traffic Congestion in the PR-22 Mainline Approximately at the Km 19.3.

Figure 3-14 Toa Baja Toll Plaza Queue at Peak-hour in the PR-22 Mainline Approximately at Km 20.0.

Figure 3-15 Toa Baja Toll Plaza Congestion in the PR-22 Mainline Approximately at Km 21.3.

Figure 3-16 Traffic Condition After the Toa Baja Toll Plaza at the PR-22 Approximately in km 23.0.

At the exit of the PR-22 DTL, the existing signage and exit lanes are different in both directions. The EB direction has the passenger cars exit at the right side, and the BRT lane exit at the left side. The WB direction has the passenger cars exit located at the left side and the BRT lane exit at the right lane. Also, the signage configuration for both directions present inconsistencies. In the EB direction, the BRT signage has a yellow plaque illustrating the exit gate for passenger cars, meanwhile, at the WB direction, the yellow plaque is illustrating the exit gate for the BRT system.

Based on the information gathered from the videos inside of the DTL, it demonstrated an increased use of vehicles in the EB direction in comparison with the WB direction, inconsistencies in the signage configuration of the DTL exit, and speeding driving behavior. The location and design of the pylons, crash cushions and signage for both directions were used to locate them into the simulated scenarios. In the PR-22 mainline, the focus of the inspection was to identify and locate the existing signage for the simulated scenarios.

3.1.4 Development of Scenarios: UPRM Driving Simulator

The development of scenarios for the UPRM driving simulator is a four-phase procedure that includes the use of three commercial software tools. The procedure was created in collaboration with the University of Massachusetts Amherst and the University of Wisconsin-Madison. The first phase consists of the generation of the roadway with the existing dimension. This included the six lanes in the general-purpose lanes, the two DTL lanes and their respective shoulders, and pavements markings using the computer software AutoCAD Civil 3D. The existing barriers separating the general-purpose lanes and the DTL was created as well using AutoCAD Civil 3D special tool of 3D generation. When the combination of all the pertinent elements of the roadway was modelled, the file was exported as a .dxf file. The dimensions of the lanes, shoulders and barriers was obtained by the “as built” blueprints provided by METROPISTAS and PRHTA.

The second phase consists of used Blender 2.49b as an interface for the developed file in AutoCAD and the simulated software used for the simulation. In this step, the elements in the .dxf files created in AutoCAD Civil 3D acquired the pertinent material, texture and other visual features to the roadway. The created materials included the pavement asphalt and markings texture for the roadway, concrete texture for the traffic barriers and the grass texture for the roadside. Then the file was exported as .vrml files for the next step.

The third phase consists of importing the .vrml files into the Internet Scene Assembler (ISA) software Library. This computer program is used to develop the simulated scenarios compatible with the UPRM driving Simulator. The program allows to combine the generated roadway with all the elements and the texture with the existing library of elements in ISA such as pylons, crash cushions, sings trees, buildings amongst others. Even more important, is that this program allows the generation of computer vehicles and their driving behavior. The driving behavior of the vehicles are based on a series of parameters that include the lane width, shoulder width, roadway width, shoulder location, travel way direction, surface type, lane distribution, amongst others. The traffic flow elements are associated with a value between 0 a 1.0 (0 is no vehicle and 1.0 is maximum software capacity of 52 vehicles). In terms of our scenario, the traffic flow selected was quasi free flow on level D to C (HCM).

The final phase consisted of evaluating the created scenarios and verifying if every element is designed and located correctly. If any of the elements are not designed or located correctly, the procedure is repeated until it is properly corrected.

3.2 SIMULATED DTL SCENARIOS DESCRIPTION

Since the PR-22 Dynamic Toll Lane is a reversible facility; two scenarios layouts were developed. The first layout taken in consideration is the eastbound direction (Toa Baja towards Bayamón) and the second layout taken in consideration is the westbound direction (from Bayamón to Toa Baja). Both layouts have a total length of 4.97 mi. Each layout was created connecting a set of "tiles" (see Figure 3-17). A "tile" is a specific segment of the roadway that was design using the "As-Built" plans of the PR-22 DTL. Table 3-2 depicts the length of each tile segment for the specific layout. A reduction in total length of the PR-22 and DTL of 1.47 mi was done to reduce the exposition of virtual scenarios to the subject drivers.

Table 3-2. Length Segment of Each Scenario Layout

Eastbound Layout	
Tile Segment	**Segment Length (mi)**
Prior to the DTL entrance	0.37
DTL entrance	1.24
Pocket lane in the left	0.87
Overpass bridge columns mainline separation	0.37
Pocket lane in the right	0.87
DTL exit	1.00
After the DTL exit	0.25
Westbound Layout	
Tile Segment	**Segment Length (mi)**
Prior to the DTL entrance	0.25
DTL entrance	1.00
Pocket lane in the left	0.87
Overpass bridge columns mainline separation	0.37
Pocket lane in the right	0.87
DTL exit	1.24
After the DTL exit	0.37

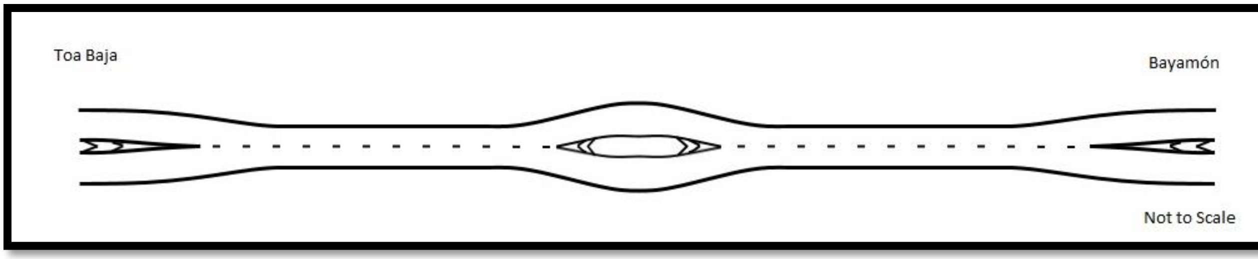


Figure 3-17 Not to Scale Top View of the Simulated PR-22 DTL Scenario

3.3 SIMVISTA SIMULATION RUNTIME

The SimCreator® Simulation Runtime was used to run the simulation and gather information of each subject participant in the workstation. The runtime display is composed of seven slots that must be filled prior to the beginning of the simulation. The seven slots are: SimCreator Model, SimCreator Datafile, Run Lengths, Experimental Name, Participant ID, Driver ID and Store Data. "SimCreator Model" slot was used to specify the .cmp file (which contains the required information for the simulation equipment to be operated) that operated the UPRM Driving Simulator. The "SimCreator Datafile" slot was used to specify the file with the desired scenario that is going to be evaluated. The "Run Length" slot specifies the time longitude (specifically in seconds) in which the scenario will be running. The "Experiment Name" slot was used to specify in which age block was the subject participant #1, #2 or #3 for the 18-25, 26-45 and 46-70 age groups respectively. For example, if the experiment name is 2, the subject participant corresponds to the 26-45 age group. The "Participant ID" slot was used to specify the subject's ID number, which was assigned in the questionnaire form. For example, the subject number 1 was the first participant of the study, therefore, subject number 54 was the last participant of the study. The "Driver ID" slot was used to specify the specific scenarios that the subject ran. For example, Driver

ID 19 corresponds to the scenario 19. The “Store Data” slot was used to specify the place in which all the information is going to be stored. All the information of the run scenario is gathered in a .plt file with the name assigned in the Experimental Name, Participant ID and Driver ID slots. This file assists in the process of analyzing of data since all the required information of the participant is illustrated in the name of the file. Figure 3-18, illustrated the SimCreator Runtime Display.

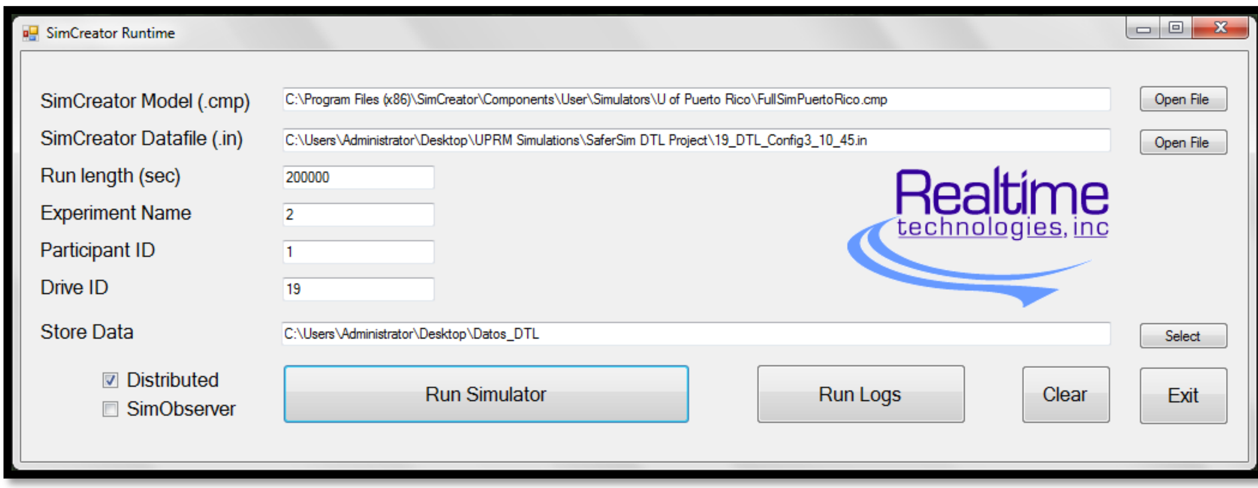


Figure 3-18 Example of the SimCreator Runtime Display.

3.4 DATA PROCESSING

For each subject participant scenario, the SimCreator/SimVista software generated 4 different files with .PLT and .HDR extensions. The file with .PLT extension contains the information required for the analysis. A R® script, developed by UPRM SAFER-SIM Research Assistant Enid M. Colón Torres, was used to gather all the information in one file and perform statistical procedures. Then, a script in R® changed the .PLT extension into a .CSV file with a matrix of N rows and M columns. Where the N is the number of observations, and M is the number of variables. In this case, 2,547,288 observations and 14 variables were selected, which created a 2,547,288 x 14 matrix.

The new .CSV file is used to find the mean values of the variables required. Then, the file is ready to perform statistical analysis, generate subsets, and plots of the driving behavior in the DTL. Once the basic scenario was created the experimental scenarios was created using the same methodology presented in this chapter. The methodology used for the identification and selection of the experimental scenarios are presented in the following chapter.

CHAPTER 4. RESEARCH METHODOLOGY

This chapter presents the research methodology followed in the PR-22 DTL driving simulation study. The research methodology consists of eight (8) task that are illustrated in Figure 4-1 and describe below.

Initially, the pertinent safety and operational issues associated with DTL were identify. The source of information came from METROPISTAS and technical publications. Examples of such issues are concern to operational speeds and driver's decision making at the DTL exit.

Second task, a comprehensive literature review was performed associated with safety and operational issues, emphasizing four major's areas, Manages Lanes, Geometric Design, Driving Simulation and Freeway Safety, covering over 35 years of literature.

The third task consisted of the generation of scenarios that used the experimental design of full factorial design of 27 scenarios and the selection of the independent variables (time of the day (morning, afternoon and night), Lane Width (10, 11 and 12 ft.), and Posted Speed Limit (45, 55 and 65 mph)) and selection of dependent variables (Operational Speed, Acceleration Noise and Lateral Position).

Fourth and fifth task are associated with the development of the scenarios and the selection of zones of interest. The process of the identification, generalization, and creation of the scenarios to be evaluated. The rationale of the selection of the zones is explained in the fifth task using the stopping sight distance measurement.

Sixth task comprised of the data collection, from the selection of participants, study protocol and the sequence of scenarios in which the participants saw the scenarios. Seventh task, data analysis, consisted of two statistical models, namely, Mixed Linear Model and Random Forest, a non-linear model ensemble based methodology using decision trees and bootstrapping samplings.

Finally, conclusions and recommendations are described to potential improve the safety and operation changing the geometric characteristics and posted speed limit inside the PR-22 DTL. Further research and additional recommendations for the simulation and driving simulator are addressed.

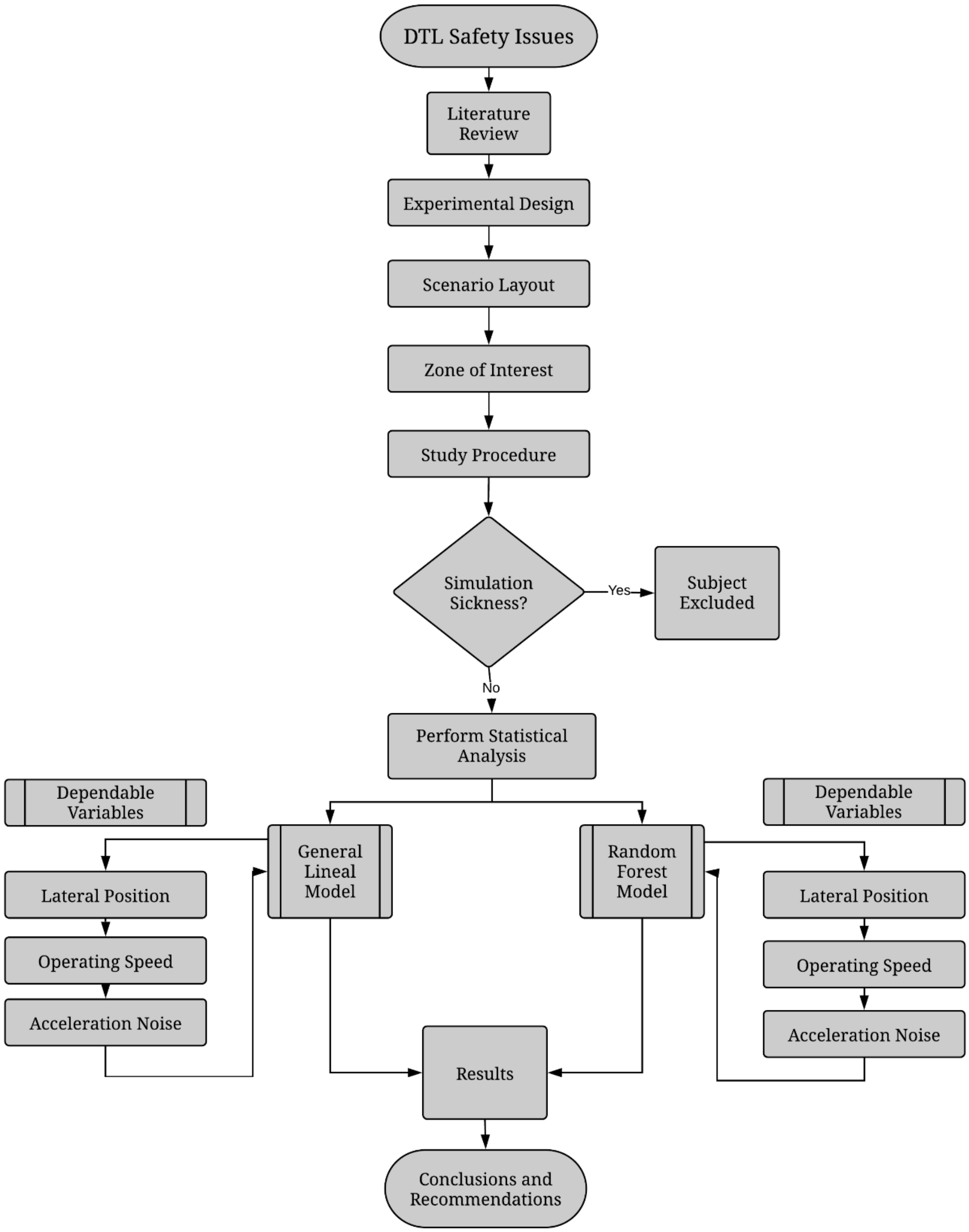


Figure 4-1 Research Methodology.

4.1 LITERATURE REVIEW

The literature review for this research covers over 35 years of studies in four major areas, Managed Lanes, Driving Simulation, Geometric Characteristics and Freeway Safety. The pertinent findings are illustrated in Chapter two.

4.2 EXPERIMENTAL DESIGN

The experimental design used for this research project is a general linear model (Montgomery, 2013). This type of design is used when multiple independent variables are evaluated at different levels of interest. This design allows acquired pertinent information about main effects, the double and triple interaction between the principal factors (independent variables) evaluated and takes in consideration all the possible scenarios that can be evaluated for the independent variables. Therefore, this design allows to gather data for different variables for each subject participating, reducing the necessary scenarios per participant needed. Furthermore, decreasing the exposure of virtual scenarios per subject driver reduced the possibility of simulation sickness, an effect that must be avoided in driving simulator studies. Initially, a Randomized 3^K Full Factorial Design was take in consideration. However, this design has two major limitations namely, the amount of subject participant to complete the factorial design (189 subjects) and each subject should complete all the scenarios evaluated, therefore, the duration of the study may influence the subject dropouts' due to simulation sickness.

Using a custom 3^3 Factorial Design, twenty-seven (27) virtual scenarios were developed based on the three independent variables evaluated, namely, Time of Day Condition, Lane Width, and Posted Speed Limit. In each of the independent variables, three different levels were evaluated. For the Time of Day Condition variable, the levels of interest evaluated were morning, afternoon and night condition. Likewise, the Lane Width variable was evaluated in three different levels: 10, 11, and 12 feet wide, where the 12 feet wide lane is the current DTL condition. Finally, the Posted Speed Limit variable was evaluated in three levels of interest, namely, 45, 55, and 65 mph, where the 45 mph posted speed limit is the current DTL condition. Table 4-1 describes all evaluated scenarios for this research study.

A nuisance factor was defined by Montgomery as "*a design factor that probably has an effect on the response, but we are not interested in that effect*" (Montgomery et al., 2013). To reduce the source of variability of a nuisance factor that is controllable (e.g. age, weight, or knowledge), a block design technique is used to systematically eliminate its effects on the response. Therefore, a Block Design will be used to quantify the effect of each treatment (level of interest for each independent variable) in three homogenous age groups, namely, 18-25, 26-45 and 46 to 70 years of age.

Table 4-1. Scenarios Evaluated in this Research Study.

Scenario	Time of Day Condition			Lane Width (ft)			Speed limit (mph)		
	Morning (EB)	Afternoon (WB)	Nighttime (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

4.2.1 Independent Variables

Five independent variables, namely, Time of Day Condition, Lane Width, Posted Speed Limit, zones of interest and age groups were evaluated. The time of the day variable was evaluated in three configurations, namely, morning, afternoon and night. The morning condition corresponds to the operation of the DTL in the eastbound direction towards Bayamón. Likewise, the afternoon and night conditions correspond to the operation of the DTL in the westbound direction towards Toa Baja. In regard to the Lane Width variable, three configurations were evaluated, namely, 10, 11, and 12 feet wide. Where the 12 feet wide lane is the current DTL condition. The Posted Speed Limit variable was evaluated in three levels of interest, namely, 45, 55, and 65 mph. Seven (7) zones of interest changing geometric characteristics (DTL entrance, pocket lane at the left side, prior, during and after the bridge piers, pocket lane at the right side and the DTL exit) will be used to analyze the driving behavior. Age group blocks, 18-25, 26-45 and 46 to 70 years of age, will be used to analyze the effects by age. The randomness of the subject, the two directions of operation of the DTL reversible facility as well as the traffic flow in peak hours were taken into consideration.

4.2.2 Dependent Variables

Three dependent variables will be evaluated, operating speed, acceleration noise and lateral position, to make a safety evaluation and compare the driving behavior inside the DTL under different environmental and geometrical conditions.

The Operating Speed variable has been established in the MUTCD as: "*Operating Speed is a speed at which a typical vehicle or the overall traffic operates. Operating speed might be defined with speed values such as the average, pace, or 85th-percentile speeds*" (MUTCD, 2009). Likewise, the average speed is established as "*the summation of the instantaneous or spot-measured speeds at a specific location of vehicles divided by the number of vehicles observed*". In this research project, the operating speed is established as the average speed of each subject participant in their respective zone of interest.

The Acceleration Noise variable, root-mean-square 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, Ko, 2006 and Chung and Gartner, 1973). In this research project, the acceleration noise is established as the root-mean-square of the acceleration of each subject participants in the respective zone of interest. Higher acceleration noise value will mean a higher disturbance in the traffic flows and a higher potential of crash frequency at the designated zone of interest.

Lateral position variable has been used as a key element that is affected by the geometric aspects of the roadway. Previous study has been focused in two-lane rural roads and curves. Lindheimer et al. (2016) has studied the lateral position of road users in buffered separated managed lanes collecting lateral position data in-service managed lane facilities with a range of geometric elements (Lindheimer, 2016). The lateral position will be calculated with the average lane position of each driver in comparison with the center of the driving lane. Then, lateral position will be used to identify the behavior of subject drivers inside of a barrier separated managed lane and its relationship with cross-section width.

4.3 SCENARIO DEVELOPMENT

Scenario development consists of several procedures that includes visual inspection and generation of virtual environment using three commercial programs, namely, AutoCAD Civil 3D, Blender 2.49b and Internet Scene Assembler (ISA). Chapter 3 describes the procedure to perform the scenario developments to be used in the driving simulator of the University of Puerto Rico.

4.4 ZONE OF INTEREST

Seven zones of interest were selected for this research project. These zones were selected *a priori* to identify the driving behavior of all subject drivers. The zone selected are: DTL entrance, pocket lane at the left, prior to the bridge mainline separation, during the overpass bridge columns mainline separation segment, after the bridge separation mainline connection, pocket lane at the right side and the DTL exit. Figure 4-2 through Figure 4-15 illustrate the visualization of each zone of interest.

Figure 4-2 Simulation Visualization of the DTL Entrance EB Direction.

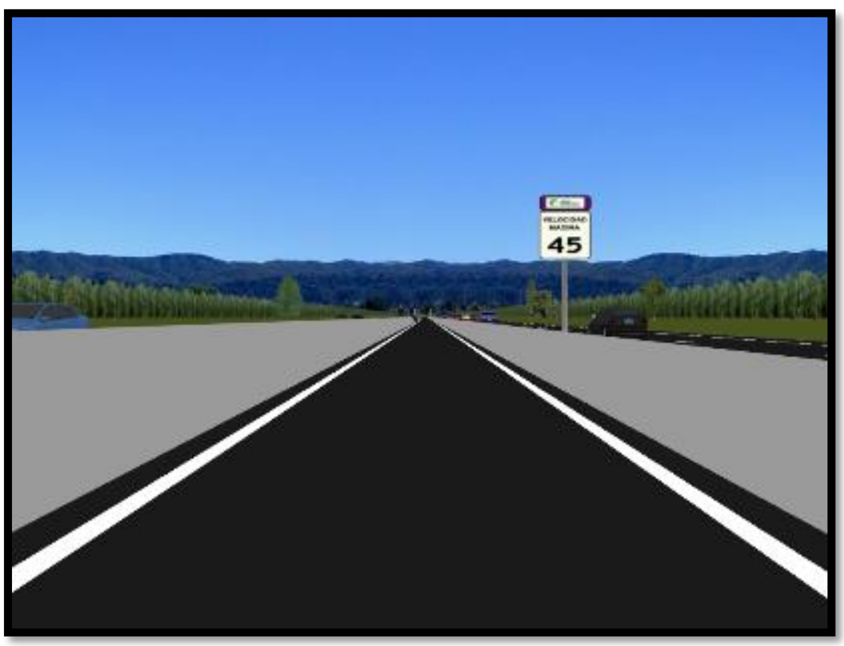


Figure 4-3 Simulation Visualization of the DTL Entrance Westbound Direction.

Figure 4-4 Simulation Visualization of the DTL Pocket Lane at Right Side in the EB Direction.

Figure 4-5 Simulation Visualization of the DTL Pocket Lane at Right Side in the WB Direction

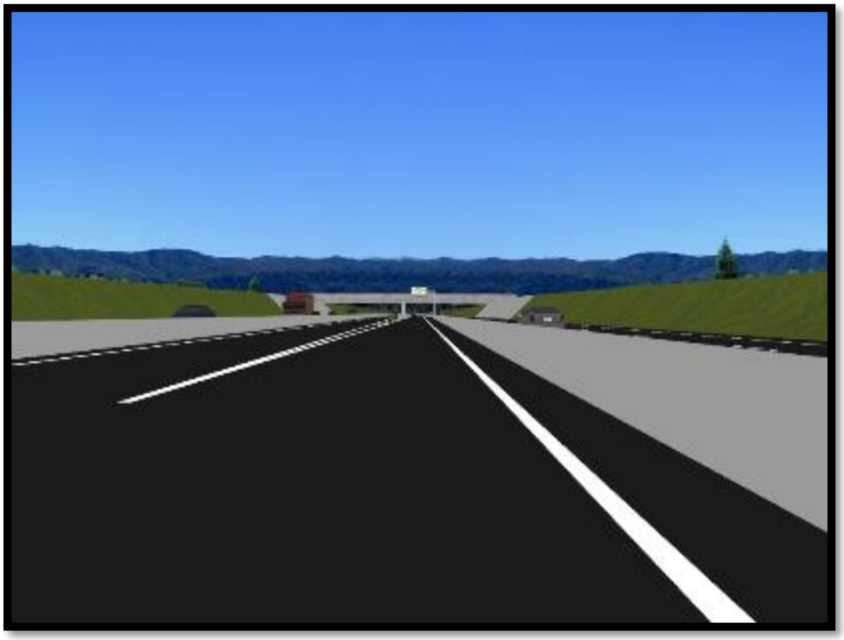


Figure 4-6 Simulation Visualization Prior the Bridge Separation in the EB Direction.

Figure 4-7 Simulation Visualization Prior the Bridge Separation in the WB Direction.

Figure 4-8 Simulation Visualization of Bridge Separation in the EB Direction.

Figure 4-9 Simulation Visualization of Bridge Separation in the WB Direction.

Figure 4-10 Simulation Visualization After the Bridge Separation in the EB Direction.

Figure 4-11 Simulation Visualization After the Bridge Separation in the WB Direction.

Figure 4-12 Simulation Visualization of the DTL Pocket Lane at the Left Side in the EB Direction.

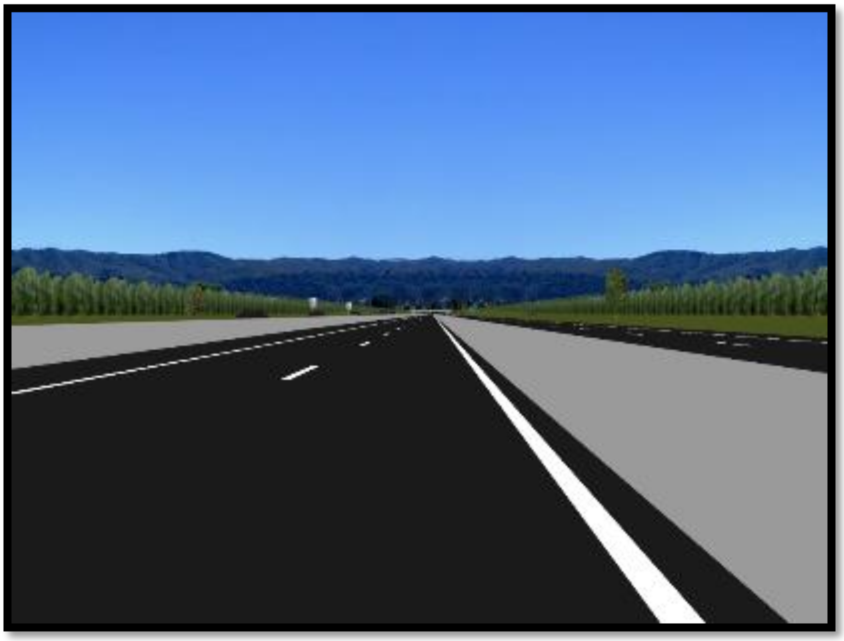


Figure 4-13 Simulation Visualization of the DTL Pocket Lane at the Left Side in the WB Direction.

Figure 4-14 Simulation Visualization of the DTL Exit in the EB Direction.

Figure 4-15 Simulation Visualization of the DTL Exit in the WB Direction.

AASHTO in 2011 states that the 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"* (AASHTO, 2011). Furthermore, the decision sight distance is needed in areas where there are usual or unexpected maneuvers, changers in cross section, and a likelihood for error in either decision making or information reception, such as roadway elements, traffic control devices (TDC's) and traffic composition (King, G. F. and H. Lunenfeld, 1971). The data collection length was selected using the decision sight distances described in the AASHTO A Policy on Geometric Design of Highways and Streets (AASHTO, 2011) section 3.2.3 and is presented in equation (3).

$$DSD = 1.47Vt + 1.075\frac{V^2}{a} \qquad (3)$$

where:

DSD = decision sight distance (ft),

t = pre-maneuver time (seconds),

V = speed (mph), and

A = driver deceleration (ft/s^2)

Regardless the direction of the virtual scenario, the respective length and zone of interest will be the same for both directions. So, for both directions, Zone 1 represented the DTL entrance, Zone 2 represented the pocket lane at the left, Zone 3 represented prior to the bridge mainline separation, Zone 4 represented overpass bridge columns mainline separation, Zone 5 represented connection after the bridge mainline separation, Zone 6 represented pocket lane in the right and Zone 7 represented the DTL exit. Table 4-2 shows the study area selected for each of the zones of interest used in this research study.

Table 4-2. Zones of Interest

Zone	Description	Zone Length (mi)
1	DTL entrance	0.46
2	Pocket lane in the left	0.29
3	Separation prior to the overpass bridge columns	0.13
4	Overpass bridge columns mainline separation	0.13
5	Connecting after the overpass bridge columns separation	0.13
6	Pocket lane in the right	0.29
7	DTL exit	0.36

4.5 STUDY PROCEDURE

4.5.1 Subject Participants

The selection of subject participants will be in accordance with the Institutional Review Board (IRB) for Protection of Human Subjects in Research of the UPRM (Protocol # 20170116) and all subject will be volunteers. The subjects were recruited from the population of METROPISTAS Officials and students, faculty and staff of the University of Puerto Rico at Mayaguez. Each participant will complete three scenarios alternating the Time of Day Condition; the other two variables will not be alternated between scenarios due to the time length of each virtual scenario. This reduced the total duration of the experiment, therefore reducing the possibility that subject suffers simulation sickness effects. To be eligible in this study, the participant should satisfy a given criteria. For instance, the subject participant should be between 18 and 70 years of age, have a valid driver's license, and have more than 18 months of driving experience. Furthermore, the participants should not suffer of epilepsy or dizziness prior, during or after the simulation study. The basic experiment will be replicated; therefore, the precision of the research finding will improve. A total of 54 subject participants, divided in two replicates (27 participants per replicate) will be recruited to be part of this research. In addition, the participants were divided in three age group (18 participants per group) for this research study. The subject distribution is illustrated in Table 4-3.

Table 4-3. Subject Participants Distribution per Group and Scenarios

Age Groups	Subject per Group	Scenarios per Subject	Replicates per Group
18-25	18	3	2
26-45	18	3	2
46-70	18	3	2

4.5.2 Study Protocol

The study protocol consisted of four step procedures. The first step consists of finding potential subjects drivers that meet the criteria requirements mention above. Once the potential subject participant was contacted, the participant was required to enter to the Transportation Engineering Laboratory located in CI-102-F in the Civil Engineering and Surveying Department in the University of Puerto Rico at Mayagüez (UPRM). To be able to participate in the study, the participant was required to fill the Informed Consent Form approved by the IRB for Protection of Human Subjects in Research of the UPRM and a pre-study questionnaire (both documents are located at the appendix). The Informed Consent Form is required for any research involving human subjects. This document contents the pertinent aspects of the research, as well as other important statements that may affect the participants. The pre-study questionnaire was used to determine the demographics and driving history of the subject participants. This document will be used to make recommendation based on the driving history of the sample evaluated and the driving behavior inside the simulated scenarios.

The second step consisted of the illustrating and explained the driving simulator of the UPRM and how every equipment works (which includes the driving wheel, gear shift and the accelerator and brake pedals) as well as the location of the speedometer and the rear mirror in the projection. Prior to the start of the pre-experiment scenario each participant was instructed to assume a role where they were driving alone in a rented vehicle. In addition, question will only be answered prior to the beginning of the research scenarios. The reason behind telling all participants to assume they are driving a rental vehicle is to ensure that they will experiment different pedals and driving wheel sensibility in comparison with their everyday vehicle. After the initial explanation of the driving simulator components, a pre-experiment scenario was given to each subject participant to guarantee that every subject was comfortable with the driving simulator and did not suffer of dizziness or any other symptom that may affect the driving behavior. If the subject participant would not complete the pre-experiment scenarios the subject participant was rejected from the study. Each participant drove the pre-experiment scenario until they were confident to control every aspect of the driving simulator. The following step was to drive the three (3) representative scenarios of the PR-22 DTL. Between each scenario, the researcher asked the subject participant if anything was all right to guarantee the subject participant did not suffer any symptom that affect the driving behavior. If a subject participant suffers of any symptom the research study was concluded and the information will not be used. The final step consists of a post-study questionnaire that will be used to improve the driving simulator experience for future research study using the UPRM driving simulator.

4.5.3 Scenario Sequence

In this research study, the scenario order was randomized to reduce the effects of bias due to the order in which the subject participants were exposed to the scenario. Furthermore, the results obtained for each of the scenarios were independent from the order in which the participants saw them. The order sequence presented in all the variate between age group. The exposure of scenario for each participant is presented in Table 4-4 through 4-6.

Table 4-4. Scenario Order for Group Age 18-25

Group Age 18-25						
First Replicate						
Subject # in Group	**Subject #**	**Age**	**Gender**	**Order**		
1	4	23	M	20	11	2
2	8	25	M	14	5	23
3	9	25	M	18	27	9
4	10	23	M	1	10	19
5	12	23	F	4	22	13
6	15	23	F	3	21	12
7	19	23	F	15	24	6
8	20	25	F	26	8	17
9	21	23	F	7	25	16
Second Replicate						
Subject # in Group	**Subject #**	**Age**	**Gender**	**Order**		
10	29	22	M	20	11	2
11	30	18	M	14	5	23
12	31	22	M	18	27	9
13	33	21	F	1	10	19
14	34	22	M	4	22	13
15	35	25	F	3	21	12
16	37	25	M	15	24	6
17	40	23	F	26	8	17
18	42	23	M	7	25	16

Table 4-5. Scenario Order for Group Age 26-45

Group Age 26-45						
First Replicate						
Subject # in Group	**Subject #**	**Age**	**Gender**	**Order**		
1	1	37	F	2	11	20
2	2	27	F	14	23	5
3	5	26	M	27	18	9
4	6	31	F	19	10	1
5	11	45	M	4	13	22
6	13	29	M	12	3	21
7	22	32	M	15	6	24
8	25	38	F	17	26	8
9	26	31	F	25	16	7
Second Replicate						
Subject # in Group	**Subject #**	**Age**	**Gender**	**Order**		
10	32	27	M	2	11	20
11	36	32	M	14	23	5
12	38	26	M	27	18	9
13	39	27	F	19	10	1
14	43	30	M	4	13	22
15	46	41	F	12	3	21
16	47	31	M	15	6	24
17	48	37	F	17	26	8
18	49	45	F	25	16	7

Table 4-6. Scenario Order for Group Age 46-70

Group Age 46-70						
First Replicate						
Subject # in Group	**Subject #**	**Age**	**Gender**	**Order**		
1	3	60	F	11	2	20
2	7	53	F	23	14	5
3	14	51	M	27	9	18
4	16	63	M	10	1	19
5	17	49	F	13	4	22
6	18	48	M	3	12	21
7	23	51	M	6	15	24
8	24	48	F	26	17	8
9	27	57	F	16	25	7
Second Replicate						
Subject # in Group	**Subject #**	**Age**	**Gender**	**Order**		
10	41	49	M	11	2	20
11	44	47	M	23	14	5
12	45	49	F	27	9	18
13	50	55	M	10	1	19
14	51	53	F	13	4	22
15	52	55	M	3	12	21
16	53	46	M	6	15	24
17	54	63	M	26	17	8
18	28	63	M	16	25	7

4.6 DATA ANALYSIS

The mixed linear and the random forest models were taken into consideration to perform the data analysis of this research project to explore both linear and non-linear patterns between independent and dependent variables. These models evaluated the effect of each independent variable on the dependent variable across the seven (7) zones of interest. Before any statistical analysis was performed for each zone a validation procedure was completed.

4.6.1 Driving Simulator Validation

With an increase in driving simulation studies, a concern has emerged about how performance metrics are collected and analyzed. Therefore, a validation process is performed. According to Blana (1997) and Young et al. (2009), such a validation process is the comparison between driving performance in the real world and driving performance in the driving simulated environment.

The average speed, (in this case the operating speed) is the most common variable used to validate the behavior between driving simulation results and the real world. For this case, six zones of interest (Entrance in EB and WB direction, Before and After the bridge piers separation and the Exits in the EB and WB direction) have been selected to validate the average speed of the DTL real environment and the DTL driving simulator scenarios with the existing condition. Data was not available for all the desired zones in this study. T-test assumptions consisted of random samples, normality and homogenous variance should not be violated. A two-sample T-test was used to compare the behavior between the two environments with a 95% confidence level. If the p-value of the two-sample test statistic evaluated is greater than 0.05, the mean speed values would not have a significant difference. In hypothesis testing the p-value is the level of marginal significance that represents the probability of the occurrence of a given event.

$$T - Test = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{4}$$

where:

$\bar{x}_1 = average\ speed\ in\ the\ real\ envioroment,$

$\bar{x}_2 = average\ speed\ in\ the\ driving\ simulator\ enrioroment,$

$s_1^2 = standard\ deviation\ in\ the\ real\ envioroment,$

$s_1^2 = standard\ deviation\ in\ the\ driving\ simulator\ enrioroment,$

$n_1 = count\ number\ in\ the\ real\ enrioroment,$ and

$n_2 = count\ number\ in\ the\ driving\ simulator\ enrioroment.$

4.6.2 General Linear Model

Operating Speed, Acceleration Noise and Lateral Position variables will be compared with respect to the three independent variables using a General Linear Model with multiple variables (eq. 5).

$$y_{i,j,k} = \beta_0 + \beta_1 * \alpha_i + \beta_2 * \gamma_j + \beta_3 * \delta_k + \beta_4 * \alpha_i * \gamma_j + \beta_5 * \alpha_i * \delta_k + \beta_6 * \gamma_j * \delta_k + \beta_7 * \alpha_i * \gamma_j * \delta_k + \mu_{i,j,k} + \varepsilon_{i,j,k} \tag{5}$$

where:

$y_{i,j,k} = Response\ Variable,$

$\beta_0 = Model\ Regression\ Intercept,$

$\alpha_i = Lane\ Width\ Varible\ Effect\ (LW\ for\ 10, 11\ and\ 12\ feet),$

$\gamma_j = Posted\ Speed\ Limit\ Effect$ (PSL for 45, 55 and 65 mph),

$\delta_k = Time\ of\ the\ Day\ Condition\ Effect$ (ToDC for morning, afternoon and nighttime),

$\mu_{i,j,k} = Subject\ Aleatory\ Effect, and$

$\varepsilon_{i,j,k} = Random\ Error\ Observation.$

This model considers the zone of interest, the independent variable, and the randomness of the subject drivers to reduce the "Family Wise Error Rate", associated with the possibility of obtaining a type I error, commonly known as false positive. A standard 95% confidence level will be used to reach statistical conclusions through an analysis of variance hypothesis test (ANOVA) and its multiple comparisons tests. This confidence level means that the p-value needs to be less than 0.05 to have sufficient evidence to detect significant difference between the variables evaluated. Analysis of Variance (ANOVA) is a test used to determine a relationship between the response variable y and a subset of the regressor variables. Three corresponding statistical assumptions are needed in order to infer from an ANOVA analysis:

- Normal distribution between the samples,
- Independence of samples and;
- Constant variance

The ANOVA analysis compares the means of the independent variables. To make inferences about the sample data, an ANOVA analysis is used with the following hypotheses:

$$H_0: \beta_1 = \beta_2 = \cdots = \beta_n$$

$$H_1: \beta_j \neq 0 \qquad \text{for at least one j}$$

where:

H_0 is the null hypothesis,

H_1 is the alternative hypothesis, and

β is the parameter of interest.

4.6.3 Random Forest Model

To enhance the statistical analysis of this research, a non-linear regression model namely, Random Forest, was used to compare and validate the results from the ANOVA analysis. In addition, this model was selected for his ability to predict the behavior of the sample data and the methodology to classify the variables without overfitting. Random Forest is a statistical method that uses independent sub sets of data to create multiple decision trees using a bootstrapping sampling strategy (random sampling). Each tree sees a different set of data and a different set of variables. The principal idea is to generate multiple models based on the decision trees and then combine (by average) the output of each of the decision trees to produce a robust prediction. With the increase of tree number, a reduction in the correlation between the trees is observed. The averaging of the trees reduces the variance and avoids the overfitting problem. This robust model allows to identify the importance of each variable and produce a prediction for each data point (Breiman and Cutler, 1984). For this model, the Scenario (Sc), Subject (S), Time of the Day Condition (ToDC), Lane Width (LW) and Posted Speed Limit (PSL) were evaluated for the Operating Speed, Acceleration Noise and Lateral Position. The results of the validation procedure, pre- and post-study questionnaire, Random Forest Model as well as the General Lineal Model are presented in the next chapter.

CHAPTER 5. RESULTS OF THE SIMULATION STUDY

In this chapter, the results of the pre-and-post-study questionnaires and of the research project are presented. This includes the results of the General Linear Model as well as the Random Forest analysis for each dependent variable (operating speed, acceleration noise and lateral position) with respect to the independent variables (Time of Day Condition (ToDC), Lane Width (LW) and Posted Speed Limit (PSL)). These models evaluate the effect of each independent variable within the seven (7) zones of interest.

5.1 SUBJECT CHARACTERISTICS

Subject participant characteristics were collected from a pre-study questionnaire where the subject completed a set of questions regarding their demographic and driving history. The characteristics asked in the questionnaire include age, gender, ethnicity, previous participation of simulation studies, driving frequency, years of driving experience, license restrictions, dizziness symptoms when driving, knowledge and using the PR-22 DTL.

A total of 54 subject participated in the simulation study of which 56% were males and 44% were female (see Figure 5-1). The 96% of the sample size in this research study classified themselves as Hispanic, while the remaining 4% are Caucasian. Twenty-six (26%) of the subject drivers have participated in previous simulation studies. The average age for the population used in the research was 36 years old with a standard deviation of 13.65. At least 63% of the subject participants have driven more than 100 miles the week prior to the research study. Sixty-seven (67) percent of the participants did not have any restriction in their driver license and 89% did not suffer from dizziness symptoms in a vehicle as a driver or as a passenger. Table 5-1 showed the relative percentage of the subject characteristics. As part of the protocol, each subject was asked if they know the PR-22 DTL and if they have ever used it. As illustrated in Figure 5-2, eighty-five percent of the participants know that Puerto Rico has a Dynamic Toll Lane (DTL) with 22% of them being typical road users of the facility.

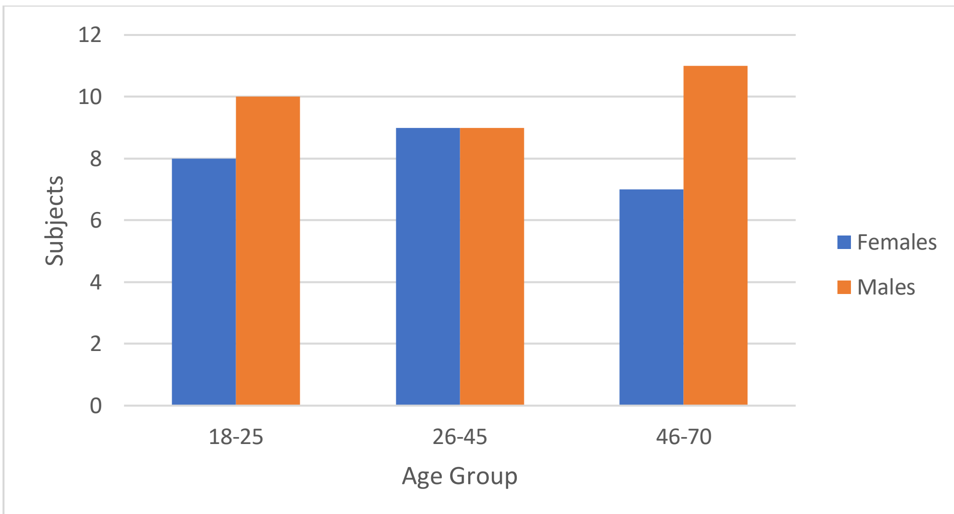


Figure 5-1 Subject Breakdown According to Group Ages.

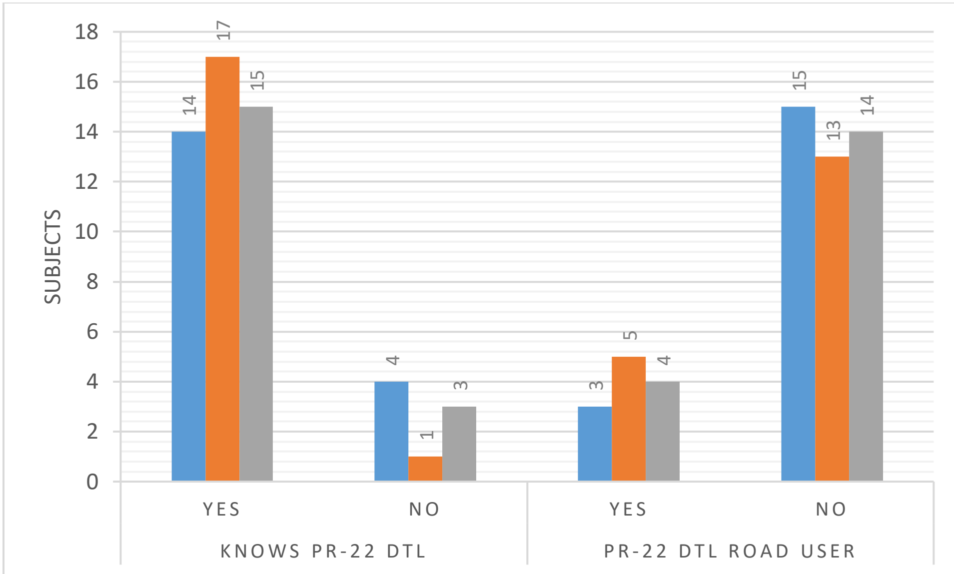


Figure 5-2 Subject Knowledge vs. Typical Road User of PR-22 DTL.

Table 5-1 Subjects Participants Characteristics.

Characteristics	Value	Percentage (%)
Race/Ethnicity	Hispanic	96
	Caucasian	4
Participated in simulation studies	Yes	22
	No	78
Driving Frequency	Less than 100 miles	37
	Between 100 and 200 miles	39
	Between 200 and 300 miles	17
	More than 300 miles	7
Driver Experience	Less than 10 years	33
	Between 10 and 20 years	22
	More than 20 years	45
Driver license restriction	None	67
	Eyeglasses/contacts lenses	33
Drivers with motion sickness while driving or as a passenger	Yes	11
	No	89

In the post-study questionnaire, the subject provided feedback about five (5) of the UPRM driving simulation elements based on their own experiences in the research study. The driving simulation elements evaluated include: real driving sensation, sound, images, brake and acceleration pedals. The experience scale goes between one (1) to five (5), where 1 is deficient and 5 is excellent. The highest score achieved was images and sound of the driving simulation, with an average of 4.42.

Also, as part of the post-study questionnaire, a section for comments were used to gather additional information of the experience. The most frequent comments were referring to the driving wheel sensibility and speed sensation. The average score from each driving simulation elements of the post-study questionnaire are presented in Table 5-2.

Table 5-2. Average Score Results of the Post-Study Questionnaire.

Driving Simulation Element	**Average Score**
Real Driving Sensation	4.10
Sound	4.42
Images	4.42
Brake Pedals	4.24
Acceleration Pedals	4.24

5.2 VALIDATION PROCEDURE

The results of the validation analysis for the PR-22 DTL at a 99% confidence level are shown in Table 5-3. This confidence level means that the p-value needs to be more than 0.01 to have sufficient evidence to validate the zones evaluated. In this case 80% of the zones evaluated resulted without significant difference in the Operating Speed variable, namely, entrance in the EB and

WB, prior the bridge piers, and in the EB and WB exits. This validated the simulated scenario, which did not have a significant difference between the two environments.

Table 5-3 Driving Simulator Validation Results.

Zone Evaluated	Real World Mean Speed (mph)	Driving Simulation Operating Speed (mph)	P-Value	Significant Difference
Entrance EB	47.2	50.6	0.024	No
Entrance WB	49.2	49.6	0.039	No
Prior Bridge Separation	54.8	48.0	0.248	No
After Bridge Separation	54.8	49.3	<0.001	Yes
Exit EB	53.2	53.6	0.233	No
Exit WB	54.9	53.2	0.09	No

Additionally, the traffic flow used in the simulation has a similar level of service when compared to the real-world facility. Driving simulation subjects were presented with scenarios that show comfort and maneuverability slightly restricted by other motorists, similar to what happens in the real-world facility.

5.3 OPERATING SPEED

The statistical analysis done for the dependent variable operating speed was a ANOVA analysis at a 95% confidence level. This statistical test was used to determine significant differences between the three independent variables (Time of Day Condition (ToDC), Lane Width (LW) and Posted Speed Limit (PSL)) when the p-value is less than 0.05. Therefore, the differences in subjects' operating speed was compared between scenarios, zones, subjects as well as age groups. The statistical analysis of each zones for the operating speed of the subjects is summarized below.

5.3.1 Zone 1: DTL Entrance

This zone represents the DTL entrance in EB and WB direction. For Zone 1, the main effects LW, PSL, and the double interactions between ToDC*LW and LW*PSL presented statistically significant differences. The ANOVA Analysis of the General Linear Model for the operating speed in Zone 1 is presented in Table 5-4. Variable Lane Width (LW) decreases the operating speed in the 12 feet lane by 10 mph and 14 mph in comparison to the 10 feet and 11 feet lanes. With the increase of the Posted Speed Limit (PSL), the operating speed also increased with a differential of 8 mph to 10 mph in the 55 mph and 65 mph posted speed limits scenarios in comparison with the 45-mph posted speed limit. The operating speed for each independent variable evaluated in Zone 1 are illustrated in Figure 5-3.

Table 5-4 Analysis of Variance Results for Operating Speed in Zone 1.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	518	103.6	2.15	0.064
ToDC	2	47.6	23.79	0.49	0.612
LW	2	5779.1	2889.54	59.9	<0.001
PSL	2	3085.7	1542.85	31.98	<0.001
Double Interaction					
ToDC*LW	4	642.5	160.63	3.33	0.012
ToDC*PSL	4	66.9	16.74	0.35	0.846
PSL*LW	4	782.1	195.53	4.05	0.004
Triple Interaction					
ToDC*LW*PSL	8	91.6	11.45	0.24	0.983
R-sq		63.72	**R-sq adj**		55.07

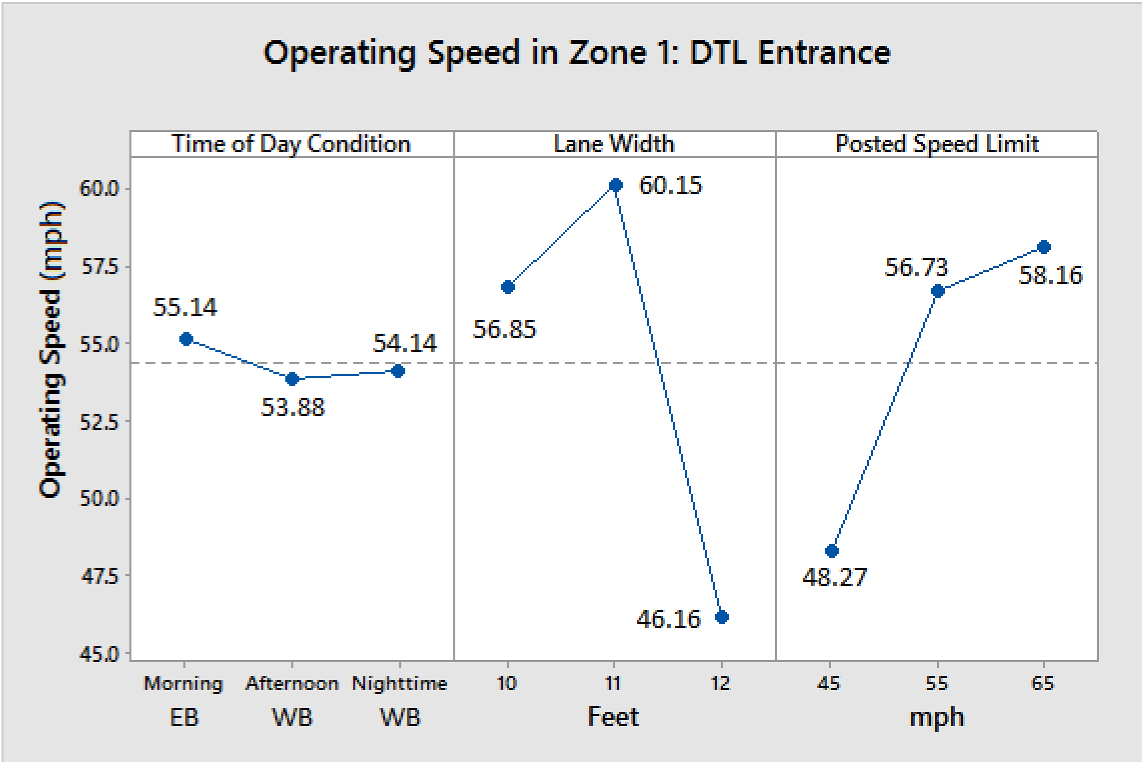


Figure 5-3 Operating Speed on Each Variable Evaluated in Zone 1.

5.3.2 Zone 2: DTL Pocket Lane

This zone is a pocket lane in the left side. In Zone 2, the main effects ToDC, LW, PSL, and the double interactions between LW*PSL presented statistically significant differences. Also, the age differential resulted significant, meaning that the subject driver's age affected the behavior in this zone. The ANOVA Analysis of the General Linear Model for the operating speed in Zone 2 is presented in Table 5-5. In Zone 2, the variable Time of Day Condition decreased the operating speed by 2 mph and 4 mph in the WB direction. The 12 feet and 11 feet Lane Width represent a reduction of 4 mph in operating speed in comparison to 10 feet wide lanes. The posted speed limits presented a differential of 8 mph in the 55-mph level and 17 mph in the 65-mph level. In all the posted speed limit levels, the results were higher operating speed that the regulated posted speed limits. The operating speed for each independent variable evaluated in Zone 2 are illustrated in Figure 5-4.

Table 5-5 Analysis of Variance Results for Operating Speed in Zone 2.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	1709.1	341.81	8.07	<0.001
ToDC	2	364.2	182.11	4.3	0.016
LW	2	528.6	264.28	6.24	0.003
PSL	2	7825.3	3912.67	92.37	<0.001
Double Interaction					
ToDC*LW	4	381	95.25	2.25	0.067
ToDC*PSL	4	313.2	78.31	1.85	0.123
PSL*LW	4	717.3	179.33	4.23	0.003
Triple Interaction					
ToDC*LW*PSL	8	284.3	35.54	0.84	0.57
R-sq		68.76	**R-sq adj**		61.32

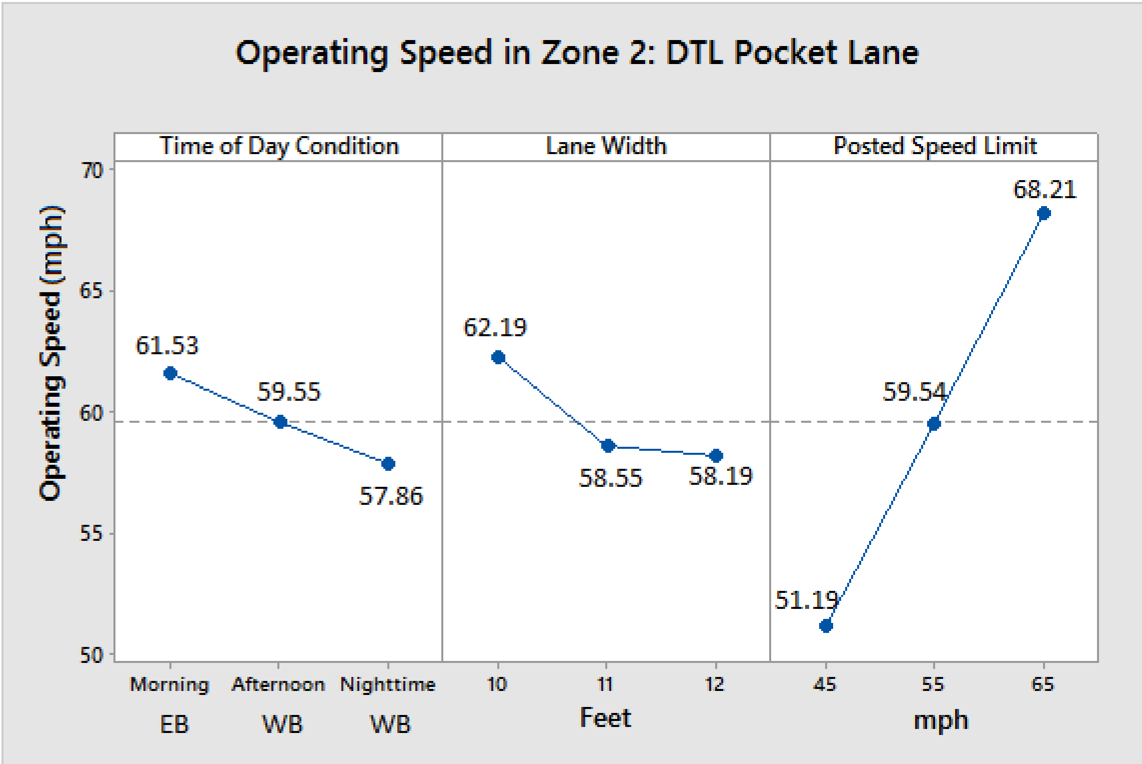


Figure 5-4 Operating Speed on Each Variable Evaluated in Zone 2.

5.3.3 Zone 3: Prior to Bridge Separation

Zone 3 represents the area prior to the bridge separation in both directions. In Zone 3, the main effects LW, and PSL presented statistically significant differences. The age differential resulted significant, meaning that the subject driver's age affected the behavior in the zone prior to the DTL mainline separation The ANOVA Analysis of the General Linear Model for the operating speed in Zone 3 is presented in Table 5-6. Variable Lane Width increased operating speed by 6 mph between the 10 feet and 11 feet wide, whereas a 2 mph increment was observed between the 11 feet to 12 feet wide. The posted speed limits increase gradually between the three levels evaluated with a differential of 9 mph to 17 mph for 55 mph and 65 mph posted speed limit levels. The operating speed of each independent variables evaluated in Zone 3 are illustrated in Figure 5-5.

Table 5-6 Analysis of Variance Results for Operating Speed in Zone 3.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	1302.7	260.53	4.79	<0.001
ToDC	2	150.8	75.41	1.39	0.253
LW	2	1144	571.98	10.52	<0.001
PSL	2	7235	3617.49	66.55	<0.001
Double Interaction					
ToDC*LW	4	346.5	86.62	1.59	0.18
ToDC*PSL	4	55	13.74	0.25	0.908
PSL*LW	4	128.5	32.12	0.59	0.67
Triple Interaction					
ToDC*LW*PSL	8	218.1	27.26	0.59	0.853
R-sq		59.96	**R-sq adj**		50.41

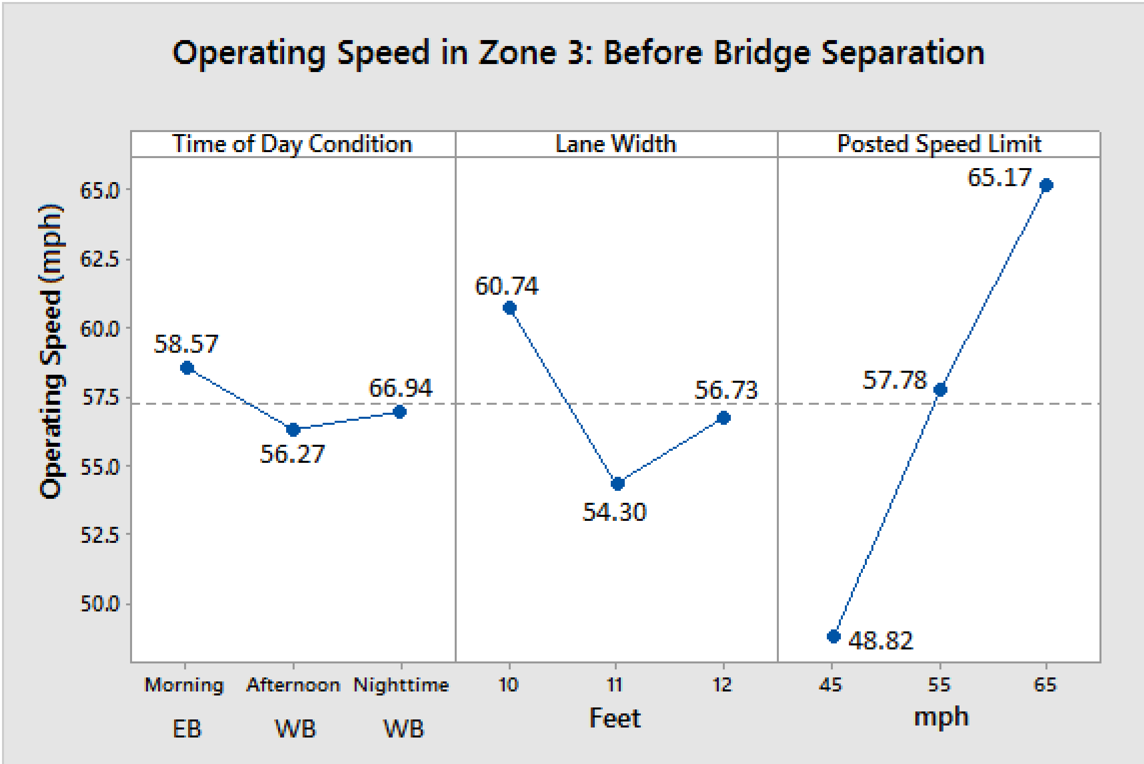


Figure 5-5 Operating Speed on Each Variable Evaluated in Zone 3.

5.3.4 Zone 4: Bridge Segment

Zone 4 includes the area separated by a concreted barrier that covers the overpass bridge columns in both directions. In Zone 4, the main effects LW and PSL presented statistically significant differences. In addition, the age differential resulted significant in the bridge separation (one lane with fixed concrete barriers). The ANOVA Analysis of the General Linear Model for the operating speed in Zone 4 is presented in Table 5-7. The direction and the Time of Day Condition do not result in significant difference but a 2 mph differential between the EB and WB direction was found. The Lane Width variable decreases continuously from the 10 feet Lane Width to the 12 feet Lane Width with a reduction of 3 mph and 4 mph to 11 feet and 12 feet lanes, respectively.

However, the posted speed limit increased the operating speed in all the levels evaluated. It was observed an increase of 8 mph from the 45 mph to 55 mph posted speed limit level and a 7 mph from 55 mph to 65 mph posted speed limit level. The operating speed of each independent variables evaluated in Zone 4 are illustrated in Figure 5-6.

Table 5-7 Analysis of Variance Results for Operating Speed in Zone 4.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	1933.9	386.78	6.6	<0.001
ToDC	2	110.4	55.18	0.94	0.392
LW	2	646.8	323.41	5.52	0.005
PSL	2	6535.4	3267.72	55.79	<0.001
Double Interaction					
ToDC*LW	4	106.8	26.69	0.46	0.768
ToDC*PSL	4	143	35.76	0.61	0.656
PSL*LW	4	273.2	68.29	1.17	0.329
Triple Interaction					
ToDC*LW*PSL	8	235.7	29.46	0.5	0.852
R-sq		56.74	**R-sq adj**		46.42

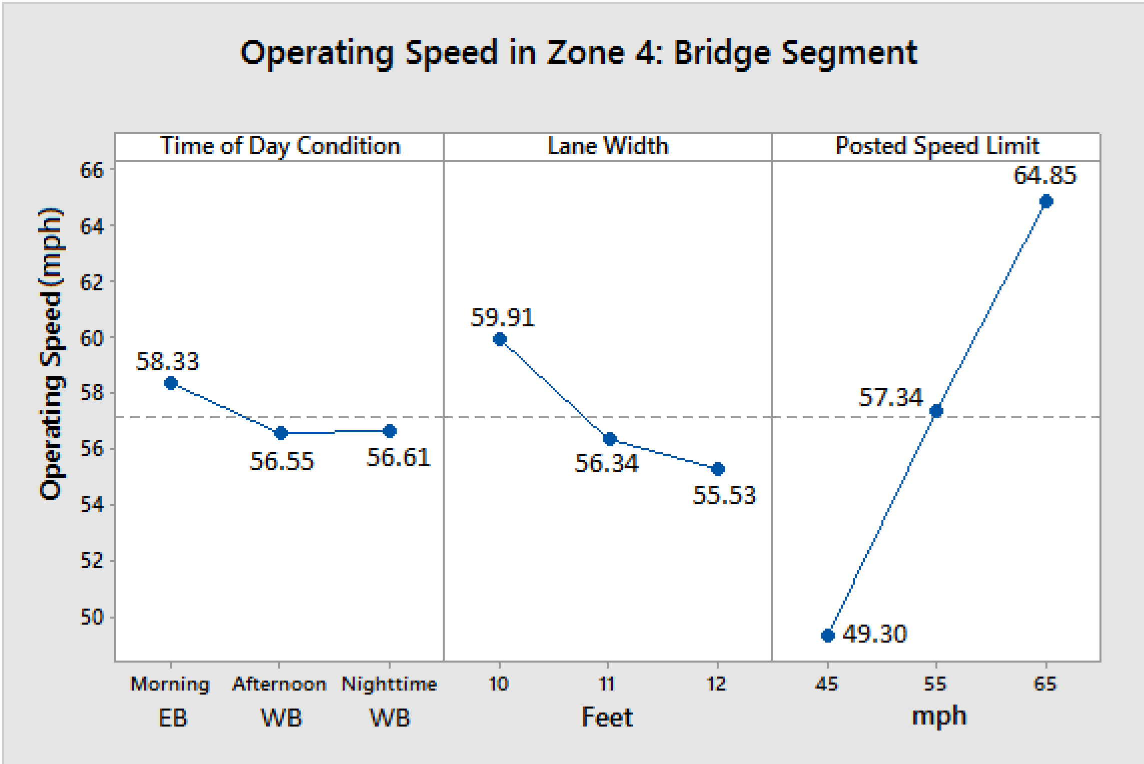


Figure 5-6 Operating Speed on Each Variable Evaluated in Zone 4.

5.3.5 Zone 5: After Bridge Connection

Zone 5 represents the area associated with the merging of the DTL mainline lanes for both directions. In Zone 5, the main effects LW and the PSL variables presented statistically significant differences. Also, the age differential resulted significant, meaning that the subject driver's age affected the behavior in the zone after the bridge columns separation. The ANOVA Analysis of the General Linear Model for the operating speed in Zone 5 is presented in Table 5-8. A differential of 2 mph in operating speed was found between the EB and WB direction. Variable Lane Width decreased operating speed by 1 mph in lanes with 10 feet and 11 feet wide whereas a 5 mph decrease was observed for areas that were 11 feet to 12 feet wide lanes. The posted speed limits presented a differential of 8 to 16 mph for all levels taken in consideration. The operating speed of each independent variables evaluated in Zone 5 are illustrated in Figure 5-7.

Table 5-8 Analysis of Variance Results for Operating Speed in Zone 5.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	1993.1	398.61	6.96	<0.001
ToDC	2	83.3	41.66	0.73	0.485
LW	2	1011.7	505.86	8.83	<0.001
PSL	2	6785.6	3392.81	59.25	<0.001
Double Interaction					
ToDC*LW	4	57	14.25	0.25	0.91
ToDC*PSL	4	71.4	17.84	0.31	0.87
PSL*LW	4	501.8	125.45	2.19	0.074
Triple Interaction					
ToDC*LW*PSL	8	393.6	49.2	0.86	0.553
R-sq		59.41	**R-sq adj**		49.74

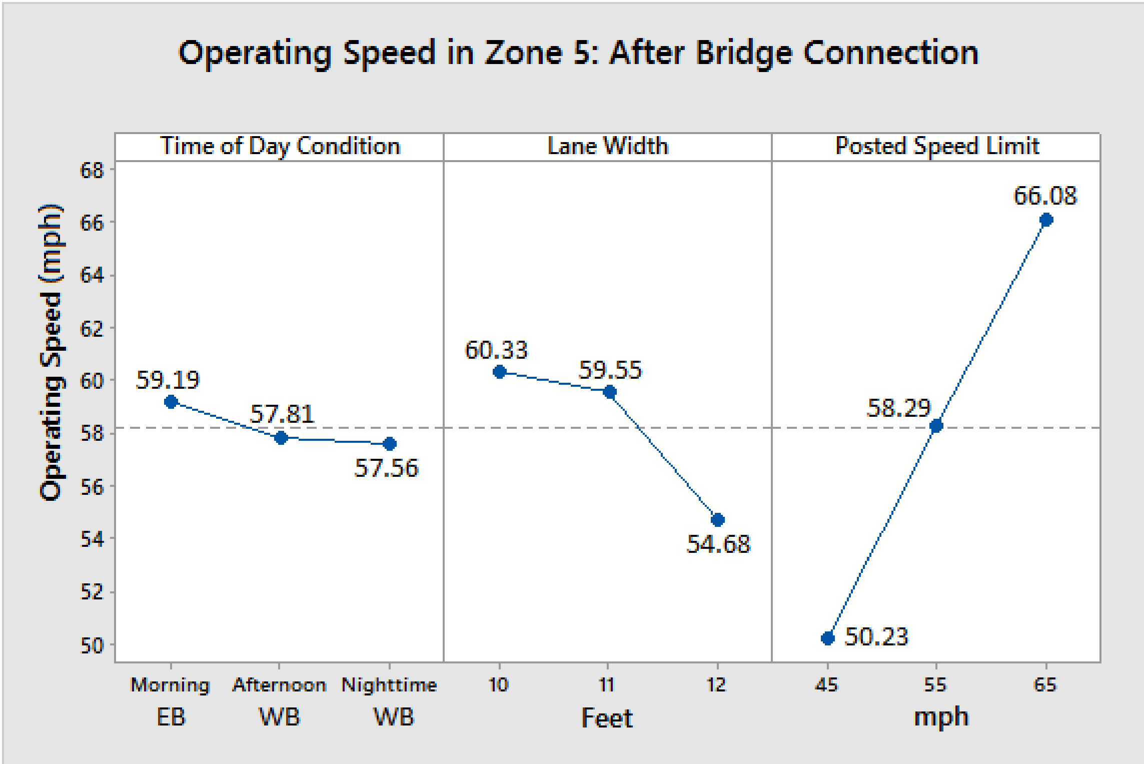


Figure 5-7 Operating Speed on Each Variable Evaluated in Zone 5.

5.3.6 Zone 6: DTL Pocket Lane

This zone is a pocket lane in the right side. In Zone 6, the main effect of PSL presented statistically significant differences. The age differential resulted significant, meaning that the subject driver's age affected the behavior. The ANOVA Analysis of the General Linear Model for the operating speed in Zone 6 is presented in Table 5-9. The operating speed in the WB direction is 2 mph higher than the operating speed of the EB direction in this zone. Variable Lane Width decreased the operating speed by 2 mph between the 10 feet and the 11 feet and 12 feet lanes wide. The operating speed observed for the Posted Speed Limit variable was increasingly between the three levels evaluated with a differential of 7 mph to 9 mph when compared between the 45 mph with the 55 mph and the 55 mph and 65 mph respectively. The operating speed of each independent variables evaluated in Zone 6 are illustrated in Figure 5-8.

Table 5-9 Analysis of Variance Results for Operating Speed in Zone 6.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	2090.6	418.13	8.09	<0.001
ToDC	2	235.9	117.97	2.28	0.106
LW	2	86.1	43.03	0.83	0.437
PSL	2	7286.1	3643.06	70.5	<0.001
Double Interaction					
ToDC*LW	4	64.4	16.1	0.31	0.87
ToDC*PSL	4	132.9	33.21	0.64	0.633
PSL*LW	4	499.4	124.86	2.42	0.052
Triple Interaction					
ToDC*LW*PSL	8	343.2	42.9	0.83	0.578
R-sq		61.52	**R-sq adj**		52.34

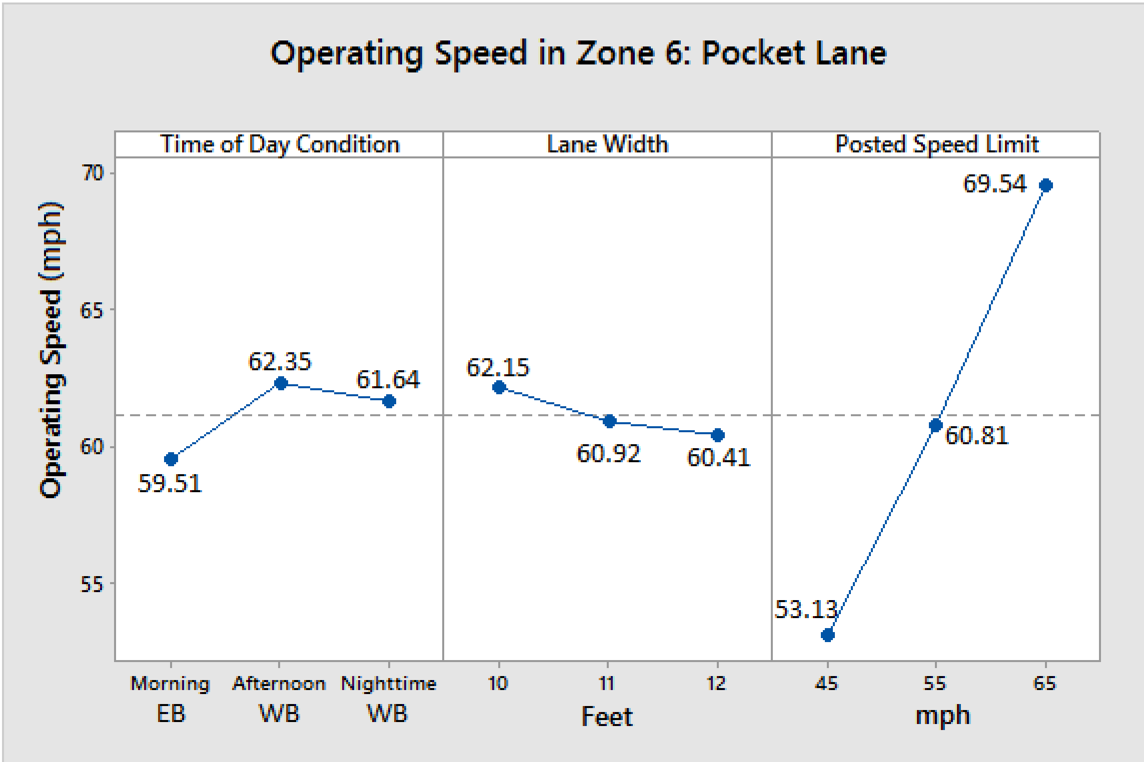


Figure 5-8 Operating Speed on Each Variable Evaluated in Zone 6.

5.3.7 Zone 7: DTL Exit

Zone 7 represents the DTL exit for both directions. In Zone 7, the main effects ToDC, PSL, and the double interaction between ToDC*LW presented statistically significant differences. The age resulted significant, meaning that the subject driver's age affected the behavior at the exit of the DTL. The ANOVA Analysis of the General Linear Model for the operating speed in Zone 7 is presented in Table 5-10. The higher operating speed was observed for the EB direction when compared with the WB direction. For the Lane Width variable, an increase in operating speed was observed when compared the 10 feet and 11 feet lanes with the 12 feet lane. The posted speed limits increase gradually between the three levels evaluated with a differential of 8 mph to 20 mph for 55 mph and 65 mph posted speed limit levels. The operating speed of each independent variables evaluated in Zone 7 are illustrated in Figure 5-9.

Table 5-10 Analysis of Variance Results for Operating Speed in Zone 7.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	832.5	166.51	2.04	<0.001
ToDC	2	767.5	383.76	4.70	0.011
LW	2	254.0	127.00	1.56	0.215
PSL	2	3118.6	1559.30	19.09	<0.001
Double Interaction					
ToDC*LW	4	840.6	210.15	2.57	0.041
ToDC*PSL	4	207.2	51.80	1.52	0.639
PSL*LW	4	495.3	123.82	1.52	0.201
Triple Interaction					
ToDC*LW*PSL	8	616.5	77.07	0.94	0.483
R-sq		40.19	**R-sq adj**		25.92

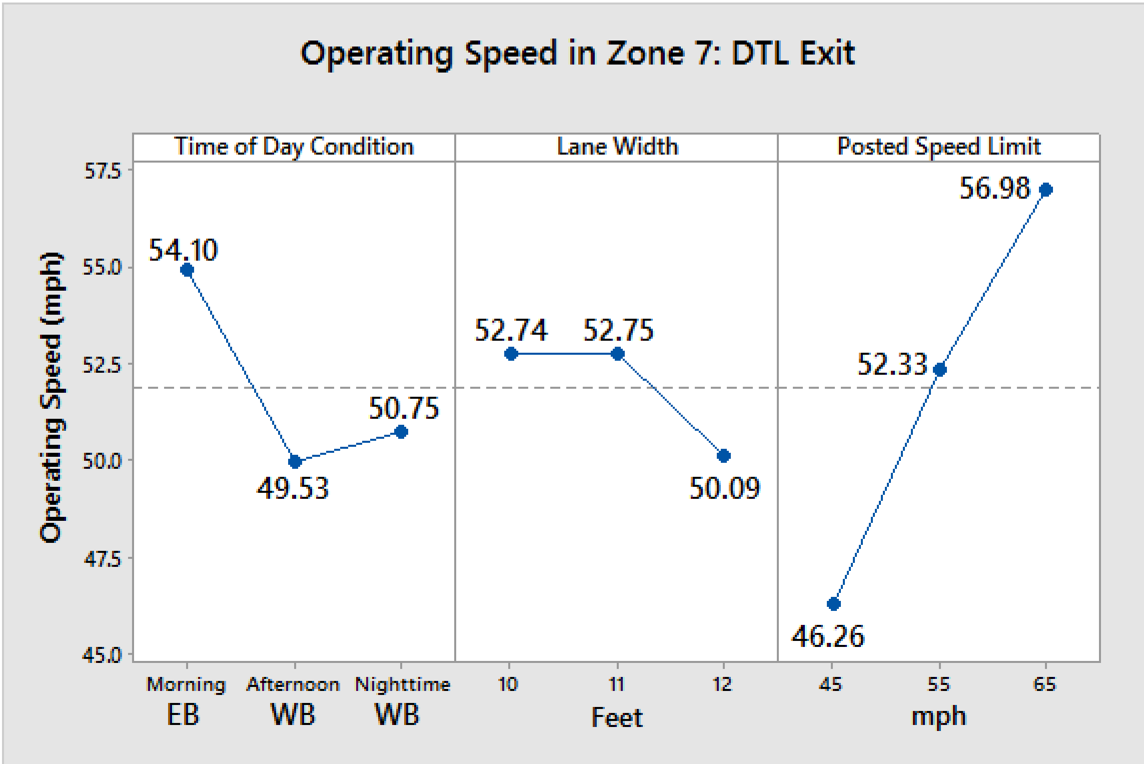


Figure 5-9 Operating Speed on Each Variable Evaluated in Zone 7.

5.4 ACCELERATION NOISE

The statistical analysis done for the dependent variable acceleration noise was a ANOVA analysis at a 95% confidence level. This statistical test was used to determine significant differences between the three independent variables (Time of Day Condition (ToDC), Lane Width (LW) and Posted Speed Limit (PSL)) when the p-value is less than 0.05. Therefore, the differences in subjects' acceleration noise was compared between scenarios, zones, subjects as well as age groups. The statistical analysis of each zones for the acceleration noise of the subjects is summarized below.

5.4.1 Zone 1: DTL Entrance

This zone represents the DTL entrance in EB and WB direction. In Zone 1, the main effect of LW and the age differential presented statistically significant differences. The ANOVA Analysis of the General Linear Model for the acceleration noise in Zone 1 is presented in Table 5-11. The Time of Day Condition did not result in significant differences between the level evaluated. However, a difference of 0.2 mph/sec and 0.1 mph/sec was observed between the morning and afternoon conditions and night and afternoon conditions. A higher acceleration noise in Zone 1 was observed in wider lanes, resulting in an increment of 0.06 mph/sec between the 10 feet and 11 feet lanes and a 0.3 mph/sec between the 11 feet and 12 feet lanes. The Posted Speed Limit did not result in significant differences however the 55 mph posted speed level shows a 0.03 mph/sec higher than the 45 and 65 mph posted speed limits. The acceleration noise of each independent variables evaluated in Zone 1 are illustrated in Figure 5-10.

Table 5-11 Analysis of Variance Results for Acceleration Noise in Zone 1

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	36.48	7.29	3.35	0.007
ToDC	2	4.45	2.22	1.02	0.362
LW	2	28.11	14.05	6.46	0.002
PSL	2	0.73	0.36	0.17	0.846
Double Interaction					
ToDC*LW	4	5.96	1.49	0.69	0.604
ToDC*PSL	4	1.10	0.27	0.13	0.973
PSL*LW	4	4.74	1.18	0.55	0.703
Triple Interaction					
ToDC*LW*PSL	8	6.85	0.85	0.39	0.922
R-sq		23.82	**R-sq adj**		5.65

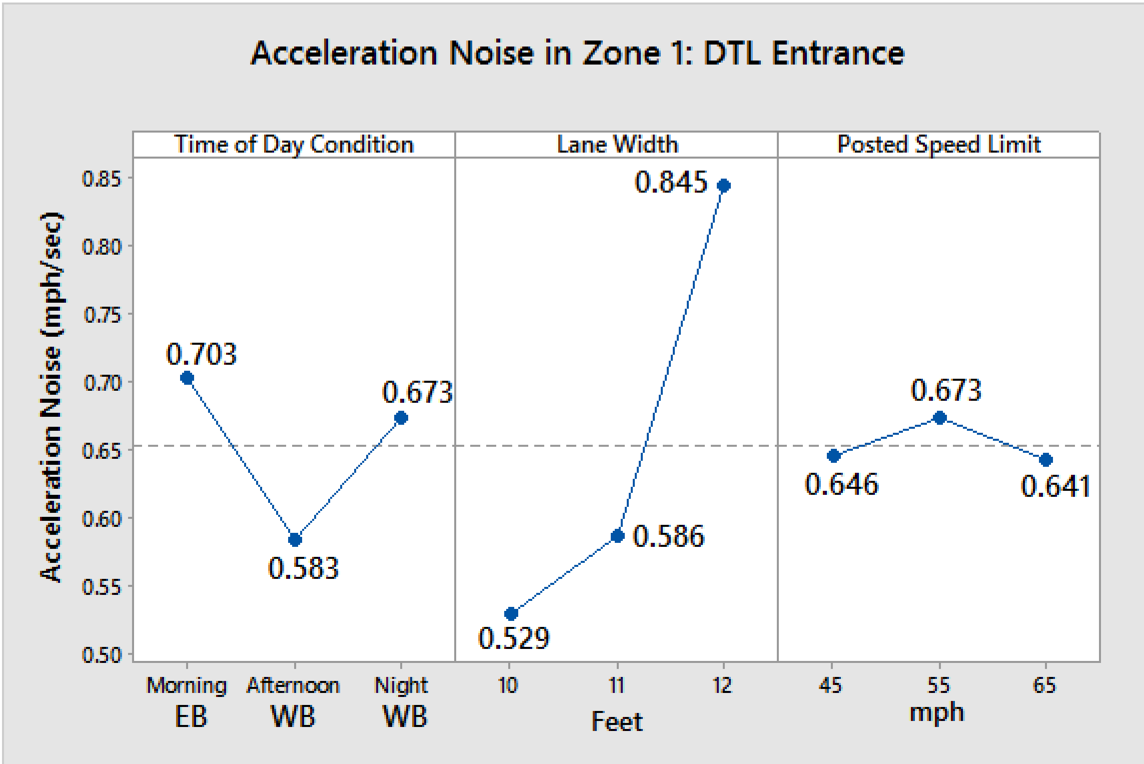


Figure 5-10 Acceleration Noise on Each Variable Evaluated in Zone 1.

5.4.2 Zone 2: DTL Pocket Lane

This zone is a pocket lane in the left side. In Zone 2, the driver's age presented statistically significant differences. The ANOVA Analysis of the General Linear Model for the acceleration noise in Zone 2 is presented in Table 5-12. The Time of Day Condition increased in the WB direction, especially in the nighttime condition with an increase of 0.15 mph/sec in comparison with the afternoon scenarios and 0.17 mph/sec in comparison with the morning scenarios. Nevertheless, the Time of Day Condition did not result in significant difference in comparison with their counterparts. In Zone 2, the higher acceleration noise was found for the 11 feet lanes scenarios with a 0.602 mph/sec, the double registered for the 10 feet lanes scenarios and 0.2

mph/sec higher in comparison with the 12 feet lane scenarios. The 45 mph posted speed limit scenarios shows a decrease in the Acceleration Noise variable resulting in a decrease of 0.9 mph/sec and 0.7 mph/sec for the 55 mph and 65 mph posted speed limit scenarios respectively. The acceleration noise of each independent variables evaluated in Zone 2 are illustrated in Figure 5-4.

Table 5-12 Analysis of Variance Results for Acceleration Noise in Zone 2.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	119.56	23.91	5.74	<0.001
ToDC	2	12.23	6.11	1.47	0.234
LW	2	19.02	9.51	2.28	0.106
PSL	2	16.91	8.45	2.03	0.135
Double Interaction					
ToDC*LW	4	15.21	3.80	0.91	0.458
ToDC*PSL	4	7.34	1.83	0.44	0.779
PSL*LW	4	39.07	9.76	2.35	0.058
Triple Interaction					
ToDC*LW*PSL	8	28.08	3.51	0.84	0.566
R-sq		32.24	**R-sq adj**		16.08

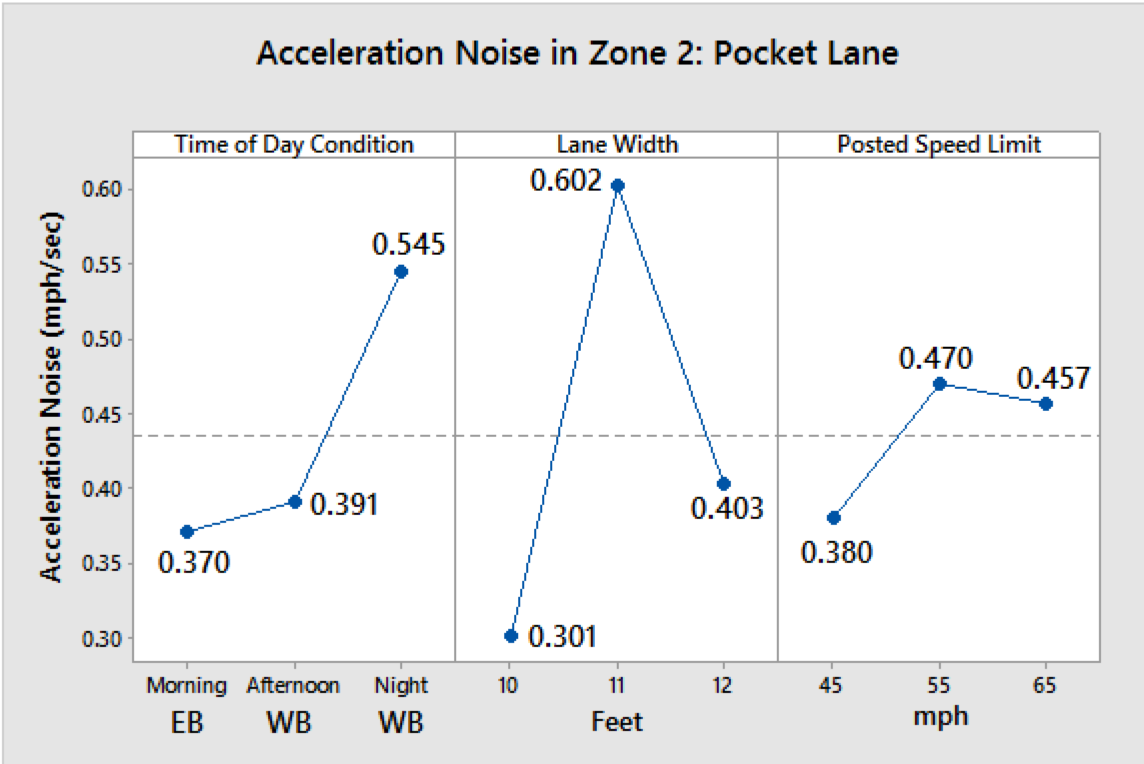


Figure 5-11 Acceleration Noise on Each Variable Evaluated in Zone 2.

5.4.3 Zone 3: Prior to Bridge Separation

Zone 3 represents the area prior to the bridge separation in both directions. In Zone 3, the main effects LW, the double interactions between PSL*LW and the triple interactions between the ToDC*LW*PSL presented statistically significant differences. Also, the age differential resulted significant, meaning that the subject driver's age affected the behavior. The ANOVA Analysis of the General Linear Model for the acceleration noise in Zone 3 is presented in Table 5-13. The zone prior to the bridge represents a decrease in acceleration noise for the WB direction and the night condition resulted in lower acceleration noise (0.532 mph/sec) in comparison with their counterparts (0.814 mph/sec in the morning condition and 0.549 mph/sec in the afternoon condition). For Zone 3 with wider lanes, higher the acceleration noise was observed. The 12 feet lane duplicated the acceleration noise in comparison to the 10 feet lane and registered a difference of 0.34 mph/sec in comparison to the 11 feet lane. The Posted Speed Limits presented a differential of 0.24 mph/sec and 0.22 mph/sec between the 45mph and 55 mph posted speed limit, and 45 mph and 65 mph posted speed limits. The acceleration noise of each independent variables evaluated in Zone 3 are illustrated in Figure 5-12.

Table 5-13 Analysis of Variance Results for Acceleration Noise in Zone 3.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	164.48	32.89	4.76	<0.001
ToDC	2	3.99	1.99	0.29	0.75
LW	2	45.74	22.87	3.31	0.04
PSL	2	19.46	9.72	1.41	0.248
Double Interaction					
ToDC*LW	4	46.25	11.56	1.67	0.16
ToDC*PSL	4	29.72	7.42	1.08	0.371
PSL*LW	4	105.35	26.33	3.81	0.006
Triple Interaction					
ToDC*LW*PSL	8	115.34	14.41	2.09	0.041
R-sq		37.14	**R-sq adj**		22.15

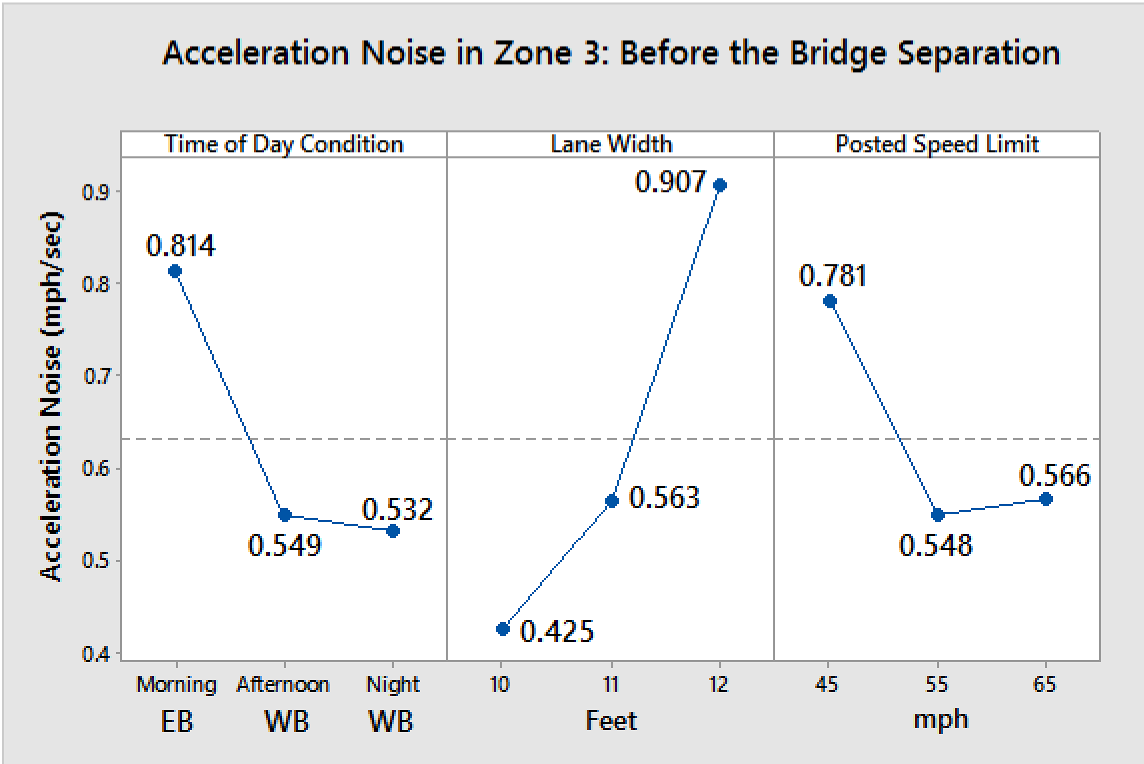


Figure 5-12 Acceleration Noise on Each Variable Evaluated in Zone 3.

5.4.4 Zone 4: DTL Bridge Separation

Zone 4 includes the area separated by a concreted barrier that covers the overpass bridge columns in both directions. In Zone 4, the double interactions between LW*PSL presented statistically significant differences. In addition, the age differential resulted significant, meaning that the subject driver's age affected the behavior in this zone. The ANOVA Analysis of the General Linear Model for the acceleration noise in Zone 4 is presented in Table 5-14. Inside of the Zone 4, the direction the acceleration noise observed in the EB direction was 0.08mph/sec less than the observed in the WB direction (0.479 mph/sec in the afternoon condition and 0.497 mph/sec in the night condition). With higher Lane Width, higher acceleration noise was detected resulting with a

0.335 mph/sec for the 10 feet lane, 0.477 mph/sec for the 11 feet lane and 0.544 mph/sec for the 12 feet lane. The Posted Speed Limits variable increased acceleration noise by 0.14 mph/sec between 55 mph and 45 mph whereas a 0.03 mph/sec decrease was observed for areas 55 mph and 65 mph scenarios. The acceleration noise of each independent variables evaluated in Zone 4 are illustrated in Figure 5-13.

Table 5-14 Analysis of Variance Results for Acceleration Noise in Zone 4.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	2.92	0.58	6.61	<0.001
ToDC	2	0.27	0.13	1.55	0.217
LW	2	0.52	0.26	2.97	0.055
PSL	2	0.08	0.04	0.49	0.615
Double Interaction					
ToDC*LW	4	0.34	0.08	0.97	0.425
ToDC*PSL	4	0.25	0.06	0.72	0.576
PSL*LW	4	1.00	0.25	2.85	0.026
Triple Interaction					
ToDC*LW*PSL	8	0.66	0.08	0.93	0.491
R-sq		34.57	**R-sq adj**		18.97

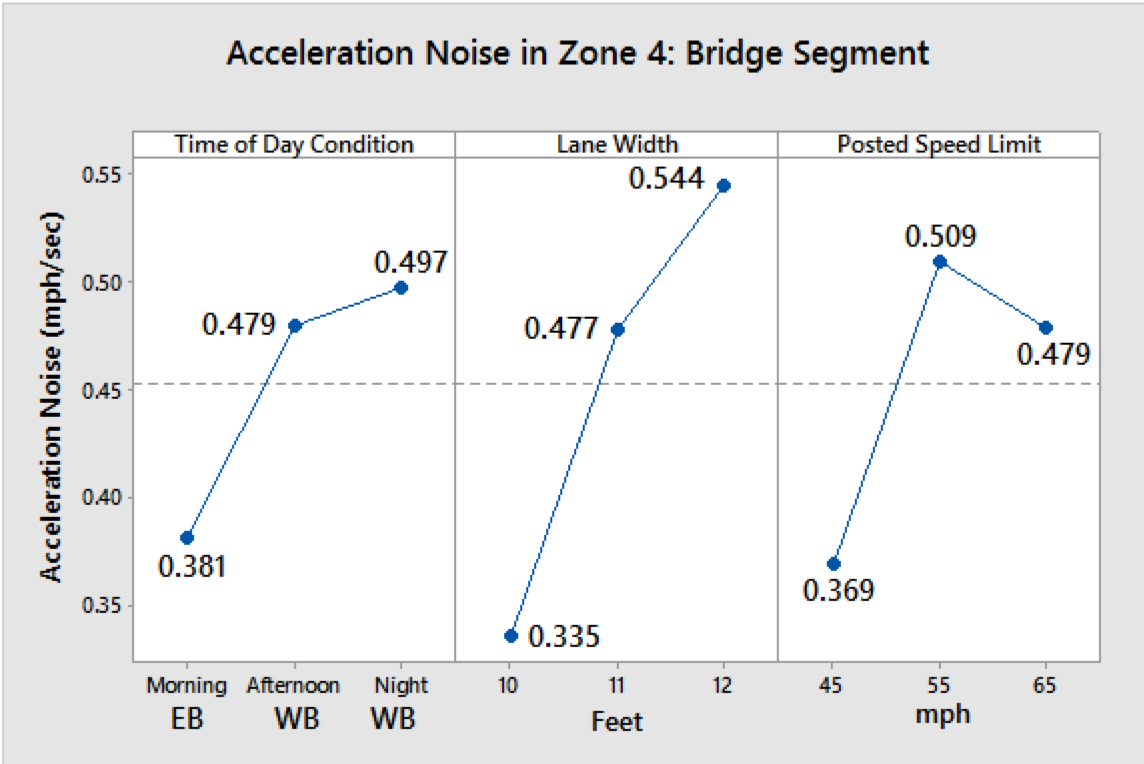


Figure 5-13 Acceleration Noise on Each Variable Evaluated in Zone 4.

5.4.5 Zone 5: After Bridge Connection

Zone 5 represents the area associated with the merging of the DTL mainline lanes for both directions. In Zone 5, the double interaction between PSL*LW and the age differential presented statistically significant differences, meaning that the subject driver's age affected the behavior. The ANOVA Analysis of the General Linear Model for the acceleration noise in Zone 5 is presented in Table 5-15. The time of the day condition variable increased acceleration noise by 0.16 mph/sec between afternoon and morning conditions whereas a 0.07 mph/sec decrease was observed for the afternoon and night conditions scenarios. The acceleration noise resulted in an increase with the wider lane (0.393 mph/sec, 0.466 mph/sec and 0.607 mph/sec, for the 10 feet, 11 feet and 12 feet width lanes). The Posted Speed Limits variable decreases acceleration noise by 0.15 mph/sec between 45 mph and 55 mph whereas a 0.19 mph/sec increase was observed for areas 65 mph and 55 mph level. The acceleration noise of each independent variables evaluated in Zone 5 are illustrated in Figure 5-14.

Table 5-15 Analysis of Variance Results for Acceleration Noise in Zone 5.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	158.50	31.70	5.92	<0.001
ToDC	2	5.95	2.97	0.56	0.575
LW	2	32.32	16.16	3.02	0.052
PSL	2	10.64	5.32	0.99	0.373
Double Interaction					
ToDC*LW	4	25.96	6.48	1.21	0.309
ToDC*PSL	4	15.26	3.81	0.71	0.585
PSL*LW	4	74.42	18.60	3.47	0.010
Triple Interaction					
ToDC*LW*PSL	8	19.18	2.39	0.45	0.890
R-sq		32.95	**R-sq adj**		16.96

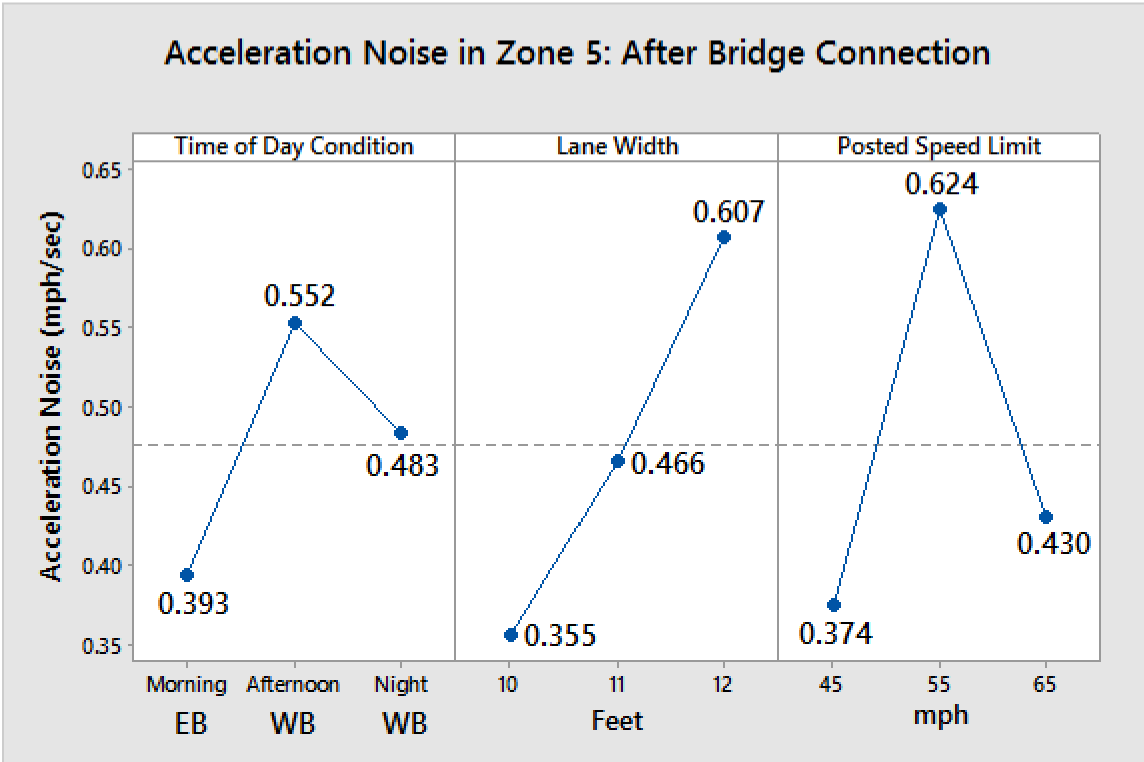


Figure 5-14 Acceleration Noise on Each Variable Evaluated in Zone 5.

5.4.6 Zone 6: DTL Pocket Lane

This zone is a pocket lane in the right side. In Zone 6, the double interactions between LW*PSL and the blocks (age differential) presented statistically significant differences. The ANOVA Analysis of the General Linear Model for the acceleration noise in Zone 6 is presented in Table 5-16. A decrease in acceleration noise was observe in the WB direction in comparison with the EB direction. In addition, the difference between the EB direction and the two WB direction was 0.17 mph/sec and 0.15 mph/sec for the afternoon and night conditions respectively. In this pocket lane, the 11 feet lane affects the Acceleration Noise variable more than the 10 feet and 12 feet lanes with a 0.10 mph/sec and 0.09 mph/sec respectively. On the Posted Speed Limit variable, the acceleration noise increased with the increase of the posted speed limit level. The acceleration noise of each independent variables evaluated in Zone 6 are illustrated in Figure 5-15.

Table 5-16 Analysis of Variance Results for Acceleration Noise in Zone 6.

Source	**Df**	**Sum Sq**	**Mean Sq**	**F-Value**	**P-Value**
Blocks	5	3.68	0.73	9.23	<0.001
ToDC	2	0.31	0.15	1.99	0.140
LW	2	0.43	0.21	2.71	0.071
PSL	2	0.06	0.03	0.38	0.684
Double Interaction					
ToDC*LW	4	0.09	0.02	0.30	0.877
ToDC*PSL	4	0.24	0.06	0.77	0.549
PSL*LW	4	1.02	0.25	3.21	0.015
Triple Interaction					
ToDC*LW*PSL	8	0.45	0.05	0.71	0.686
R-sq		37.83	**R-sq adj**		23.00

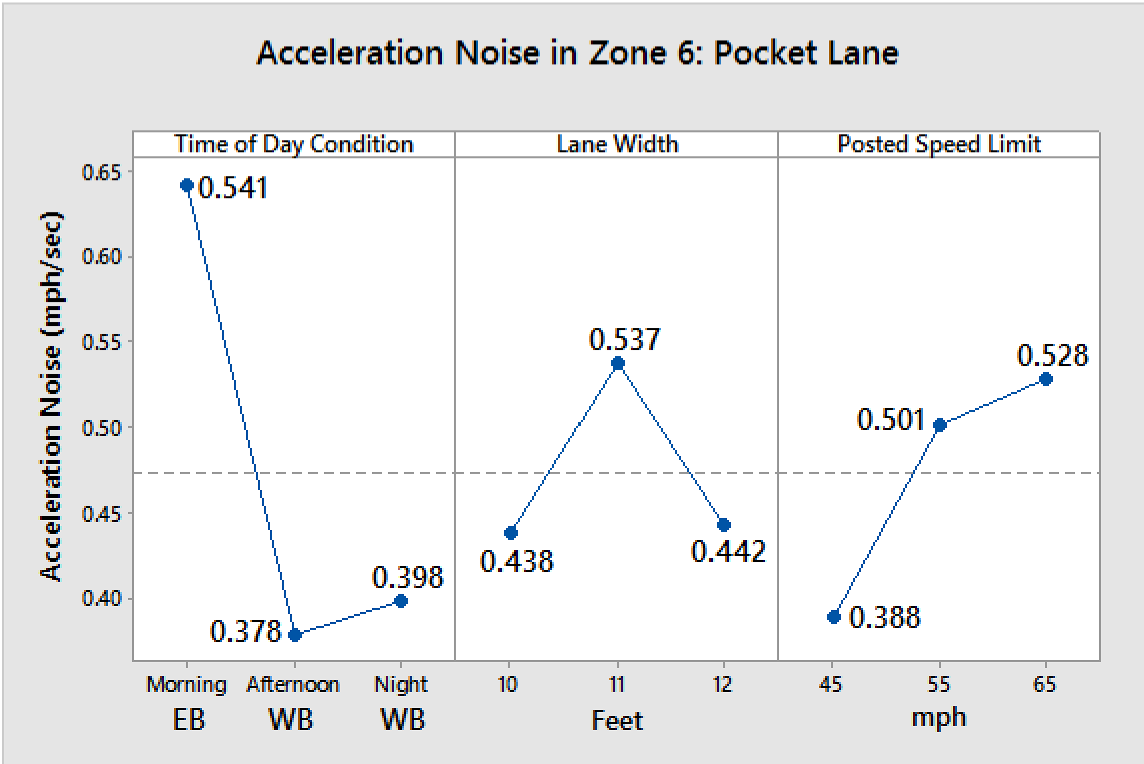


Figure 5-15 Acceleration Noise on Each Variable Evaluated in Zone 6.

5.4.7 Zone 7: DTL Exit

Zone 7 represents the DTL exit for both directions. In Zone 7, the main effects LW, PSL, and the double interactions between ToDC*LW and LW*PSL presented statistically significant differences. The ANOVA Analysis of the General Linear Model for the acceleration noise in Zone 7 is presented in Table 5-17. At the exit lane, the direction affects the acceleration noise with an observed value of 2.07 mph/sec at night, 0.15 mph/sec higher than the afternoon scenarios and 0.81 mph/sec higher than the morning and EB direction. The 11 feet lane resulted in higher acceleration noise than their counterparts (0.35 mph/sec higher than the 10 feet lane and 0.64 mph/sec higher than the 12 feet lane. The acceleration noise increased with the increment of the

Lane Width resulting in 1.14 mph/sec difference between the 65 mph and 45 mph levels and 0.46 mph/sec difference between the 65 mph and 55 mph posted speed limits levels. The 65 mph posted speed limit level resulted with a peak value of 2.28 mph/sec. The acceleration noise of each independent variables evaluated in Zone 7 are illustrated in Figure 5-16.

Table 5-17 Analysis of Variance Results for Acceleration Noise in Zone 7.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	177.00	35.40	3.63	0.004
ToDC	2	117.07	58.53	6.00	0.003
LW	2	16.39	8.19	0.84	0.434
PSL	2	44.81	22.40	2.30	0.105
Double Interaction					
ToDC*LW	4	73.64	18.41	1.89	0.116
ToDC*PSL	4	35.09	8.77	0.90	0.466
PSL*LW	4	61.80	15.45	1.58	0.182
Triple Interaction					
ToDC*LW*PSL	8	62.31	7.78	0.80	0.605
R-sq		31.68	**R-sq adj**		15.39

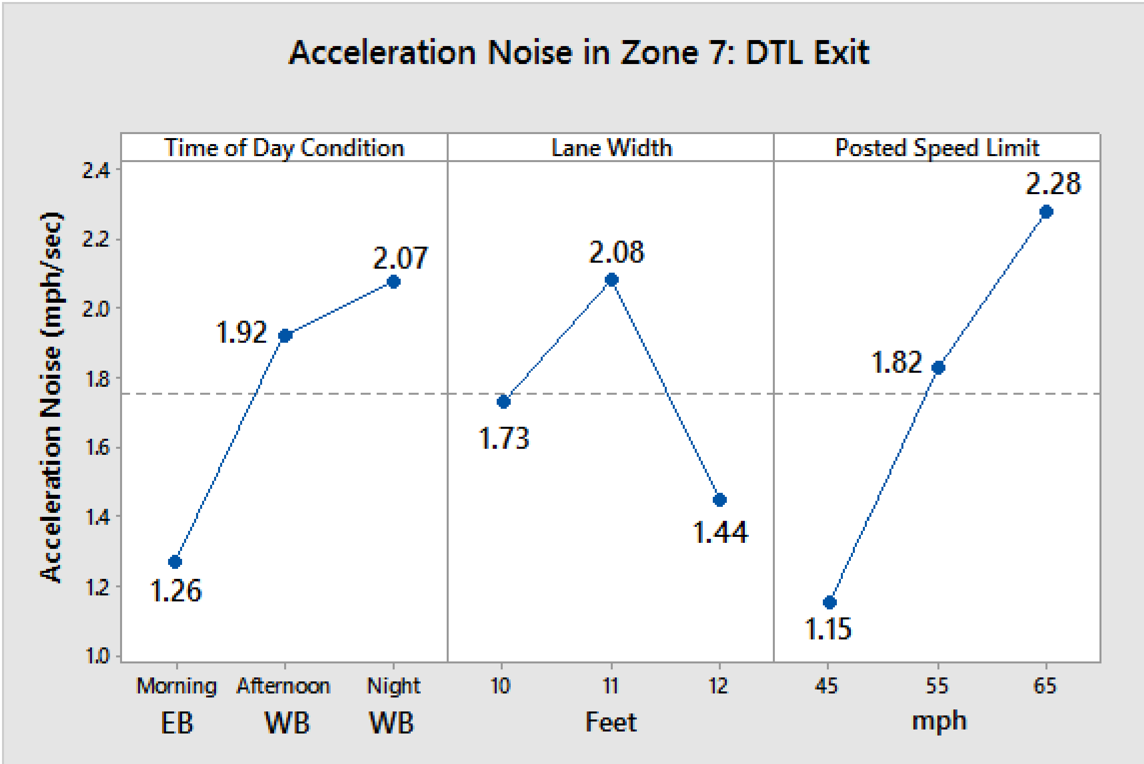


Figure 5-16 Acceleration Noise on Each Variable Evaluated in Zone 7.

5.5 LATERAL POSITION

The statistical analysis used for the dependent variable acceleration noise was a ANOVA analysis at a 95% confidence level. This statistical test was used to determine significant differences between the three independent variables (Time of Day Condition (ToDC), Lane Width (LW) and Posted Speed Limit (PSL)) when the p-value is less than 0.05. Therefore, the differences in subjects' lateral position was compared between scenarios, zones, subjects as well as age groups. The statistical analysis of each zones for the lateral position of the subjects is summarized below.

5.5.1 Zone 1: DTL Entrance

This zone represents the DTL entrance in EB and WB direction. However, since the DTL entrance only has one driving lane, there is not a lot of variation in the Lateral Position variable. Figure 5-17 illustrates the subject trajectory in the scenarios by the independent variable Time of Day Condition.

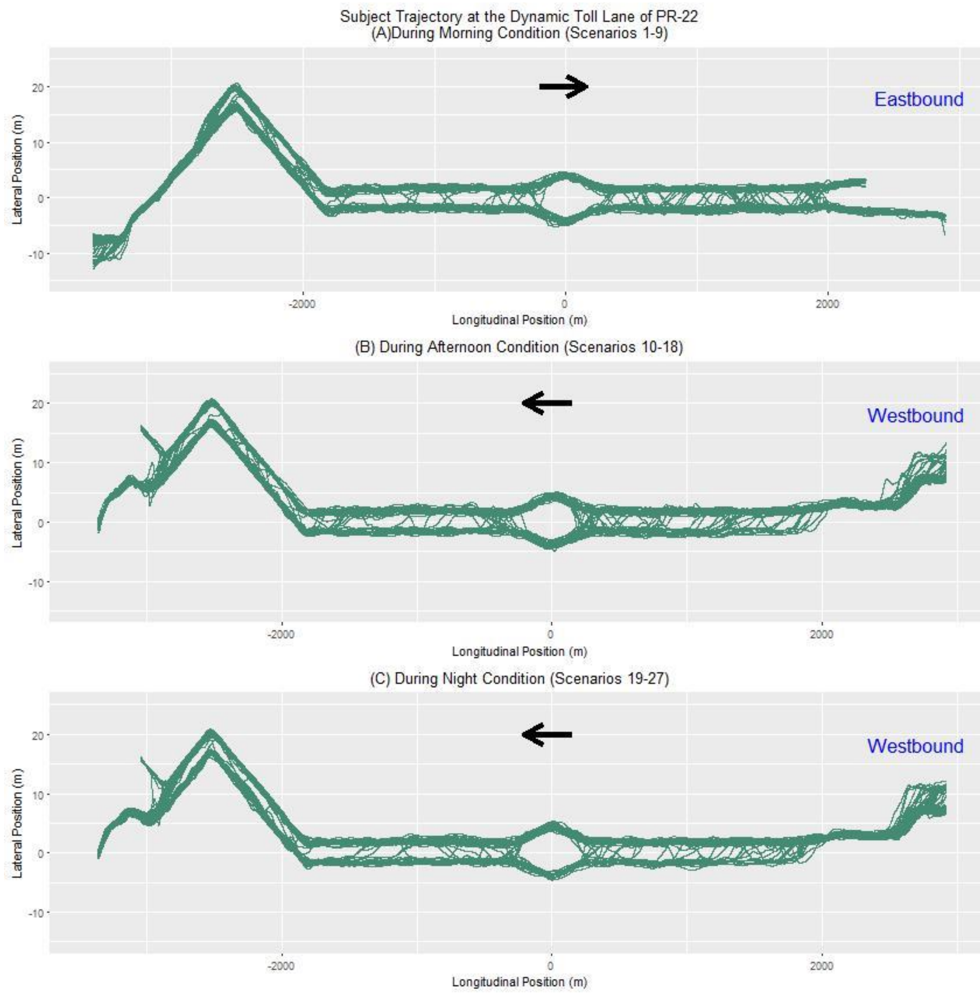


Figure 5-17 Subject Trajectories of the Simulated PR-22 DTL.

5.5.2 Zone 2: DTL Pocket Lane

This zone is a pocket lane in the left side. The results demonstrated that the double interaction between the ToDC*PSL resulting in a p-value less than 0.05. The ANOVA Analysis of the General Linear Model for the lateral position in Zone 2 is presented in Table 5-18. In Zone 2, the variable Time of Day Condition shows a differential of 0.329 feet and 0.571 feet in the Lateral Position variable between the morning vs afternoon and morning vs night conditions. The 10 feet lane increased the lateral positioning in 0.06 feet in comparison of 11 feet Lane Width whereas as increase of 0.10 feet was observed between the 11 feet and 12 feet lanes. The posted speed limits presented an increase of 0.326 feet between the 45 mph and 55-mph level and a reduction of 0.505 feet between the 55 mph and 65-mph level. The lateral position for each independent variable evaluated in Zone 2 is illustrated in Figure 5-18.

Table 5-18 Analysis of Variance Results for Lateral Position in Zone 2.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	11.476	2.2952	1.03	0.401
ToDC	2	9.072	4.5362	2.04	0.134
LW	2	0.285	0.1423	0.06	0.938
PSL	2	7.111	3.5554	1.6	0.206
Double Interaction					
ToDC*LW	4	6.831	1.7076	0.77	0.547
ToDC*PSL	4	24.924	6.231	2.81	0.028
PSL*LW	4	7.853	1.9632	0.88	0.475
Triple Interaction					
ToDC*LW*PSL	8	6.118	0.7648	0.34	0.947
R-sq		20.33	**R-sq adj**		1.33

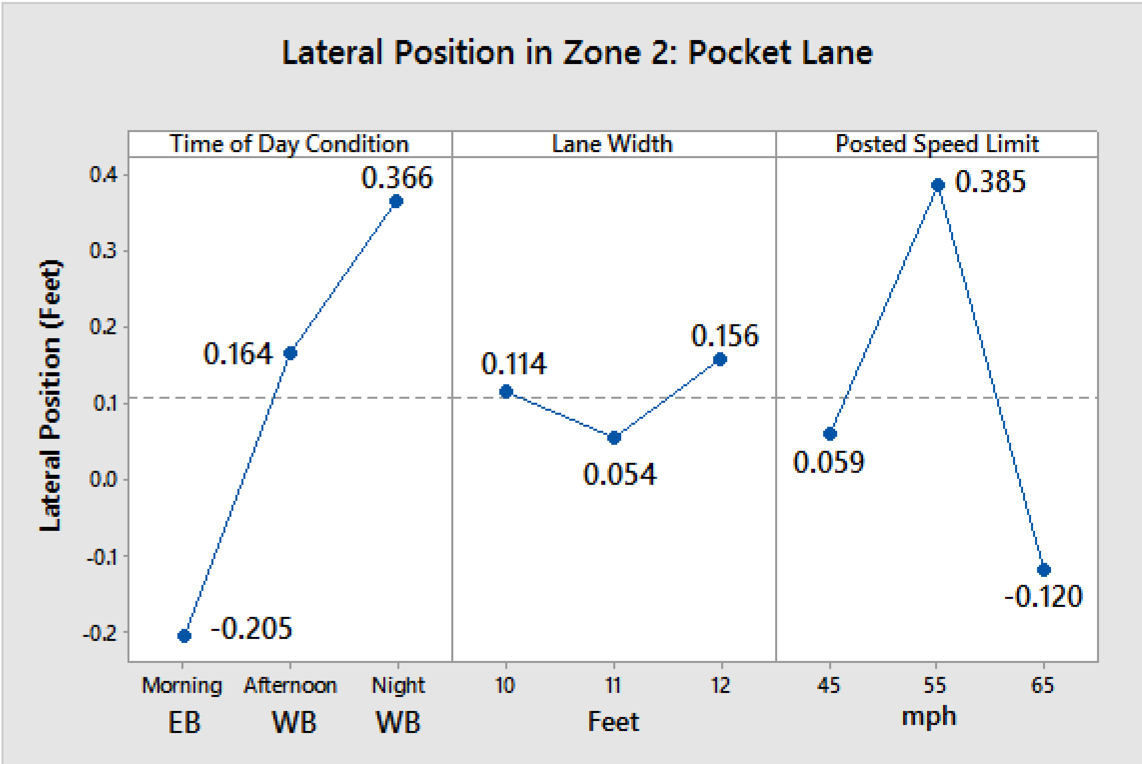


Figure 5-18 Lateral Position on Each Variable Evaluated in Zone 2.

5.5.3 Zone 3: Prior to Bridge Separation

Zone 3 represents the area prior to the bridge separation in both directions. In Zone 3, the main effect ToDC, LW and the double interaction between the ToDC*PSL affects the lateral position of the drivers. The ANOVA Analysis of the General Linear Model for the lateral position in Zone 3 is presented in Table 5-19. Time of Day Condition increases the lateral position progressively between the levels evaluated (-0.551 feet in morning condition, 0.947 feet in afternoon condition and 1.210 feet in the night condition). Prior to the bridge separation, the 11 feet lane resulted with a reduction of 0.494 feet and 1.333 feet as compared with the 10 feet and 12 feet lanes. The posted speed limits decrease gradually between the three levels evaluated with a differential of 0.710 feet between the 45 mph and 55 mph and a 0.329 foot between the 55 mph and 65 mph condition. The lateral position of each independent variables evaluated in Zone 3 are illustrated in Figure 5-19.

Table 5-19 Analysis of Variance Results for Lateral Position in Zone 3.

Source	**Df**	**Sum Sq**	**Mean Sq**	**F-Value**	**P-Value**
Blocks	5	29.9	5.98	0.89	0.488
ToDC	2	97.57	48.785	7.29	0.001
LW	2	49.14	24.572	3.67	0.028
PSL	2	30.43	15.213	2.27	0.107
Double Interaction					
ToDC*LW	4	15.22	3.806	0.57	0.686
ToDC*PSL	4	77.36	19.341	2.89	0.025
PSL*LW	4	19.38	4.844	0.72	0.577
Triple Interaction					
ToDC*LW*PSL	8	35.63	4.454	0.67	0.721
R-sq		28.95	**R-sq adj**		12.01

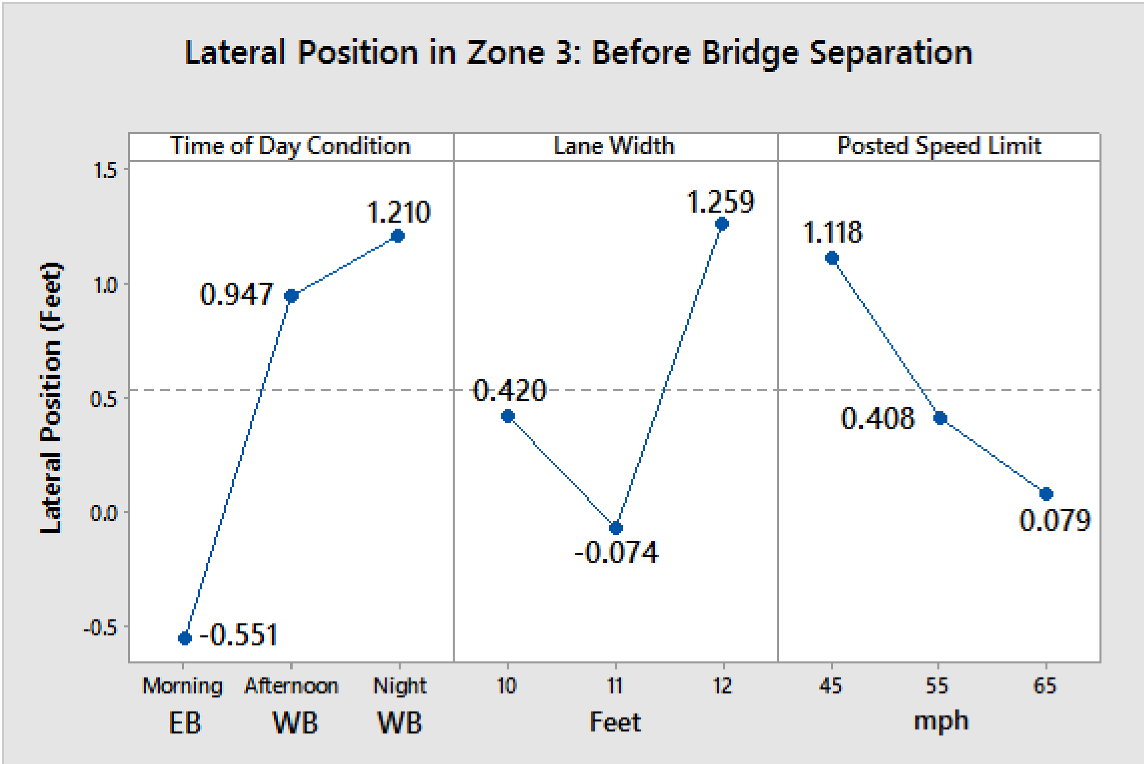


Figure 5-19 Lateral Position on Each Variable Evaluated in Zone 3.

5.5.4 Zone 4: Bridge Segment

Zone 4 includes the area separated by a concreted barrier that covers the overpass bridge columns in both directions. In Zone 4, the ToDC variable result with significant difference. The ANOVA Analysis of the General Linear Model for the Lateral Position in Zone 4 is presented in Table 5-20. The direction and the Time of Day Condition resulted in a differential of 1.631 feet in lateral position between the morning and afternoon level. However, a reduction of 0.347 feet was found in the afternoon and night conditions. The Lane Width variable did not variate between the levels evaluated with a differential of 0.031 feet between all levels (0.386 feet, 0.352 feet and 0.355 feet for the 10 feet, 11 feet and 12 feet respectively). The posted speed limit decreased the lateral position by 0.271 feet between the 45 mph and 55 mph posted speed limit whereas the lateral position increased by 0.194 feet between the 55 mph and 65 mph. The lateral position of each independent variables evaluated in Zone 4 are illustrated in Figure 5-20.

Table 5-20 Analysis of Variance Results for Lateral Position in Zone 4.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	10.601	2.1202	0.7	0.626
ToDC	2	79.856	39.9279	13.13	<0.001
LW	2	0.039	0.0194	0.01	0.994
PSL	2	2.109	1.0545	0.35	0.708
Double Interaction					
ToDC*LW	4	7.641	1.9102	0.63	0.643
ToDC*PSL	4	2.103	0.5257	0.17	0.952
PSL*LW	4	11.76	2.9399	0.97	0.428
Triple Interaction					
ToDC*LW*PSL	8	25.176	3.147	1.04	0.413
R-sq		26.06	**R-sq adj**		8.42

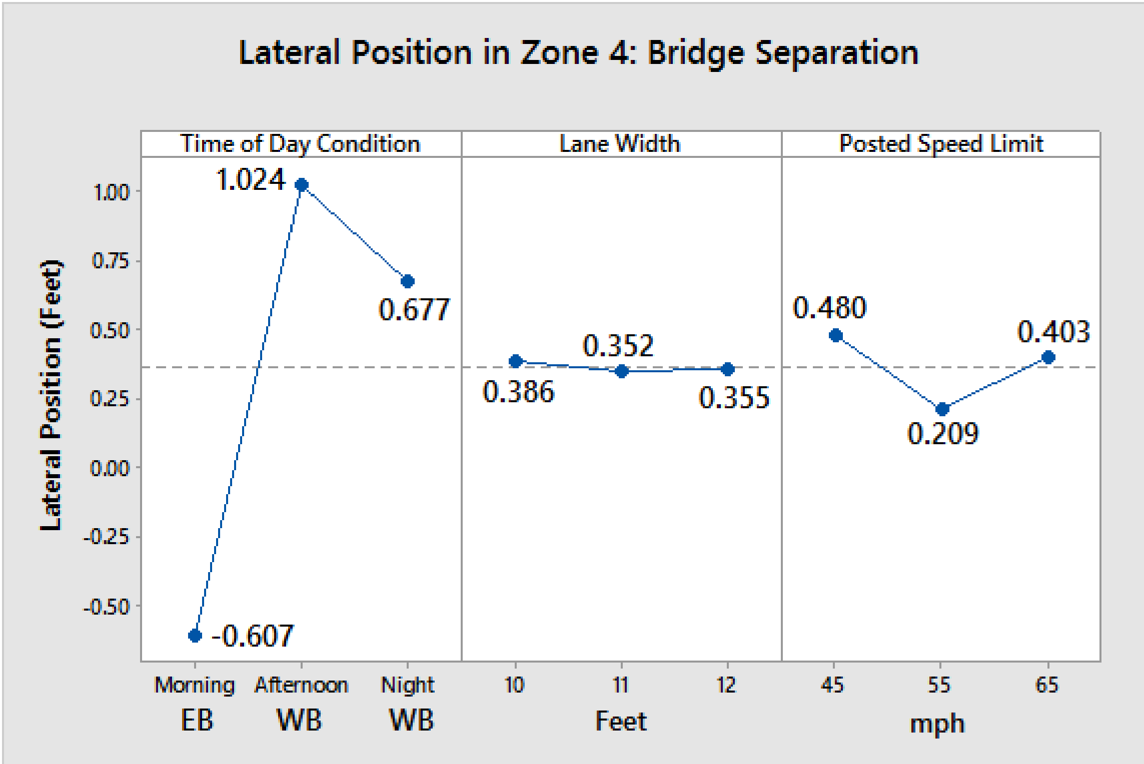


Figure 5-20 Lateral Position on Each Variable Evaluated in Zone 4.

5.5.5 Zone 5: After Bridge Connection

Zone 5 represents the area associated with the merging of the DTL mainline lanes for both directions. In Zone 5, the main effects ToDC variable presented statistically significant differences. The ANOVA Analysis of the General Linear Model for the lateral position in Zone 5 is presented in Table 5-21. In Zone 5, the lateral position increases gradually for the Time of Day Condition and Lane Width variables for all the evaluated levels (-0.498 feet morning condition, 0.393 feet afternoon condition and 0.591 feet night condition whereas -0.088 feet in 10 feet lanes, 0.270 feet for 11 feet lane and 0.303 feet for the 12 feet lane). The posted speed limits presented an increase of 0.420 feet between the 45 mph and the 55 mph and a reduction of 0.622 feet between the 55 mph and the 65mph level. The lateral position of each independent variables evaluated in Zone 5 are illustrated in Figure 5-21.

Table 5-21 Analysis of Variance Results for Lateral Position in Zone 5.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	32.327	6.465	1.29	0.27
ToDC	2	36.43	18.215	3.65	0.029
LW	2	5.095	2.548	0.51	0.602
PSL	2	10.906	5.453	1.09	0.339
Double Interaction					
ToDC*LW	4	11.996	2.999	0.6	0.663
ToDC*PSL	4	30.844	7.711	1.54	0.193
PSL*LW	4	14.838	3.709	0.74	0.565
Triple Interaction					
ToDC*LW*PSL	8	58.223	7.278	1.46	0.179
R-sq		23.61	**R-sq adj**		5.39

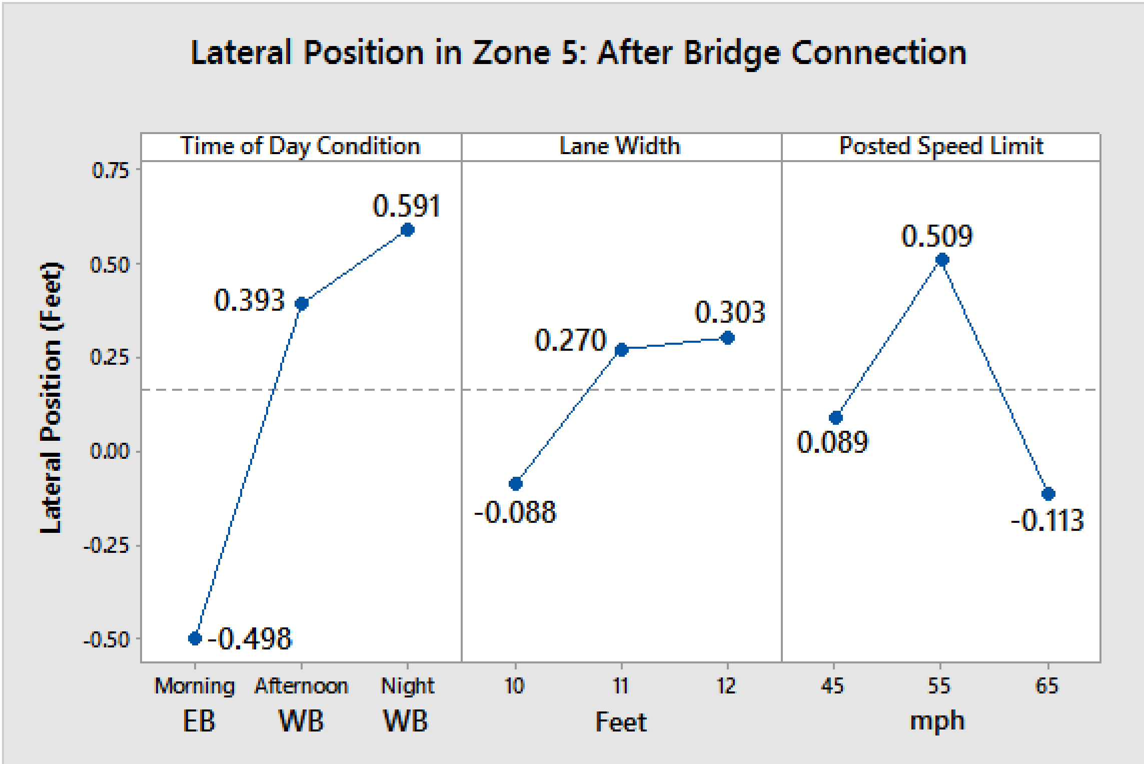


Figure 5-21 Lateral Position on Each Variable Evaluated in Zone 5.

5.5.6 Zone 6: DTL Pocket Lane

This zone is a pocket lane in the right side. In Zone 6, the main effect of ToDC presented statistically significant differences. The ANOVA Analysis of the General Linear Model for the lateral position in Zone 6 is presented in Table 5-22. The lateral position in the WB direction is at least 0.889 feet higher than the lateral position of the EB direction in this zone. The 11 feet lane shows a differential of 0.269 feet and 0.674 feet as compared with the 12 feet and 10 feet lane respectively. The lateral position observed for the posted speed limit variable decreased between the 45 mph and 55 mph scenarios, but an increase was observed between the 55 mph and the 65 mph levels. The lateral position of each independent variables evaluated in Zone 6 are illustrated in Figure 5-22.

Table 5-22 Analysis of Variance Results for Lateral Position in Zone 6.

Source	Df	Sum Sq	Mean Sq	F-Value	P-Value
Blocks	5	2.028	0.4055	0.16	0.976
ToDC	2	33.722	16.8612	6.69	0.002
LW	2	12.44	6.2198	2.47	0.890
PSL	2	8.393	4.1967	1.67	0.193
Double Interaction					
ToDC*LW	4	5.303	1.3257	0.53	0.717
ToDC*PSL	4	16.448	4.1121	1.63	0.170
PSL*LW	4	4.816	1.2039	0.48	0.752
Triple Interaction					
ToDC*LW*PSL	8	12.818	1.6022	0.64	0.746
R-sq		22.66	**R-sq adj**		4.22

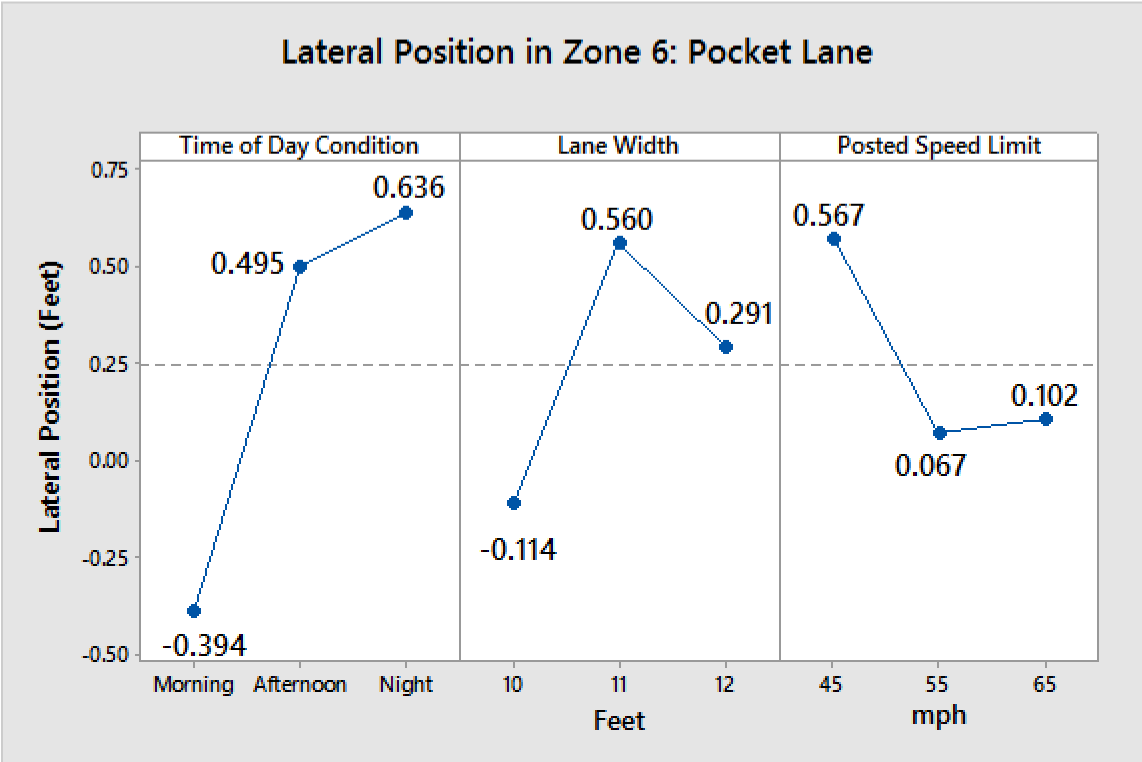


Figure 5-22 Lateral Position on Each Variable Evaluated in Zone 6.

5.5.7 Zone 7: DTL Exit

Zone 7 represent the DTL exit for both directions. Similar to what happens in Zone 1, the DTL exit only has one driving lane for passenger cars and one exclusive exit lane for the BRT. Therefore, the variation in the Lateral Position variable for subject drivers is not significant. For that reason, the analysis would be focused on the selection of which DTL exit lane the subject took. The number of subject drivers that departed the DTL using the incorrect exit lane is illustrated in Figure 5-23 and the incorrect use for each of the independent variables is shown in Table 5-23.

Table 5-23 Subject Drivers that Used the Incorrect DTL Exit (BRT Exit) by Independent Variable.

Variable	**Time of Day**	**Lane Width (Feet)**	**Posted Speed Limit (mph)**

Level	Morning	Afternoon	Night	10	11	12	45	55	65
Total	21	7	8	14	12	7	10	10	16
%	58.3	19.4	22.2	38.8	33.3	19.4	27.7	27.7	44.4

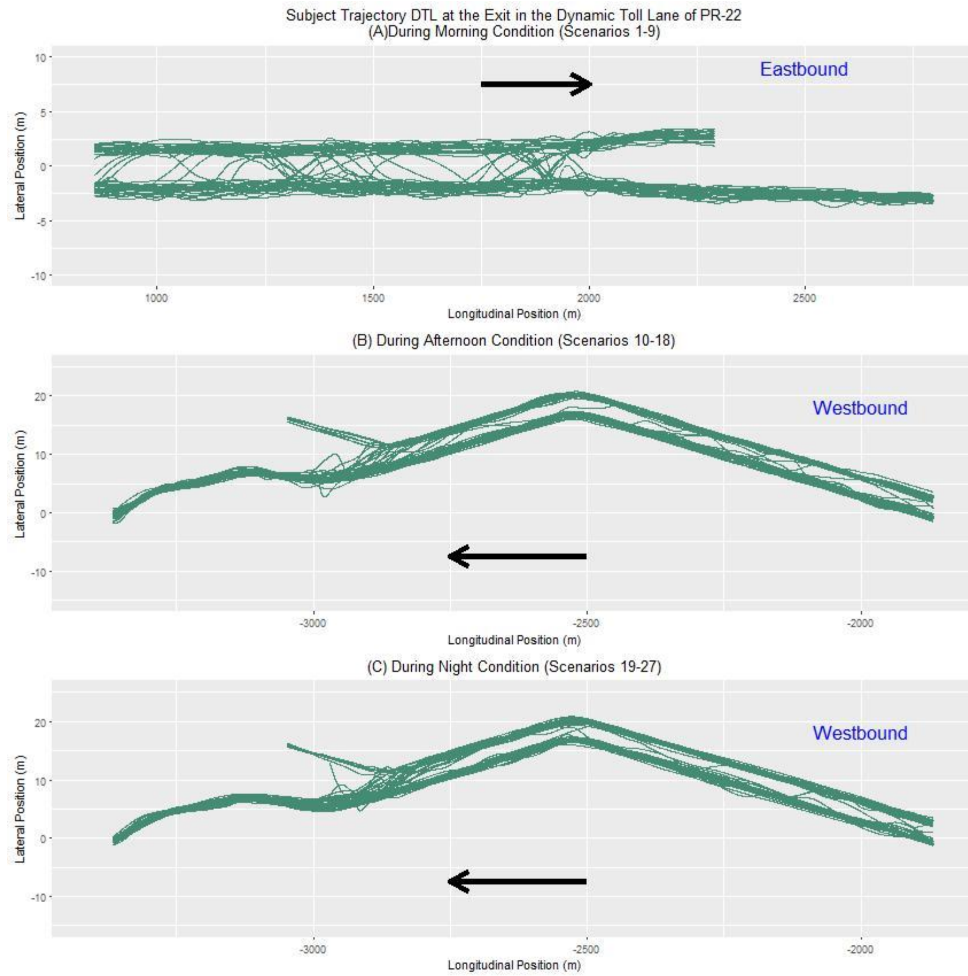


Figure 5-23 Subject Trajectories at the DTL Exit.

5.6 RANDOM FOREST MODEL RESULTS FOR OPERATIONAL SPEED

The Random Forest Model, non-linear model, was used to determine the effects and importance of independent variables: Time of Day Condition (ToDC), Lane Width (LW) and Posted Speed Limit (PSL), Scenarios (Sc) and Subjects (SN) and age blocks (Conf), in the Operating Speed variable. Higher percent of Increment in Mean Square Error (IncMSE%) represent higher importance in the model, lower percent of IncMSE represent lower importance in the model. The Random Forest Analysis of each zones for the operating speed of the subjects is summarized below.

Table 5-24 Models Summaries of the Operating Speed Variable by Zone of Interest.

Zone	**Number of Trees**	**Mean of Squared Residuals**	**% Variance Explained**
DTL Entrance	500	45.07	57.75
Pocket Lane (left side)	500	47.20	56.63
Prior Bridge Piers	500	61.31	43.71
Bridge Piers Separation	500	59.58	45.15
After Bridge Piers Separation	500	57.61	49.11
Pocket lane (right side)	500	52.04	51.71
DTL Exit	500	91.91	16.11

5.6.1 Zone 1: DTL Entrance

This zone represents the DTL entrance in EB and WB direction. In Zone 1, the Lane Width results with the higher percent on Increment of Mean Square Error (IncMSE%), therefore this variable affects the behavior of the participants. The Time of Day Condition record the lowest increment in MSE of the independent variable evaluated. Results of the Random Forest for the operating speed in Zone 1 by independent variable are presented in Figure 5-24.

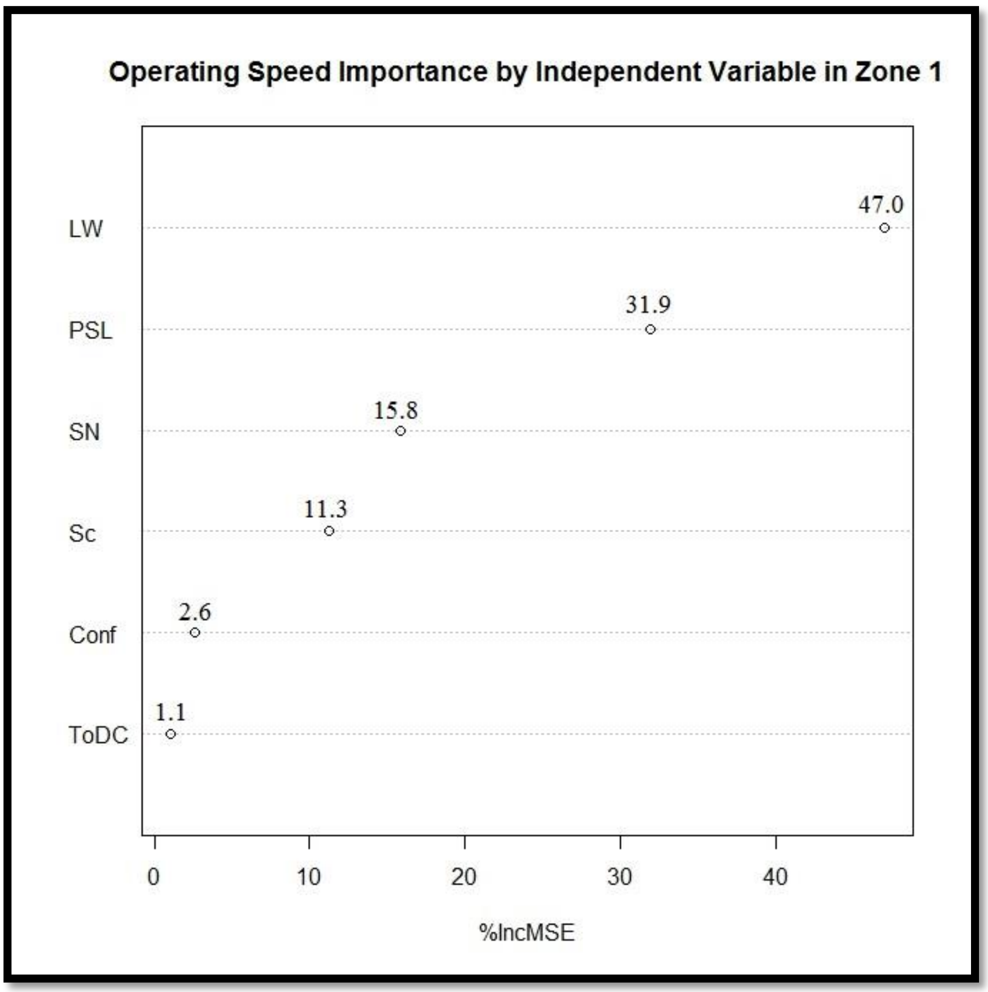


Figure 5-24 Effect of the Operating Speed Behavior by Independent Variables in Zone 1.

5.6.2 Zone 2: DTL Pocket Lane

This zone represents the pocket lanes at both direction in the left side. In Zone 2, the Posted Speed Limit results with the higher percent on IncMSE with 53.4%, follow by the Subject with 17.1%. The configuration (age group) record the lowest increment in MSE of the independent variable evaluated with 0.1%. Results of the Random Forest for the operating speed in Zone 2 by independent variable are presented in Figure 5-25.

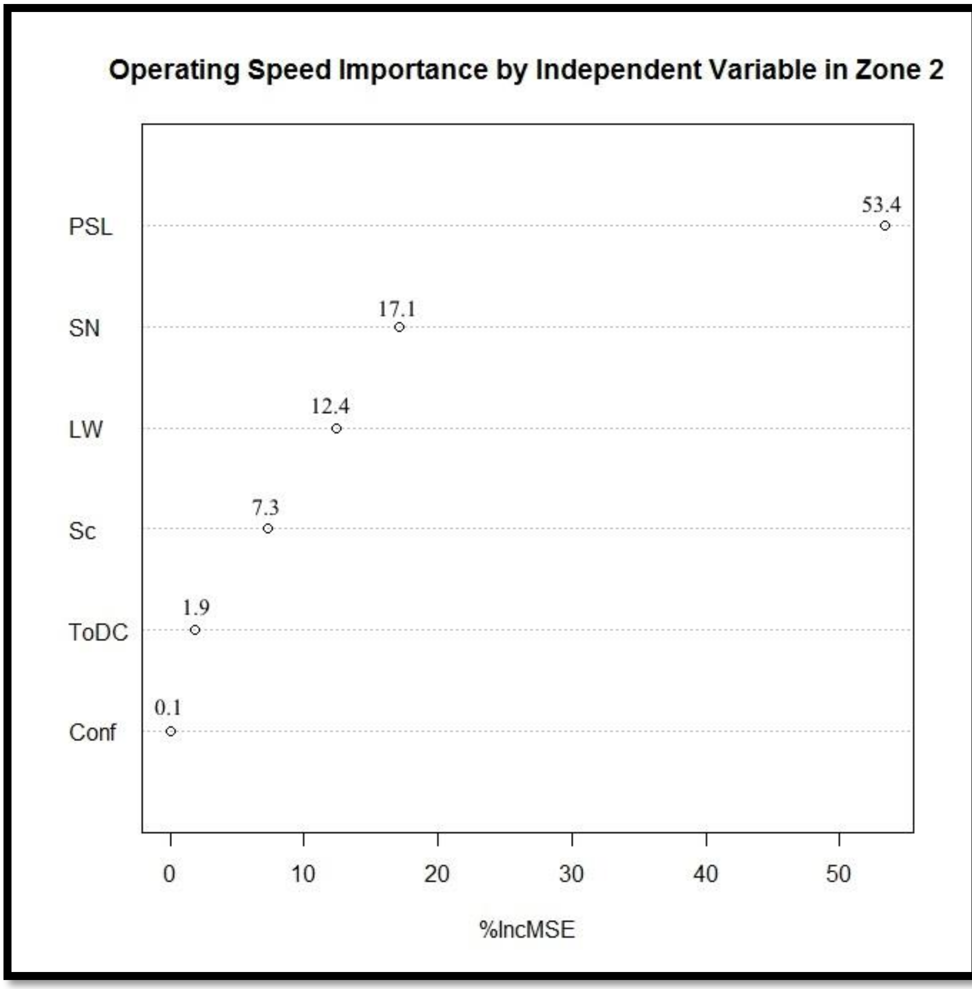


Figure 5-25 Effect of the Average Speed Behavior by Independent Variables in Zone 2.

5.6.3 Zone 3: Prior to Bridge Separation

This zone represents prior the bridge separation. In Zone 3, the Posted Speed Limit results with the higher percent on IncMSE with 51.1%, follow by the Lane Width with 10.9%. The Time of Day Condition record the lowest increment in MSE of the independent variable evaluated with -2.1%. The negative value represents that probably the varible is not predictive or not important in the model. Results of the Random Forest for the operating speed in Zone 3 by independent variable are presented in Figure 5-26.

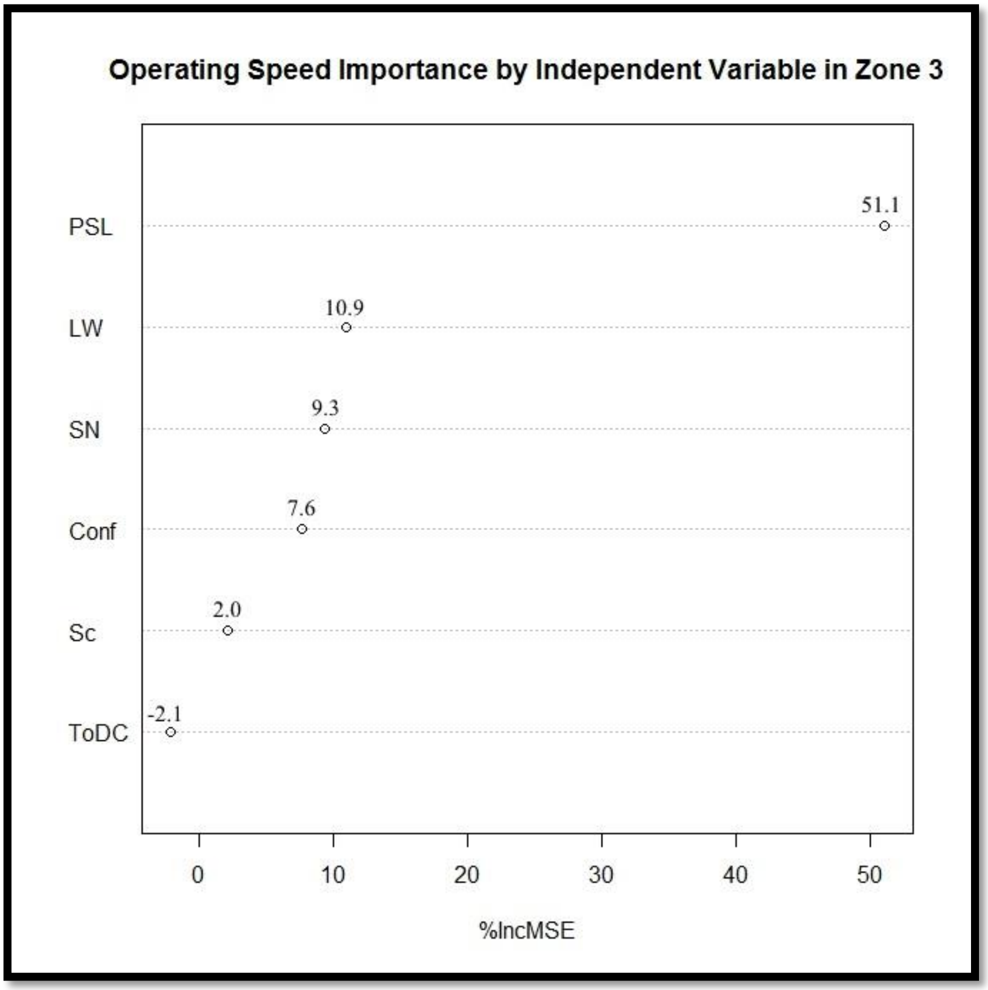


Figure 5-26 Effect of the Average Speed Behavior by Independent Variables in Zone 3.

5.6.4 Zone 4: DTL Bridge Separation

This zone represents the bridge separation in which the Posted Speed Limit results with the higher percent on IncMSE with 47.0%, follow by the Subject with 16.4%. The Time of Day Condition record the negative value in this zone, therfore varible is not important in the model. Results of the Random Forest for the operating speed in Zone 4 by independent variable are presented in Figure 5-27.

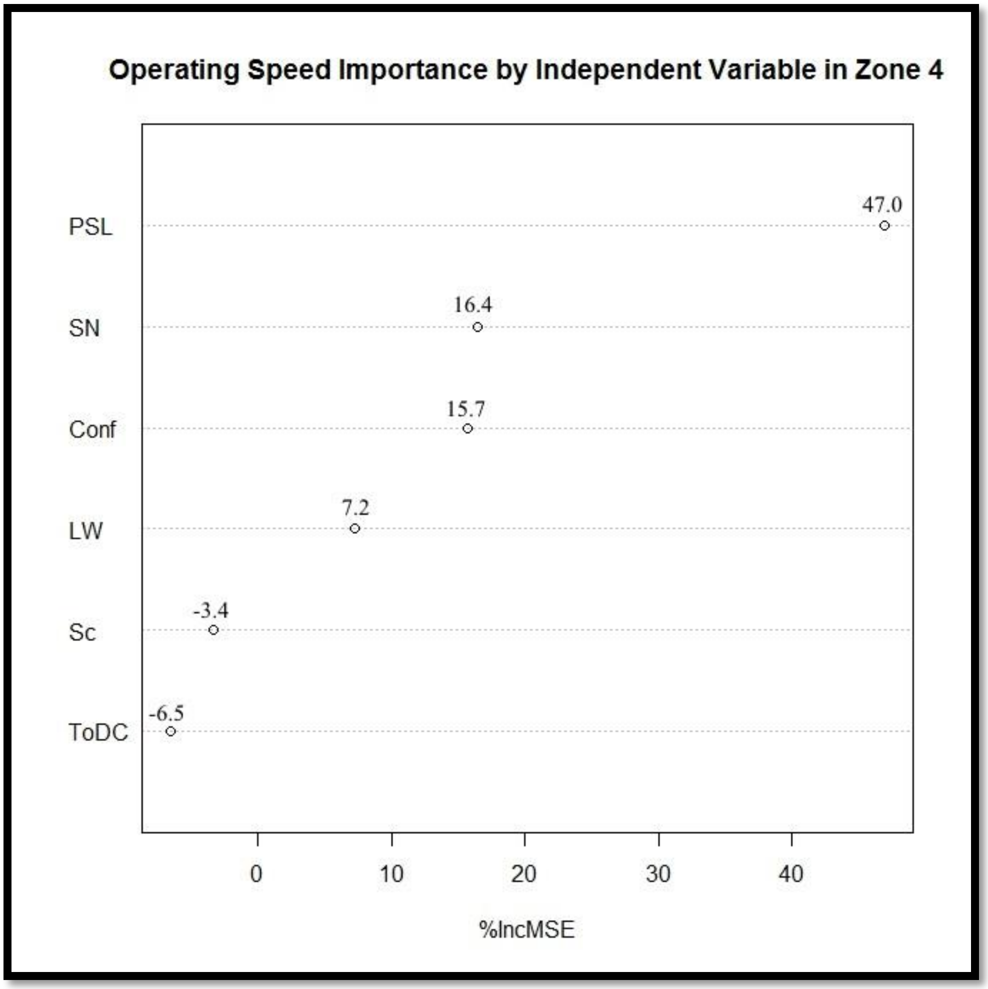


Figure 5-27Effect of the Average Speed Behavior by Independent Variables in Zone 4.

5.6.5 Zone 5: After Bridge Connection

For Zone 5, the Posted Speed Limit results with the higher percent on IncMSE with 42.0%, follow by the Subject with 18.5%. The lowest IncMSE observed was for the Time of Day and Scearios variable with a -5.0% and 1.1% respectively. Results of the Random Forest for the operating speed in Zone 5 by independent variable are presented in Figure 5-28.

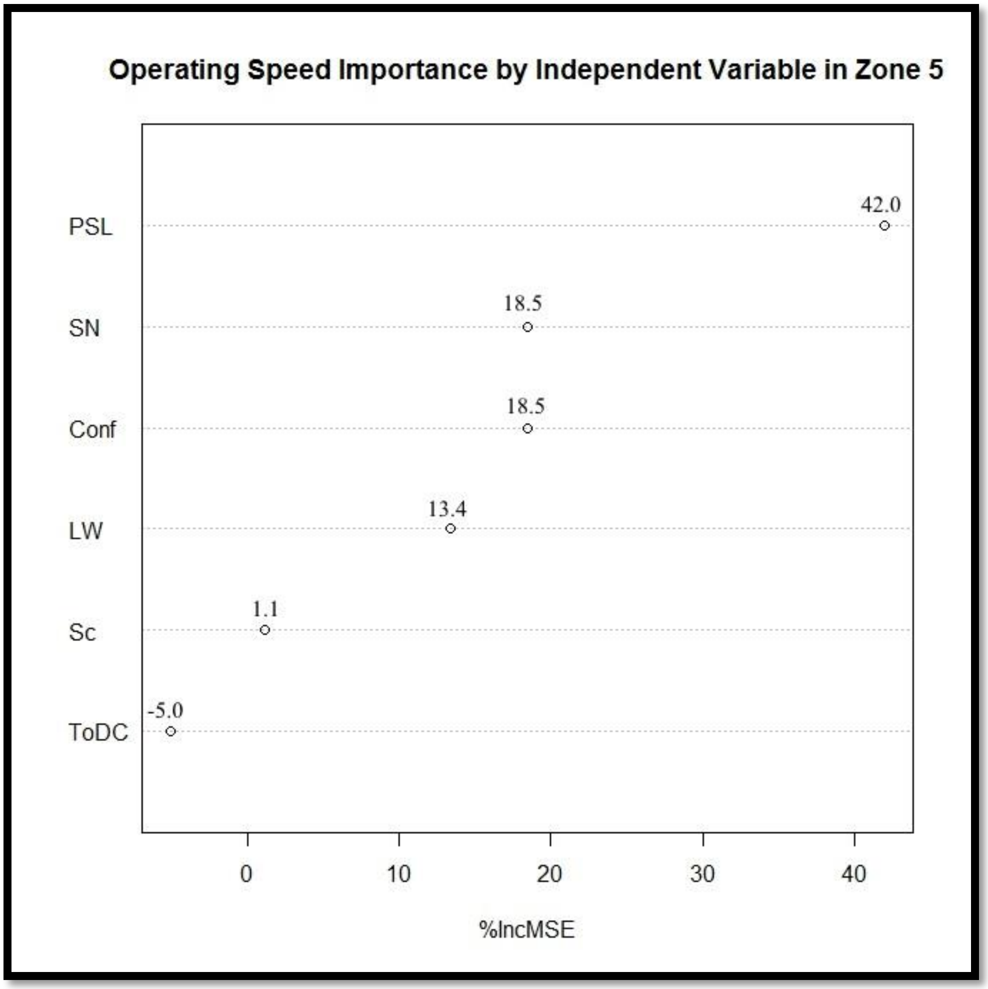


Figure 5-28 Effect of the Average Speed Behavior by Independent Variables in Zone 5.

5.6.6 Zone 6: DTL Pocket Lane

This zone represents the DTL pocket lane at both direction on the right side. The higher variable affecting the operanting speed in Zone 6 was the Posted Speed Limit and the Subjects with 48.3% and 20.1% IncMSE, respectively. The lowest observed increment was for the Time of Day Condition with -1.0%. Results of the Random Forest for the operating speed in Zone 6 by independent variable are presented in Figure 5-29.

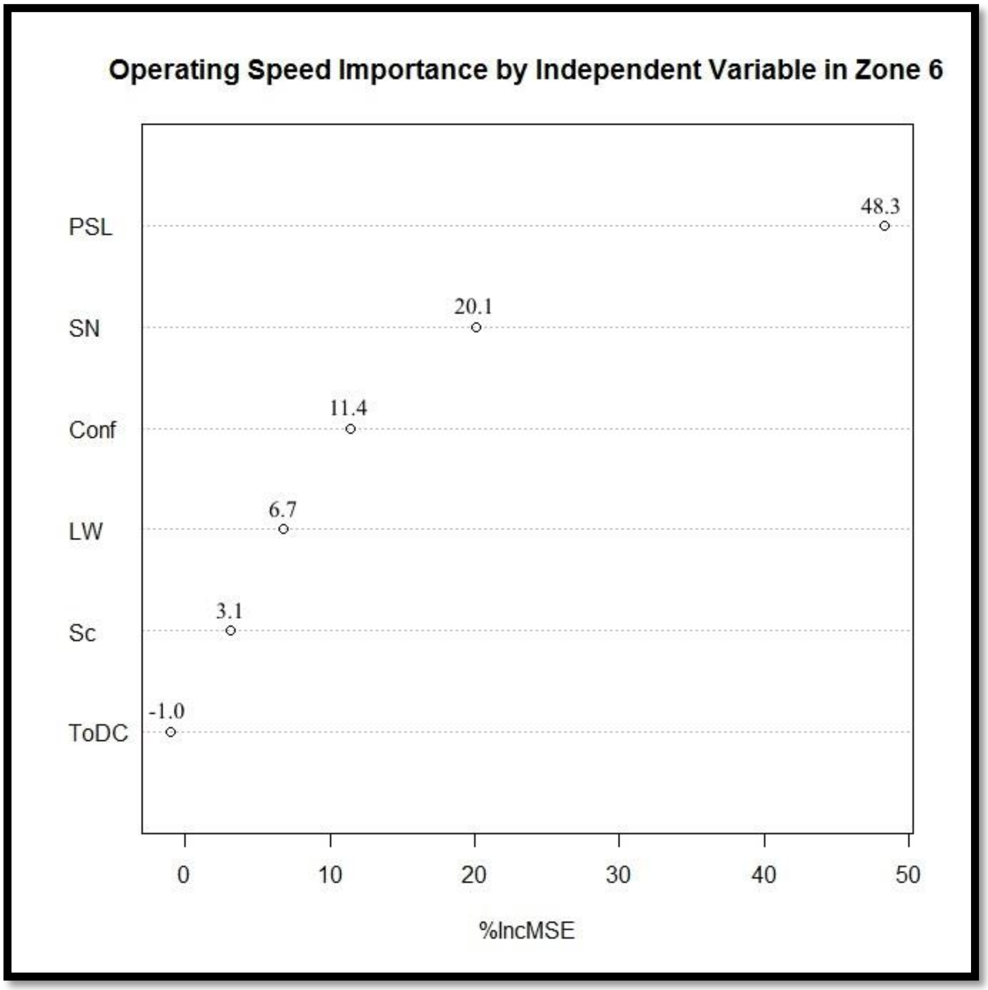


Figure 5-29 Effect of the Average Speed Behavior by Independent Variables in Zone 6.

5.6.7 Zone 7: DTL Exit

In the DTL Exit (Zone 7) the Posted Speed Limit results with the higher percent on IncMSE with 23.9%, follow by the Scenario with 9.5%, in the Operating Speed variable. The lowest the percet of increment in MSE in Zone 7 was observed in the subject varible. Subject Results of the Random Forest for the operating speed in Zone 7 by independent variable are presented in Figure 5-30.

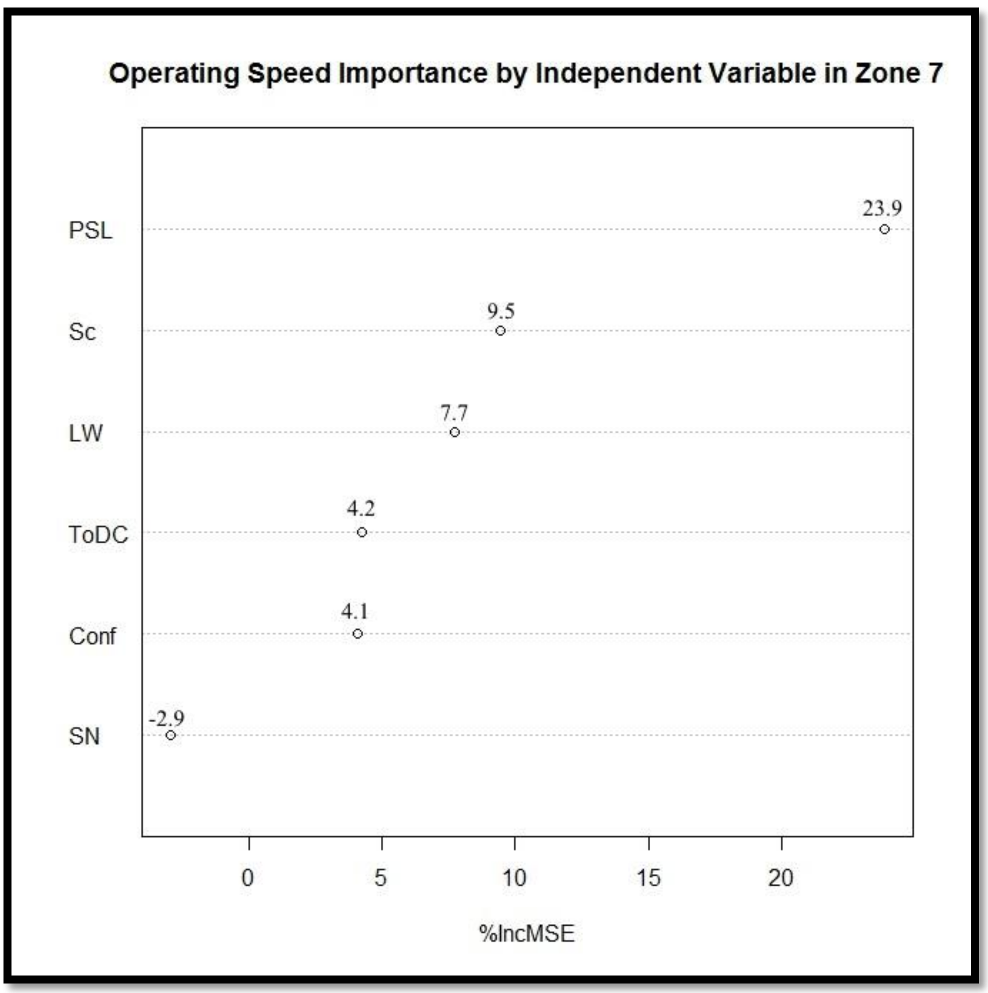


Figure 5-30 Effect of the Average Speed Behavior by Independent Variables in Zone 7.

5.7 RANDOM FOREST MODEL RESULTS FOR ACCELERATION NOISE

The Random Forest Model, non-linear model, was used to determine the effects and importance of independent variables: Time of Day Condition, Lane Width and Posted Speed Limit, scenarios, and subjects, in the Acceleration Noise variable. Higher percent of Increment in Mean Square Error (IncMSE) represent higher importance in the model, lower percent of IncMSE represent lower importance in the model. The Random Forest Analysis of each zones for the acceleration noise of the subjects is summarized below.

Table 5-25Models Summaries of the Acceleration Noise Variable by Zone of Interest

Zone	**Number of Trees**	**Mean of Squared Residuals**	**% Variance Explained**
DTL Entrance	500	0.04	-3.54
Pocket Lane (left side)	500	0.06	3.54
Prior Bridge Piers	500	0.19	7.88
Bridge Piers Separation	500	0.06	-4.75
After Bridge Piers Separation	500	0.08	-7.45
Pocket lane (right side)	500	0.06	-2.42
DTL Exit	500	0.83	5.28

5.7.1 Zone 1: DTL Entrance

This zone represents the DTL entrance in EB and WB direction. In Zone 1, the Lane Width variable result with the highest IncMSE% in this model, 6.3% in the Acceleration Noise variable. The lowest observed value of increment was observed for the Time of Day Condition variable with -5.6%. Results of the Random Forest for the accelerationo noise in Zone 1 by independent variable are presented in Figure 5-31.

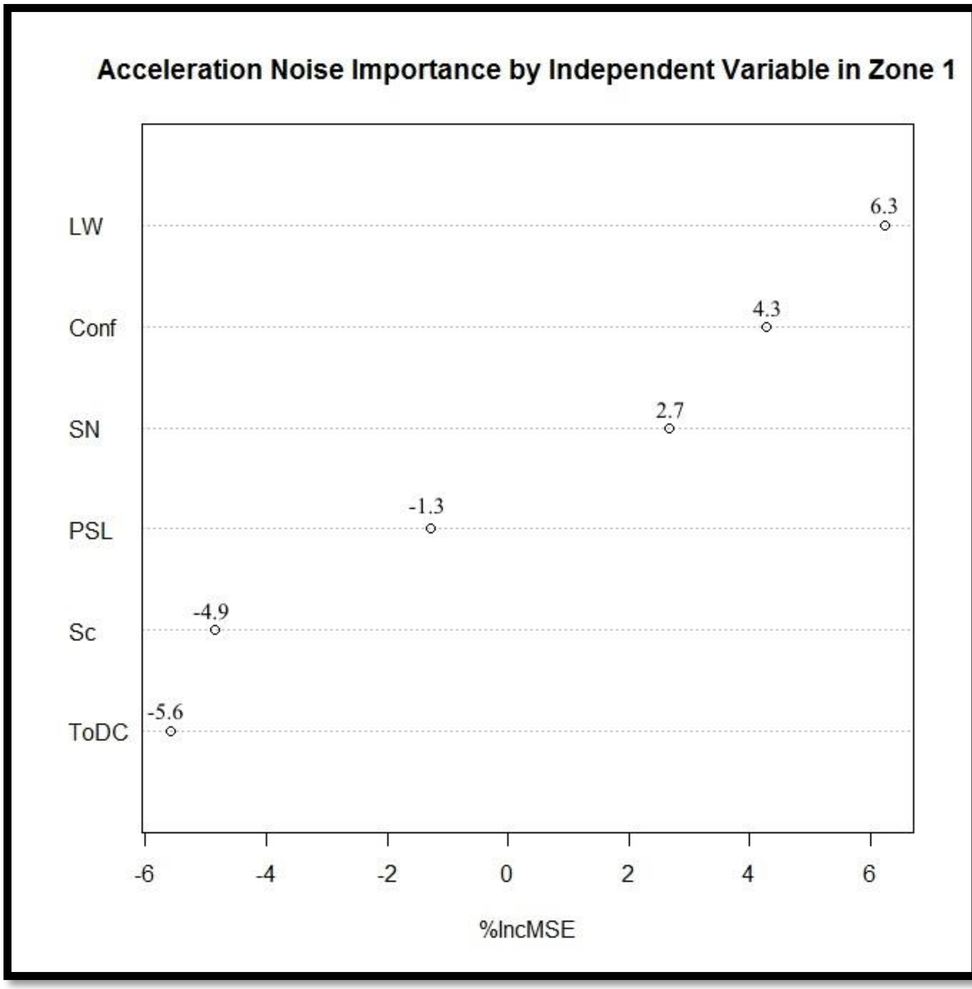


Figure 5-31 Effect of the Acceleration Noise Variable by Independent Variables in Zone 1.

5.7.2 Zone 2: DTL Pocket Lane

This zone represents the DTL pocket lanes at the left side. In Zone 2, the Lane Width and the subject variables results with the highest IncMSE%, 7.5% and 7.0%, respectively for the acceleration noise Random Forest model. The Time of Day Condition variable record the lowest increment with -3.8%. Results of the Random Forest for the accelerationo noise in Zone 2 by independent variable are presented in Figure 5-32.

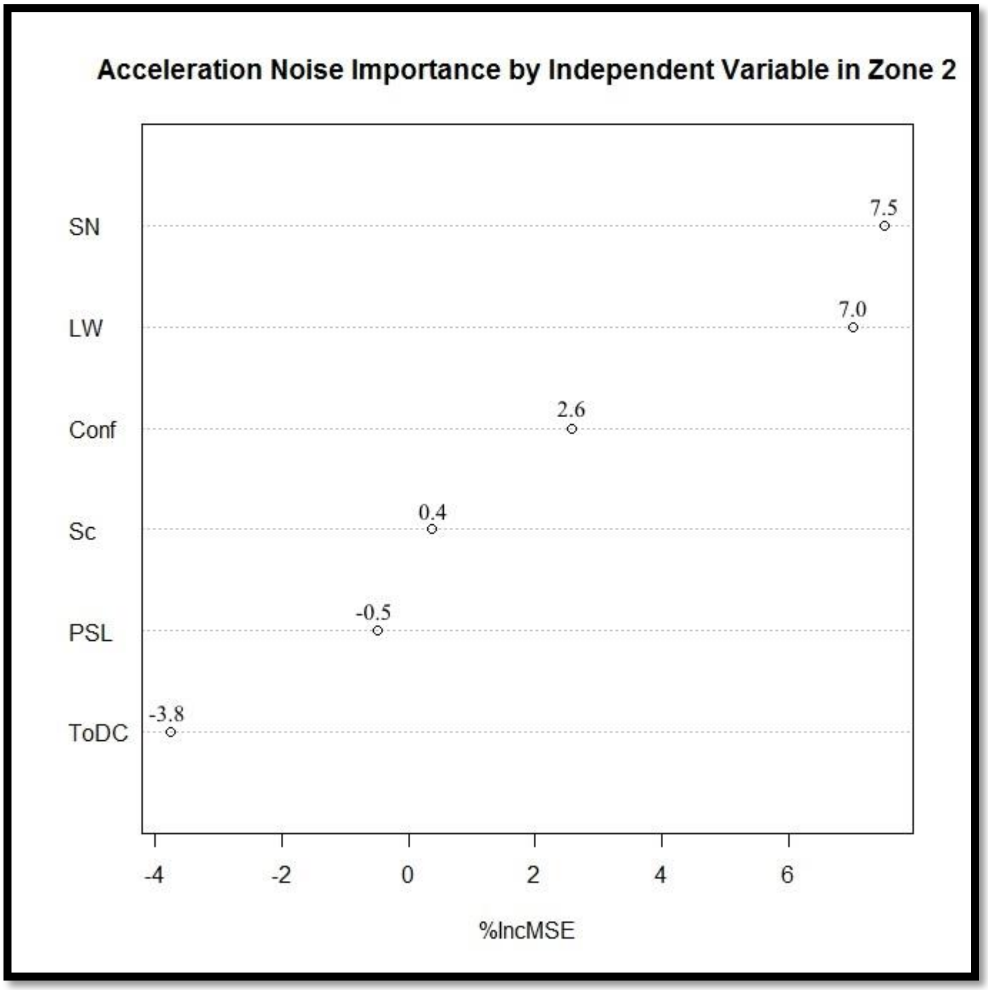


Figure 5-32 Effect of the Acceleration Noise Variable by Independent Variables in Zone 2.

5.7.3 Zone 3: Prior to Bridge Separation

This zone represents the DTL segment prior the bridge separation at both directions. For Zone 3, the Scenario and the Lane Width variables results with the highest IncMSE%, 8.9% and 5.6%, respectively for the acceleration noise Random Forest model. In this zone the lowest increment of mean square error was found in the Posted Speed Limit with a 0.8% increment. Results of the Random Forest for the accelerationo noise in Zone 3 by independent variable are presented in Figure 5-33.

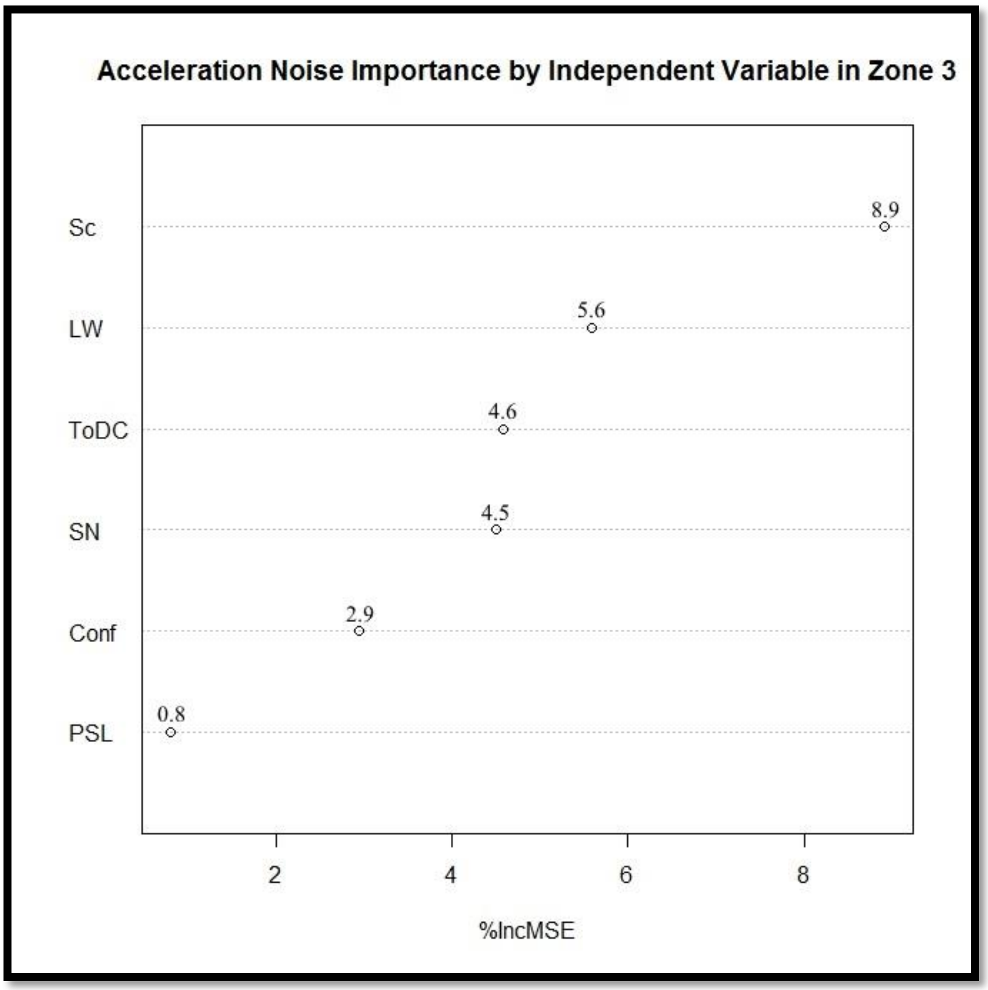


Figure 5-33 Effect of the Acceleration Noise Variable by Independent Variables in Zone 3.

5.7.4 Zone 4: DTL Bridge Separation

This zone represents the DTL segment in the bridge separation segment. In Zone 4, the subject variables result with positive IncMSE% of 2.2%. The lowest increment was found in the Time of Day Condition with -3.5% IncMSE. Results of the Random Forest for the accelerationo noise in Zone 4 by independent variable are presented in Figure 5-34.

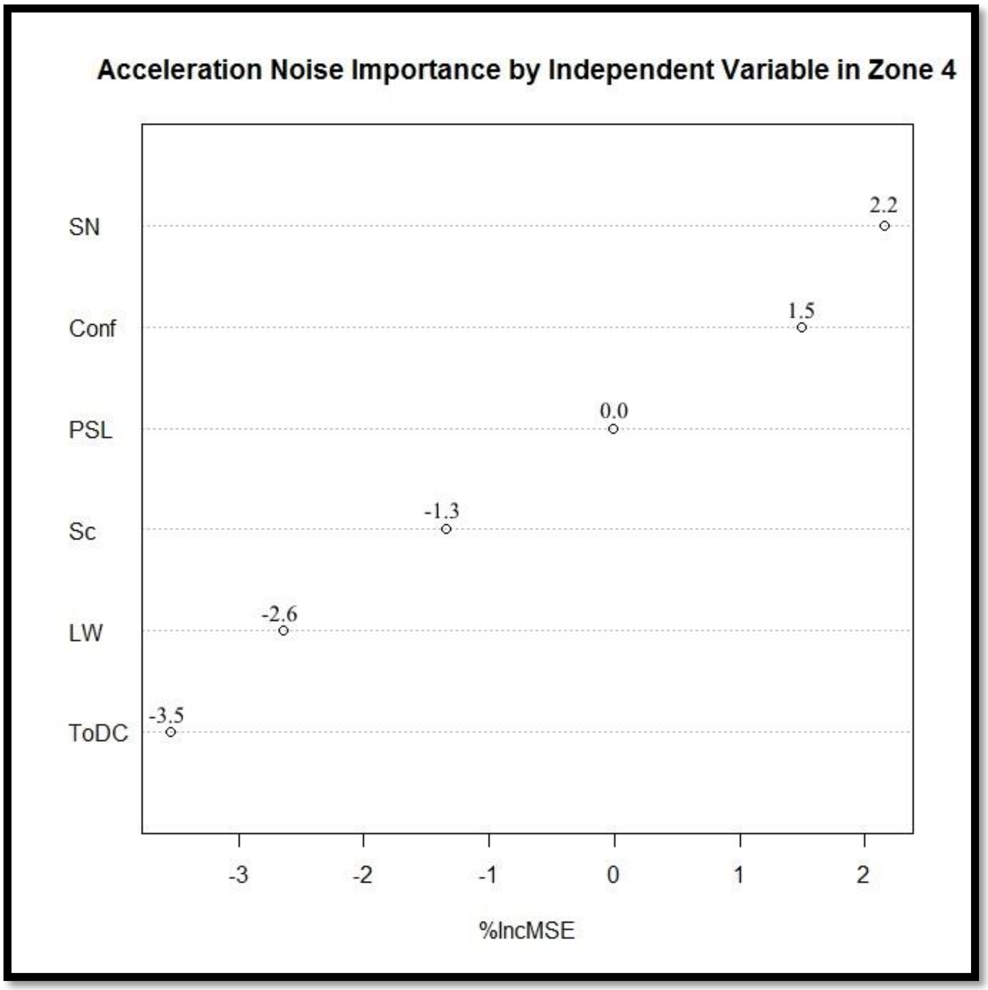


Figure 5-34 Effect of the Acceleration Noise Variable by Independent Variables in Zone 4.

5.7.5 Zone 5: After Bridge Connection

This zone represents the DTL segment after the bridge connection. In Zone 5, the subject variables result with positive IncMSE% of 7.5%. The lowest increment was found in the Posted Speed Limit with -3.4% IncMSE. Results of the Random Forest for the accelerationo noise in Zone 5 by independent variable are presented in Figure 5-35.

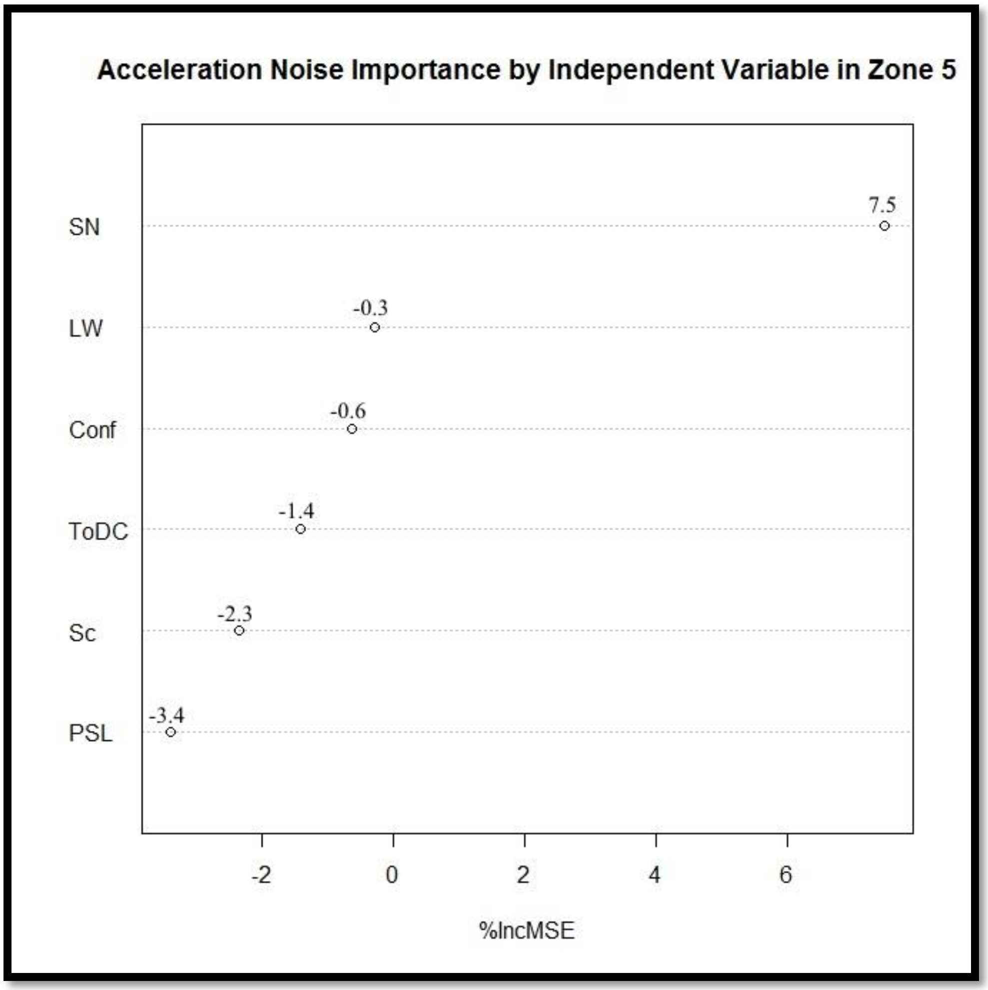


Figure 5-35 Effect of the Acceleration Noise Variable by Independent Variables in Zone 6

5.7.6 Zone 6: DTL Pocket Lane

This zone represents the DTL pocket lanes at the right side at both directions. The subject and Lane Width variable results with the positive IncMSE% in the Random Forest Model for the Acceleration Noise variable with 10.9% and 2.8%. The lowest increment was found in the Scenario with -6.5% IncMSE. Results of the Random Forest for the accelerationo noise in Zone 6 by independent variable are presented in Figure 5-36.

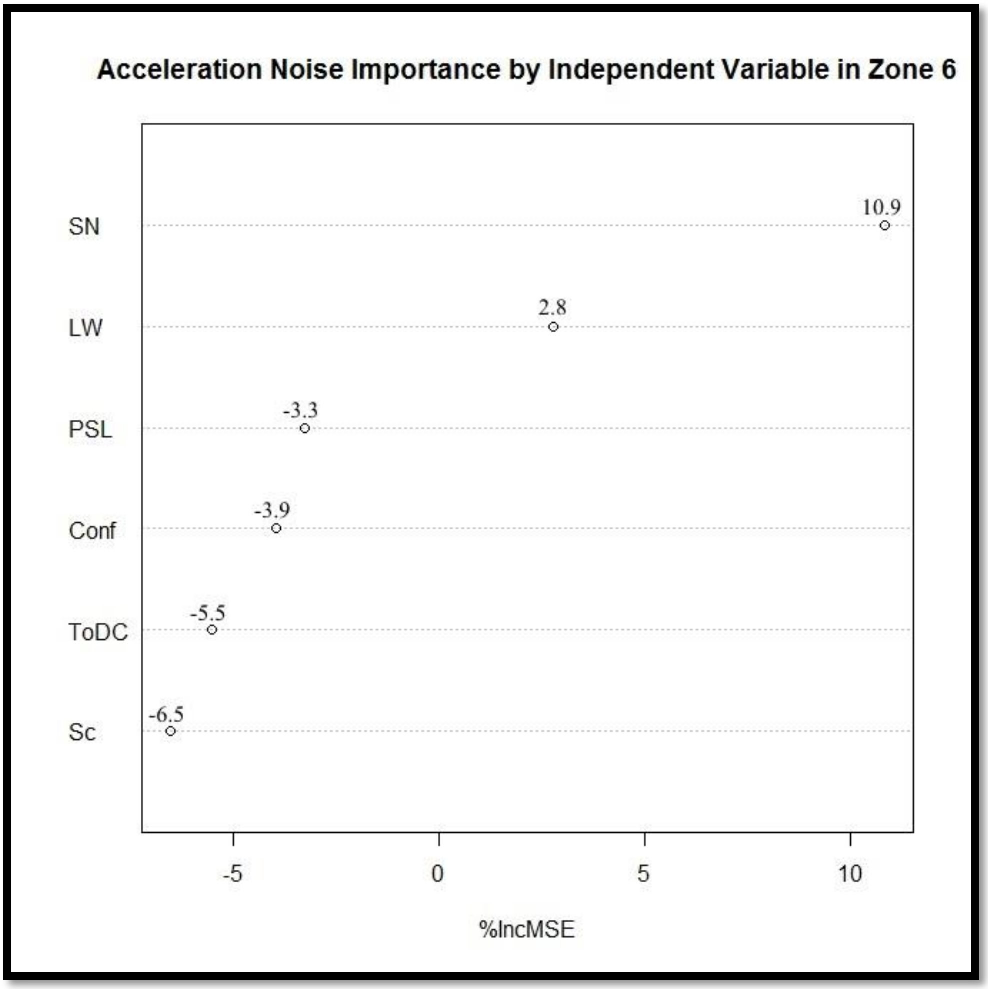


Figure 5-36 Effect of the Acceleration Noise Variable by Independent Variables in Zone 6.

5.7.7 Zone 7: DTL Exit

This zone represents the DTL Exit segment in the EB and WB directions. In Zone 7, the Lane Width variable record the highest IncMSE% of 9.7% follow by the subject variable 8.3%. The Time of Day Condition variable record the lowest increment of mean square error with -3.3%. Results of the Random Forest for the accelerationo noise in Zone 7 by independent variable are presented in Figure 5-37.

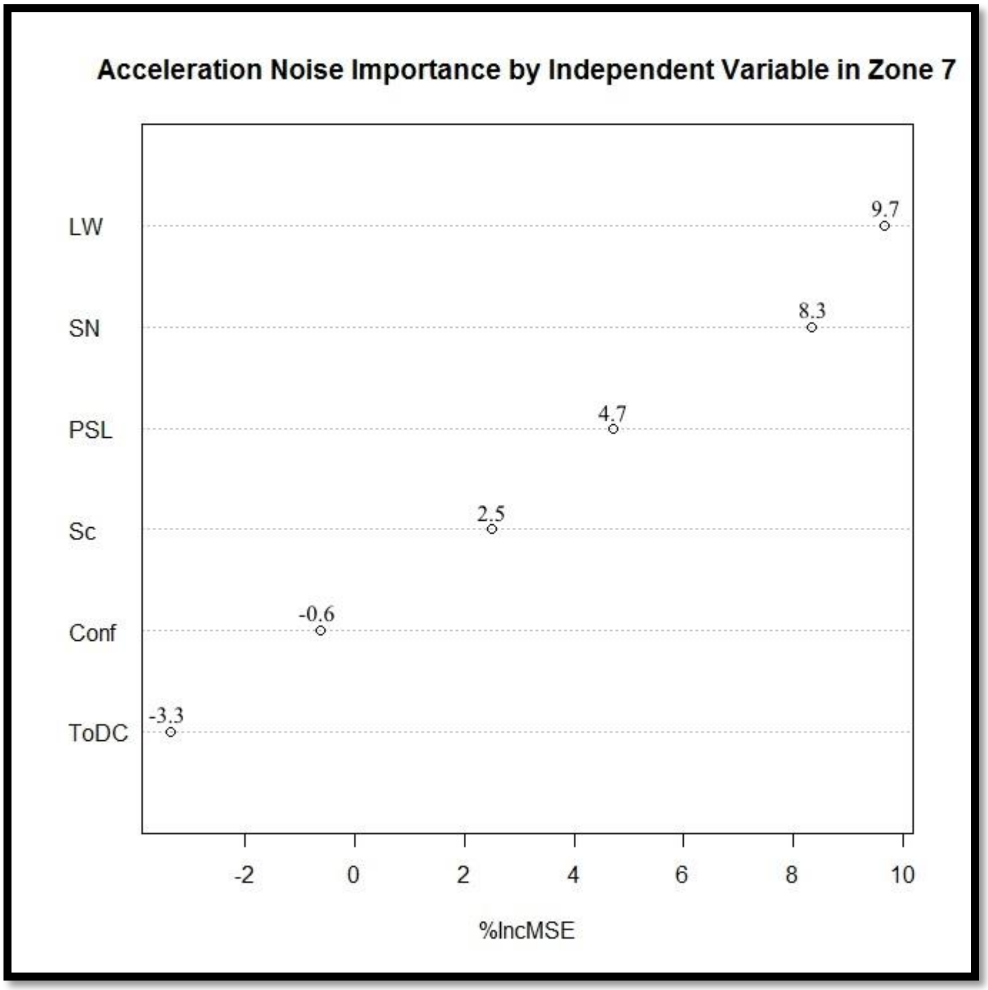


Figure 5-37 Effect of the Acceleration Noise Variable by Independent Variables in Zone 7.

5.8 RANDOM FOREST MODEL RESULTS FOR LATERAL POSITION

The Random Forest Model, non-linear model, was used to determine the effects and importance of independent variables: Time of Day Condition, Lane Width and Posted Speed Limit, scenario, and subjects, in the Lateral Position variable. Higher percent of Increment in Mean Square Error (IncMSE%) represent higher importance in the model, lower percent of IncMSE represent lower importance in the model. The Random Forest Analysis of each zones for the lateral position of the subjects is summarized below.

Table 5-26 Models Summaries of the Lateral Position Variable by Zone of Interest

Zone	**Number of Trees**	**Mean of Squared Residuals**	**% Variance Explained**
DTL Entrance	500	0.10	87.02
Pocket Lane (left side)	500	2.41	-7.61
Prior Bridge Piers	500	7.09	6.24
Bridge Piers Separation	500	3.27	1.03
After Bridge Piers Separation	500	5.64	-7.58
Pocket lane (right side)	500	2.78	-6.32
DTL Exit	500	4.84	73.21

5.8.1 Zone 1: DTL Entrance

This zone represents the DTL entrance at both directions. For Zone 1, the Scenarios and the Time of Day Condition variables records the highest IncMSE% with 24.07 and 22.4%. The lowest increment was found for the Subject variable with -0.7% IncMSE. Results of the Random Forest for the lateral position in Zone 1 by independent variable are presented in Figure 5-38.

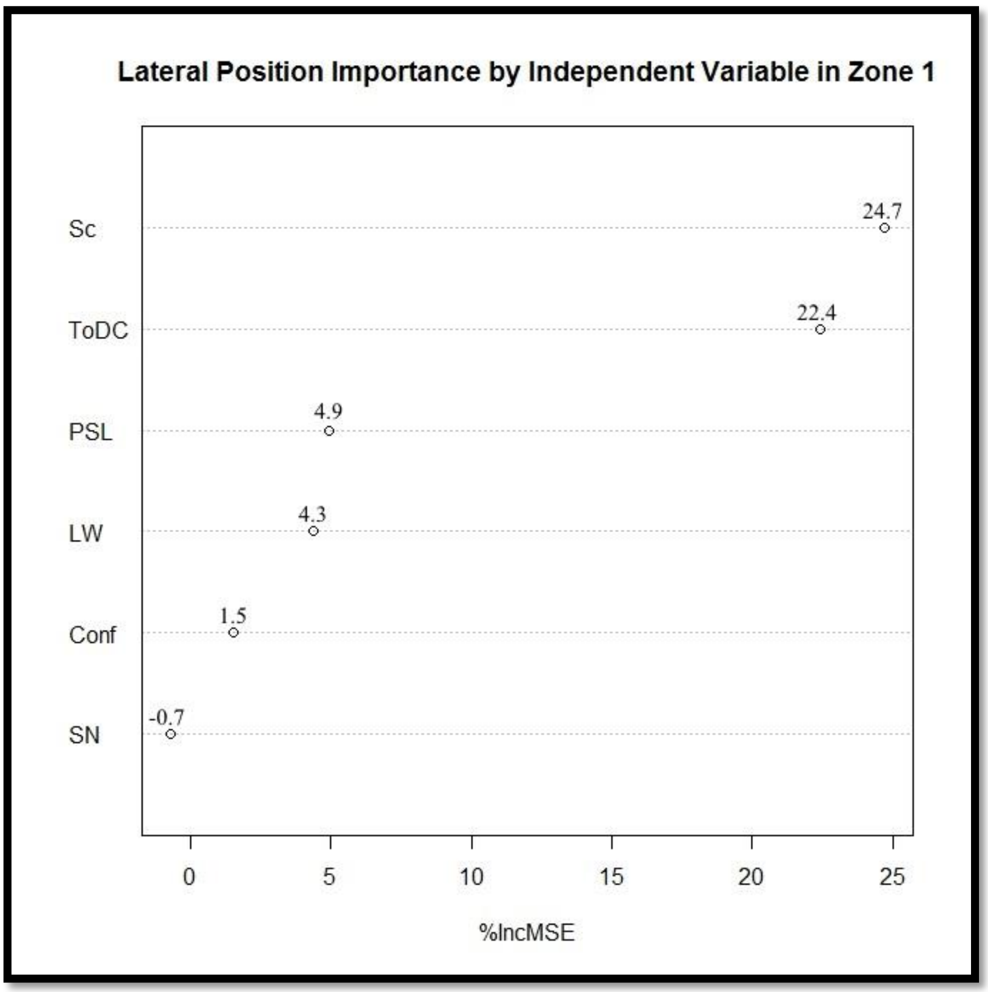


Figure 5-38 Effect of the Lateral Position Variable by Independent Variables in Zone 1.

5.8.2 Zone 2: DTL Pocket Lane

This zone represents the DTL pocket lanes at the left side. In Zone 2, Time of Day Condition and Posted Speed Limit variables results with the highest IncMSE%, 2.1% and 0.9%, respectively. The Configuration and the Lane Width variables was found to be the lowest IncMSE% with -3.1% and -1.3%, respectively. Results of the Random Forest for the lateral position in Zone 2 by independent variable are presented in Figure 5-39.

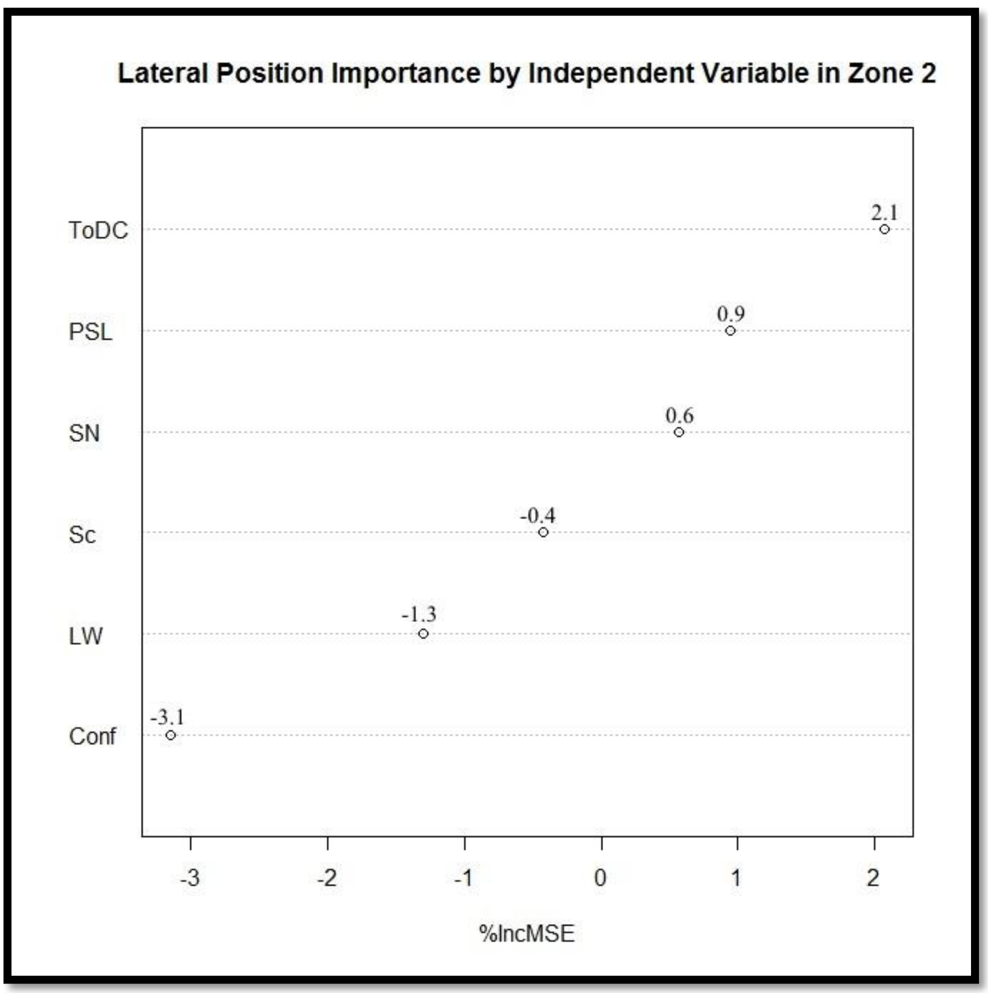


Figure 5-39 Effect of the Lateral Position Variable by Independent Variables in Zone 2.

5.8.3 Zone 3: Prior to Bridge Separation

This zone represents the DTL segment prior to the bridge separation at both directions. The Scenarios and Time of Day Condition variables results with the highest IncMSE%, 11.9% and 10.6%, respectively for the lateral position Random Forest model. The Configuration variable record the lowest increment with -0.5%. Results of the Random Forest for the lateral position in Zone 3 by independent variable are presented in Figure 5-40.

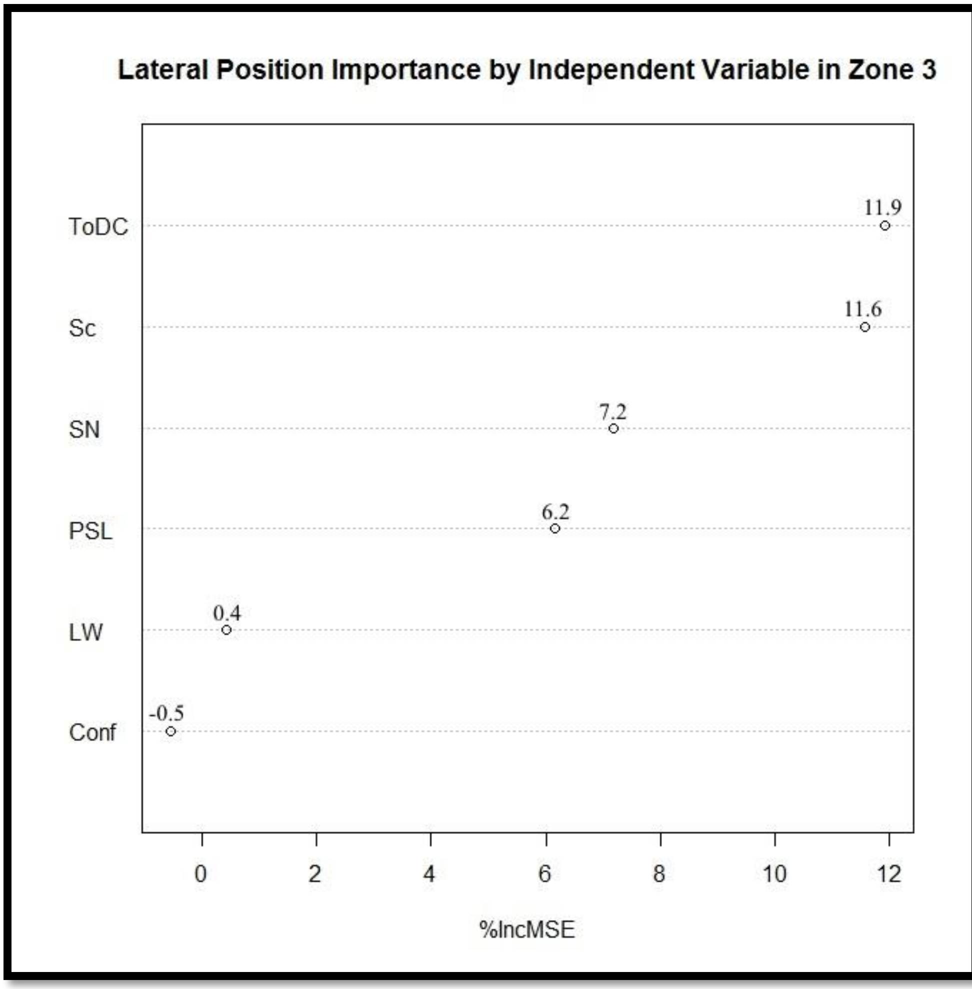


Figure 5-40 Effect of the Lateral Position Variable by Independent Variables in Zone 3.

5.8.4 Zone 4: DTL Bridge Separation

Zone 4 represents the DTL segment at the bridge separation at both directions. The Time of Day Condition variables was found to be the highest IncMSE% with 13.3% for the lateral position in the Random Forest model. The Posted Speed Limit variable record the lowest increment with -6.6%. Results of the Random Forest for the lateral position in Zone 4 by independent variable are presented in Figure 5-41.

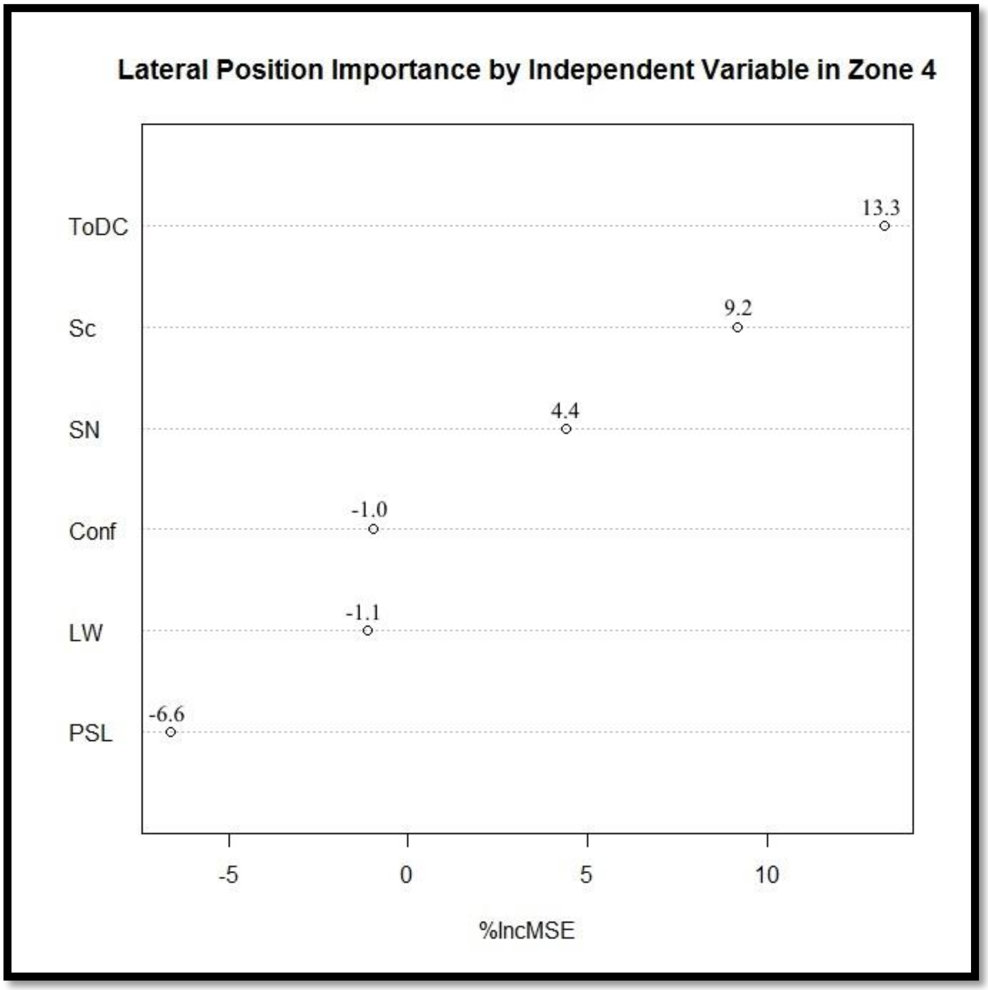


Figure 5-41 Effect of the Lateral Position Variable by Independent Variables in Zone 4

5.8.5 Zone 5: After Bridge Connection

This zone represents the DTL segment after the bridge connection at both directions. In Zone 5 was observed that the Subject and Scenario variables results with the highest IncMSE%, 3.3% and 2.9%, respectively, for the lateral position in the Random Forest model. The Configuration variable record the lowest increment with -6.7%, meaning that the variable is not important in the model. Results of the Random Forest for the lateral position in Zone 5 by independent variable are presented in Figure 5-42.

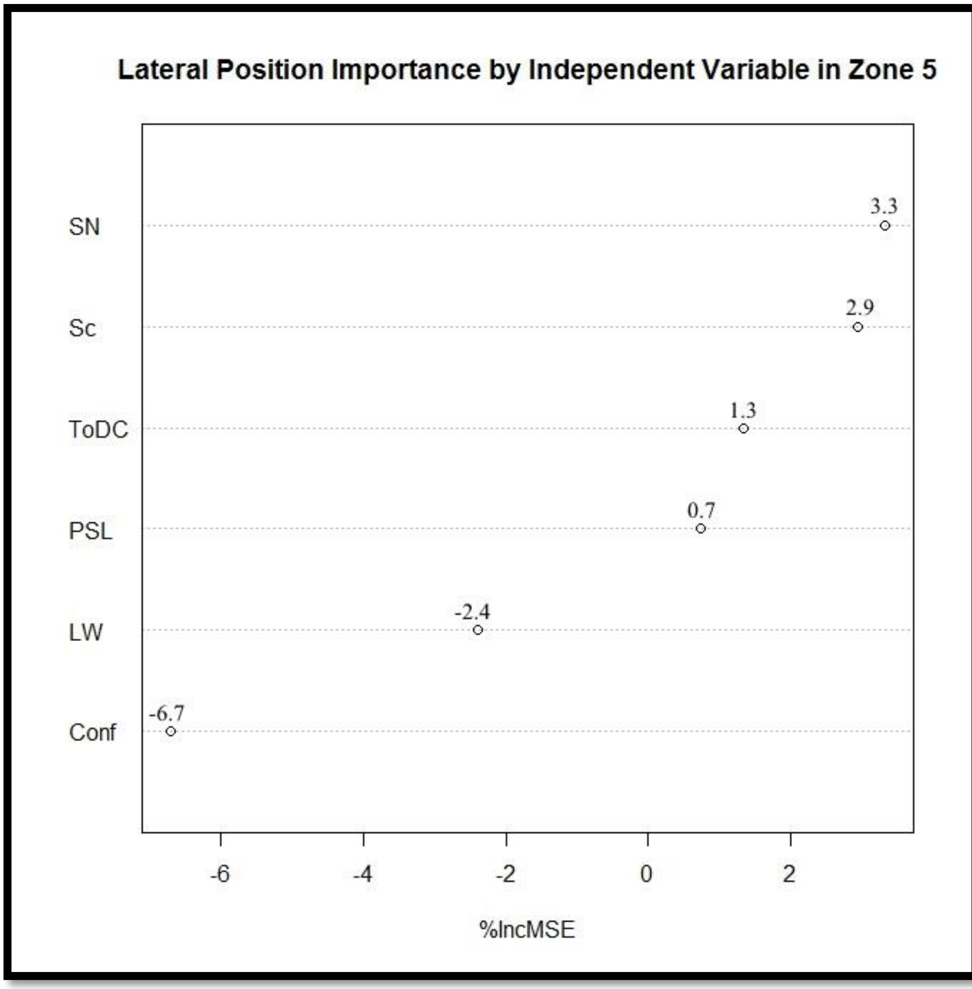


Figure 5-42 Effect of the Lateral Position Variable by Independent Variables in Zone 5.

5.8.6 Zone 6: DTL Pocket Lane

This zone represents the DTL pocket lanes at the right side at both directions. The Scenarios and Time of Day Condition variables results with the highest IncMSE% in the Random Forest Model for the Lateral Position variable with 6.8% and 6.5%, respectively. The lowest increment was found in the Configuration variable with -6.4% IncMSE. Results of the Random Forest for the accelerationo noise in Zone 6 by independent variable are presented in Figure 5-43.

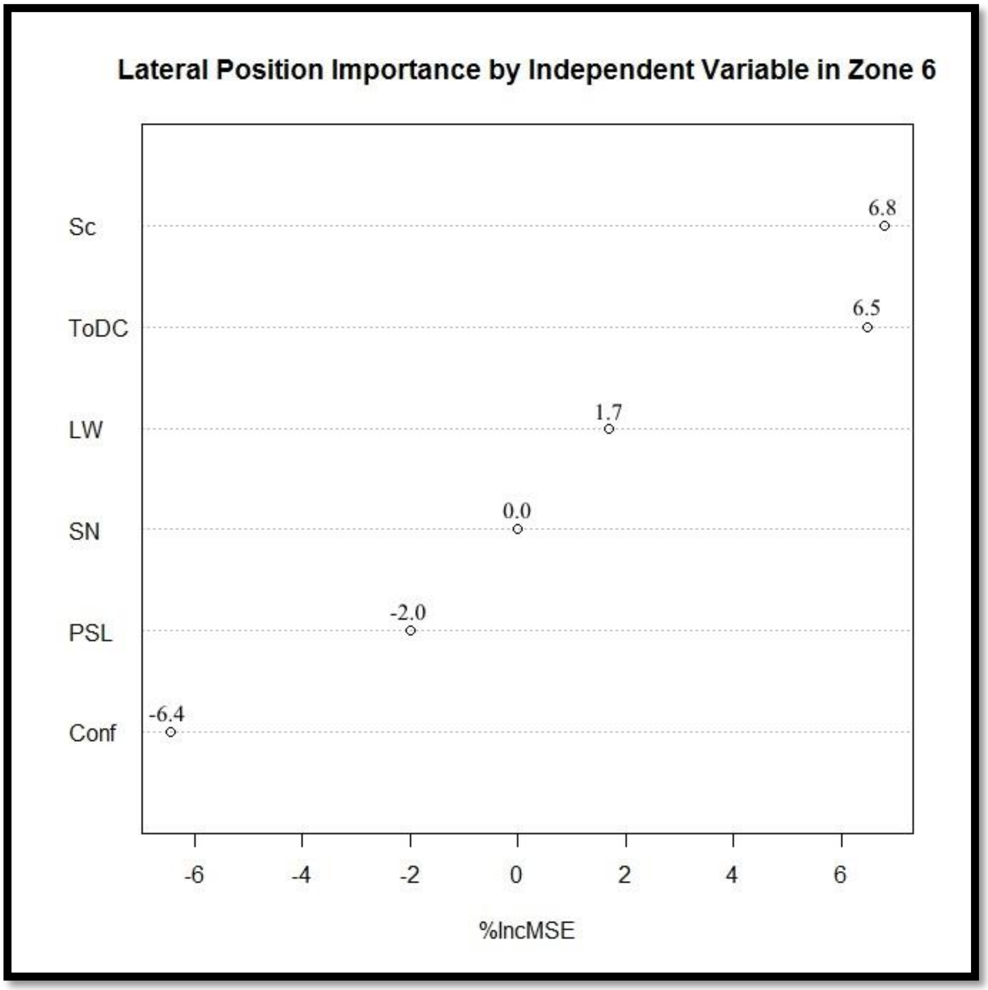


Figure 5-43 Effect of the Lateral Position Variable by Independent Variables in Zone 6.

5.8.7 Zone 7: DTL Exit

This zone represents the DTL exit gate at both directions. In Zone 7, similar to what happen in Zone 1 (DTL Entrance), the Scenario and the Time of Day Condition variables records the highest IncMSE% with 25.8% and 20.7%. The lowest increment was found for the Subject variable with -3.0% IncMSE (same variable records the lowest percent IncMSE in Zone 1). Results of the Random Forest for the lateral position in Zone 1 by independent variable are presented in Figure 5-44.

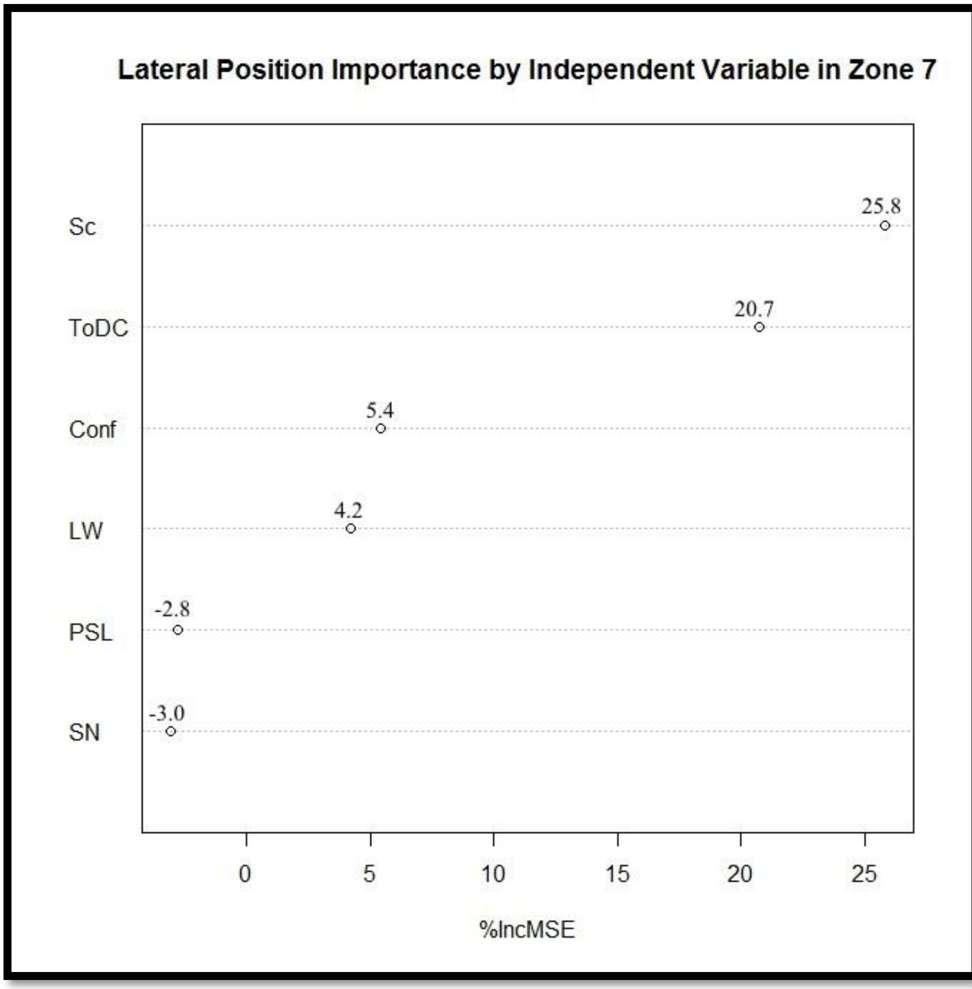


Figure 5-44 Effect of the Lateral Position Variable by Independent Variables in Zone 7.

5.9 DRIVERS' CONFUSION AT THE DTL EXIT

The administration officials of the PR-22 DTL have raised their attention to the number of drivers that used the incorrect DTL exit. The DTL has two exits, passenger cars exit (EB at the right and in the WB at the left) and the BRT exit (EB at the left and in the WB at the right). The EB direction has the highest observations of using the incorrect exit with 39% of the evaluated scenarios. Similarly, 30% of all the participants used the exclusive bus lane exit in scenarios with 65 mph

Posted Speed Limit scenarios, whereas 30% used the incorrect exit while traveling scenarios with Lane Widths of 10 feet.

The current configuration of roadside and overhead signage used for the exit gates for the EB and WB direction do not comply with the basic requirements of TCDs cited in Section 1A.02, Uniformity in TCDs cited in Section 1A.02 and Design of Signs cited in Section 2A.06 of the Manual on Uniform Traffic Control Devices (MUTCD) Part 1 (FHWA, 2009).

MUTCD Part 1 Section 1A.02 stated that:

> *"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."*

MUTCD Part 1 Section 1A.06 stated that:

"Uniformity of devices simplifies the task of the road user because it aids in recognition and understanding, thereby reducing perception/reaction time. Uniformity assists road users, law enforcement officers, and traffic courts by giving everyone the same interpretation. Uniformity assists public highway officials through efficiency in manufacture, installation, maintenance, and administration. Uniformity means treating similar situations in a similar way. The use of uniform traffic control devices does not, in itself, constitute uniformity. A standard device used where it is not appropriate is as objectionable as a non-standard device; in fact, this might be worse, because such misuse might result in disrespect at those locations where the device is needed and appropriate."

MUTCD Part 1 Section 2A.06 stated that:

*"**Standard:***

***Uniformity in design shall include shape, color, dimensions, legends, borders, and illumination or retro-reflectivity.**"*

Point C of the basic requirements of MUTCD of Section 1A.02 (convey a clear, simple meaning) was not satisfied since more than 1/5 of the subject participants were confused by the terminology in the TCDs, using the exclusive BRT lane exit as the express lane exit. Section 1A.06 and Section 2A.06 establish uniformity as one of the elements that simplify and assists road users. However, the existing configuration of signage on both direction is not uniform. Figure 5-45 and Figure 5-46 illustrated the existing configuration of signage prior to the exit gate in Spanish. As can be seen the signage did not have the same uniformity for each direction with differential in shape and color. In the EB direction the "Exit Only" ("Solo Salida") is used for the passenger cars exit. However, the same shape and color is used to identify the BRT exit gate at the WB direction as illustrated in Figure 5-45 and Figure 5-46. This could generate confusion since the message is for the same purpose but for different types of vehicle.

Figure 5-45 Existing Configuration of Signage Prior to the DTL Exit at EB Direction.

Figure 5-46 Existing Configuration of Signage Prior to the DTL Exit at WB Direction.

Additionally, in the WB direction a “Do Not Enter” (R5-1) sign, located at the roadside of the BRT exit gate, is not properly used since the used is this sign is regulatory to all vehicle types. The MUTCD stated that the R5-1 shall be used where traffic is prohibited from entering a restricted roadway. Commuters who see the BRT using this exclusive lane exit may interpreted that it is correct to use this lane even though it is an exclusive lane only for BRT use.

5.10 OPERATING SPEED DISCUSSION

The operating speed results demonstrated that the speed variates with respect to the independent variables in all zones evaluated. The Time of Day Condition affects the driver behavior in two (2) of the seven (7) zones evaluated (pocket lane at the left side and in the DTL Exit). At the pocket lane, the operating speed shows a reduction in speed at the WB direction going to a 57.86 mph at night. At the DTL exit, the speed reduced in the WB direction. This shows a tendency that the direction inside the DTL may influence the drivers' operating speed.

The Lane Width variable results in significant differences in the first five zones when evaluated for the Operating Speed. Opposite to the expected, the narrow lane increased the speed inside the DTL. The 10 feet lane shows higher speed in all the zone except in the Zone 1, where the 11 feet lane shows a higher speed than the 10 feet lane. Also, the 11 feet lane shows higher speed than the 12 feet lane, except in Zone 3.

The Posted Speed Limit results with significant difference in all the zones evaluated. The Posted Speed Limit increases the operating speed of drivers. All the mean speed in scenarios with 45 mph and 55 mph were higher than the posted speed limit. The speed in scenarios of 65 mph were higher in the DTL pocket lanes (left side), prior to the bridge separation and after the bridge connection. The operating speed were 4.60 mph and 2.54 mph higher in scenarios with the current condition and the 55 mph scenarios of posted speed limits respectively. However, on average, the speed on the 65 mph posted speed limit scenarios is lower than the posted speed limit with an average speed of 63 mph. It was expected that the operating speed were higher than the posted speed limits.

In terms of the Random Forest Model the independent variable that shows the highest increment in MSE was the Posted Speed Limit. Out of the seven zones the Posted Speed Limit results with the highest IncMSE% six times (and was the second highest in the other zone). This model validates the results of the General Linear Model results that found statistical differences between the levels evaluated (i.e. 45, 55 and 65 mph).

5.11 ACCELERATION NOISE DISCUSSION

The acceleration noise results demonstrated that the acceleration is influenced by the independent variables selected in this study. The Time of Day Condition affects the driver acceleration in two of the zones evaluated, prior to the bridge separation and in the DTL exit. As it was expected, an increase in acceleration noise was detected at divergent areas. A higher acceleration noise was observed at night condition at the exit gate resulting in a 2.07 mph per second deviation. Also, the WB direction results in a higher deviation in acceleration as compared with the EB direction except in the separation of DTL lanes where the EB direction results with a higher acceleration than the WB direction. It assumes that the current signage configuration may affect the acceleration. The existing configuration does not comply the uniformity and this may have created confusion at the divergent segments. The crash frequency in this area may increase since the area is a hazard point in terms of the acceleration noise.

The Lane Width variable resulted in significant difference in six (6) out of the seven (7) zones when evaluated for the Acceleration Noise. Narrow lanes decrease the acceleration noise except in the pocket lane and DTL exit. Nevertheless, at the exit gate the 12 feet lane decrease the acceleration noise more than the 10 feet and 11 feet lanes. The Posted Speed Limit results with significant difference in five (5) zones evaluated. The 55 mph posted speed limit scenarios show higher variation in acceleration however the 65 mph scenario result with the higher average variation with 0.768 mph/sec, follow by the 55 mph scenario with 0.735 mph/sec and lastly the 45 mph scenario with 0.584 mph/sec. The highest variation is seen at the exit gate with the 65 mph scenario. This value is expected since the subject driver should have deaccelerated to enter in DTL exit gate that consists of one lane with fixed concreted barriers at both side of the lane.

In terms of the Random Forest Model the independent variable that shows the highest increment in MSE was the Lane Width. The Lane Width records higher variation in the Acceleration Noise variables in the access points (DTL entrance and Exit) as well as the first pocket lane (at the left side). The model validates the results of the General Linear Model that found statistical differences between the levels evaluated (i.e. 10, 11 and 12 feet).

5.12 LATERAL POSITION DISCUSSION

Lateral Position results demonstrated that the position is influenced by the Time of the Day Condition and the direction selected in this study. Statistical difference in the positioning of the drivers was observed prior the separation of the DTL mainline until the exit zone.

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. Nevertheless, the most incorrect actions by scenarios were found to be in the eastbound direction where the exit was in the right lane.

In accordance with the results of the General Linear Model the Time of Day Condition records the highest importance for the Random Forest Model. It was expected that the direction as well as the time of the day affect the positioning of subject drivers' inside the DTL.

This chapter present the statistical models used to evaluate the driving behavior of subject participants based on the dependable variable evaluate, namely, Operating Speed, Acceleration Noise and Lateral Position. The next chapter will comprise of the conclusion and recommendation for this study based on the statistical analysis.

CHAPTER 6. CONCLUSIONS AND RECOMENDATIONS

This chapter provides the conclusions and recommendations of this research study that consisted of 54 subjects, divided in three age blocks (18-25, 26-45 and 46-70 years), for three virtual scenarios of the PR-22 DTL with three independent variables, namely, Time of Day Condition (morning, afternoon and night), Lane Width (10 feet, 11 feet or 12 feet) and Posted Speed Limit (45 mph, 55 mph or 65 mph). Three dependent variables, namely, Operating Speed, Acceleration Noise and Lateral Position, were used to evaluate the driving behavior of the participants on seven zones of interest. The purpose for selecting these seven zones was to evaluate the operational and safety effect of the geometrical characteristics and posted speed limits inside the DTL facility. This study represents the first ever driving simulation study using the scenarios of the PR-22 DTL and the UPRM driving simulator.

6.1 CONCLUSIONS

Based on the integrated analysis of the Puerto Rico PR-22 DTL, a managed lane facility using the UPRM driving simulator, the following conclusions were made:

- The generation of the first ever PR-22 DTL driving simulation scenario was completed with subject participants from Puerto Rico using the UPRM driving simulator.

- The first hypothesis was rejected since narrow lanes present higher operating speed and higher lateral position than wider lanes. However, narrow lanes show less variation in acceleration noise.

- The second hypothesis which stated that "subject drivers will tend to have higher speed profiles than the posted speed limit", was not rejected since the operating speed was higher in all the 45 mph scenarios, in six out of seven of the 55 mph scenarios and in four out of seven of the 65 mph scenarios.

- The third hypothesis was rejected since the number of observations associated with subject drivers mistakenly using the DTL exit was higher in the EB direction than the WB direction. In 22% of the scenarios evaluated, the subject drivers used the incorrect exit, exiting through the exclusive BRT lane. Fifty-eight percent of those maneuvers where in the morning in the EB direction and forty-two percent in the afternoon in the WB direction. This subject driver confusion is probably because the TDC's in the DTL exit didn't satisfy the recommended practice and fundamental principle for an effective TCD namely, "give adequate time for proper response" and uniformity for EB and WB directions.

- The fourth and last hypothesis that was evaluated stated that "Diverging segments will present a higher variation in the variables operating speed, lateral position and acceleration noise" known as safety hazard point, was not rejected since the zone prior to the bridge separation and the DTL exit resulted in higher variation in operating speed, acceleration noise and lateral position. For this reason, these areas should be known as a safety hazard points.

- Using the prediction of the Random Forest Model, the variables Operating Speed and Acceleration Noise present less variability with a 60 mph posted speed limit in the first six zones evaluated (see Appendix page 229 to 258). Meanwhile, the posted speed with less variability is the 55 mph for the DTL exit zone. This posted speed limit will provide a smooth transition to the PR-22 freeway that have a 55 mph posted speed limit.

- In terms of geometric characteristics, the prediction models present less variability in the Acceleration Noise variable for the 10 ft wide lanes. The proposed lane width range to operate the BRT is between 10.5 ft lane and 11.5 ft. Based on the prediction model this selection of Lane Width should reduce the acceleration noise in the PR-22 DTL as compared with the existing condition.

- The Random Forest and General Linear Model shows similar results and trends associated with the three dependent variables evaluated, namely, Operating Speed, Acceleration Noise and Lateral Position.

- The overhead signage at the DTL exit (at both directions) do not comply with the basic requirements of TCDs cited in Section 1A.02, Uniformity in TCDs cited in Section 1A.02 and Design of Signs cited in Section 2A.06 of the Manual on Uniform Traffic Control Devices (MUTCD) Part 1 revised in 2012.

- The Operating Speed variable results has statistical significant difference in the seven (7) zones evaluated and the highest increment in mean square error in the Random Forest Model in six (6) out of seven (7) zones for the Posted Speed Limit variable, meaning that the posted speed limit is the most important variable to determine the operating speed of the drivers.

- The Acceleration Noise resulted in statistical significant difference in six (6) out of the seven (7) zones evaluated for the Lane Width variable. Similar the Random Forest Model found out that the Lane Width variable is the most important variable in three (3) out of seven (7) zones. The access points associated with high crash frequency in managed lanes present the highest increase in deviation in Acceleration Noise of 2.07 mph/sec.

- The direction as well as the condition of the day (i.e. morning, afternoon and nighttime) affects the positioning of the drivers inside the DTL. The Time of Day Condition results significant in five (5) out of seven (7) and was between the two most important variables in the Random Forest model in all the seven (7) zones evaluated.

6.2 RECOMMENDATIONS

This section will comprise the recommendations for the UPRM driving simulator and the proposed treatment for the PR-22 Dynamic Toll Lane (DTL) in the short, medium and long term. This section includes recommendations for the driving simulators, proposed speed limit inside the DTL and geometric characteristics.

6.2.1 Speed Limit inside the DTL

Four recommendations associated with speed limit inside the DTL are presented below:

- In the short term, Present the research findings to PRTHA and Metropistas Executives associated with the proposed posted speed limit of 60 mph inside the DTL and 55 mph in the exit gate in the exit gate taking in consideration the zones that validated in this study (entrance gate in the EB and WB direction, prior the separation of the DTL lane due to the bridge piers, and in the exit gate in the EB and WB direction).

- The results indicated that the 60 mph speed limit shows less variability in the acceleration noise (used as a surrogate measure of the expected crash frequency) and Operating Speed variables in the first six zones evaluated. To keep a smooth transition to the PR-22 freeway is recommended that the posted speed limit in the exit zone of the DTL should set to 55 mph. This combination of posted speed limit may reduce the acceleration noise that is experienced in the existing condition.

- In the medium term, consider the implementation the proposed speed limit in the DTL facility with the adequate educational campaign showing the operational benefits of increasing the speed without sacrificing safety to road users.

- In the long term, conduct an on-site study to evaluate the effectiveness of the proposed speed limit and driving behaviors of motorist inside the DTL and exit gates including the extended 2.2 km segment.

6.2.2 Geometric Characteristics inside the DTL

Three recommendations associated with the geometric characteristics inside the DTL are shown below:

- In the short term is recommended to study the effects of changing only the lane width variable in the UPRM simulator without changing other independent variables that may affect the operating speed with the simulated traffic.

- In the medium term, implement the optimum lane width with the corresponding pavement marking inside the DTL facility.

- In the long term, conduct an on-site study to evaluate the optimums lane width and its effect with in-service DTL traffic.

6.2.3 UPRM Driving simulator

Five recommendations associated with the UPRM Driving Simulator are presented below:

- In the short term, improve the fidelity of the UPRM driving simulator (driving wheel, accelerator and brake pedal sensitivity). The subject participants that participated in the post-study questionnaire selected these three elements as the most needed to improve the driving experience.

- In addition, in a short term, an improvement should be made in the simulated DTL zones to validate the results with the real-world environment.

- In the medium term, understand the traffic generation and composition in the SimCreator Module to represent a more realistic experience to the in-service DTL traffic. The creation of the BRT vehicles and their inclusion in the traffic mix should also be evaluated.

- Also, the fidelity related with the simulation software should be improved to simulate the sun glare. The sun glare affects the understanding of overhead signage at the DTL during the morning peak-hour. The sun glare should be evaluated in the future and determine the effects on the motorist.

- In the long term, consider the inclusion of motion axis in the UPRM driving simulator to improve the driving experience and evaluate additional elements such as rolling terrains and roundabouts.

6.3 FUTURE RESEARCH

Further research should be made to evaluate the proposed countermeasures and the PR-22 DTL extension to contribute improving the freeway safety.

- Evaluate potential countermeasures that can improve road safety in the PR-22 DTL and replace existing overhead signage (i.e. variable overhead message signs configurations and application of flashing beacons).

- In the post-simulation questionnaire, the subject participants stated that the phrase “Carril Expreso” or “Carril Exclusivo” (“Express Lane” or “Exclusive Lane” in English) may be confusing. Therefore, the proposed treatment shall determine which exit gate is for the BRT and the passenger cars without the use of the phrase “Express Lane” or “Exclusive Lane”, since the use of these phrases may affect the decision making at the exit gate.

- Additional studies should be made to evaluate the driving behavior at the current EB direction exit gate.

- Evaluate the driving behavior at the current EB direction exit gate which stated operation in April 2017 and its 2.2 km farther from the original EB exit. Therefore, it is recommended to evaluate the behavior of drivers in that zone, since this research study found that the most incorrect use of the DTL exit was at the EB direction.

- The driving simulator presents a great opportunity to evaluate the safety and operation outcomes of the new TCDs as well as the extension in the PR-22.

- Further research should be made to evaluate the effects of familiar and unfamiliar drivers of the PR-22 DTL.

- The effect of the subject participant driving across the virtual scenario should be evaluated because this effect is present in each of the zone of interest. Due to the likelihood of simulation sickness the participant where exposed to three representative scenarios, the further research will focus on study the possibility of exposed the participant to more scenarios without suffering simulation sickness.

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APPENDIX

Comité para la Protección de los Seres Humanos en la Investigación
CPSHI/IRB 00002053
Universidad de Puerto Rico – Recinto Universitario de Mayagüez
Decanato de Asuntos Académicos
Call Box 9000
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25 de enero de 2017

Johnathan Ruiz González
Ingeniería Civil
RUM

Estimado estudiante:

El Comité para la Protección de los Seres Humanos en la Investigación (CPSHI) ha considerado su Solicitud de Revisión y demás documentos sometidos para el estudio titulado ***Operation and Safety Evaluation of Roadway Geometrics in the PR-22 Dynamic Toll Lane Using a Driving Simulator (#Protocolo 20170116).***

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

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

Por tanto, aprobamos su investigación con las anteriores dispensas. La aprobación tiene vigencia de un año a partir de hoy; esto es, desde el 25 de enero de 2017 hasta el 24 de enero de 2018. Le recordamos que la aprobación emitida por nuestro comité no lo exime de cumplir con cualquier otro requisito institucional o gubernamental relacionado al tema o fuente de financiamiento de su proyecto.

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

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

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

Cordialmente,

Dr. Rafael A. Boglio Martínez
Presidente
CPSHI/IRB

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ESTUDIO DE SIMULACION DE PLAZA DE PEAJE

FORMULARIO DE CONSENTIMIENTO INFORMADO

Investigador Principal: Johnathan J. Ruiz González

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

Título de Proyecto: Operation and Safety Evaluation of Roadway Geometrics in the PR-22 Dynamic Toll Lane Using a Driving Simulator

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

iii) Usted se sentará en el simulador, y se le dará una simulación de práctica para familiarizarse con el simulador de conducción. Una vez usted se sienta cómodo con el simulador, usted manejará a través de un trayecto que tomará cerca de 2 a 3 minutos para cada escenario virtual en que conducirá. Si en algún momento del trayecto siente molestia o cinetosis/mareo, informe al investigador de inmediato para que se detenga la simulación. No habrá ningún tipo de penalidad, o efecto adverso al estudio porque su participación no pueda ser completada.

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

En términos de la operación del simulador de conducción, existe un leve riesgo de cinetosis (mareos). Un pequeño por ciento de los participantes que manejan el simulador podrían experimentar sensación de nauseas o nausea real. El experimento ha sido trabajado para minimizar el riesgo. Se recomienda que 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 molestia o nauseas, 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 guie a su hogar o a buscar atención medica si es necesario.

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

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

Los resultados de esta investigación serán publicados en revistas de investigación científica y serán presentados en conferencias y simposios de entidades científicas profesionales. Los resultados de esta investigación también serán publicados en la tesis de maestría del investigador principal, Johnathan J. Ruiz González. Los resultados podrían ser utilizados por los investigadores aprobados para propósitos internos. Ningún participante será identificable en los reportes o publicaciones ya que ni el nombre ni las iniciales de ningún participante serán utilizados. Para mantener confidencialidad de los archivos, los investigadores utilizarán códigos para identificar a cada sujeto, en vez de nombres, para todos los datos recolectados mediante cuestionarios y los datos recolectados durante su utilización del simulador. Los datos serán asegurados en el Laboratorio de Transportación de la UPR Mayagüez y solo serán accesibles por el investigador principal, y cualquier otro investigador aprobado para el estudio.

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

9. ¿RECIBIRÉ ALGUN TIPO DE COMPENSACION MONETARIA POR PARTICIPAR DE ESTE ESTUDIO?

No. Su participación en este estudio es completamente voluntaria.

10. ¿QUÉ PASA SI TENGO UNA PREGUNTA?

Si tiene alguna pregunta sobre el experimento o cualquier otro asunto relativo a su participación en este experimento, o si sufre de alguna lesión relacionada a la investigación como resultado del estudio, puede llamar al investigador, Johnathan J. Ruiz González, al (787) 673-0747 o johnathan.ruiz1@upr.edu. Si, durante el estudio o después de, usted desea discutir su participación o preocupaciones en cuanto al mismo con una persona que no participe directamente en la investigación puede comunicarse con el Comité para la Protección de los Seres Humanos en la Investigación del Recinto Universitario de Mayagüez al (787) 832-4040 ext. 6277 ó 6347 o cpshirum@uprm.edu. Una copia de este formulario de consentimiento será provista 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 si tiene algún riesgo o incomodidad.

13. DECLARACIÓN DE CONSENTIMIENTO VOLUNTARIO DEL SUJETO

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

____

Nombre en letra de molde del participante Fecha

Firma del participante

14. DECLARACIÓN DEL EXPERIMENTADOR

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

Firma de la persona que obtiene el consentimiento informado Fecha

CPSHI / IRB - RUM
No. 00002053
JAN 25 2017/JAN 24 2018
APROBADO

SAFER SIM
SAFETY RESEARCH USING SIMULATION
UNIVERSITY TRANSPORTATION CENTER

UNIVERSIDAD DE PUERTO RICO
RECINTO UNIVERSITARIO DE MAYAGUEZ
DEPARTAMENTO DE INGENIERIA CIVIL

¡Saludos! Necesito su ayuda como conductor voluntario para una innovadora investigación de seguridad en las carreteras con el primer simulador de conducción de Puerto Rico.

REQUISITOS:

- Edad: mayor de 18 años
- Licencia de conducir
- Fecha: 30 de enero al 25 de febrero del 2017
  - o Horario: lunes a viernes 8:00 am a 5:00 pm
  - o Solamente 1 hora de tu tiempo
- Lugar: Salón CI 102-F del Departamento de Ingeniería Civil y Agrimensura

Si está interesado(a) por favor llene la siguiente tabla y yo me estaré comunicando con usted a la mayor brevedad posible.

Nombre	Edad	Sexo	Teléfono	Día disponible	Hora disponible

Si desea más información comuníquese con,

Johnathan Ruiz email: johnathan.ruiz1@upr.edu. Cel. 787-673-0747

CPSHI / IRB - RUM
No. 00002053
JAN 25 2017 JAN 24 2018
APROBADO

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: (marque todas las que apliquen)

☐ Afroamericano ☐ Asiático

☐ 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:

___

___

___

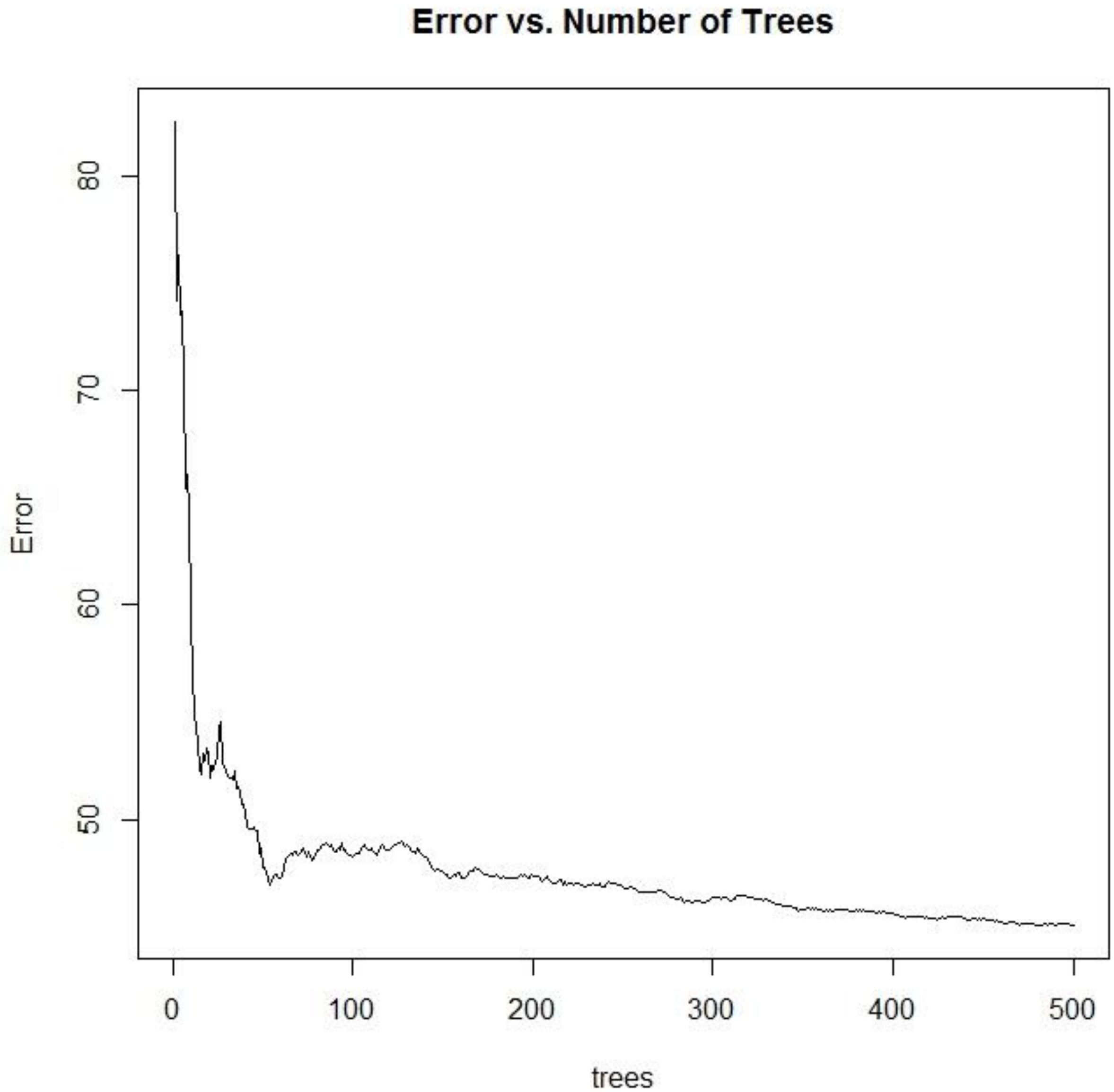

Figure B-1. Random Forest Tree Plot for Operating Speed Variable in Zone 1.

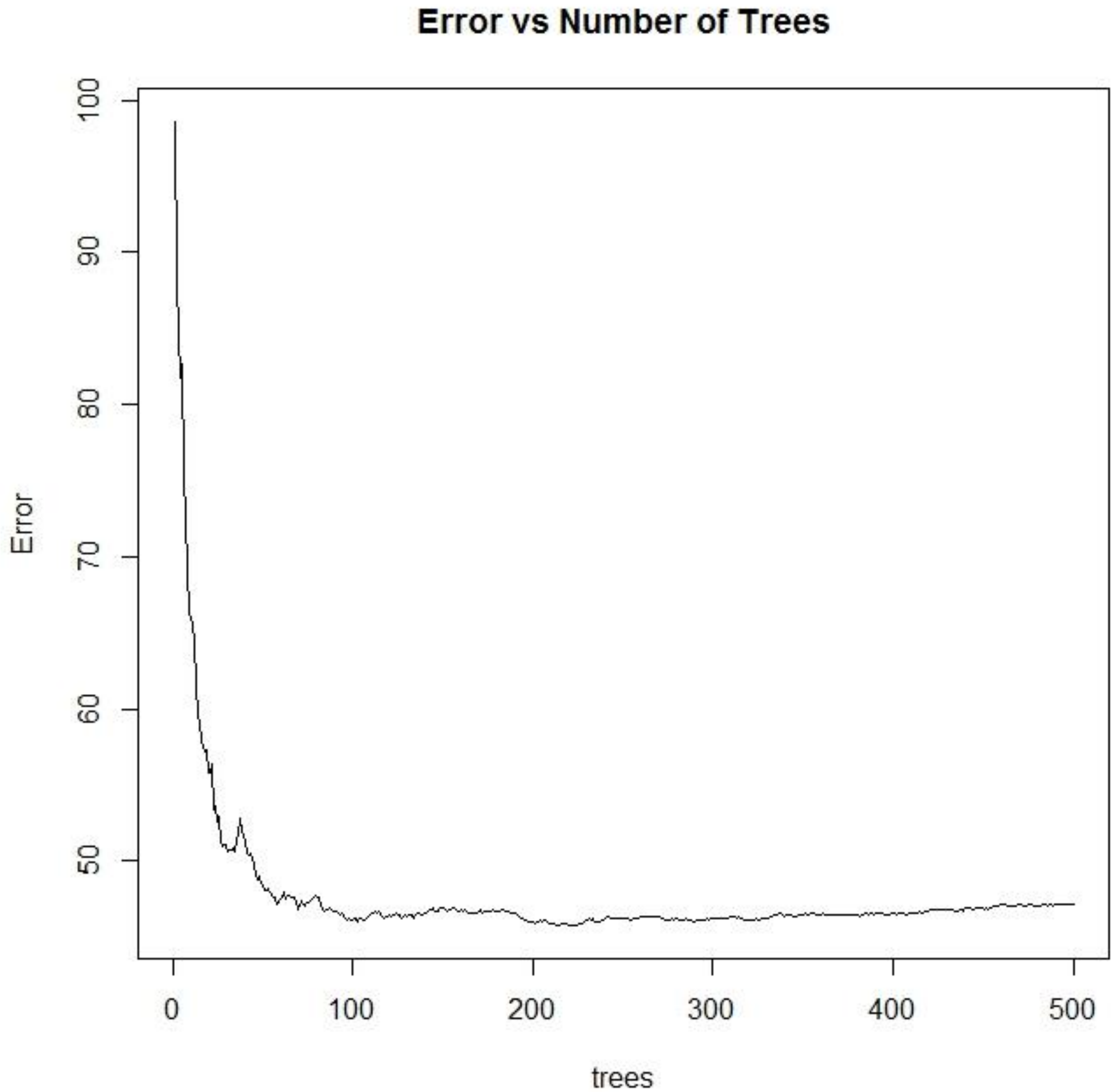

Figure B-2. Random Forest Tree Plot for Operating Speed Variable in Zone 2.

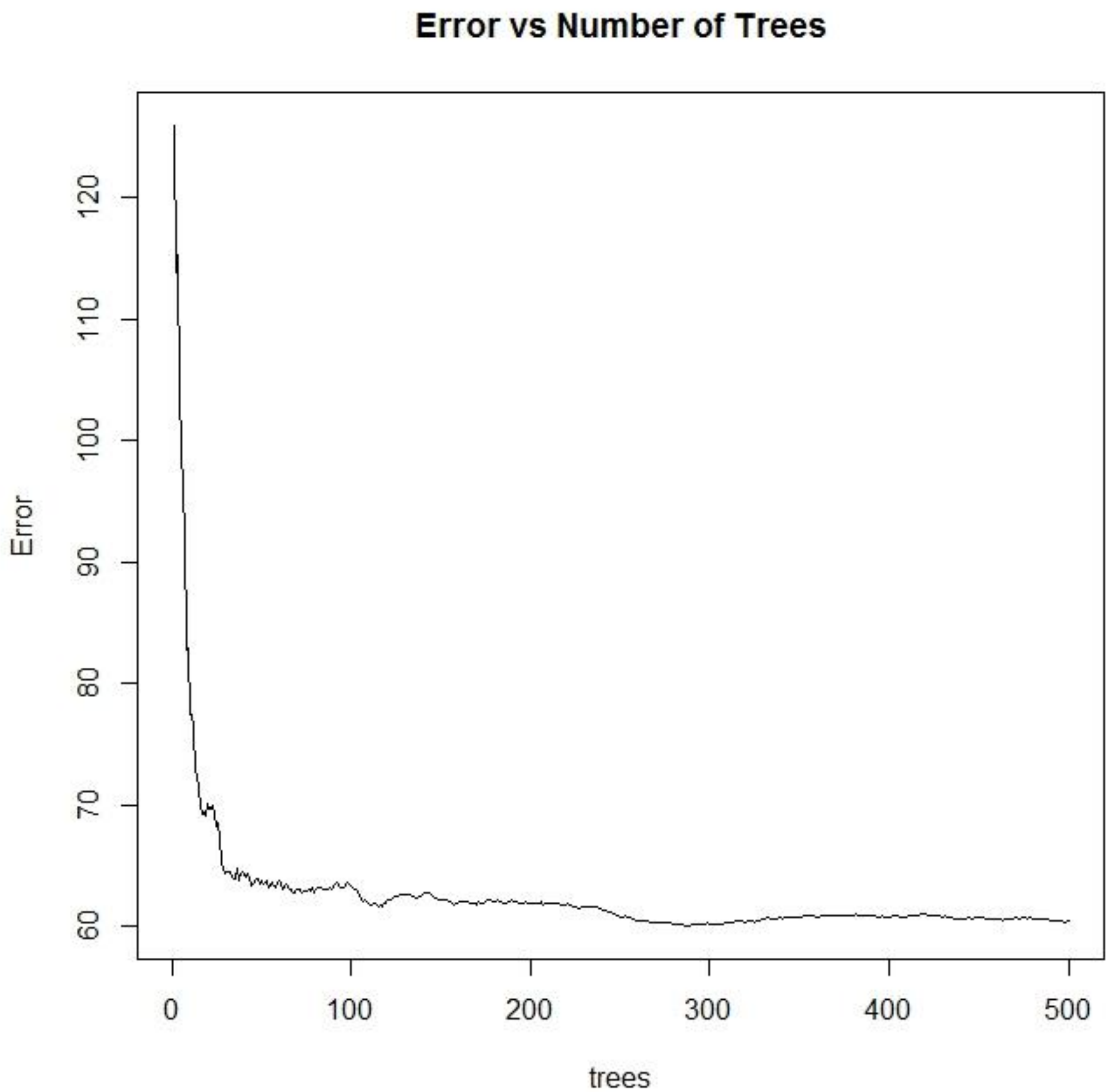

Figure B-3. Random Forest Tree Plot for Operating Speed Variable in Zone 3.

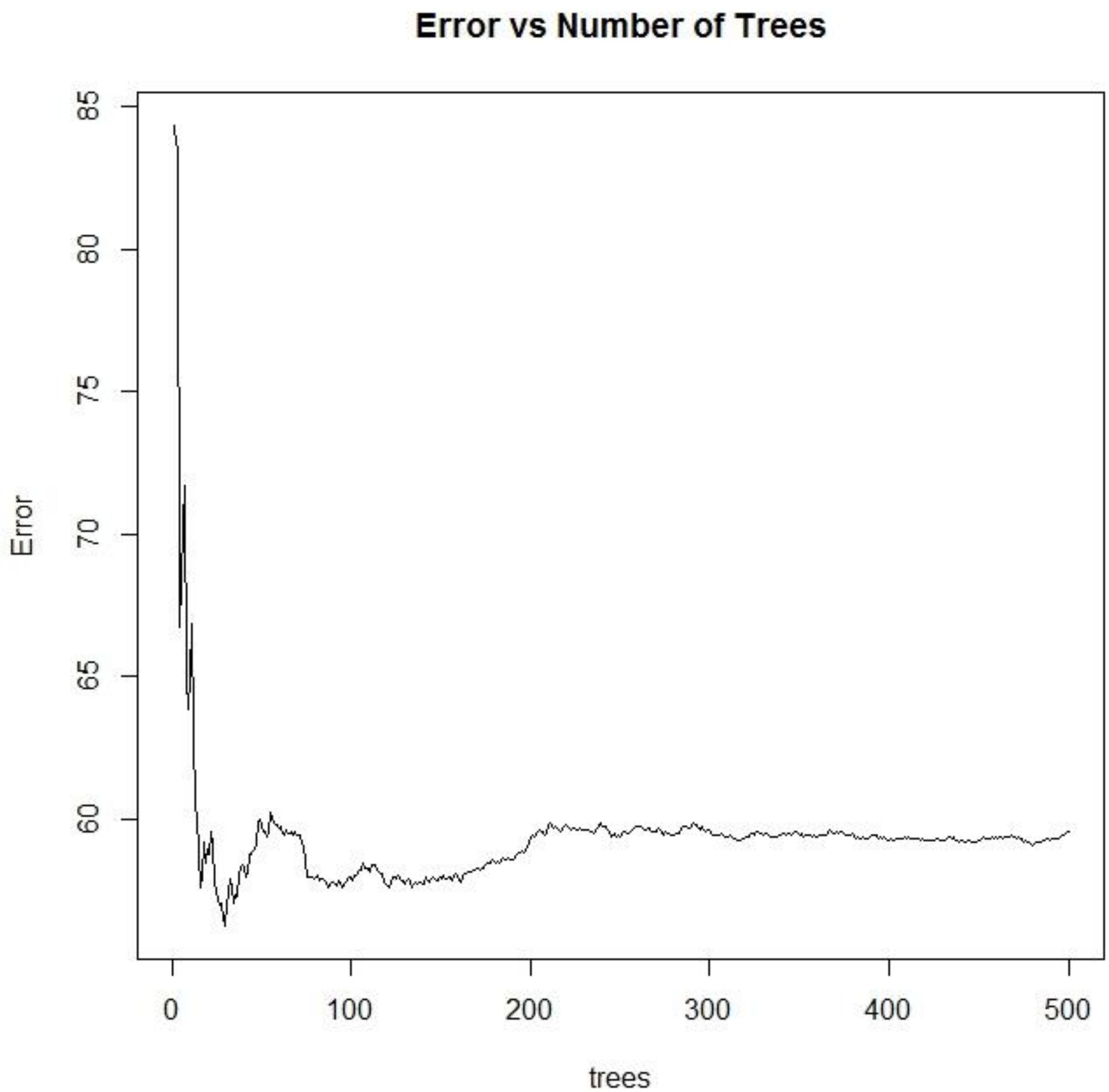

Figure B-4. Random Forest Tree Plot for Operating Speed Variable in Zone 4.

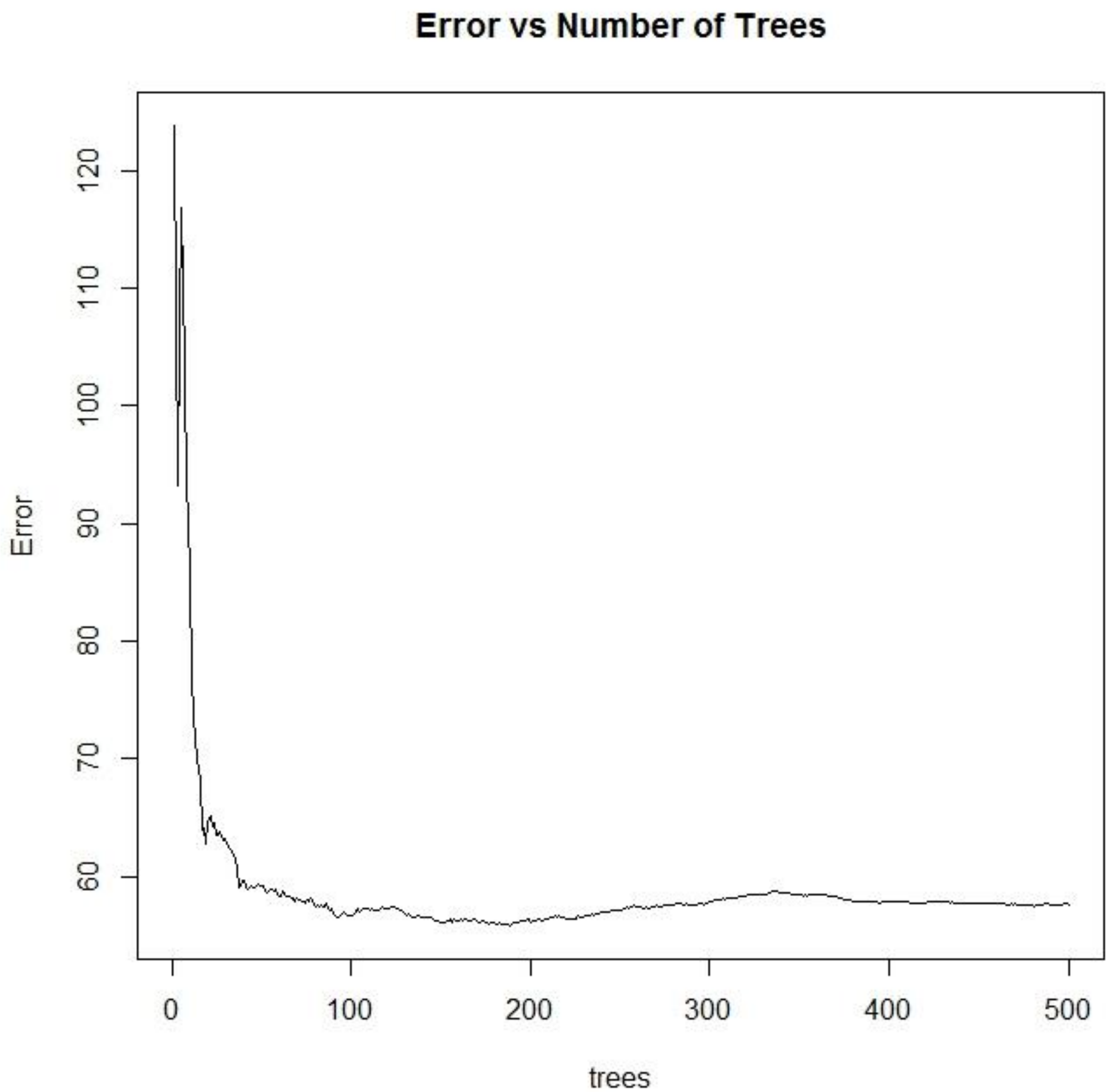

Figure B-5. Random Forest Tree Plot for Operating Speed Variable in Zone 5.

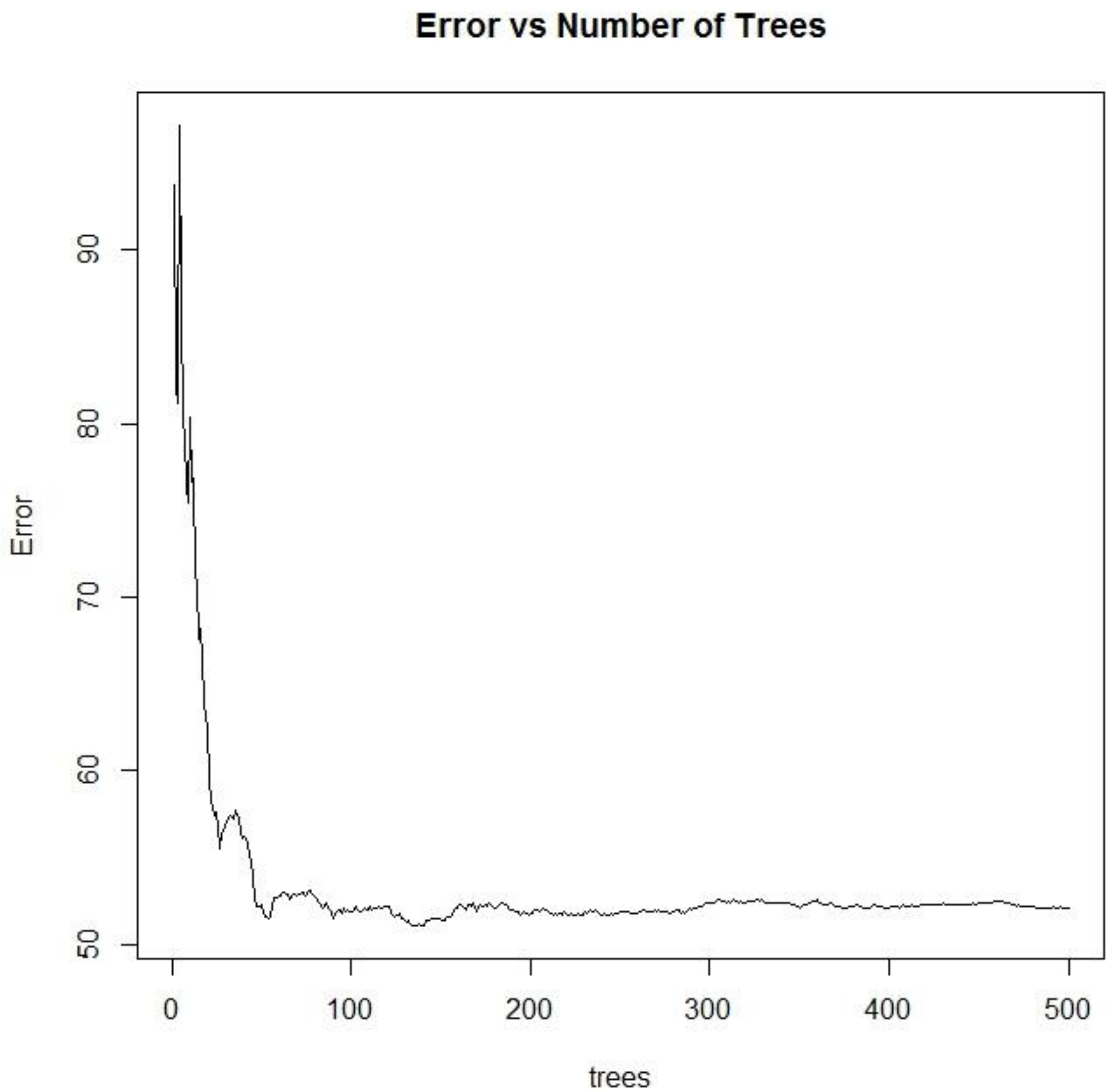

Figure B-6. Random Forest Tree Plot for Operating Speed Variable in Zone 6.

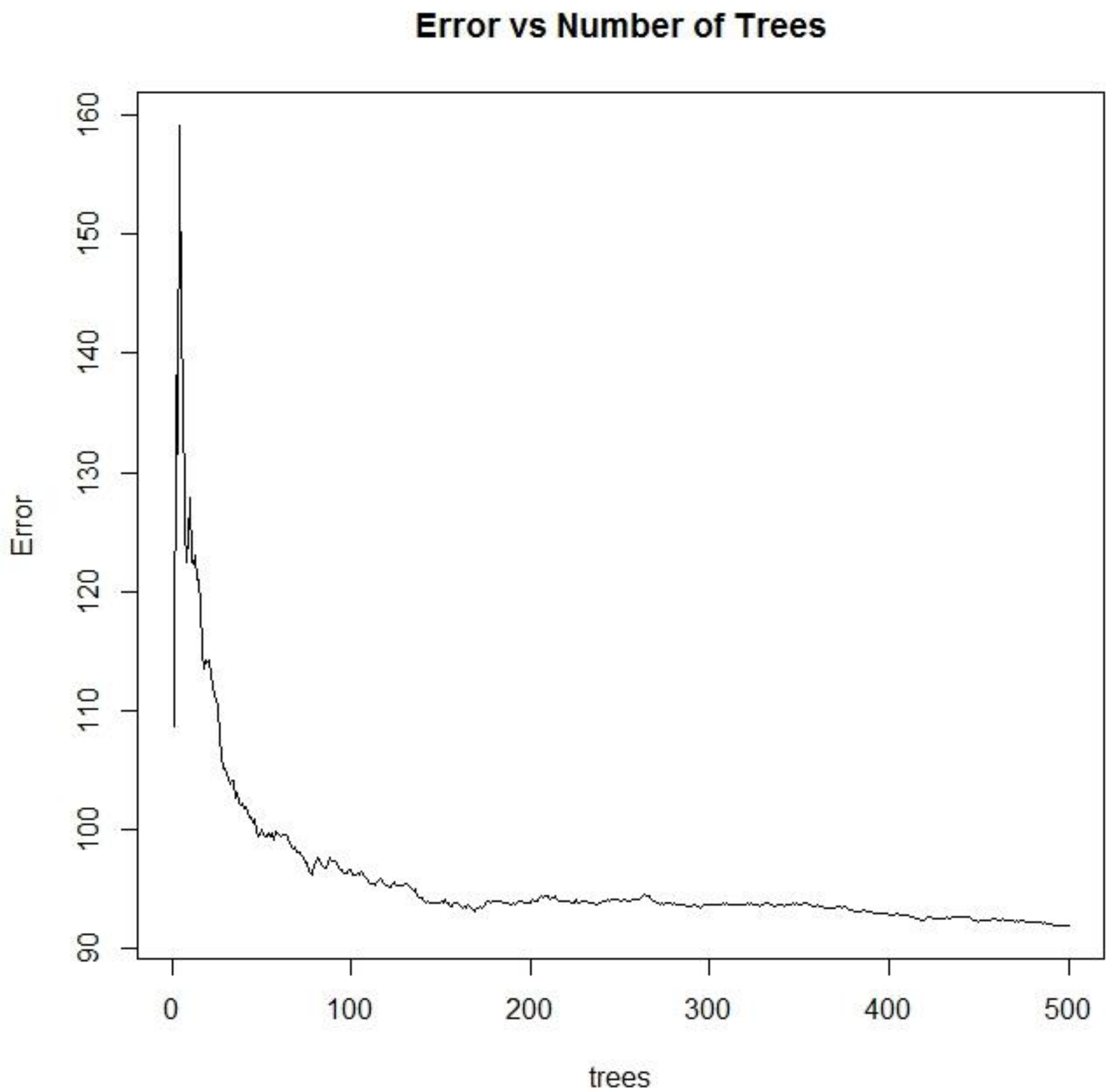

Figure B-7. Random Forest Tree Plot for Operating Speed Variable in Zone 7

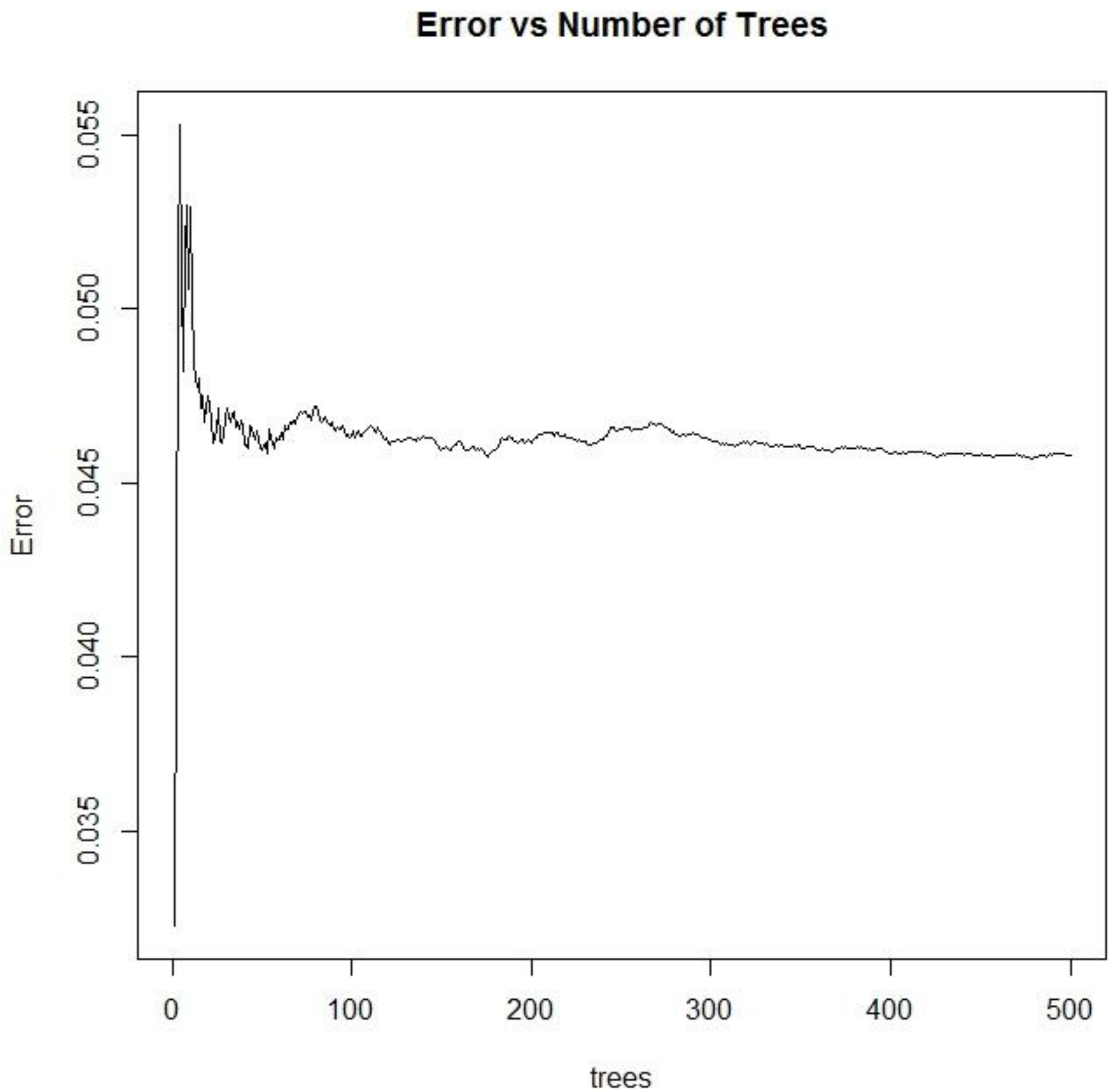

Figure B-8. Random Forest Tree Plot for Acceleration Noise Speed Variable in Zone 1.

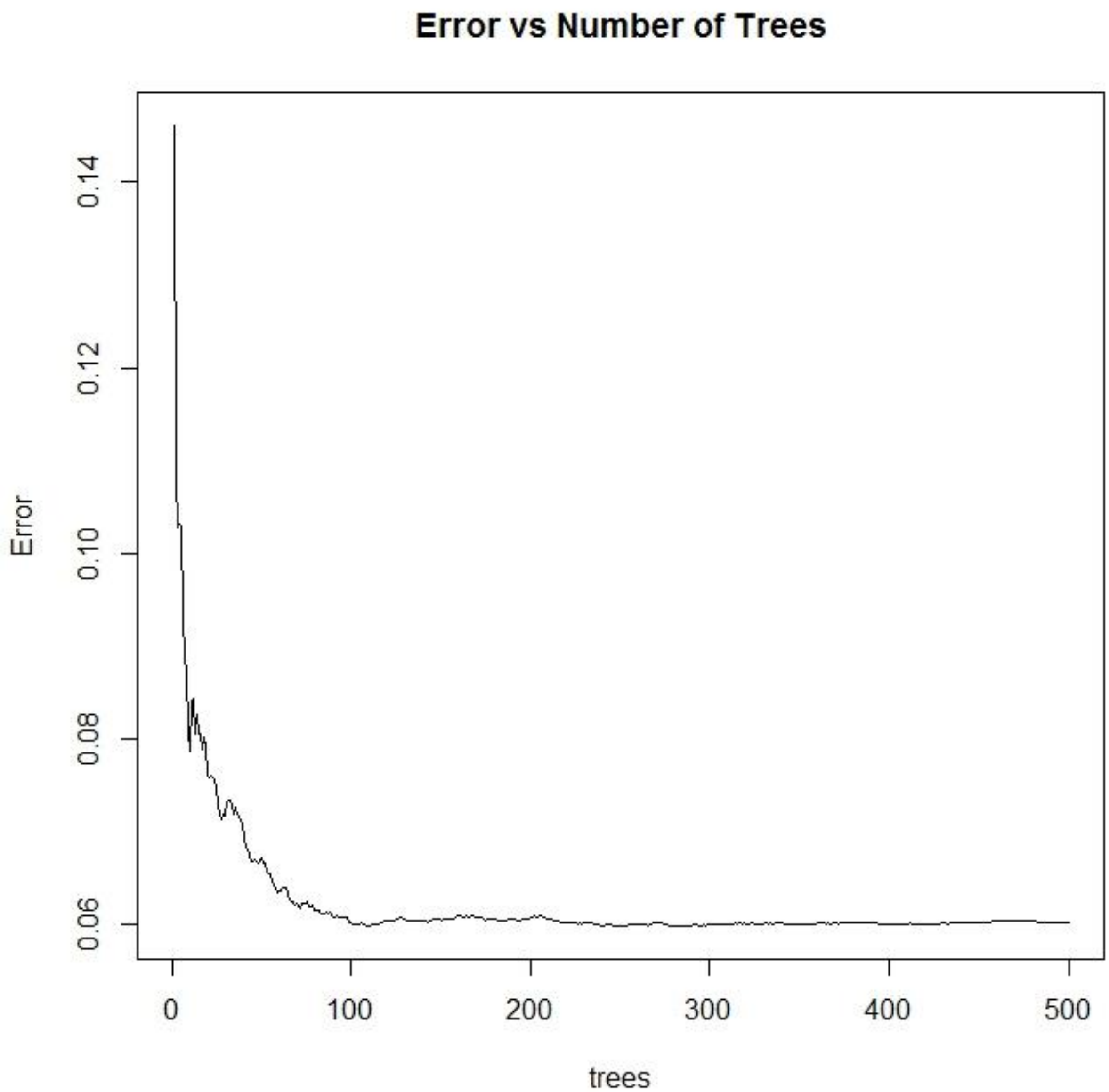

Figure B-9. Random Forest Tree Plot for Acceleration Noise Speed Variable in Zone 2.

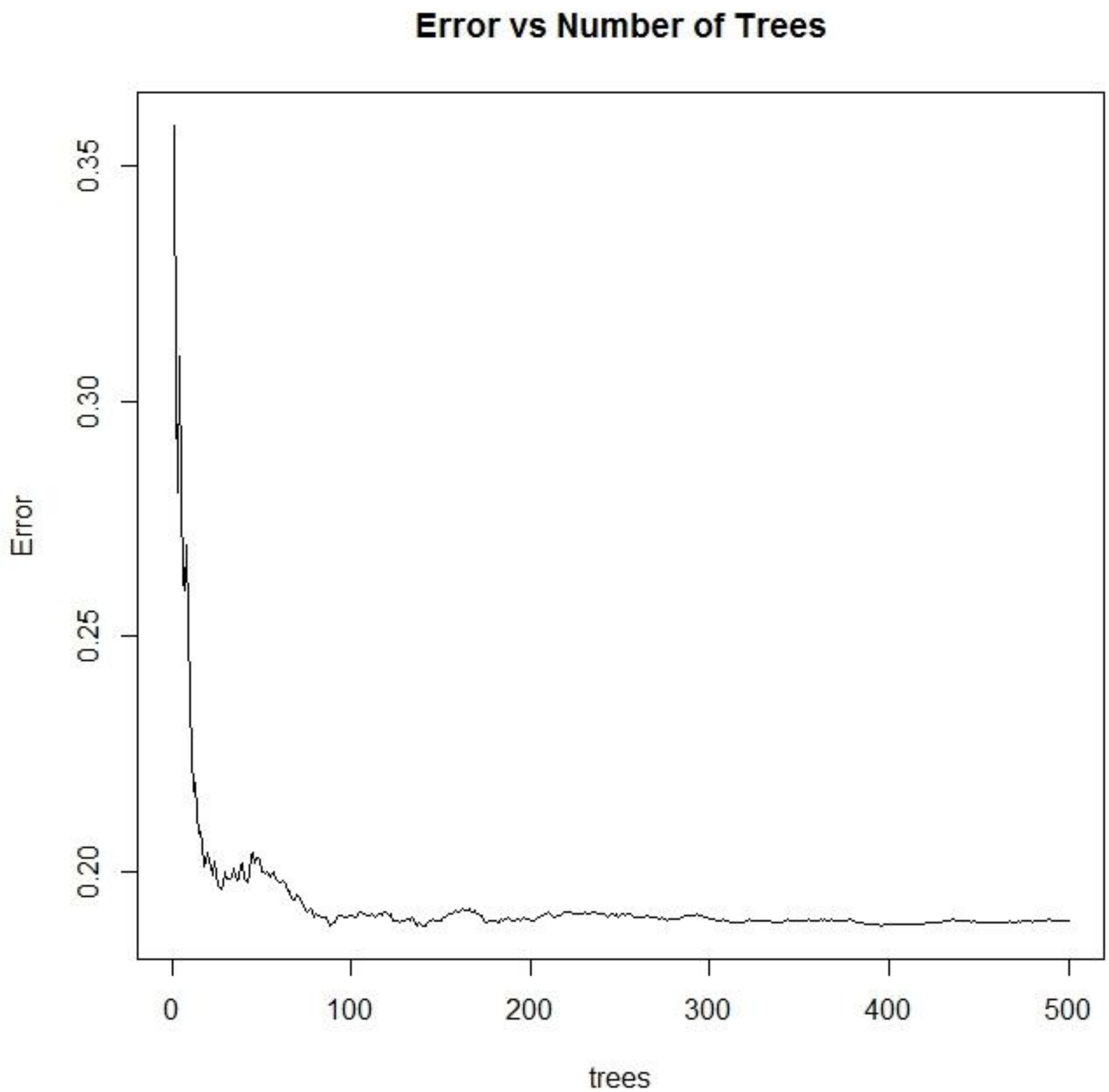

Figure B-10. Random Forest Tree Plot for Acceleration Noise Speed Variable in Zone 3.

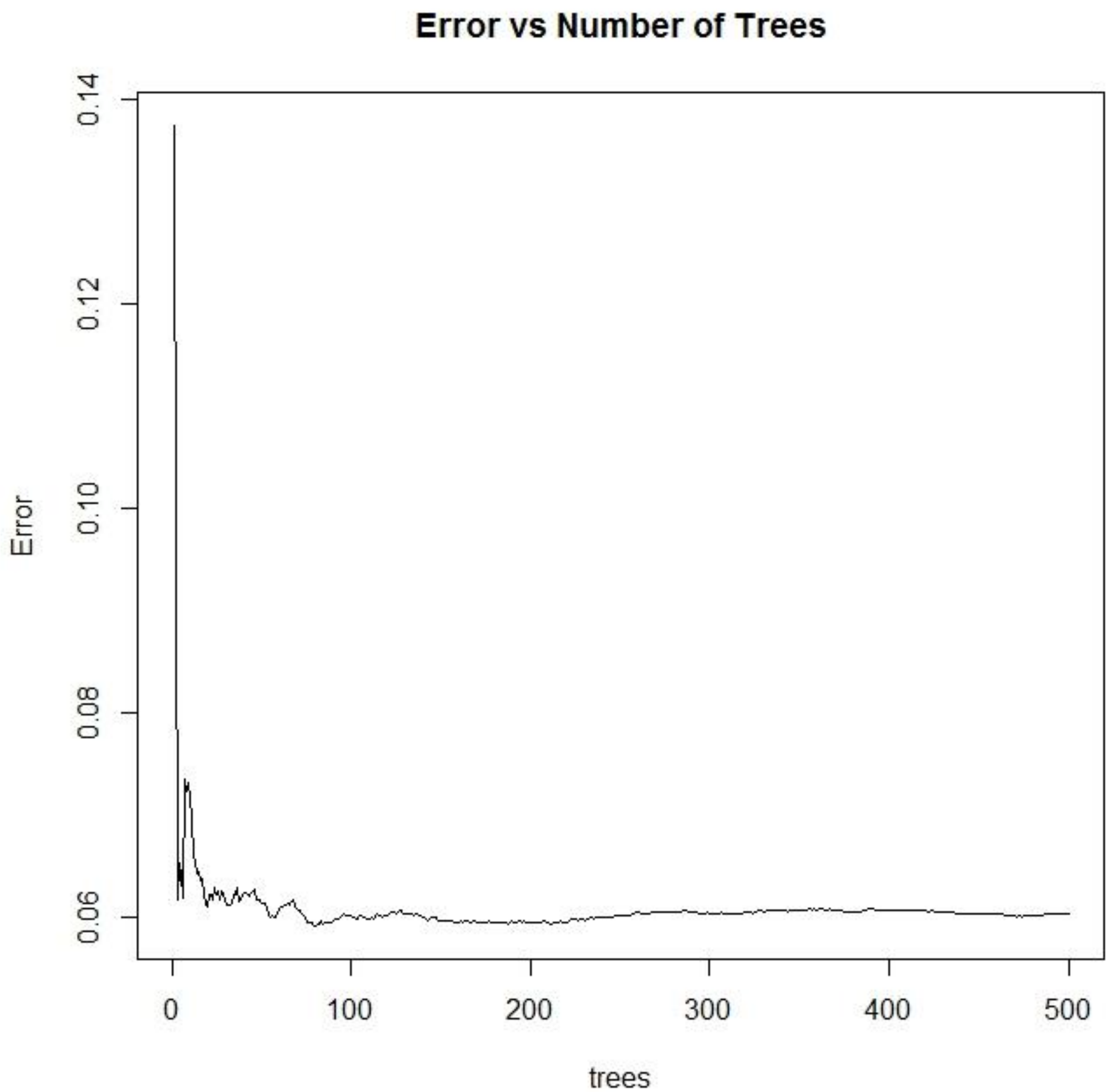

Figure B-11. Random Forest Tree Plot for Acceleration Noise Speed Variable in Zone 4.

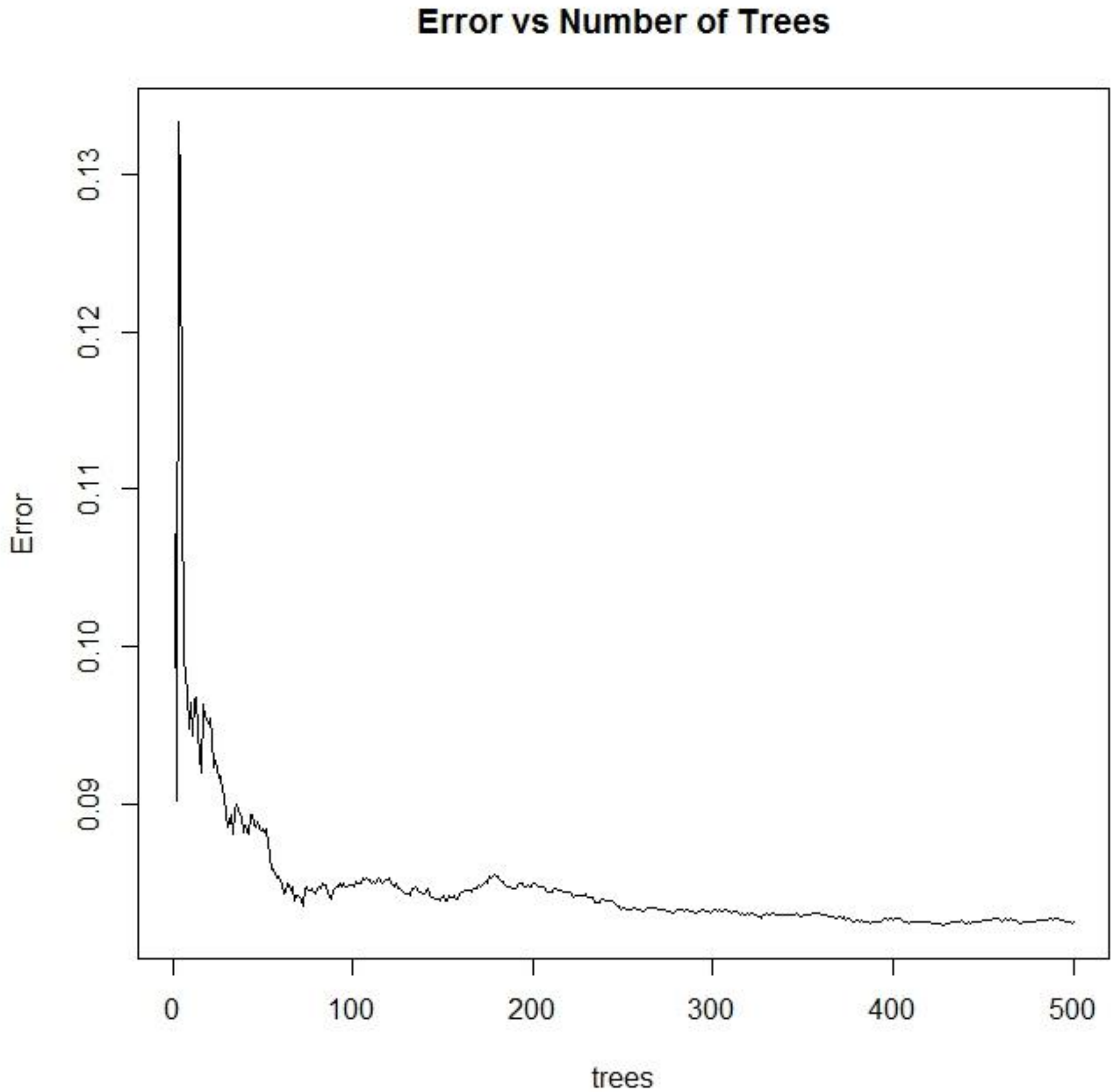

Figure B-12. Random Forest Tree Plot for Acceleration Noise Speed Variable in Zone 5.

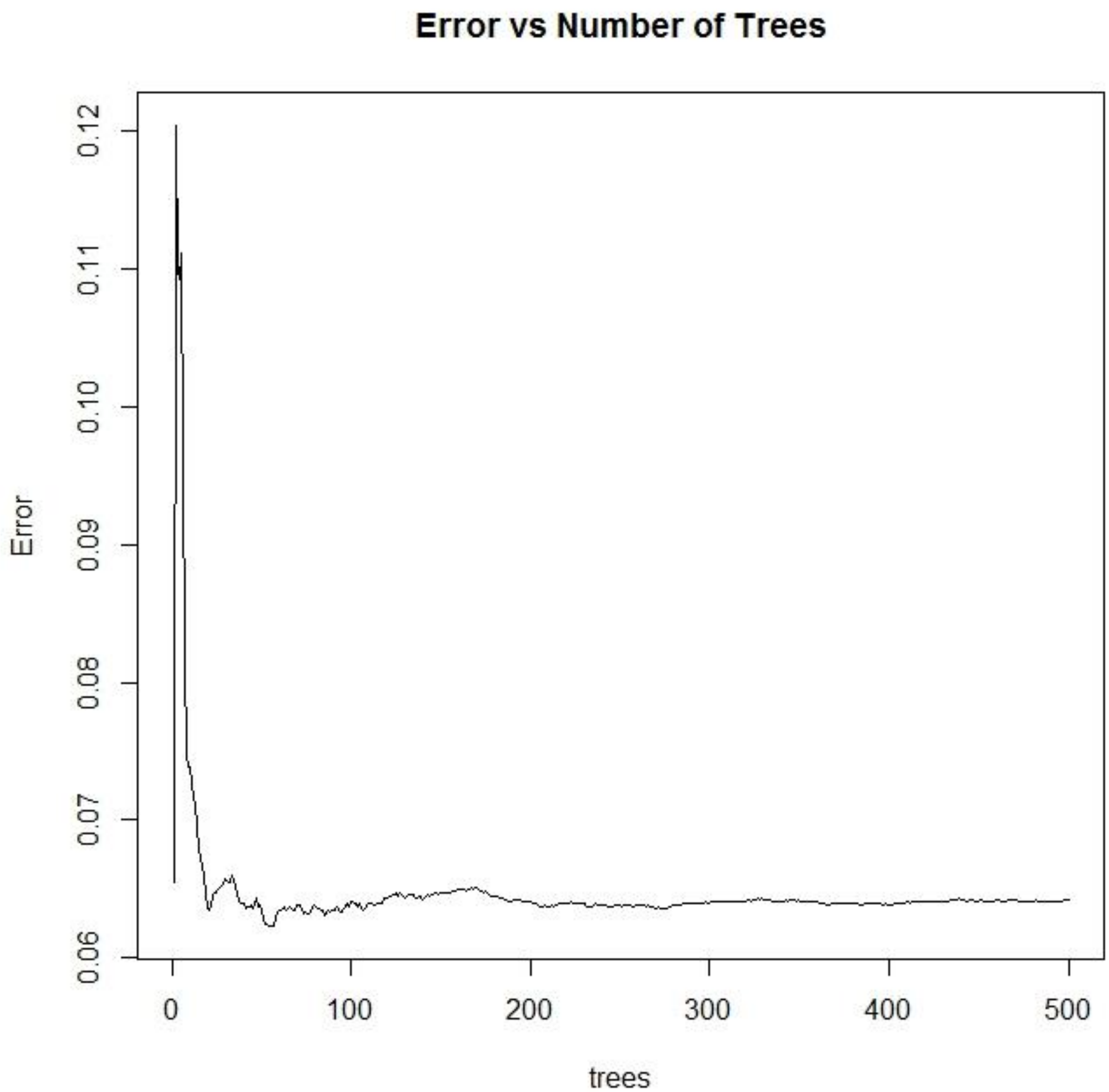

Figure B-13. Random Forest Tree Plot for Acceleration Noise Speed Variable in Zone 6.

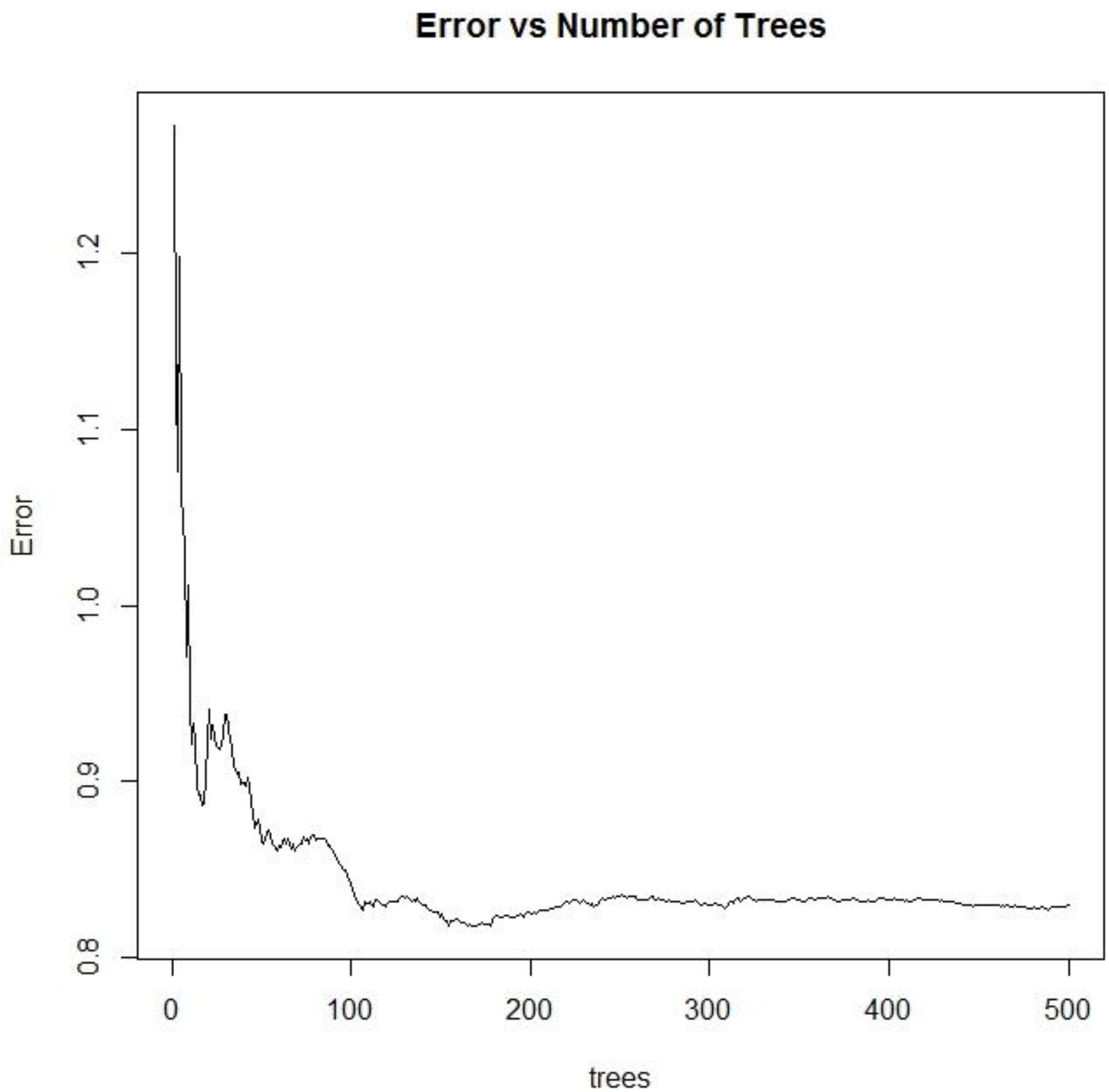

Figure B-14. Random Forest Tree Plot for Acceleration Noise Speed Variable in Zone 7.

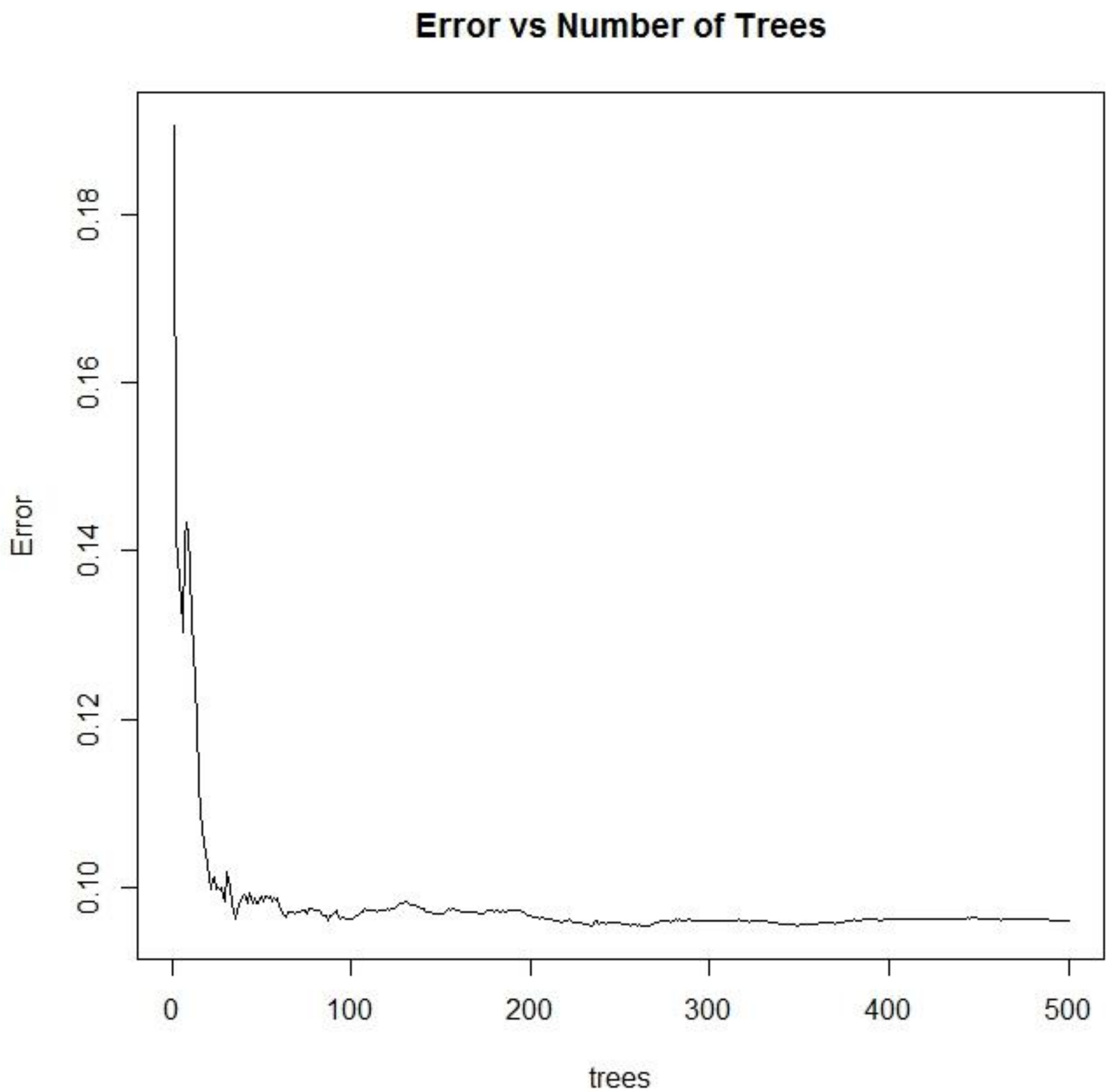

Figure B-15. Random Forest Tree Plot for Lateral Position Variable in Zone 1.

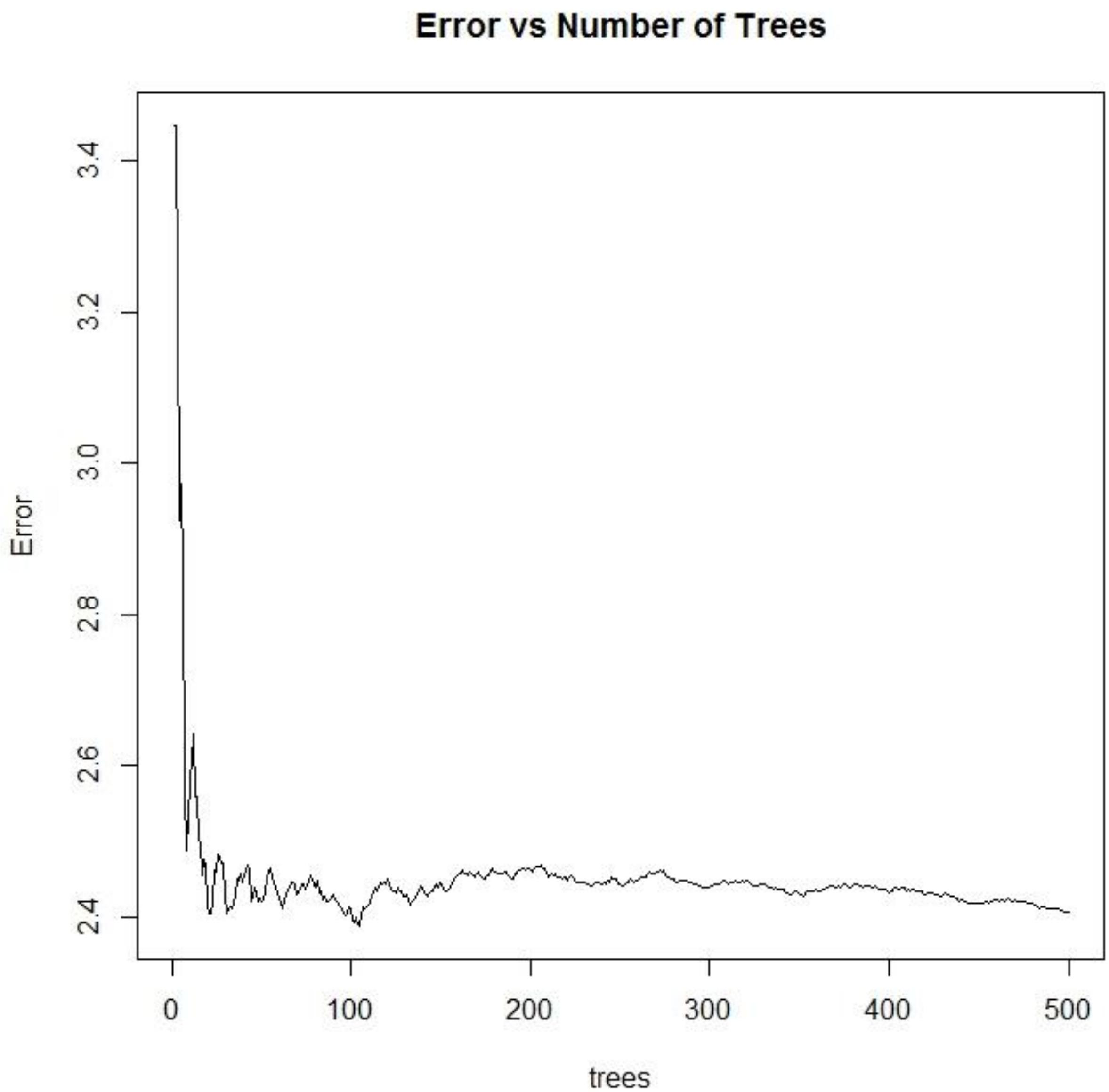

Figure B-16. Random Forest Tree Plot for Lateral Position Variable in Zone 2.

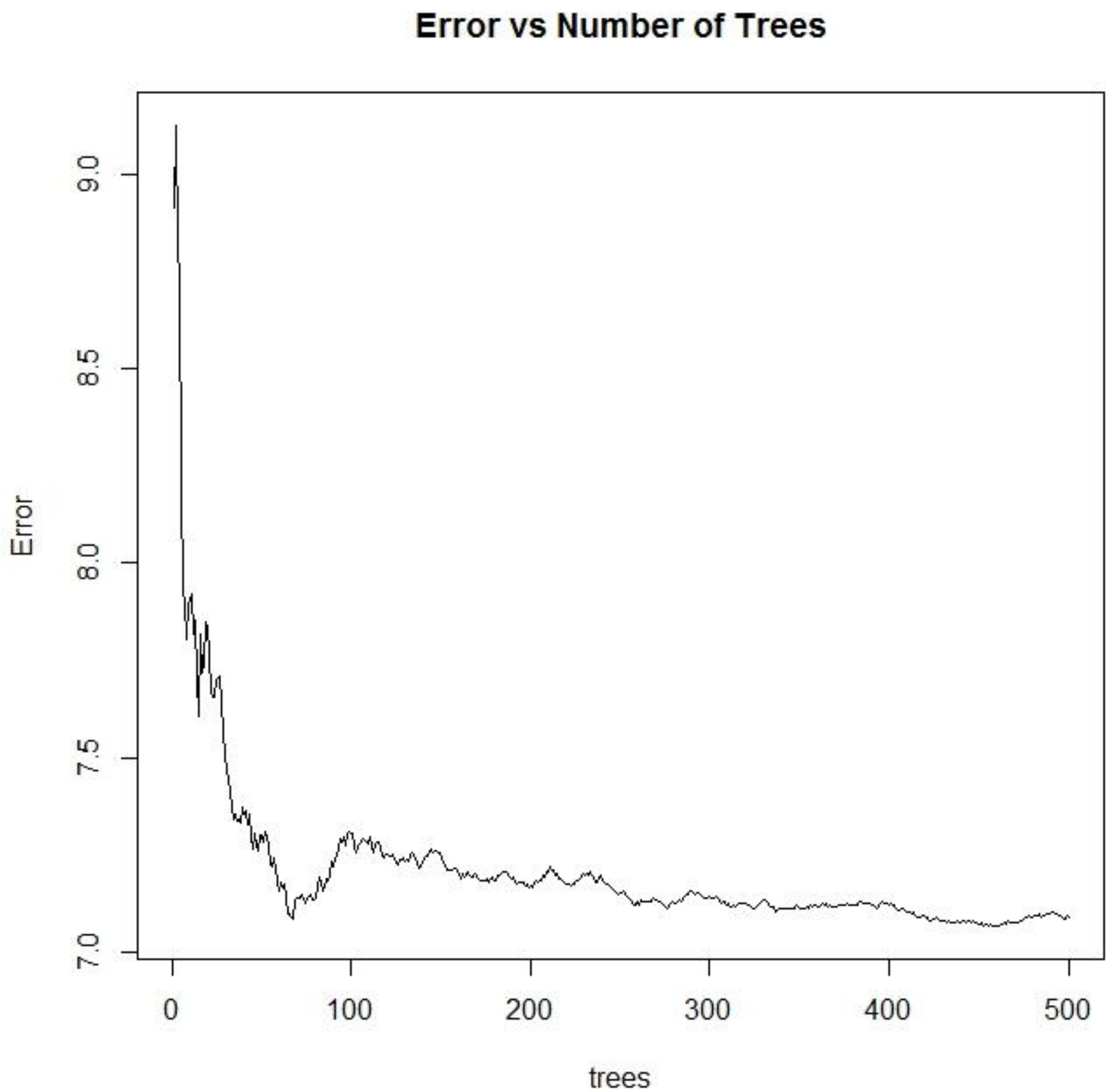

Figure B-17. Random Forest Tree Plot for Lateral Position Variable in Zone 3.

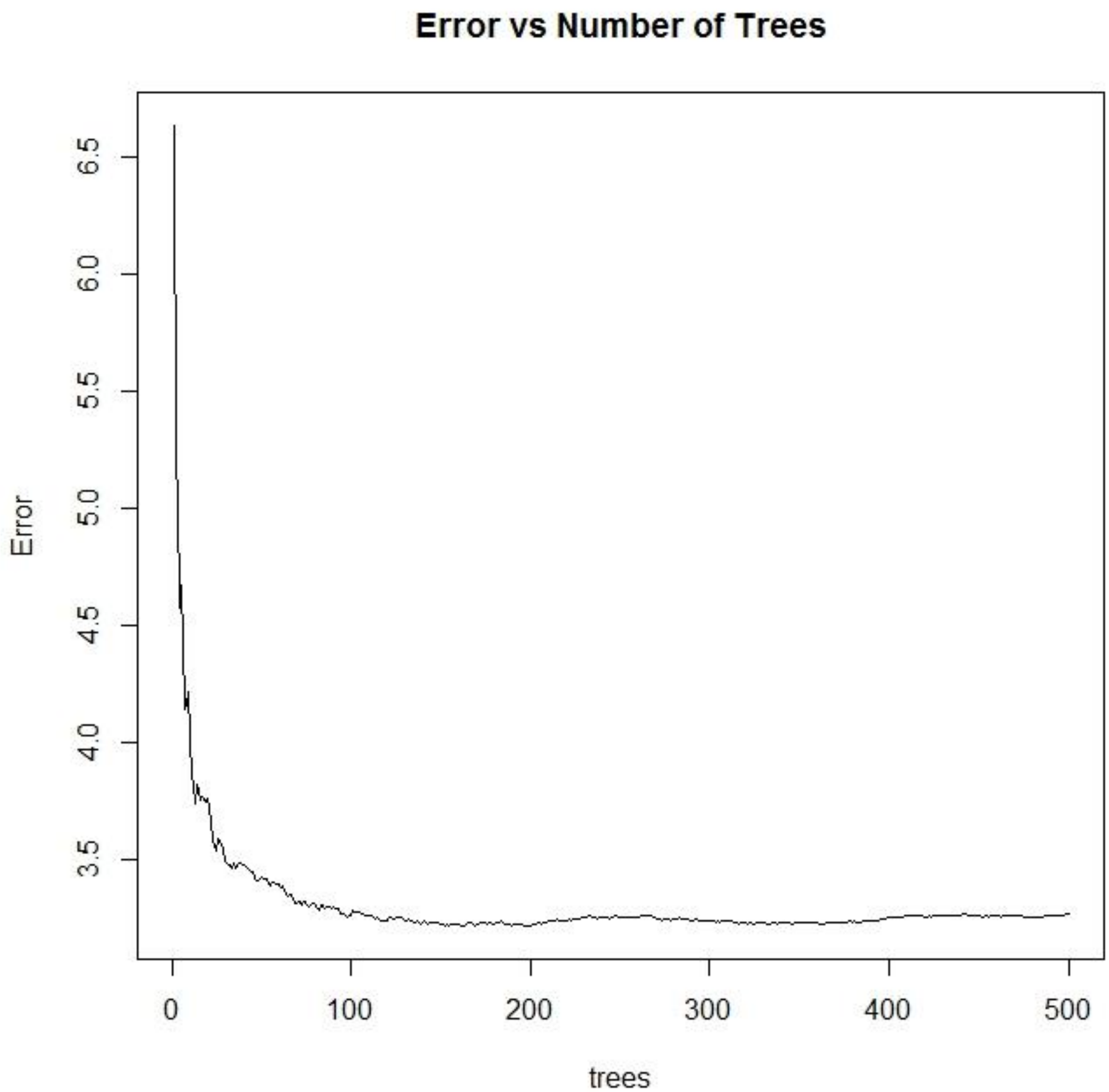

Figure B-18. Random Forest Tree Plot for Lateral Position Variable in Zone 4.

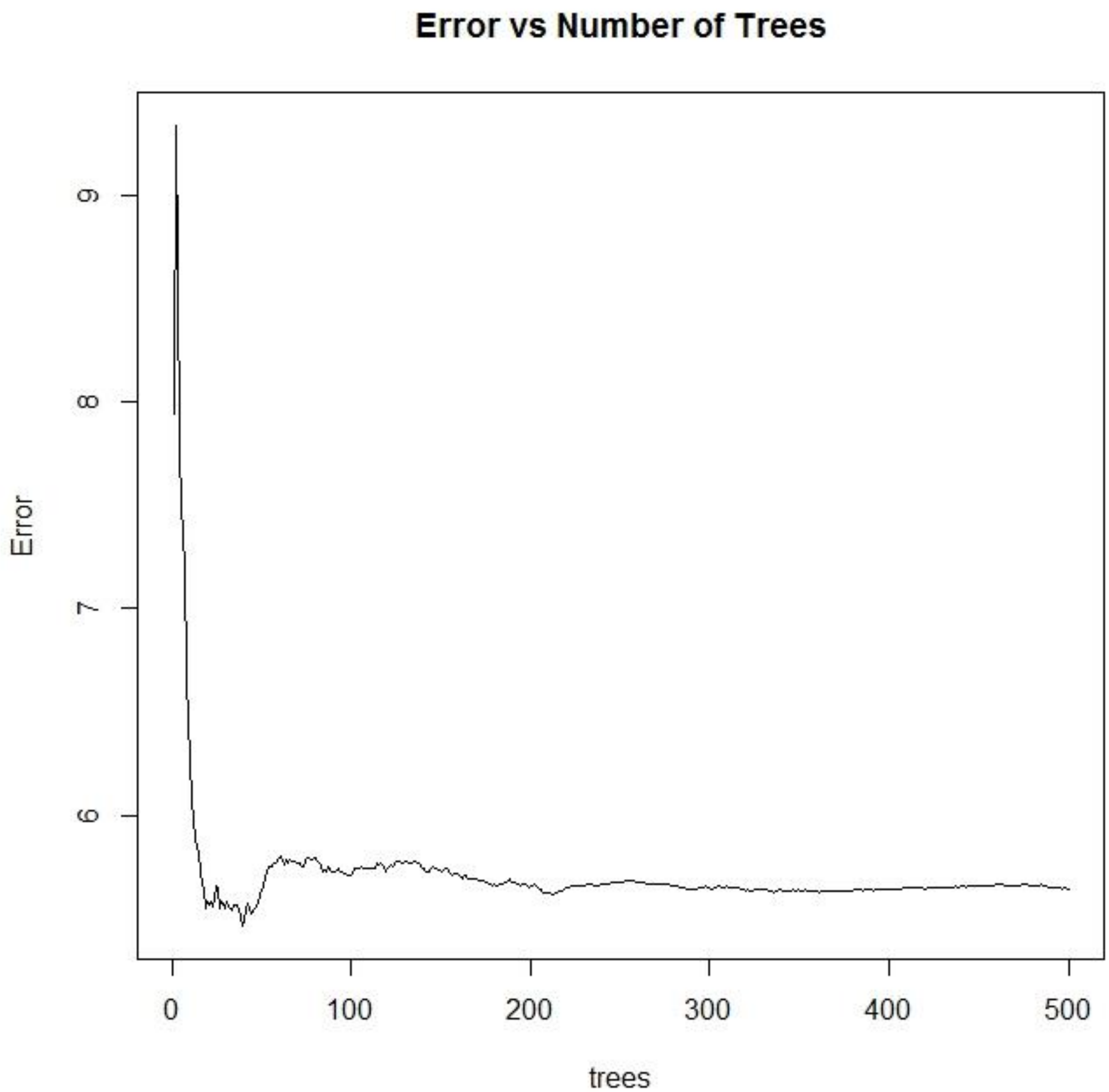

Figure B-19. Random Forest Tree Plot for Lateral Position Variable in Zone 5.

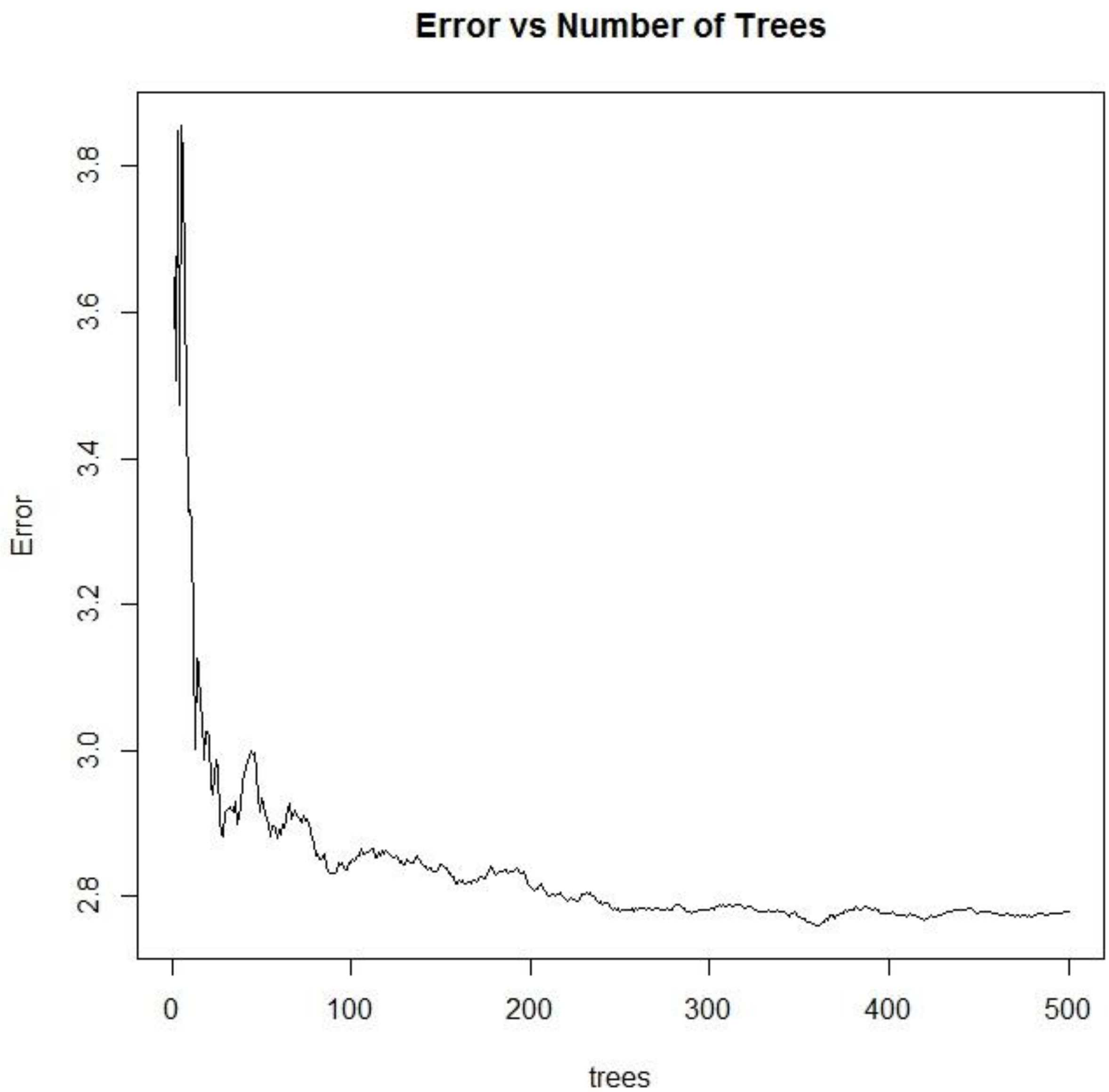

Figure B-20. Random Forest Tree Plot for Lateral Position Variable in Zone 6.

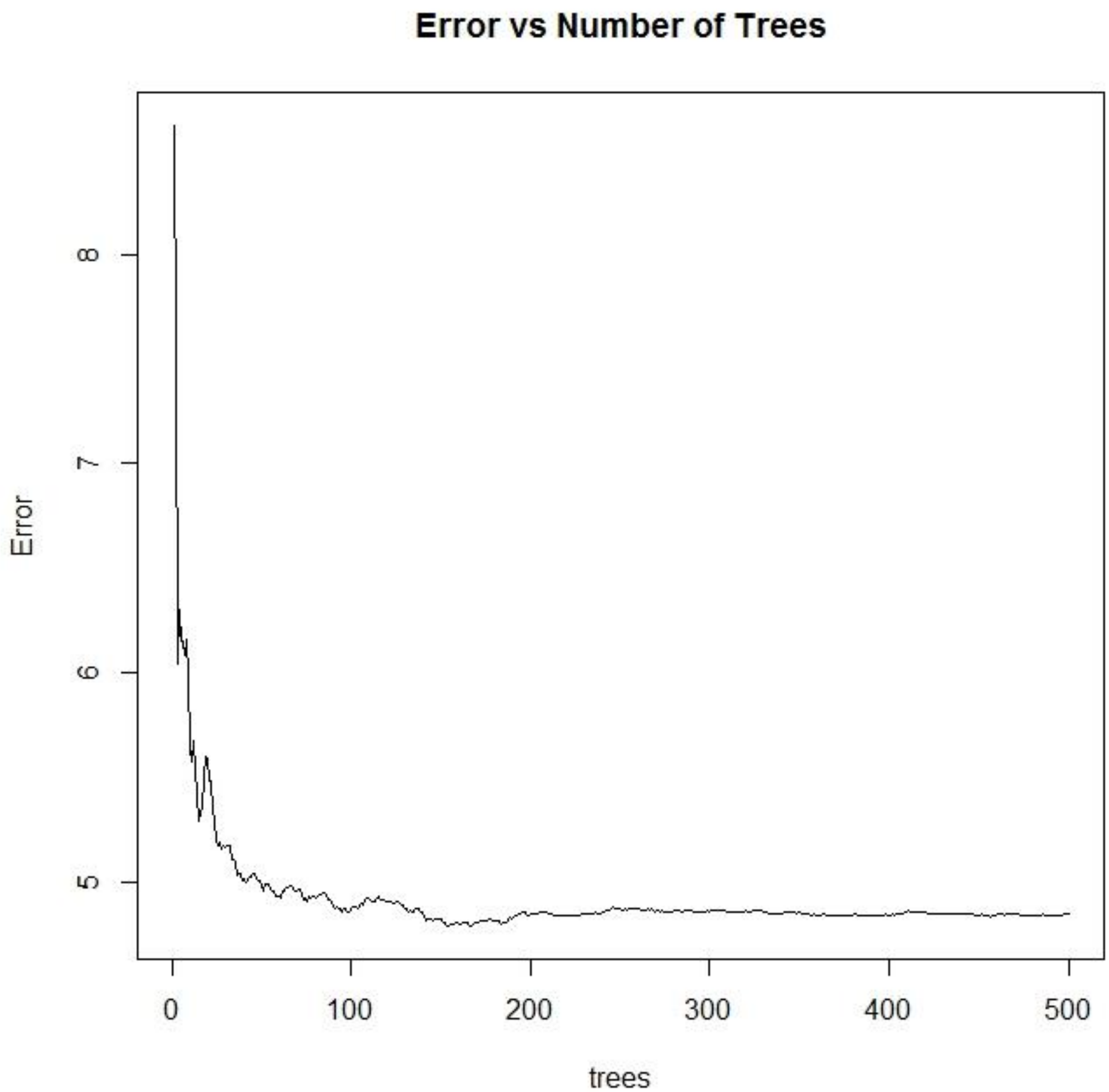

Figure B-21. Random Forest Tree Plot for Lateral Position Variable in Zone 7.

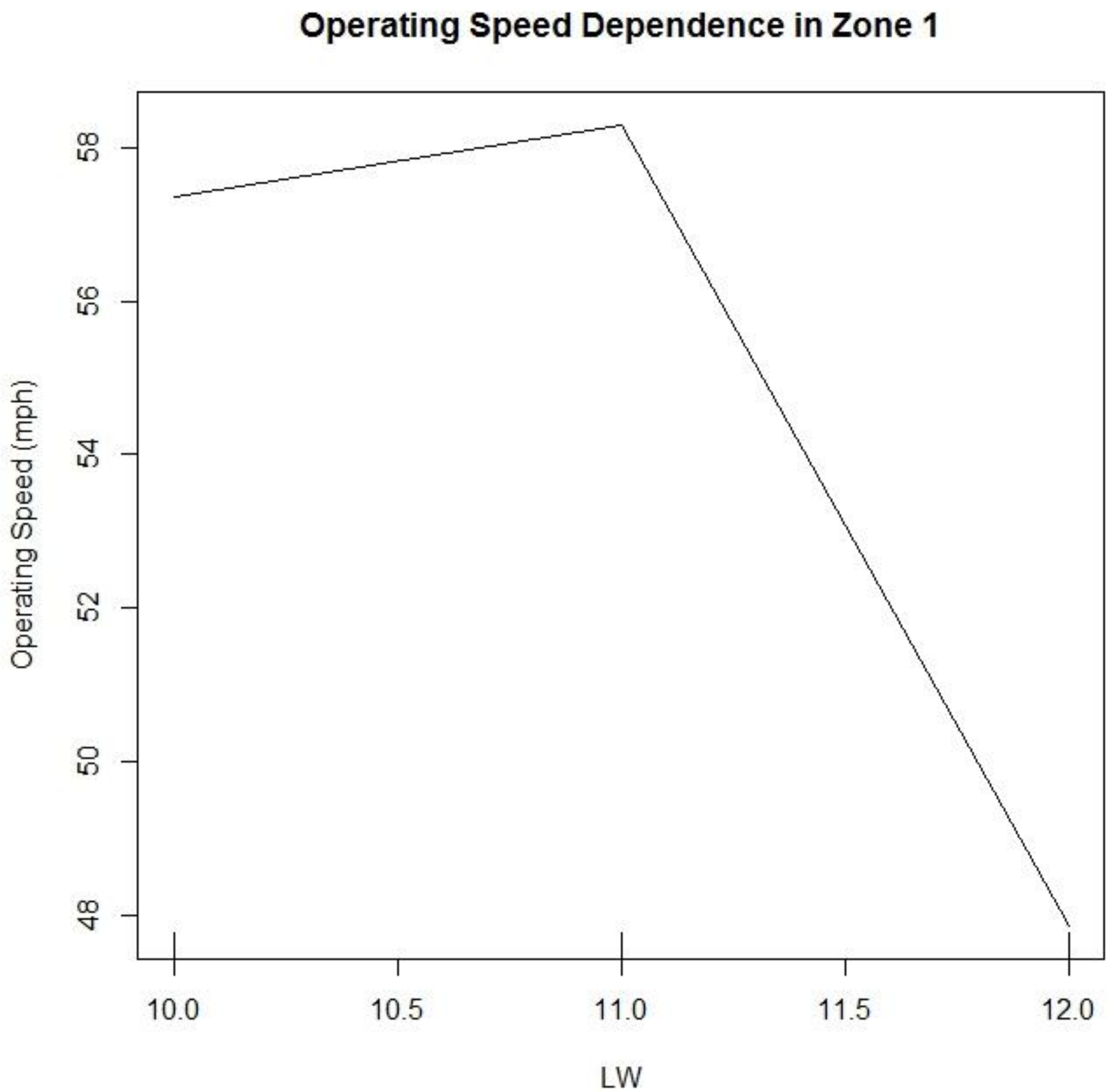

Figure C-1. Random Forest Lane Width Operating Speed Dependence in Zone 1.

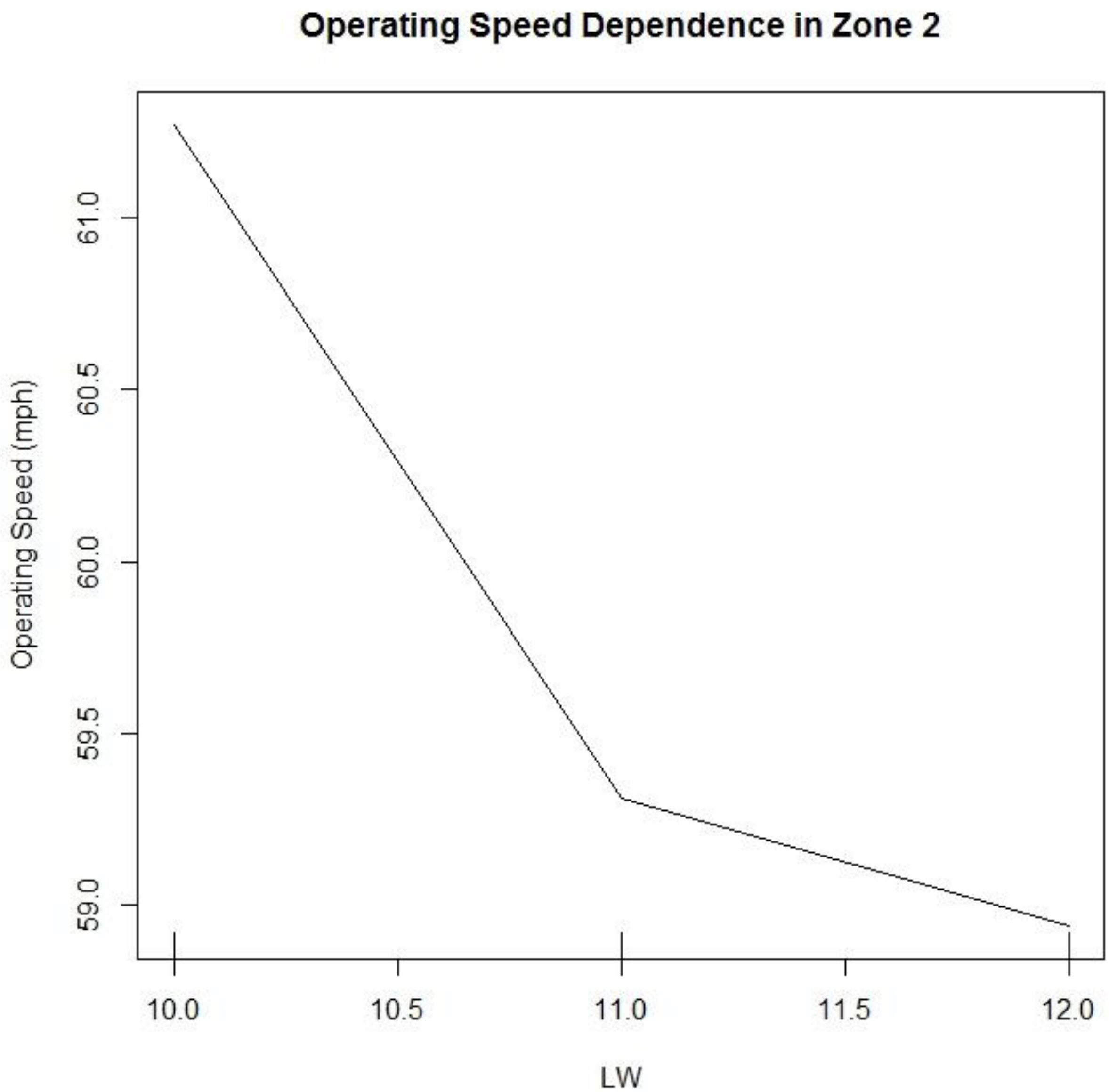

Figure C-2. Random Forest Lane Width Operating Speed Dependence in Zone 2.

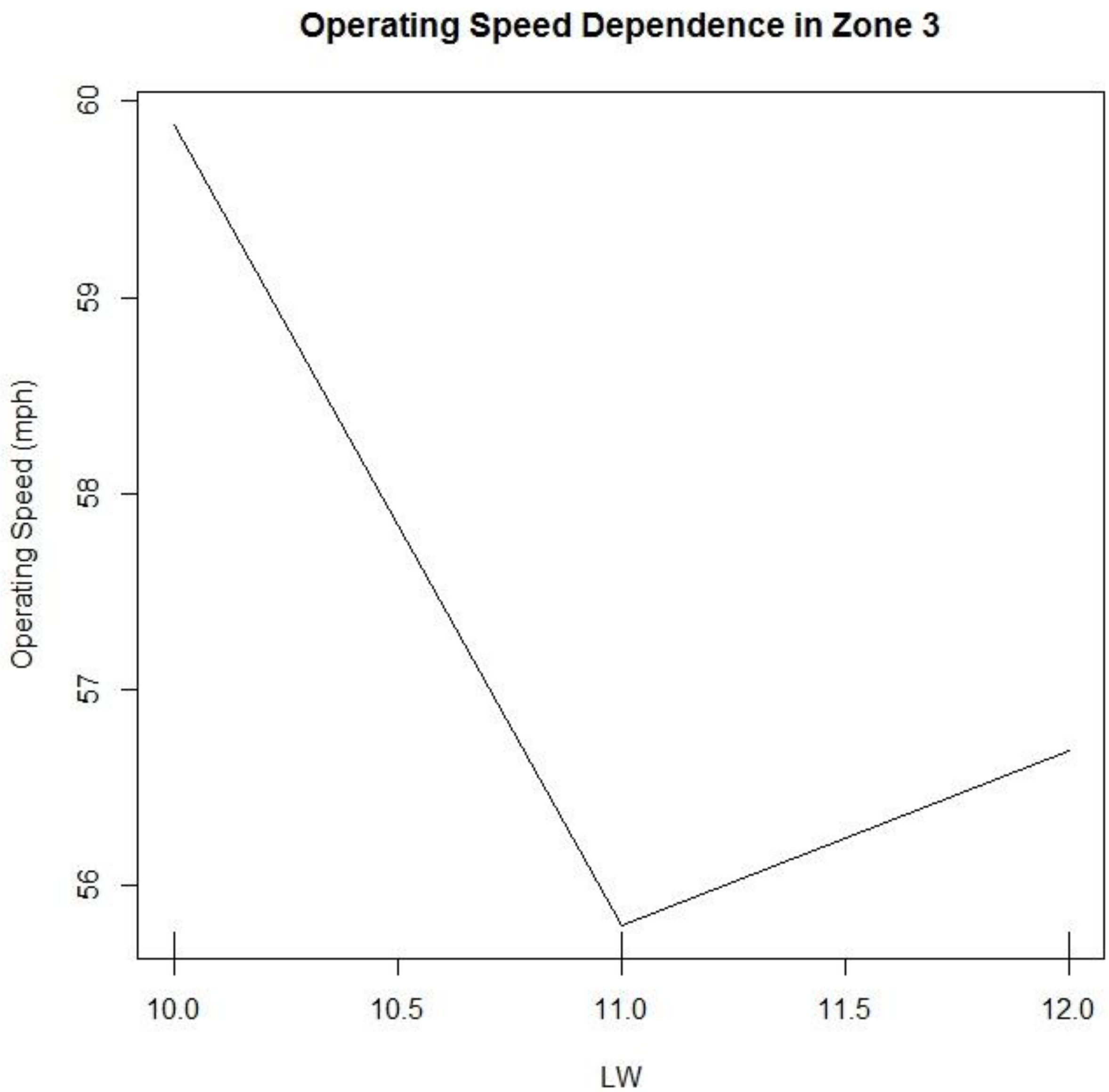

Figure C-3. Random Forest Lane Width Operating Speed Dependence in Zone 3.

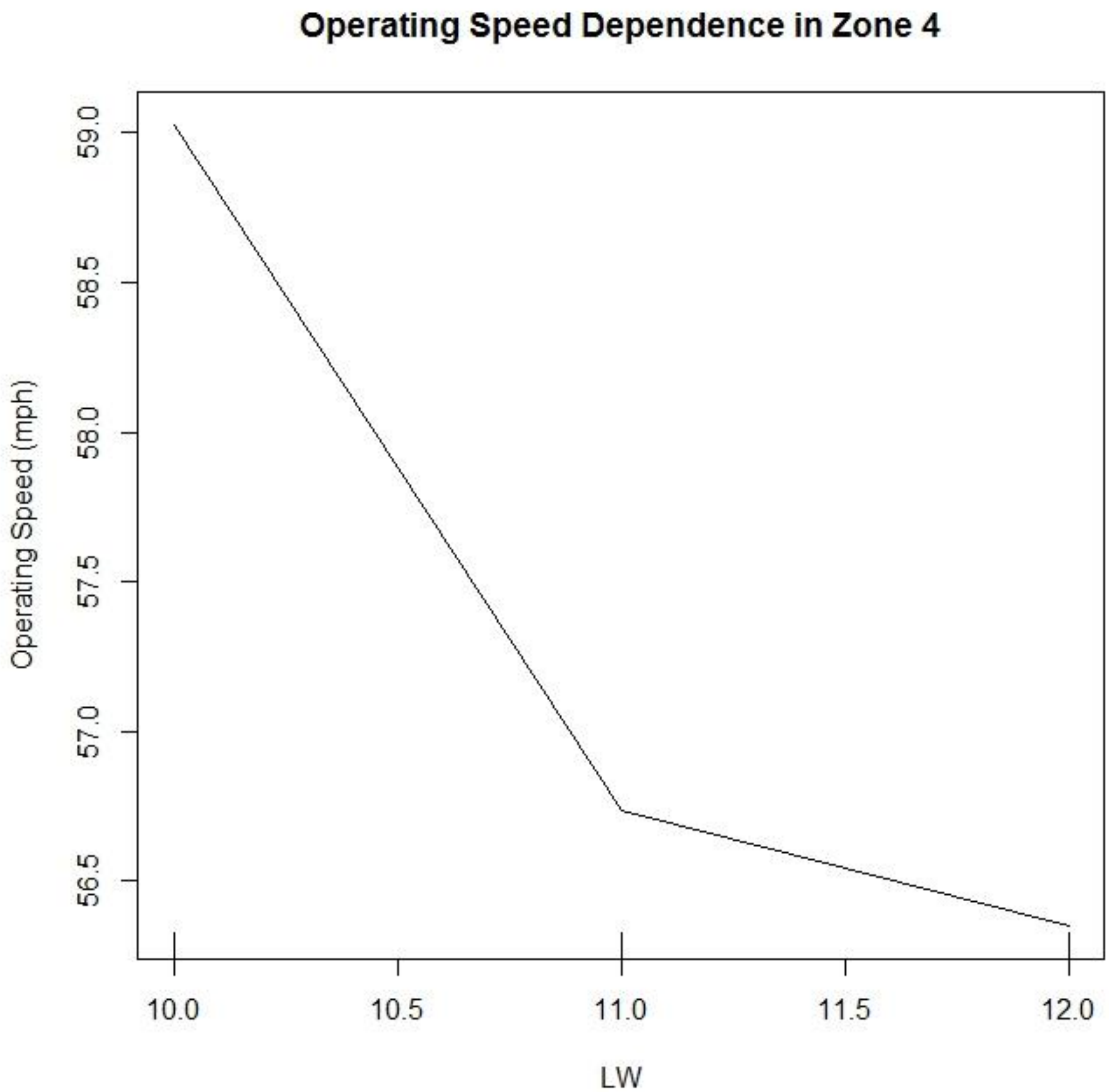

Figure C-4. Random Forest Lane Width Operating Speed Dependence in Zone 4.

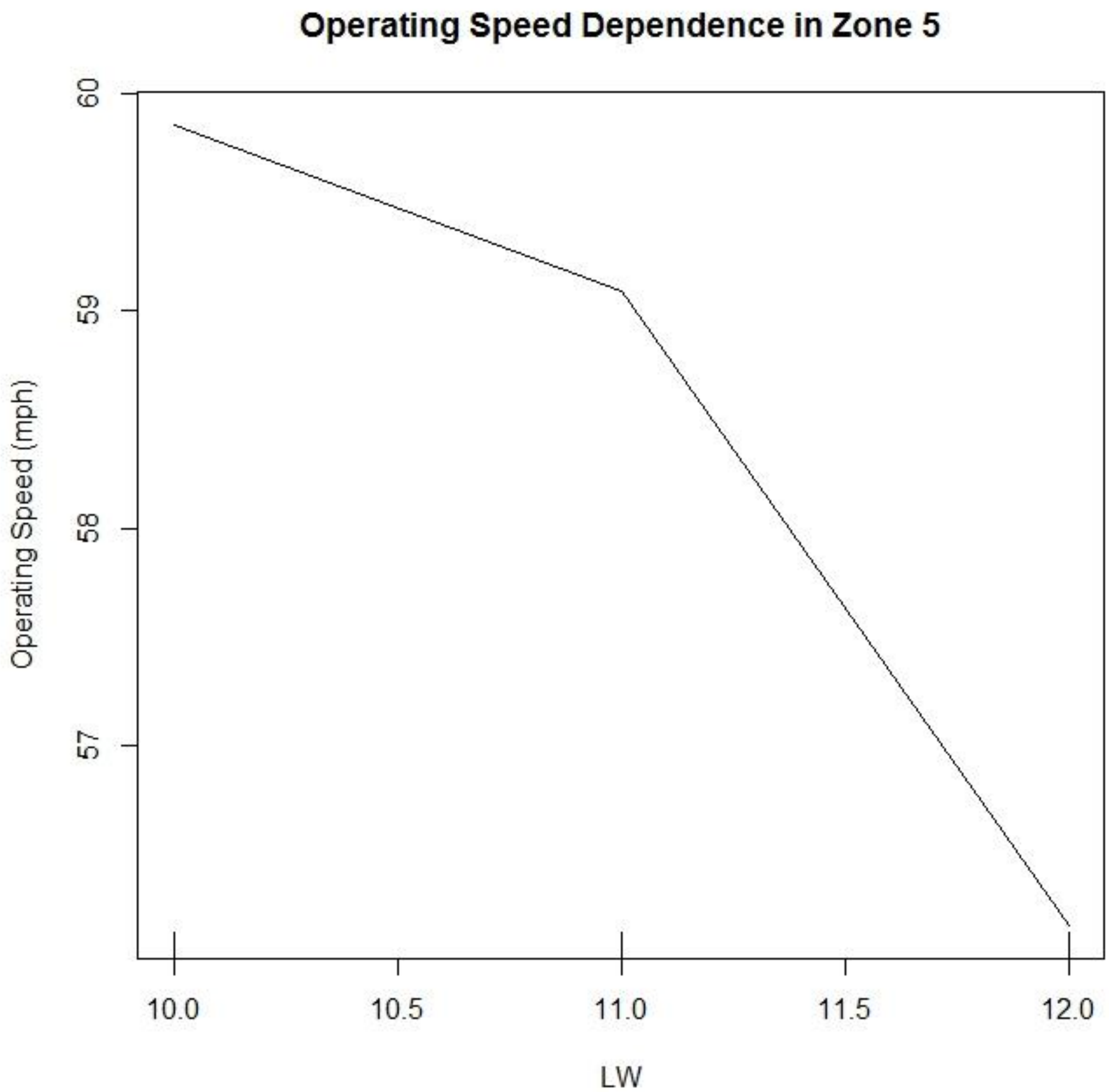

Figure C-5. Random Forest Lane Width Operating Speed Dependence in Zone 5..

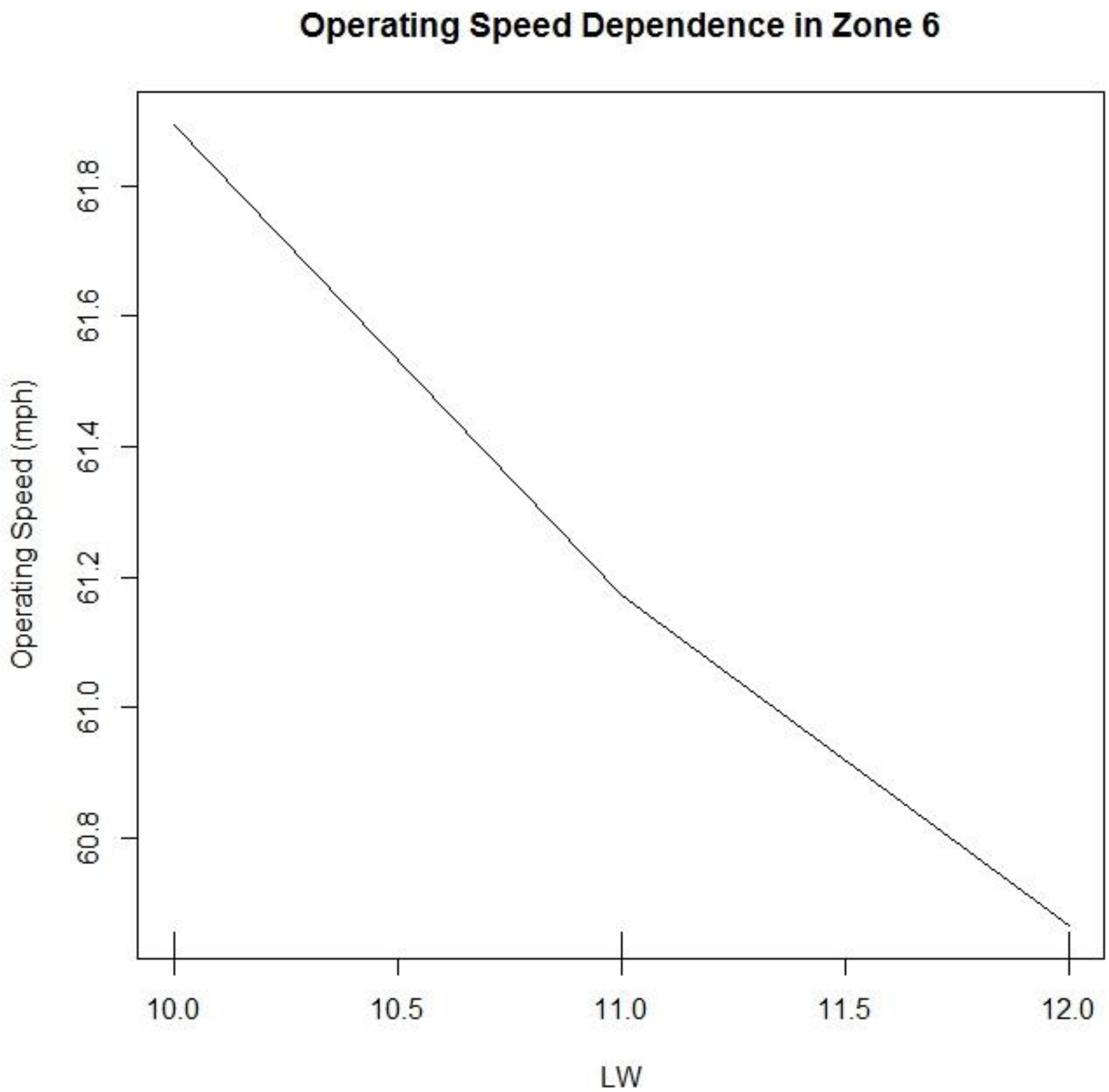

Figure C-6. Random Forest Lane Width Operating Speed Dependence in Zone 6.

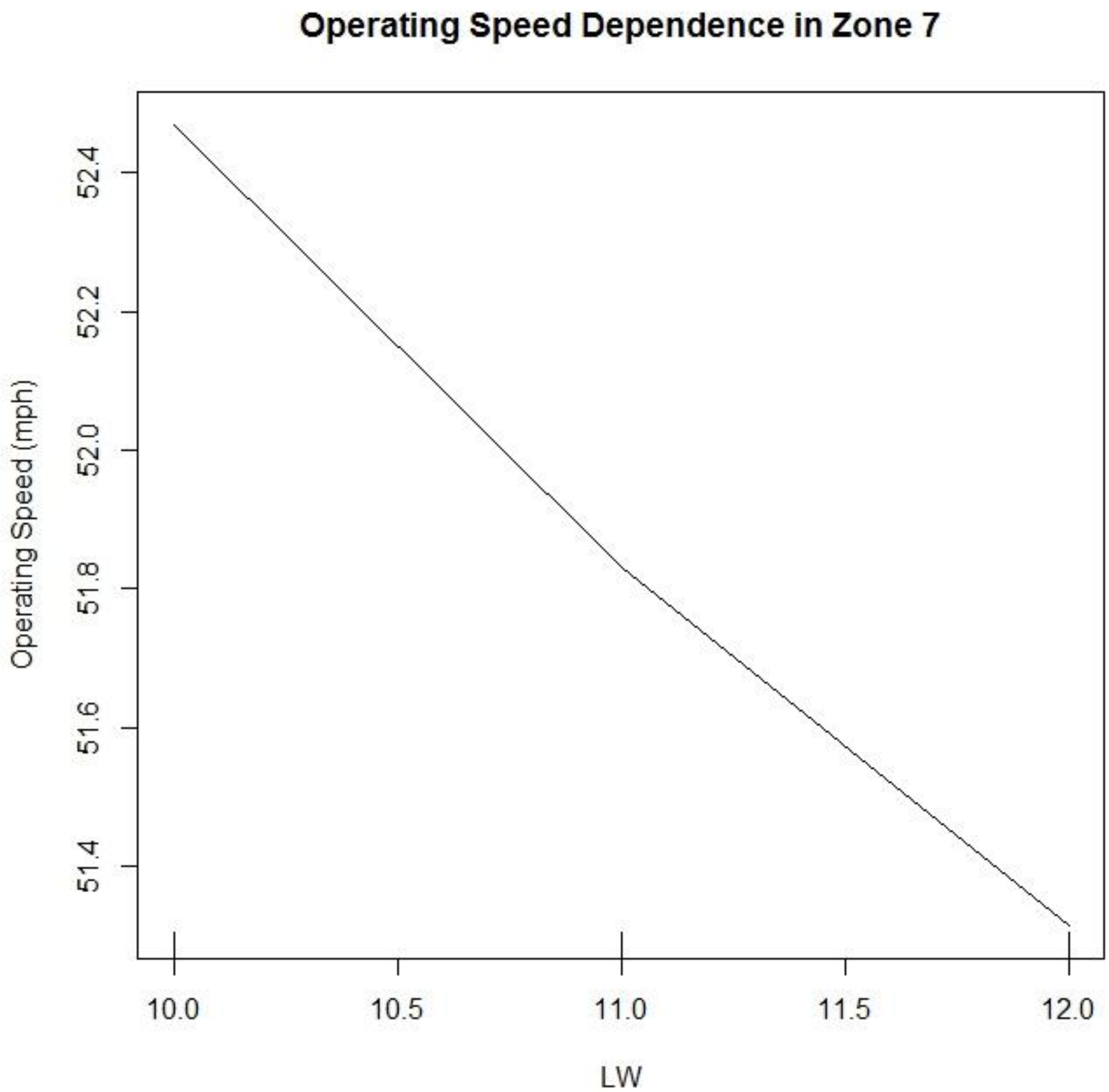

Figure C-7. Random Forest Lane Width Operating Speed Dependence in Zone 7.

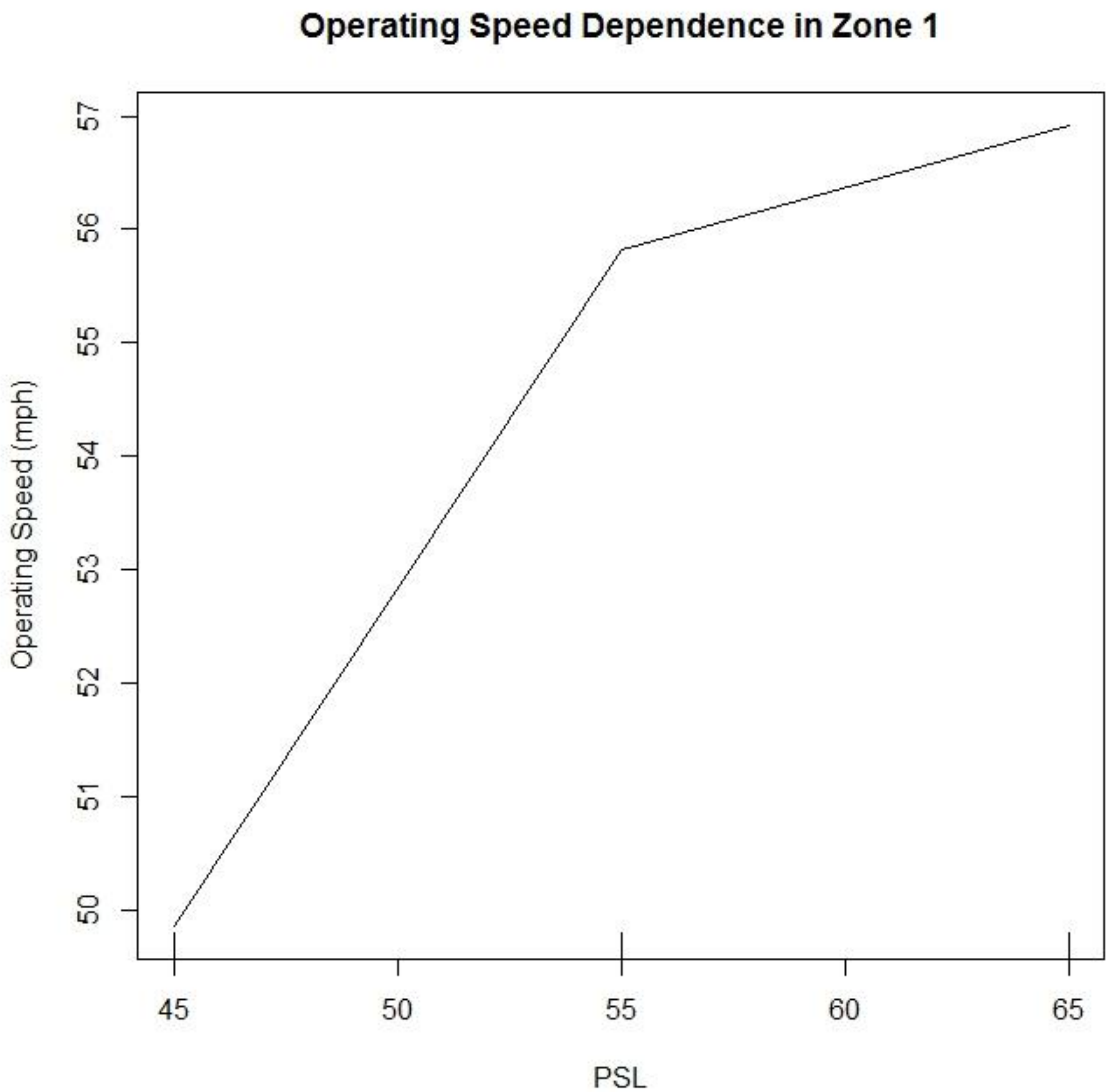

Figure C-8. Random Forest Posted Speed Limit Operating Speed Dependence in Zone 1.

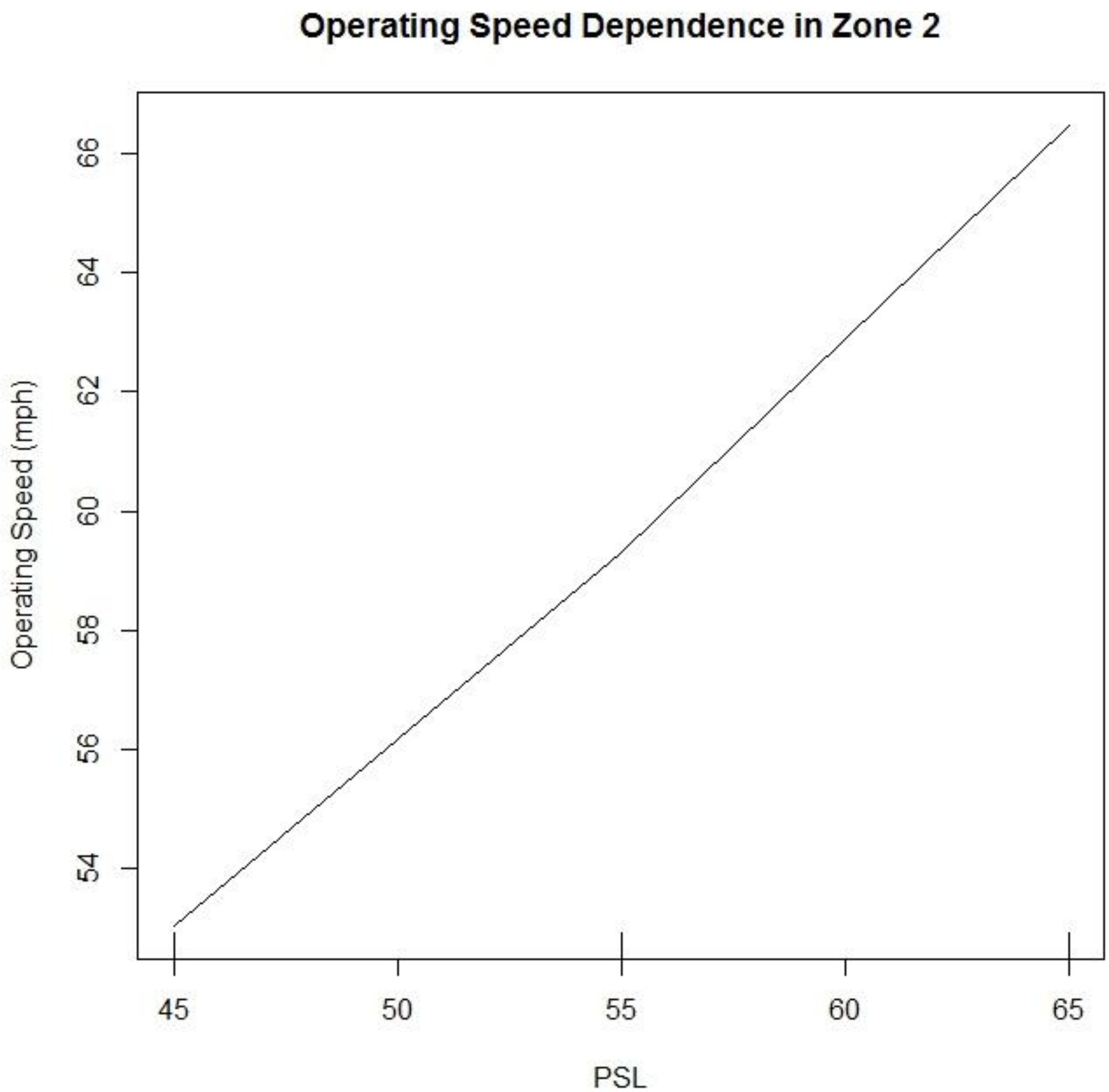

Figure C-9. Random Forest Posted Speed Limit Operating Speed Dependence in Zone 2.

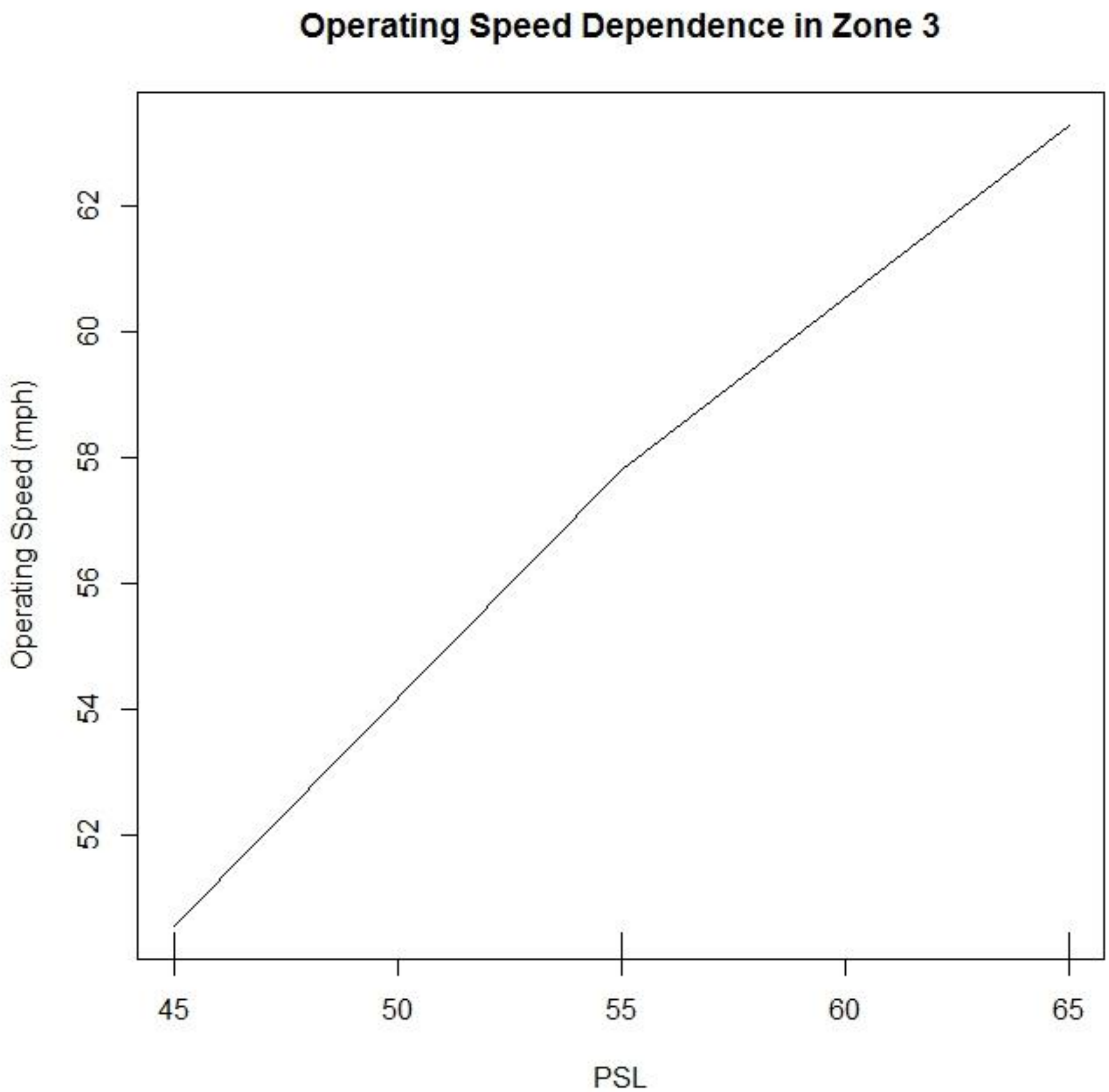

Figure C-10. Random Forest Posted Speed Limit Operating Speed Dependence in Zone 3.

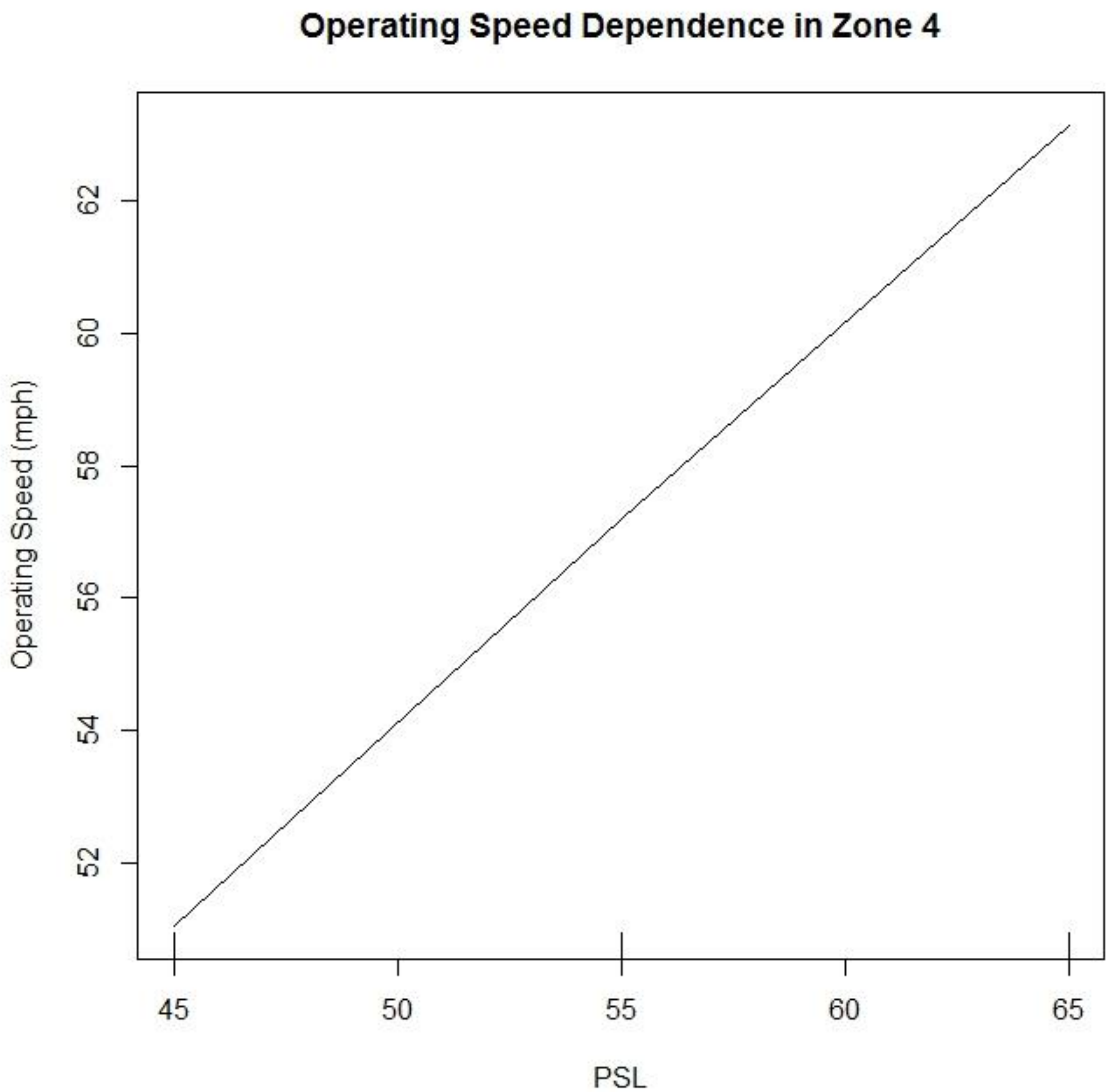

Figure C-11. Random Forest Posted Speed Limit Operating Speed Dependence in Zone 4.

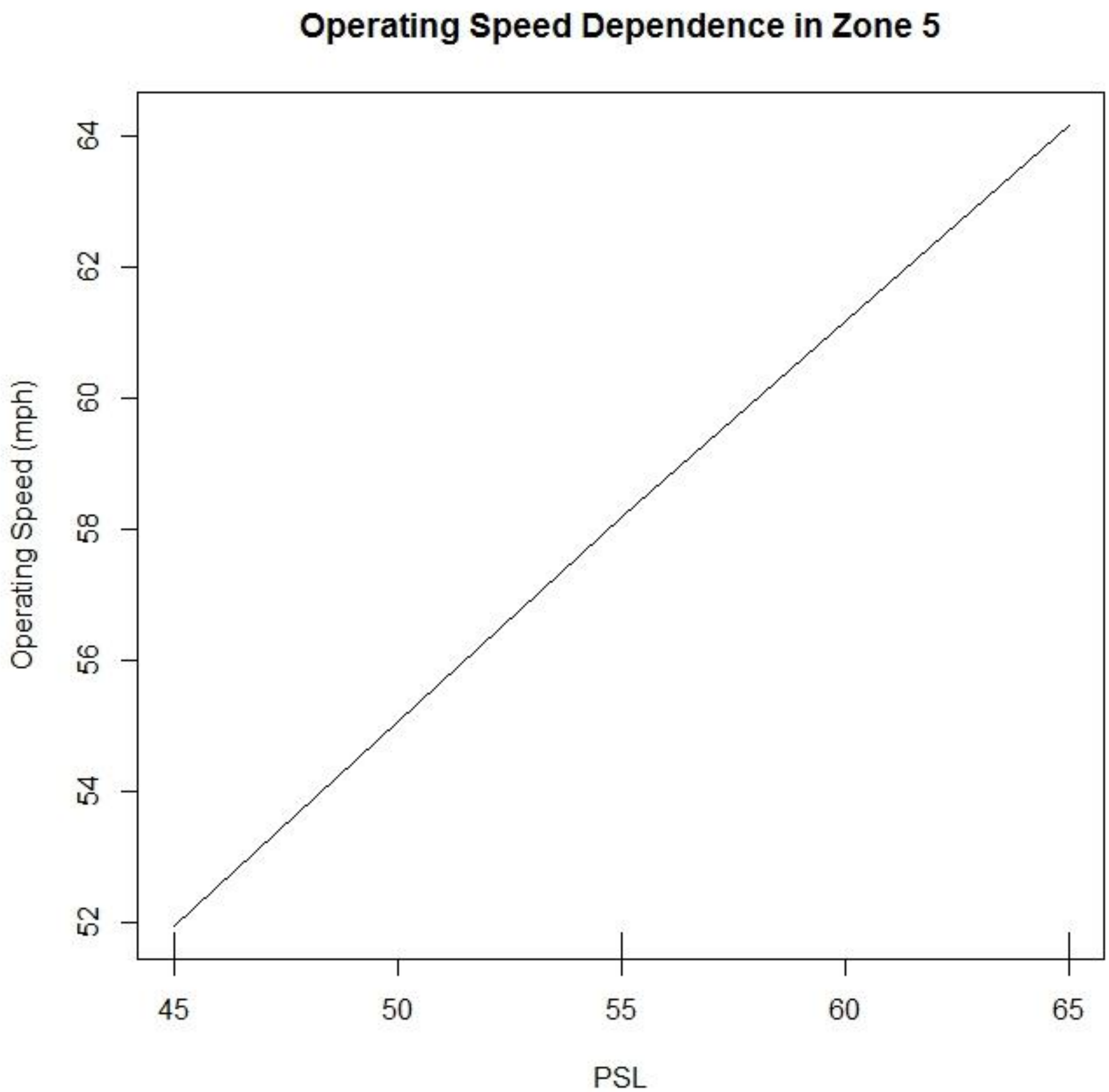

Figure C-12. Random Forest Posted Speed Limit Operating Speed Dependence in Zone 5.

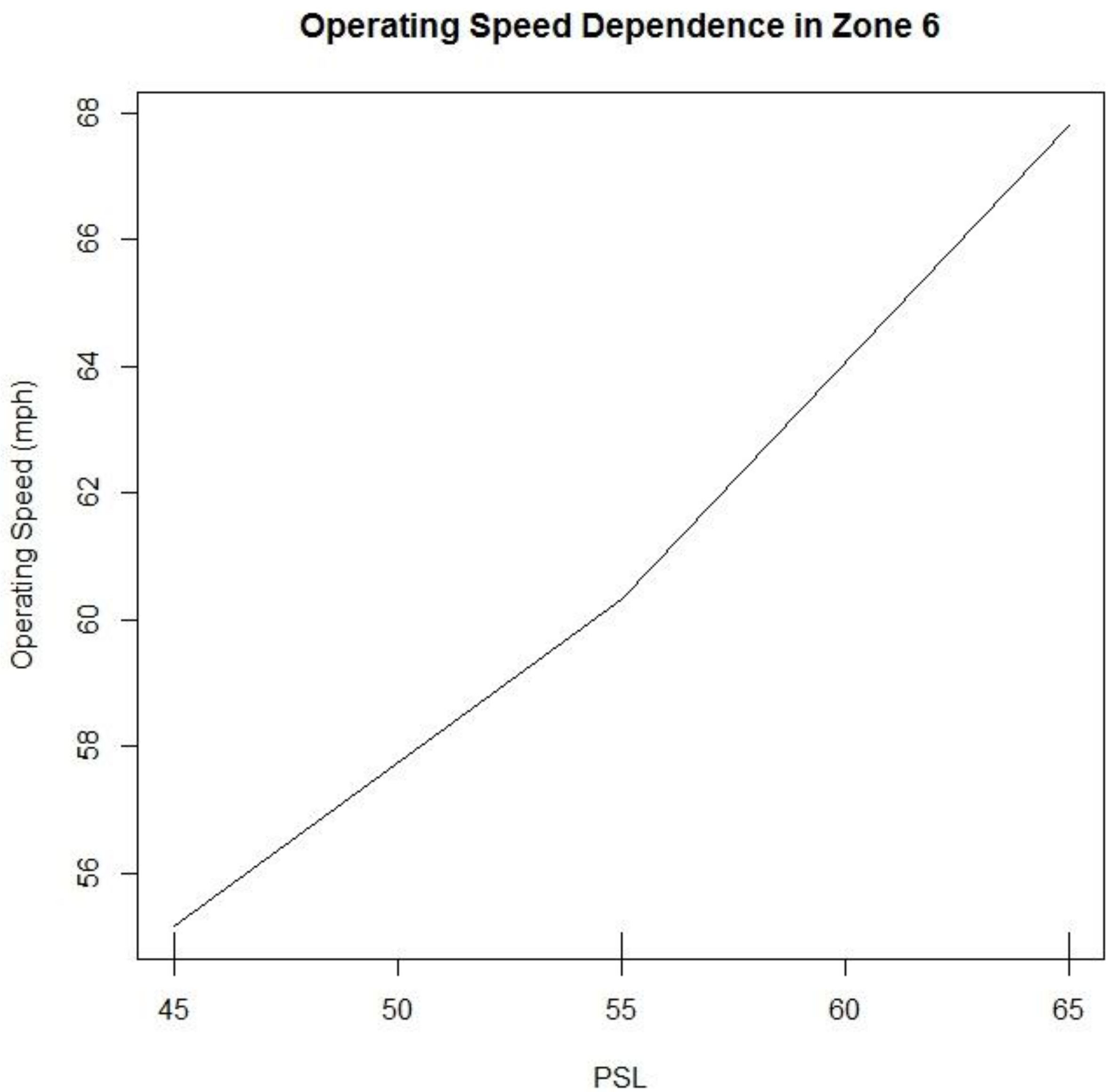

Figure C-13. Random Forest Posted Speed Limit Operating Speed Dependence in Zone 6.

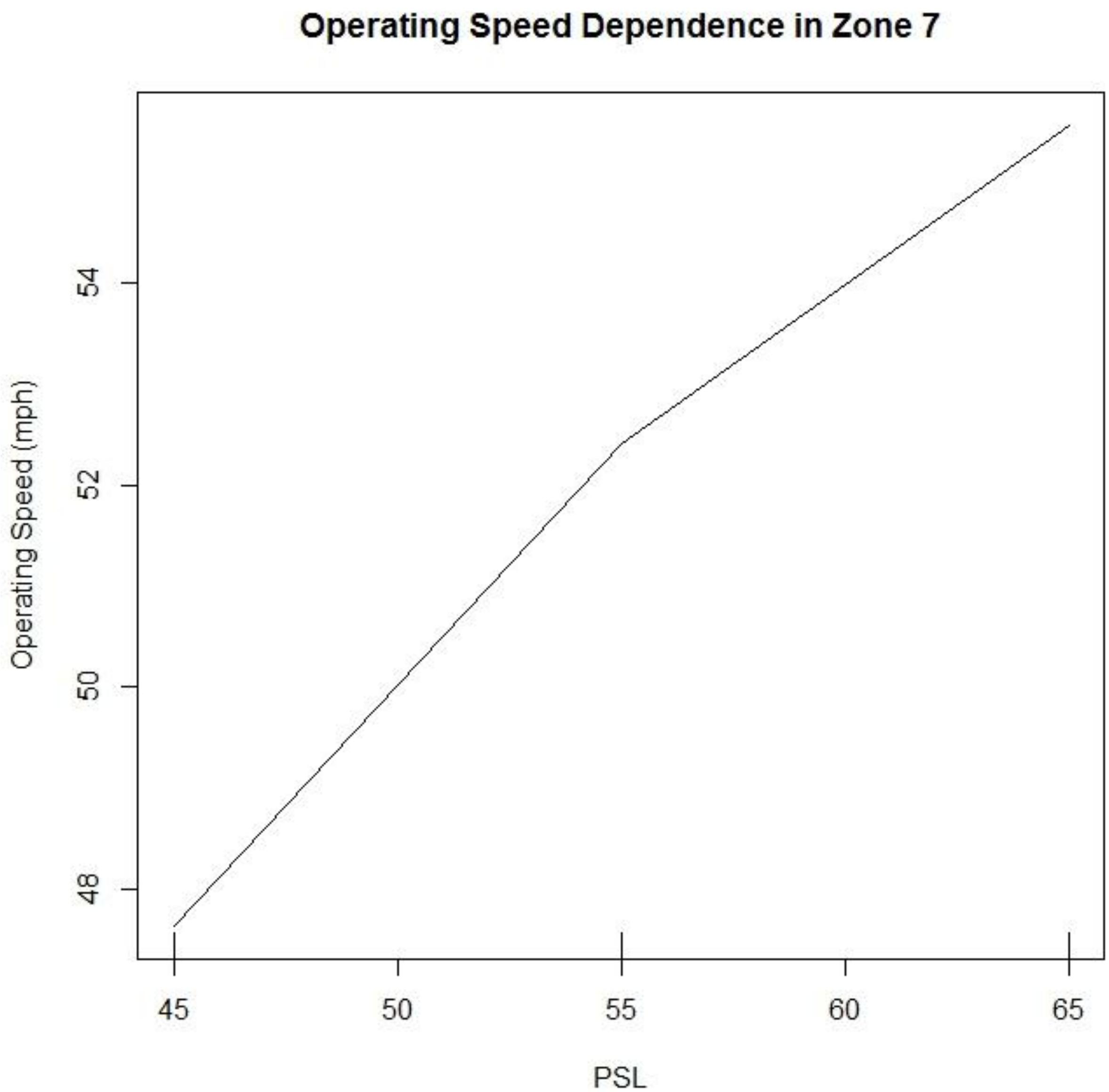

Figure C-14. Random Forest Posted Speed Limit Operating Speed Dependence in Zone 7.

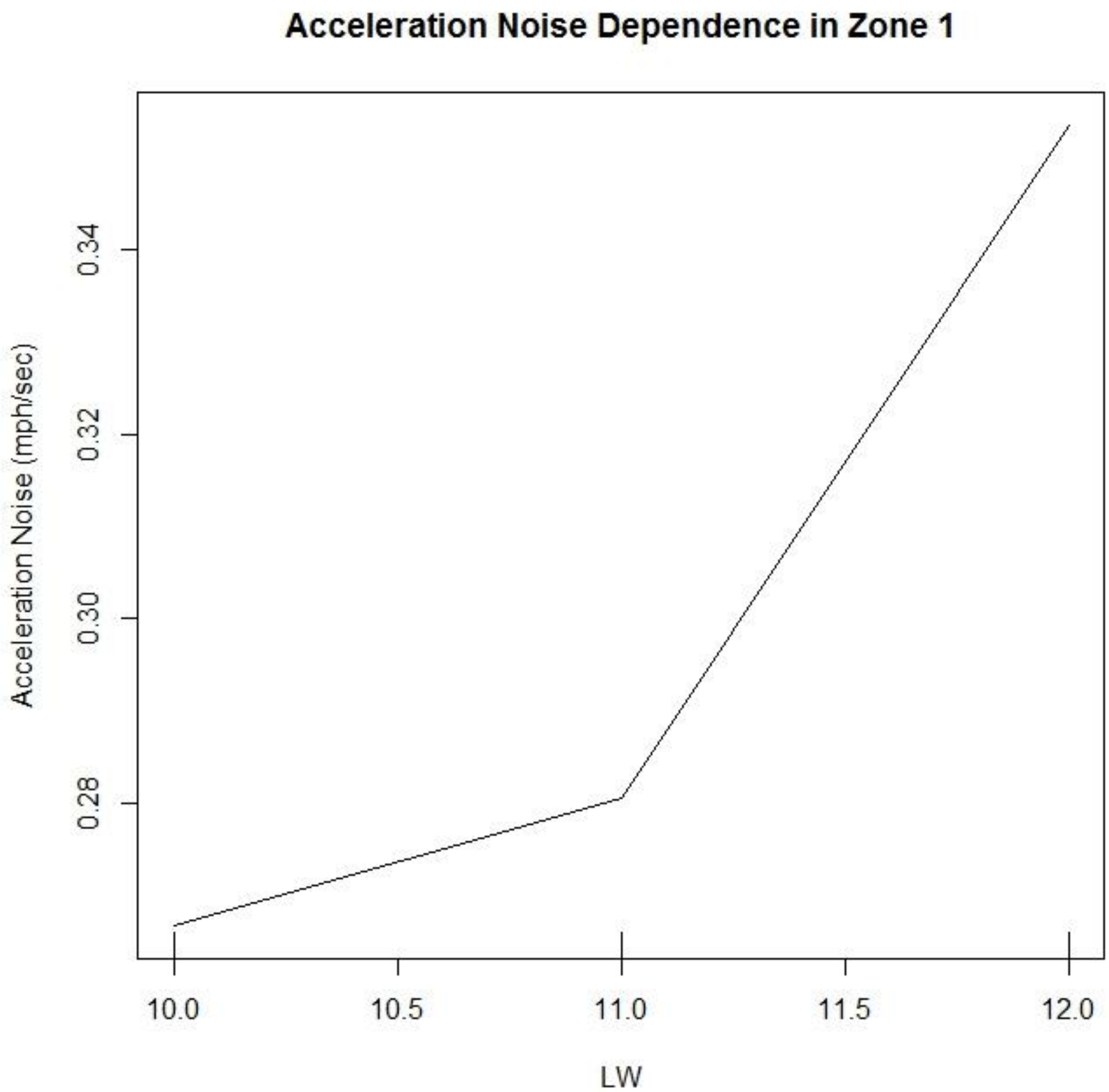

Figure C-15. Random Forest Lane Width Acceleration Noise Dependence in Zone 1.

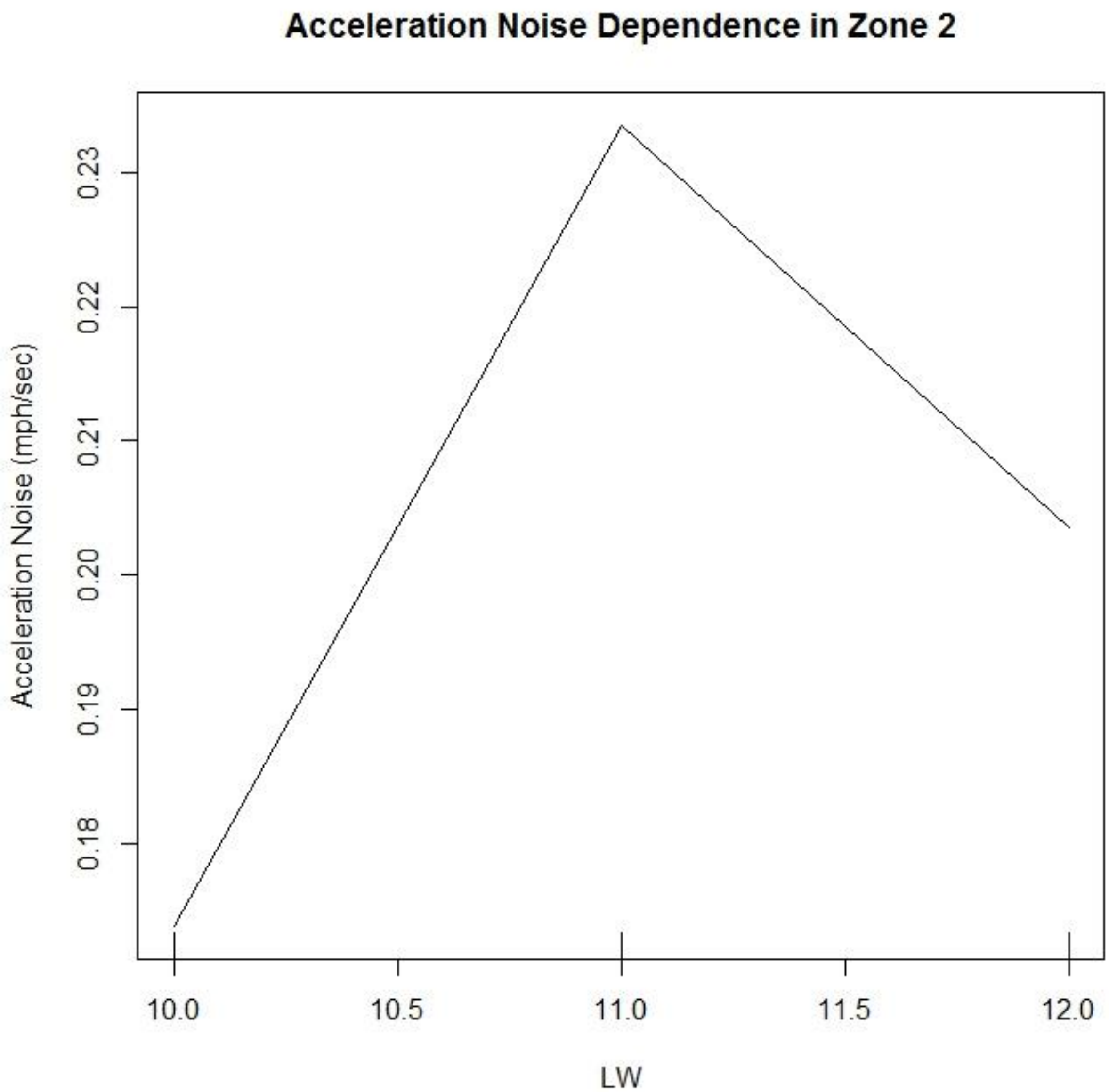

Figure C-16. Random Forest Lane Width Acceleration Noise Dependence in Zone 2.

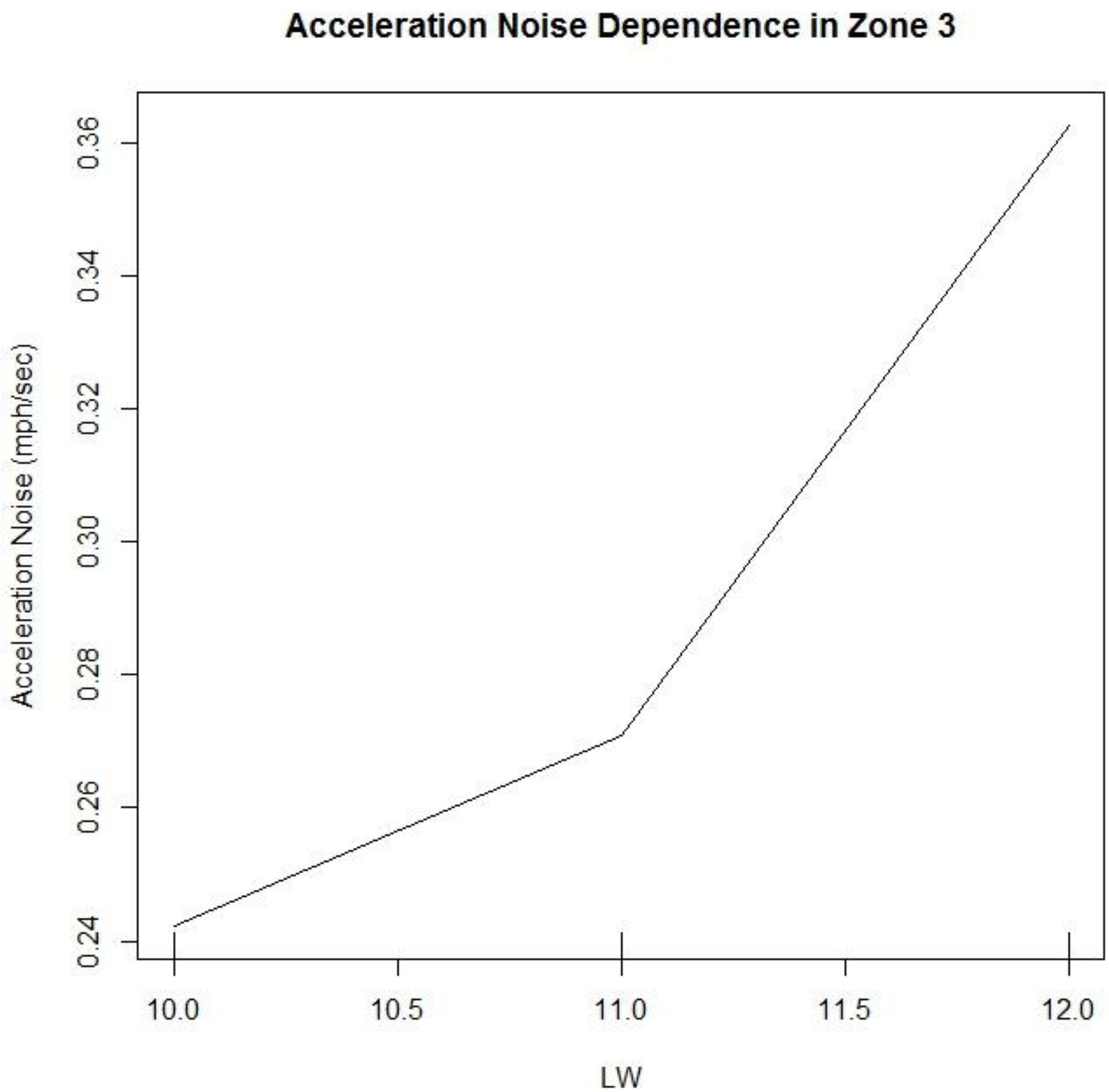

Figure C-17. Random Forest Lane Width Acceleration Noise Dependence in Zone 3.

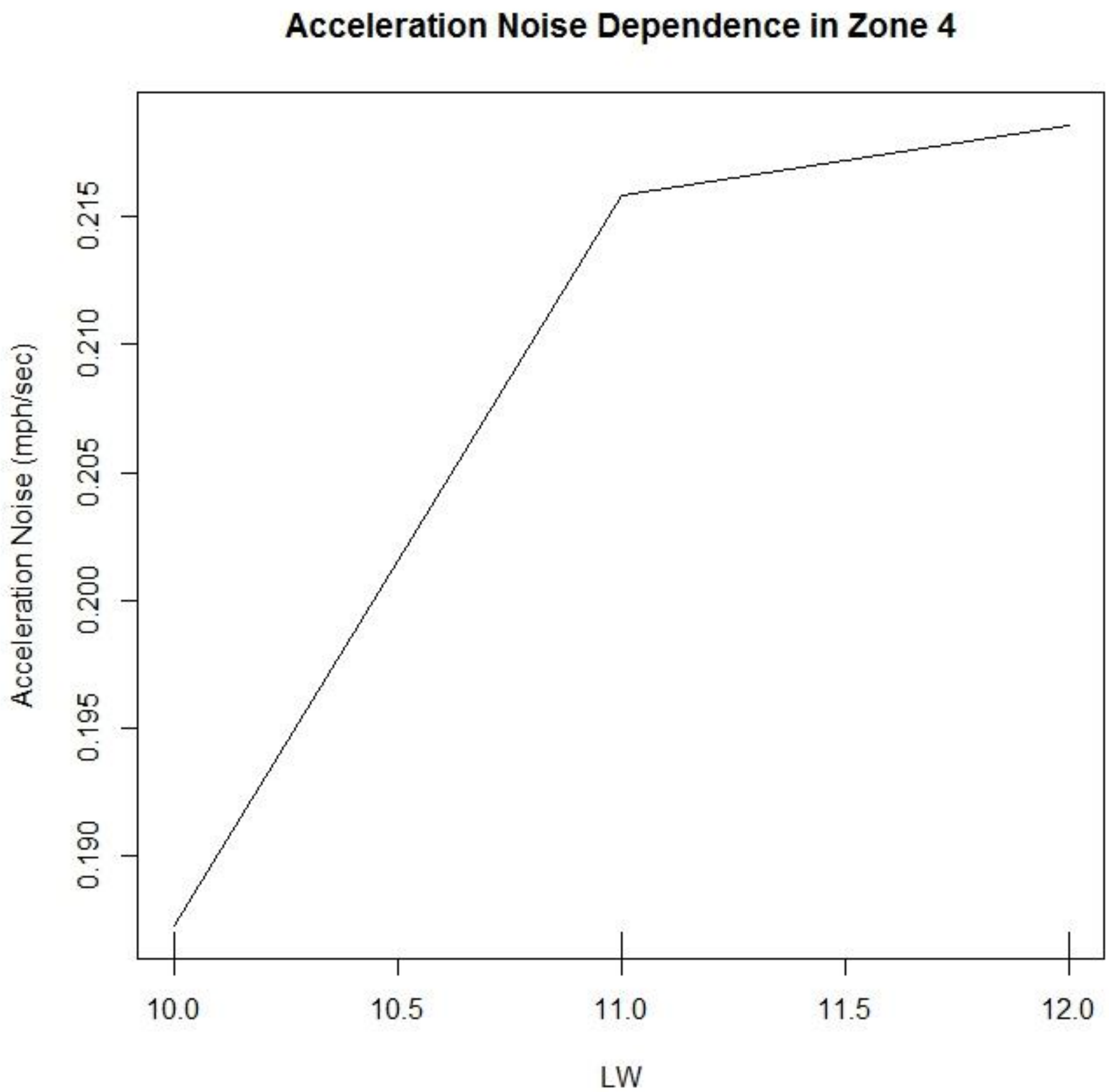

Figure C-18. Random Forest Lane Width Acceleration Noise Dependence in Zone 4.

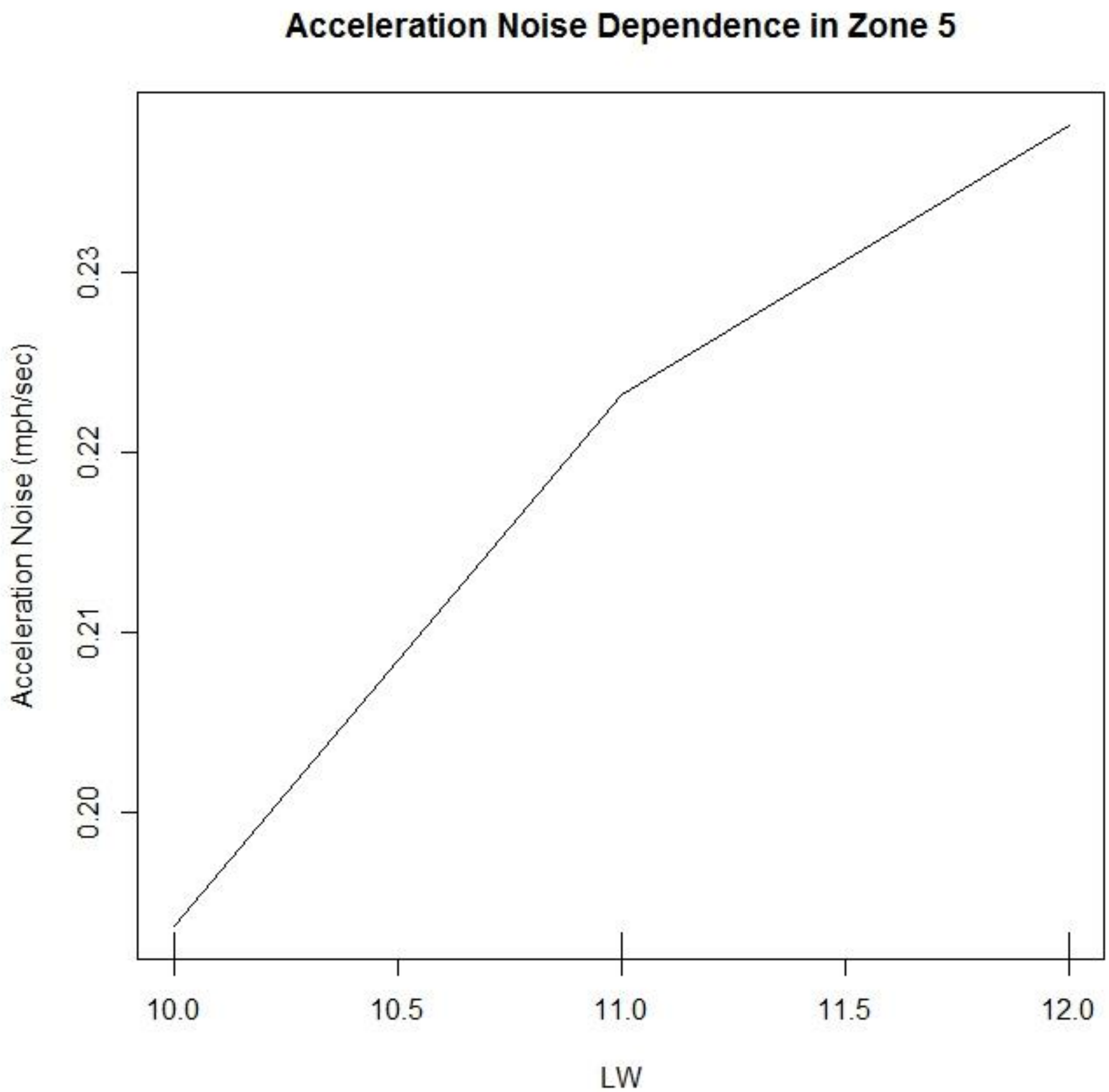

Figure C-19. Random Forest Lane Width Acceleration Noise Dependence in Zone 5.

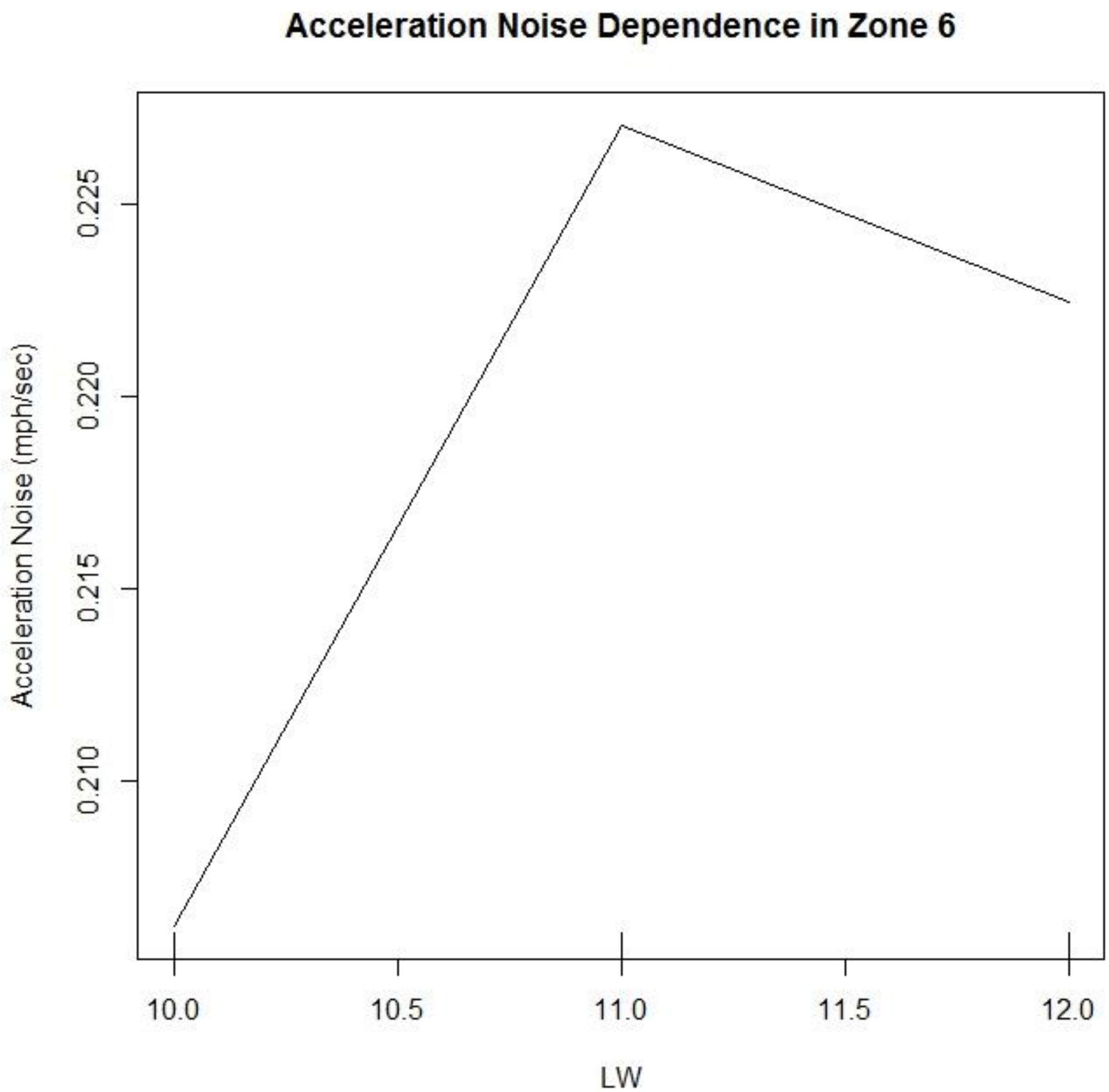

Figure C-20. Random Forest Lane Width Acceleration Noise Dependence in Zone 6.

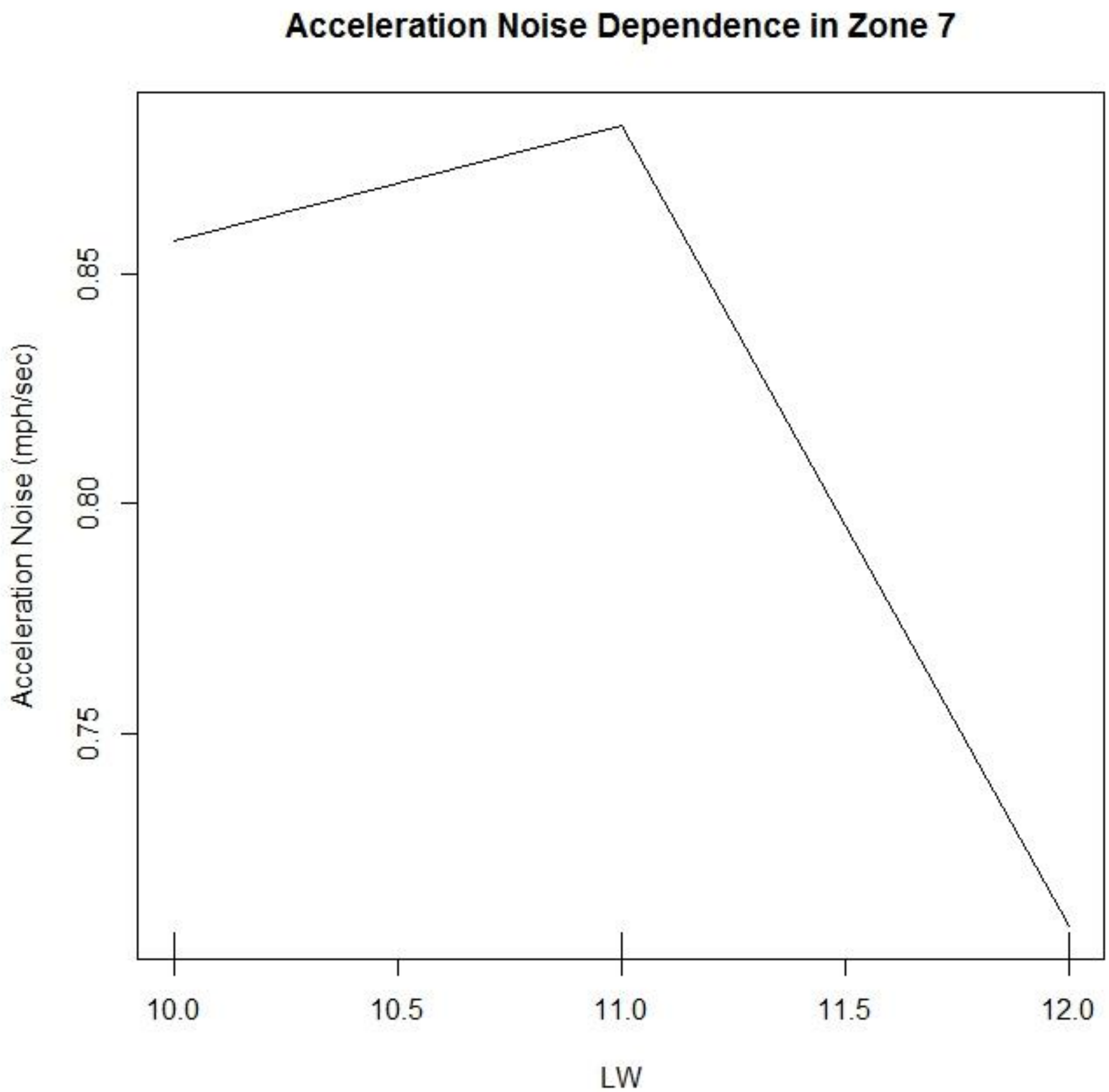

Figure C-21. Random Forest Lane Width Acceleration Noise Dependence in Zone 7.

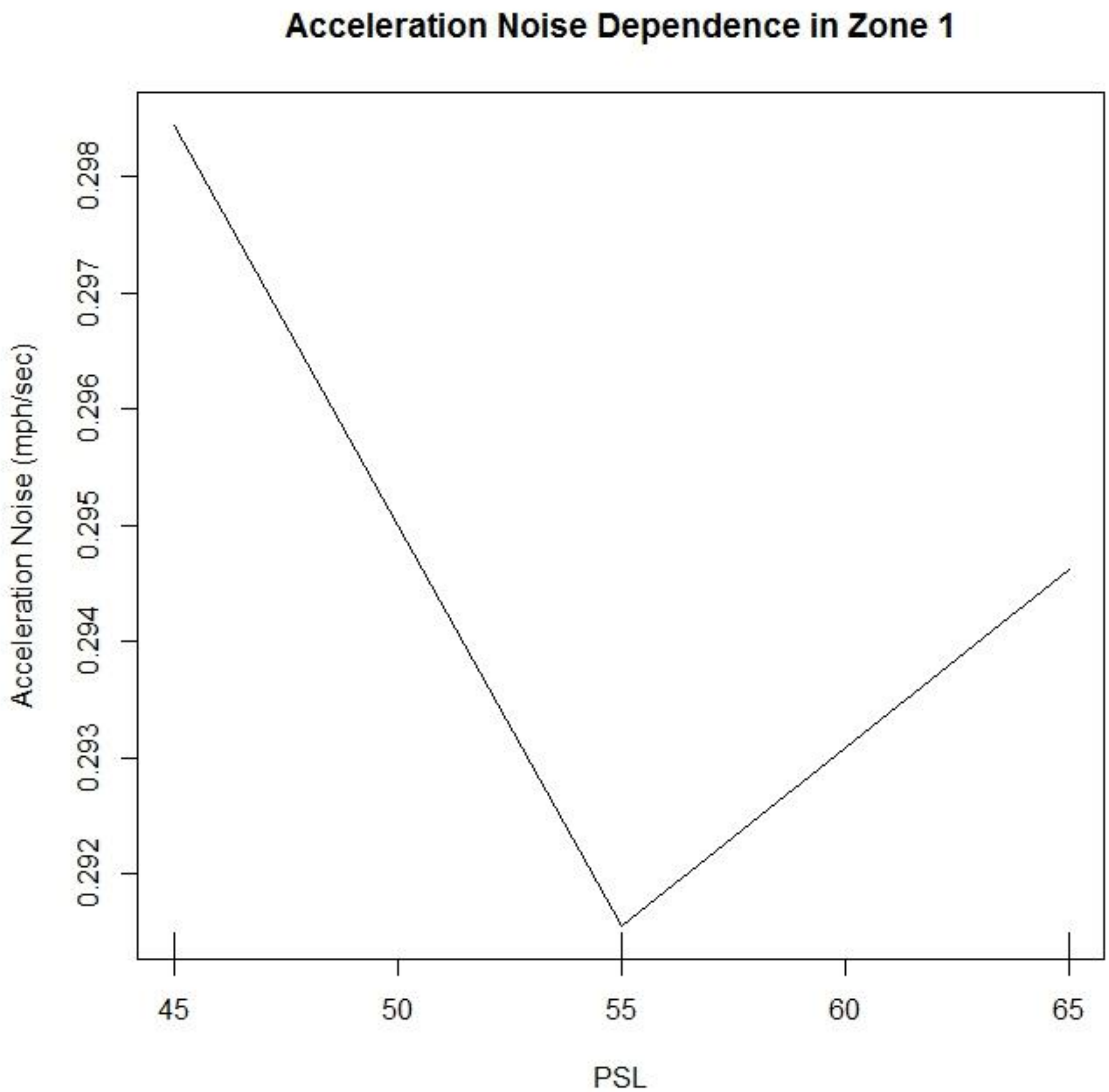

Figure C-22. Random Forest Posted Speed Limit Acceleration Noise Dependence in Zone 1.

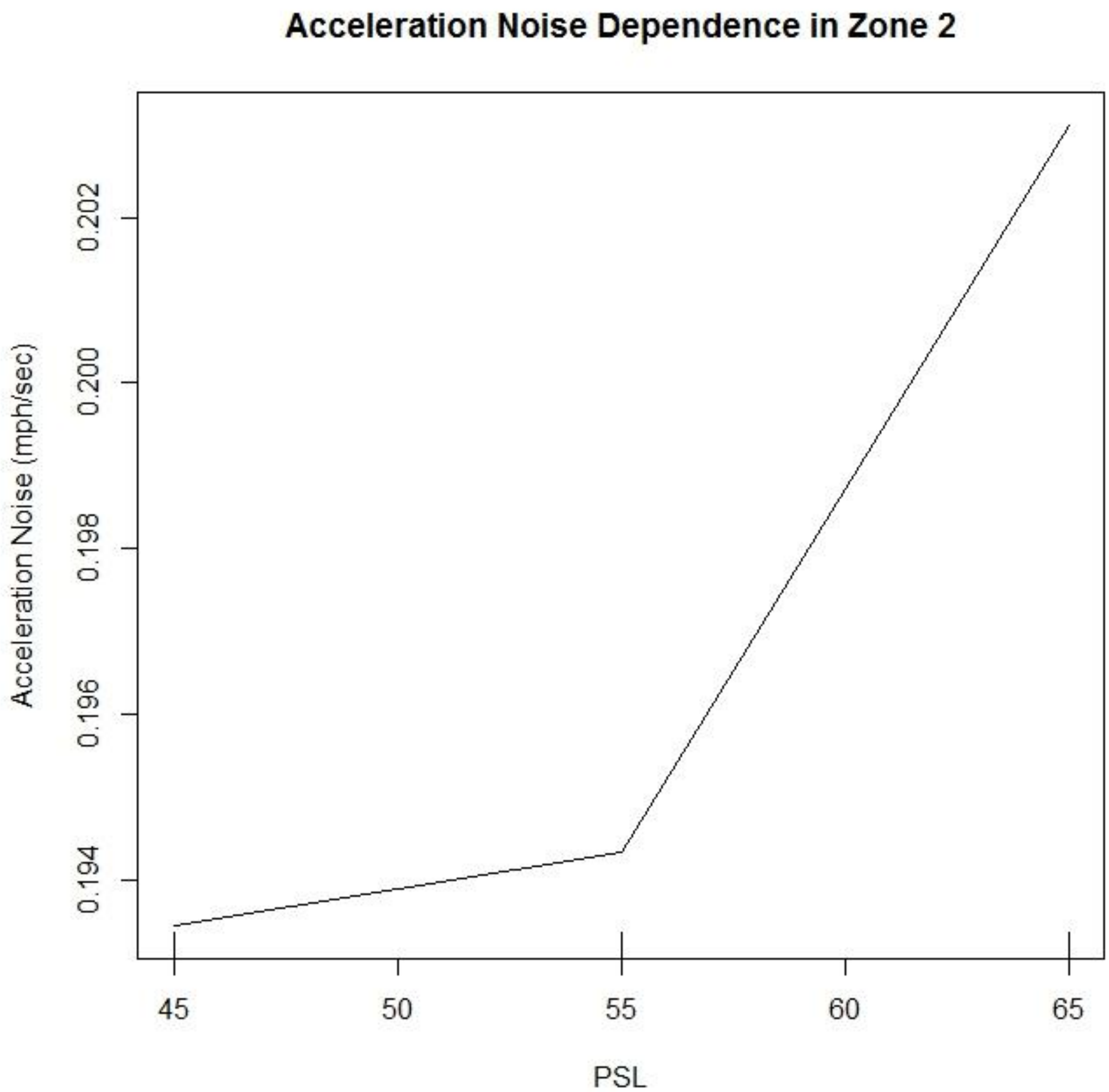

Figure C-23. Random Forest Posted Speed Limit Acceleration Noise Dependence in Zone 2.

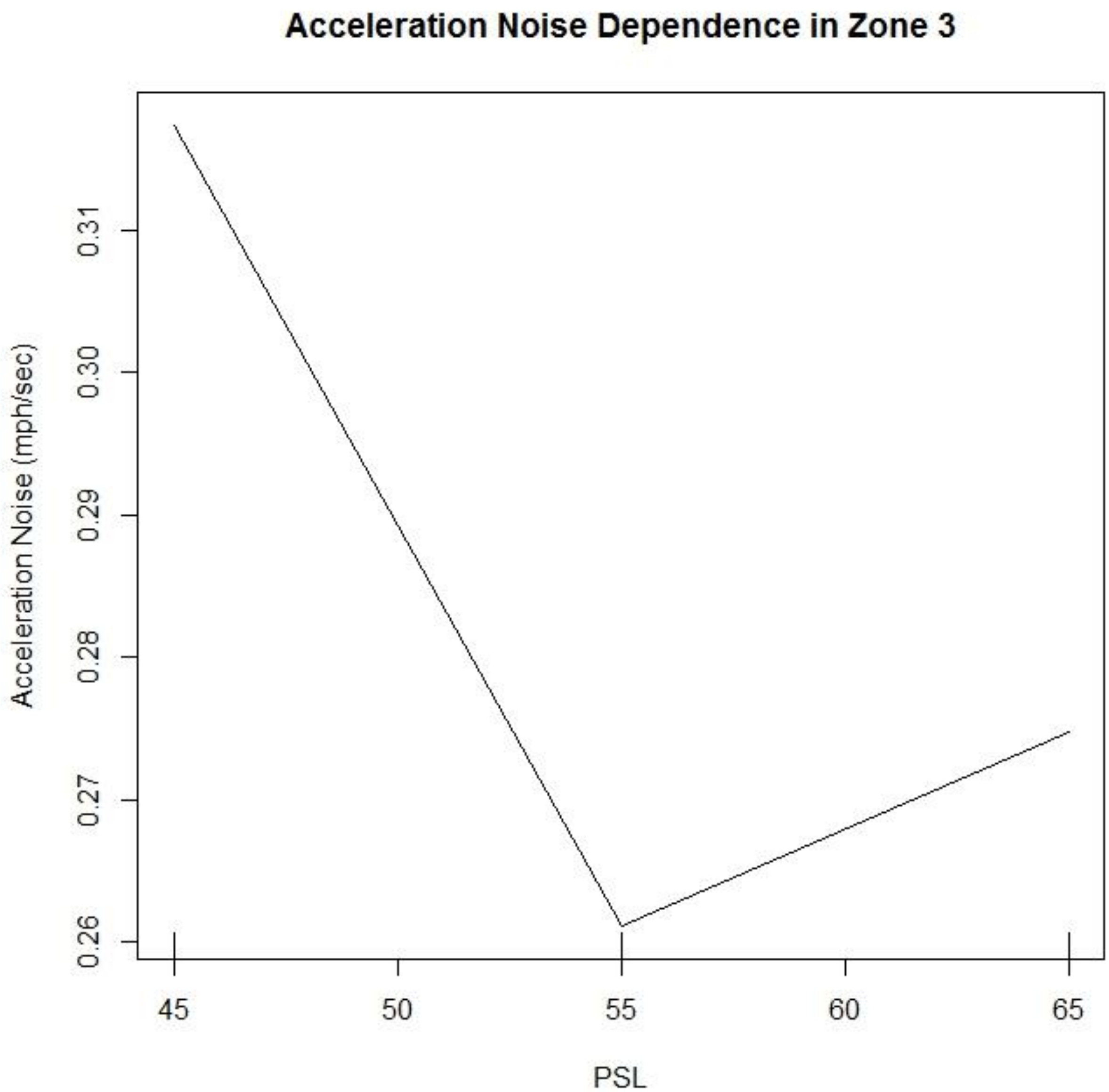

Figure C-24. Random Forest Posted Speed Limit Acceleration Noise Dependence in Zone 3.

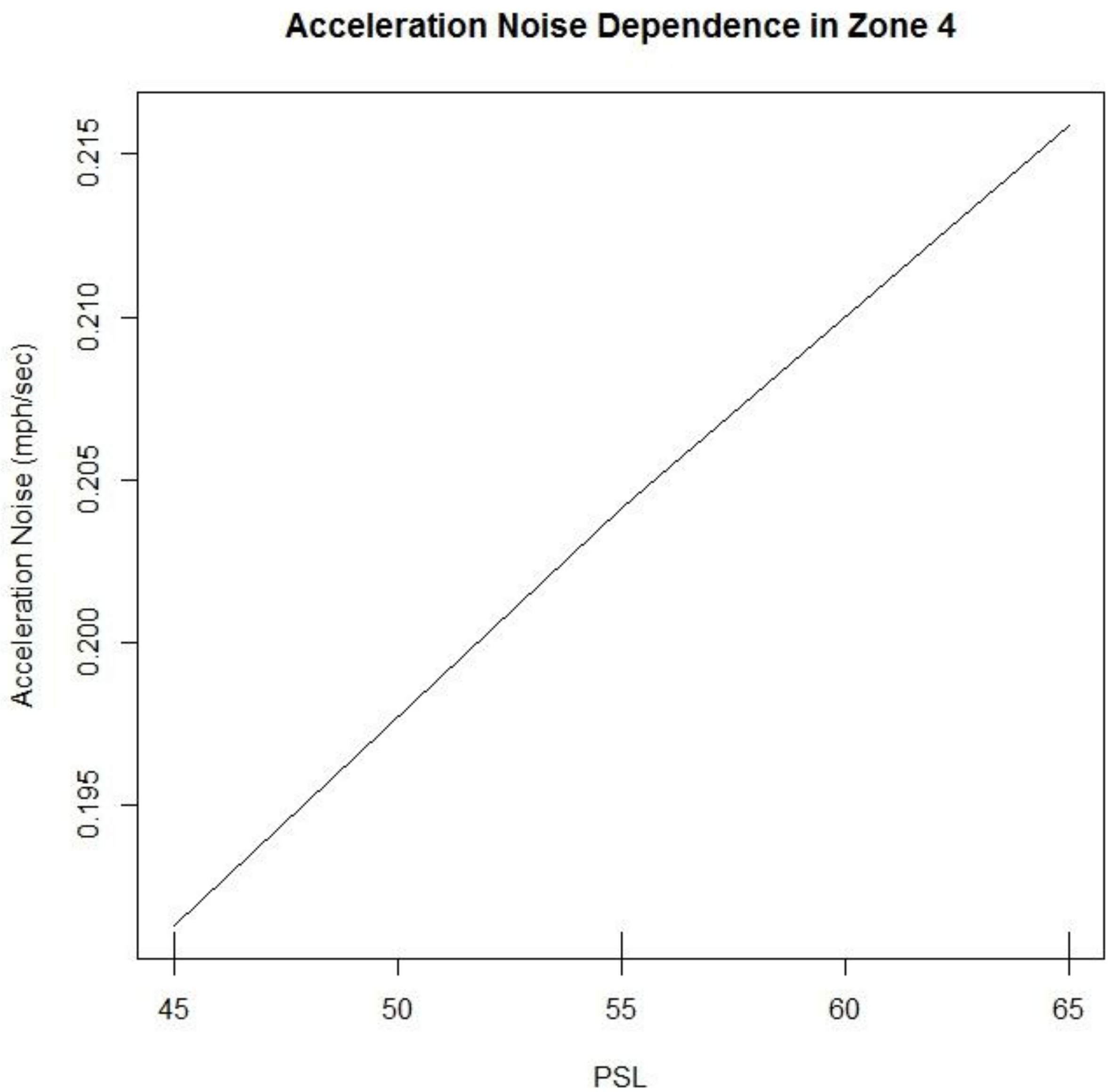

Figure C-25. Random Forest Posted Speed Limit Acceleration Noise Dependence in Zone 4.

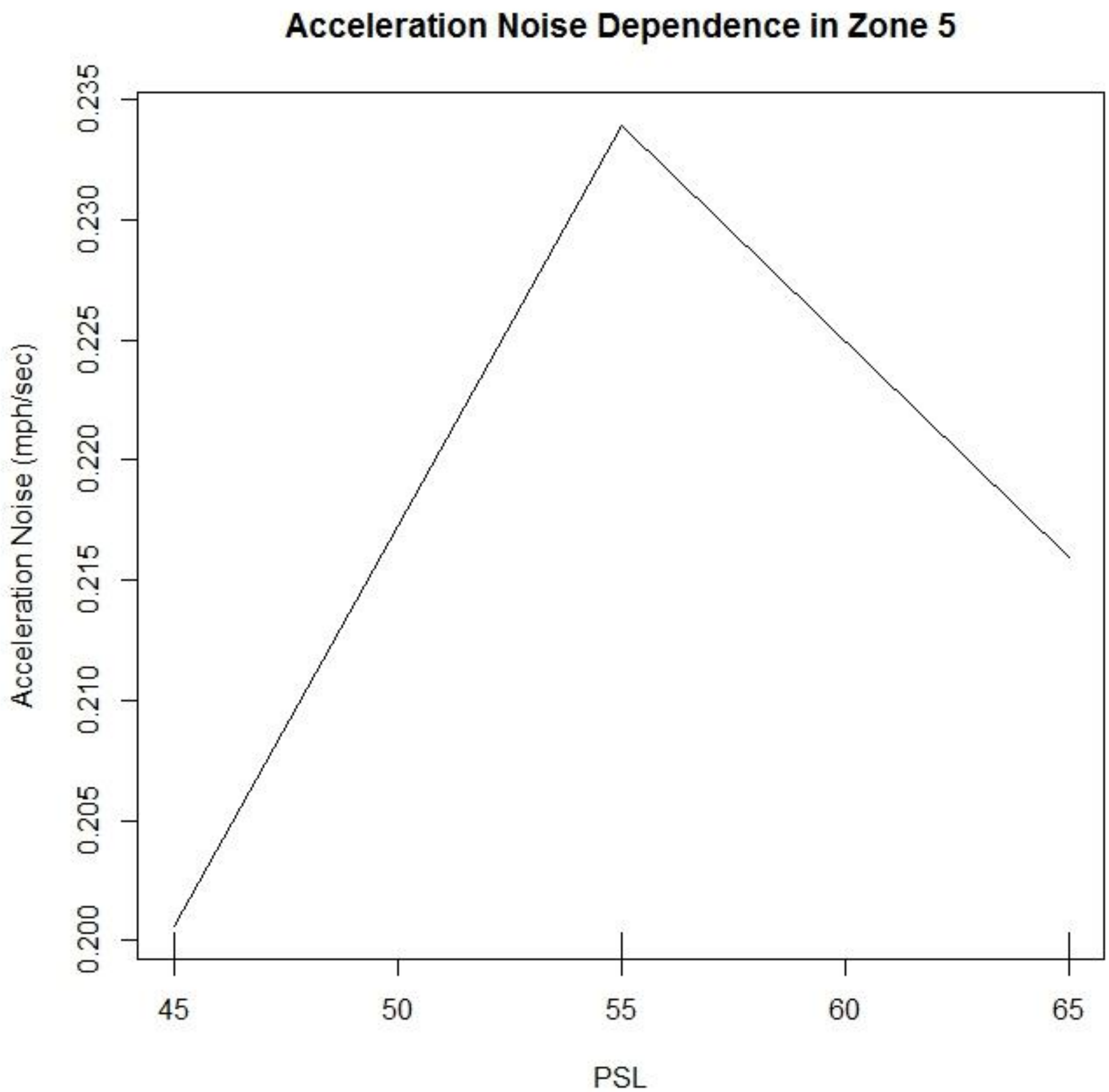

Figure C-26. Random Forest Posted Speed Limit Acceleration Noise Dependence in Zone 5.

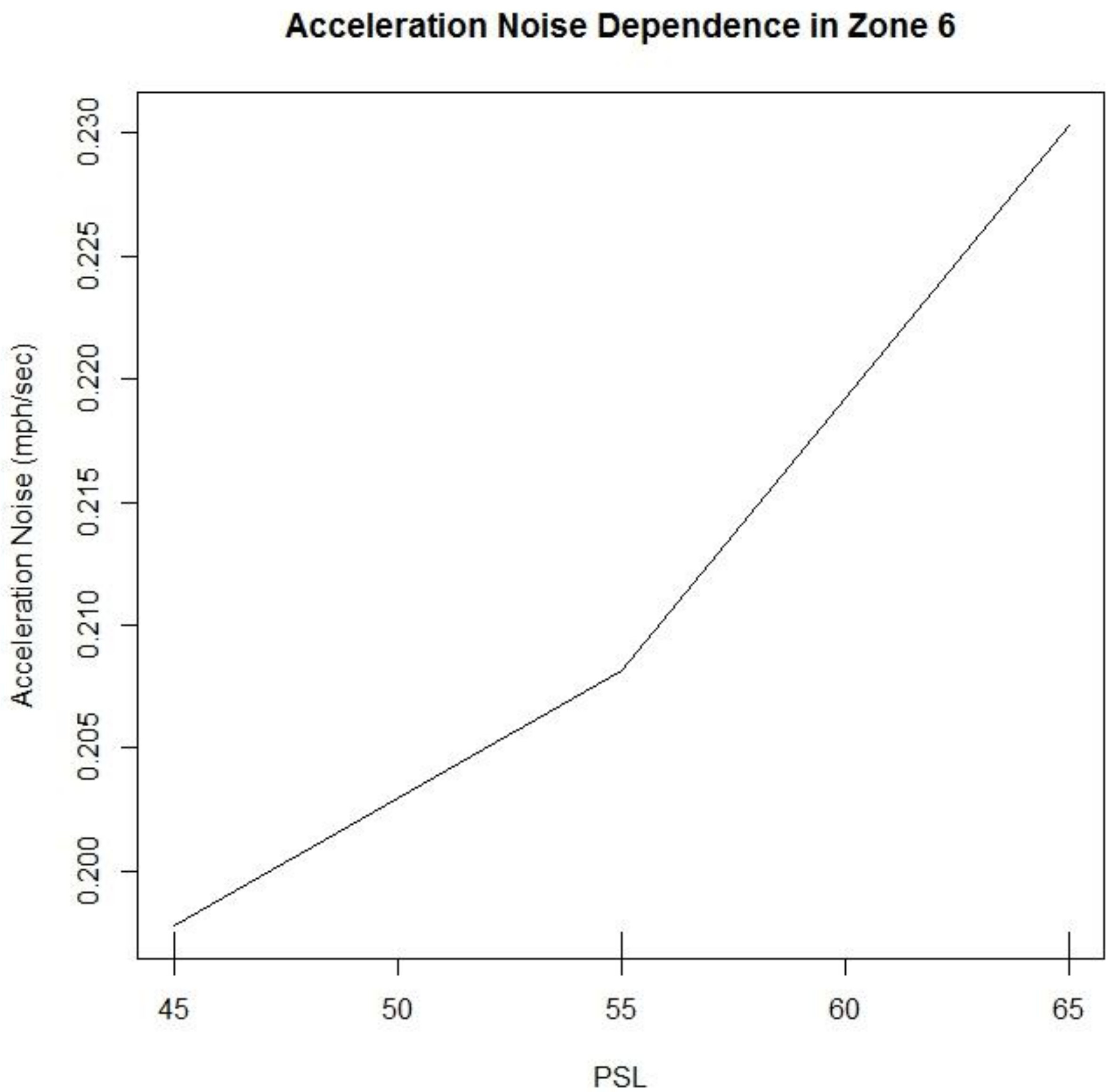

Figure C-27. Random Forest Posted Speed Limit Acceleration Noise Dependence in Zone 6.

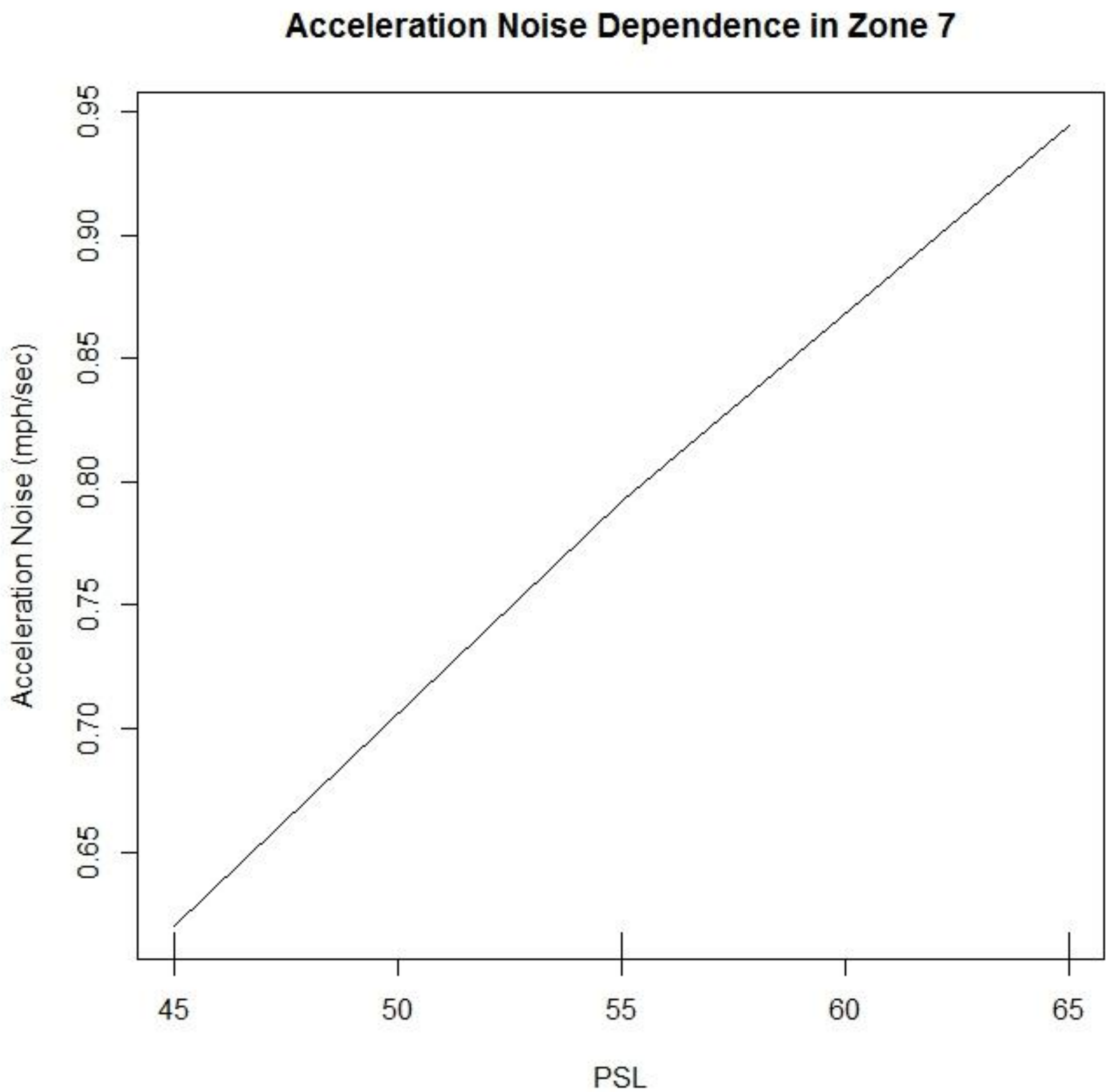

Figure C-28. Random Forest Posted Speed Limit Acceleration Noise Dependence in Zone 7.

Table D-1. Operating Speed (mph) by Independent Variable Level in Zone 1.

Posted Speed Limit (mph)	Lane Width (ft)	Operating Speed (mph)
45	10	52.1
	11	53.5
	12	39.2
55	10	61.7
	11	59.8
	12	48.7
65	10	56.7
	11	67.2
	12	50.6

Table D-2. Operating Speed (mph) by Independent Variable Level in Zone 2.

Posted Speed Limit (mph)	Lane Width (ft)	Operating Speed (mph)
45	10	52.7
	11	49.9
	12	51.0
55	10	65.1
	11	55.2
	12	58.3
65	10	68.8
	11	70.5
	12	65.3

Table D-3. Operating Speed (mph) by Independent Variable Level in Zone 3.

Posted Speed Limit (mph)	**Lane Width (ft)**	**Operating Speed (mph)**
45	**10**	**50.7**
	11	**47.2**
	12	**48.5**
55	**10**	**62.4**
	11	**53.8**
	12	**57.1**
65	**10**	**69.1**
	11	**61.9**
	12	**64.5**

Table D-4. Operating Speed (mph) by Independent Variable Level in Zone 4.

Posted Speed Limit (mph)	**Lane Width (ft)**	**Operating Speed (mph)**
45	**10**	**49.9**
	11	**49.3**
	12	**48.7**
55	**10**	**62.3**
	11	**55.1**
	12	**54.6**
65	**10**	**67.6**
	11	**64.6**
	12	**62.4**

Table D-5. Operating Speed (mph) by Independent Variable Level in Zone 5.

Posted Speed Limit (mph)	Lane Width (ft)	Operating Speed (mph)
45	10	50.3
	11	51.7
	12	48.7
55	10	63.5
	11	57.7
	12	53.6
65	10	67.2
	11	69.3
	12	61.7

Table D-6. Operating Speed (mph) by Independent Variable Level in Zone 6.

Posted Speed Limit (mph)	Lane Width (ft)	Operating Speed (mph)
45	10	53.3
	11	51.8
	12	54.2
55	10	63.0
	11	58.6
	12	60.9
65	10	70.1
	11	72.4
	12	66.2

Table D-7. Operating Speed (mph) by Independent Variable Level in Zone 7.

Posted Speed Limit (mph)	Lane Width (ft)	Operating Speed (mph)
45	10	48.3
	11	48.6
	12	42.0
55	10	54.4
	11	50.6
	12	52.0
65	10	55.6
	11	59.1
	12	56.3

Table D-8. Acceleration Noise (mph/ sec) by Independent Variable Level in Zone 1.

Posted Speed Limit (mph)	**Lane Width (ft)**	**Acceleration Noise (mph/sec)**
45	**10**	**0.52**
	11	**0.51**
	12	**0.91**
55	**10**	**0.59**
	11	**0.51**
	12	**0.93**
65	**10**	**0.48**
	11	**0.74**
	12	**0.70**

Table D-9. Acceleration Noise (mph/sec) by Independent Variable Level in Zone 2.

Posted Speed Limit (mph)	**Lane Width (ft)**	**Acceleration Noise (mph/sec)**
45	**10**	**0.23**
	11	**0.52**
	12	**0.39**
55	**10**	**0.45**
	11	**0.47**
	12	**0.49**
65	**10**	**0.22**
	11	**0.82**
	12	**0.33**

Table D-10. Acceleration Noise (mph/sec) by Independent Variable Level in Zone 3.

Posted Speed Limit (mph)	**Lane Width (mph)**	**Acceleration Noise (mph/sec)**
45	**10**	**0.52**
	11	**0.43**
	12	**1.39**
55	**10**	**0.50**
	11	**0.28**
	12	**0.87**
65	**10**	**0.26**
	11	**0.98**
	12	**0.46**

Table D-11. Acceleration Noise (mph/sec) by Independent Variable Level in Zone 4.

Posted Speed Limit (mph)	**Lane Width (mph)**	**Acceleration Noise (mph/sec)**
45	**10**	**0.27**
	11	**0.36**
	12	**0.47**
55	**10**	**0.42**
	11	**0.34**
	12	**0.77**
65	**10**	**0.31**
	11	**0.74**
	12	**0.39**

Table D-12. Acceleration Noise (mph/sec) by Independent Variable Level in Zone 5.

Posted Speed Limit (mph)	**Lane Width (mph)**	**Acceleration Noise (mph/sec)**
45	**10**	**0.23**
	11	**0.34**
	12	**0.56**
55	**10**	**0.62**
	11	**0.40**
	12	**0.86**
65	**10**	**0.22**
	11	**0.67**
	12	**0.41**

Table D-13. Acceleration Noise (mph/sec) by Independent Variable Level in Zone 6.

Posted Speed Limit (mph)	Lane Width (mph)	Acceleration Noise (mph/sec)
45	10	0.25
	11	0.39
	12	0.53
55	10	0.70
	11	0.42
	12	0.39
65	10	0.37
	11	0.81
	12	0.41

Table D-14. Acceleration Noise (mph/sec) by Independent Variable Level in Zone 7.

Posted Speed Limit (mph)	**Lane Width (mph)**	**Acceleration Noise (mph/sec)**
45	**10**	**1.11**
	11	**0.78**
	12	**1.57**
55	**10**	**2.09**
	11	**2.05**
	12	**1.35**
65	**10**	**1.99**
	11	**3.44**
	12	**1.43**

Table D-15. Lateral Position (ft) by Independent Variable Level in Zone 1.

Posted Speed Limit (mph)	Lane Width (ft)	Lateral Position (ft)
45	10	2.9
	11	3.0
	12	2.9
55	10	2.9
	11	2.9
	12	3.1
65	10	2.8
	11	2.9
	12	2.8

Table D-16. Lateral Position (ft) by Independent Variable Level in Zone 2.

Posted Speed Limit (mph)	Lane Width (ft)	Lateral Position (ft)
45	10	0.2
	11	-0.1
	12	0.1
55	10	0.5
	11	0.6
	12	0.1
65	10	-0.3
	11	-0.4
	12	0.3

Table D-17. Lateral Position (ft) by Independent Variable Level in Zone 3.

Posted Speed Limit (mph)	**Lane Width (ft)**	**Lateral Position (ft)**
45	**10**	**0.9**
	11	**0.7**
	12	**1.8**
55	**10**	**0.3**
	11	**-0.8**
	12	**1.6**
65	**10**	**0.1**
	11	**-0.1**
	12	**0.3**

Table D-18. Lateral Position (ft) by Independent Variable Level in Zone 4.

Posted Speed Limit (mph)	Lane Width (ft)	Lateral Position (ft)
45	10	1.0
	11	0.2
	12	0.3
55	10	-0.2
	11	0.4
	12	0.4
65	10	0.4
	11	0.5
	12	0.4

Table D-19. Lateral Position (ft) by Independent Variable Level in Zone 5.

Posted Speed Limit (mph)	**Lane Width (ft)**	**Lateral Position (ft)**
45	**10**	**-0.2**
	11	**0.3**
	12	**0.1**
55	**10**	**0.3**
	11	**0.1**
	12	**1.1**
65	**10**	**-0.5**
	11	**0.4**
	12	**-0.3**

Table D-20. Lateral Position (ft) by Independent Variable Level in Zone 6.

Posted Speed Limit (mph)	Lane Width (ft)	Lateral Position (ft)
45	10	0.0
	11	1.0
	12	0.7
55	10	-0.2
	11	0.1
	12	0.3
65	10	-0.1
	11	0.5
	12	-0.1

Table D-21. Lateral Position (ft) by Independent Variable Level in Zone 7.

Posted Speed Limit (mph)	Lane Width (ft)	Lateral Position (ft)
45	10	5.4
	11	5.1
	12	4.3
55	10	5.1
	11	4.4
	12	4.9
65	10	5.3
	11	5.5
	12	4.8