Human Factors Study to Understand Driver Behavior on Managed Lane Facilities

Final Report

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605 Suwannee Street, MS 26
Tallahassee, FL 32399-0450

Prepared by:

Florida International University
Department of Civil & Environmental Engineering
10555 West Flagler Street, EC 3628
Miami, FL 33174

University of Central Florida
Department of Civil, Environmental, and Construction Engineering
4000 Central Florida Blvd.
Orlando, FL 32816

Project Manager: Gail M. Holley

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DISCLAIMER

METRIC CONVERSION TABLE

U.S. UNITS TO SI* (MODERN METRIC) UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	inches	25.400	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.610	kilometers	km
mm	millimeters	0.039	inches	in
m	meters	3.280	feet	ft
m	meters	1.090	yards	yd
km	kilometers	0.621	miles	mi

AREA

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in^2	square inches	645.200	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.470	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

VOLUME

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
fl oz	fluid ounces	29.570	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

NOTE: volumes greater than 1,000 L shall be shown in m^3.

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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16. Abstract

The Florida Department of Transportation (FDOT) has several managed lane facilities throughout the state. Managed lanes (MLs) are commonly constructed adjacent to general-purpose lanes (GPLs) to improve mobility. The objective of this research was to understand driver behavior on managed lane facilities, specifically pertaining to the type of separation between the MLs and the GPLs. This research employed a naturalistic driving study and a driving simulator study to examine how separation type affects driver behavior on ML facilities. Three separation types; pylons, buffer areas, and concrete barriers were analyzed utilizing naturalistic driving data, while two separation treatments; separation width defined by single solid lines or double solid lines, and separation height defined by 24" or 28" in curved sections were analyzed utilizing the driving simulator.

The driving simulator study was conducted at the University of Central Florida (UCF) using a compact version (miniSim^{TM}) of the National Advanced Driving Simulator (NADS) developed by the University of Iowa. Participants experienced various driving scenarios along a 6-mile roadway with single-lane ML and 2-lane ML sections. Separation width (single solid or double solid lines) was examined in both straight and curved sections, while separation height (24-inch and 28-inch pylons) was evaluated only in curved sections. Results revealed higher mean speeds and shorter fixation durations with double solid lines combined with 28-inch pylons in curved segments. Lane deviation away from the separator was greater with double solid lines combined with 24-inch pylons. Over half of the participants reported double solid lines and 28-inch pylons as being more noticeable.

The naturalistic driving study examined how drivers behave in the real world on ML facilities with different separation treatments. Data from ML facilities in Florida and Washington State was collected from the Regional Integrated Transportation Information System (RITIS) and the Second Strategic Highway Research Program (SHRP2), respectively. Performance measures analyzed included lane utilization, travel speed, and lane deviation. Findings revealed that concrete barriers and pylon separations result in decreased lane utilization compared to buffer separation by 12.8% and 8.6%, respectively, on the leftmost GPL. On the rightmost ML, lane utilization increased by 2% with concrete barriers and decreased by 20% with pylon separations compared to buffer separation. Buffer separation resulted in higher average speeds on MLs. Drivers in the ML adjacent to the separator tend to drive away from the separator for all separation types, with the greatest magnitude observed on buffer-separated ML facilities.

This research provides FDOT and other transportation agencies with a better understanding of the effects of different ML separation treatments between the MLs and GPLs on driver behavior, enabling agencies to implement treatments aimed at improving safety and mobility on ML facilities.

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Managed Lanes, Separation Types, Pylons, Buffer, Concrete Barrier

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EXECUTIVE SUMMARY

The Florida Department of Transportation (FDOT) has several managed lane facilities throughout the state. Managed lanes (MLs) are commonly constructed adjacent to general-purpose lanes (GPLs) and offer various benefits, such as additional travel lanes for longer, more regional trips around congested urban areas, improved transit services, hurricane and emergency evacuation assistance, and better system connectivity between critical limited access facilities.[1] The ML facilities in operation, under construction, or in the planning phase in Florida are located in four major regions/FDOT Districts: Northeast Florida (D2), Central Florida (D5), West Central Florida (D7), and Southeast Florida (D4 and D6).

The objective of this research was to understand driver behavior on managed lane facilities, specifically pertaining to the type of separation between the MLs and the GPLs. This research employed two types of human factors analyses: a naturalistic driving study and a driving simulator study. The focus of the two studies was to examine how the ML separation type affects driver behavior on ML facilities. Three separation types; pylons, buffer areas, and concrete barriers were analyzed utilizing naturalistic driving data, while two separation treatments; separation width defined by single solid lines or double solid lines, and separation height defined by 24" or 28" in curved sections, were analyzed utilizing the driving simulator.

A comprehensive literature review was conducted on managed lane separation types, with the emphasis on the three focus types. Existing guidelines specific to separation treatments were also reviewed. Available literature on human factors and driver behavior related to the three separation types was also reviewed. While previous studies have established that human factors and driver behavior represent an integral component and potential profound influence on various aspects of transportation and road safety, gaps in research, with respect to driver behavior and managed lane separation types, are present. Studies and information on driving simulation were also reviewed.

Driving Simulator Study

A driving simulator study was conducted to understand how different age groups of drivers; younger (18-34), middle-aged (35-64), and older (65+) behave in managed lane facilities with various combinations of delineator (pylon) heights and separation pavement markings in a controlled setting using a driving simulator and eye tracking device. The experiment was conducted at the Intelligent Transport Systems lab at the University of Central Florida (UCF) using a compact version (miniSim^{TM}) of the National Advanced Driving Simulator (NADS) developed by the Driving Safety Research Institute (DSRI) at the University of Iowa.

The simulation model consisted of a 6-mile roadway with two sections: 4 GPLs + 1 ML and 3 GPLs + 2 MLs. Both sections contained straight and curved segments. Separation width (single solid or double solid lines) was examined in both straight and curved sections, while separation height (24-inch and 28-inch pylons) was evaluated only in curved sections. Data from 60 participants were included in the analysis.

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[1] Perez et al. (2012). *Priced Managed Lane Guide 2012* (Report No. FHWA-HOP-13-007). https://ops.fhwa.dot.gov/publications/fhwahop13007/fhwahop13007.pdf.

Performance factors examined included deceleration, speed, speed differential, lane deviation, steering angle, and visual attention. Key findings from the driver simulator study include:

- Separations with double solid lines resulted in higher deceleration rates at ML entry segments.
- Separation height had no significant fixed effect on the deceleration rate.
- 67.5% of participants reported that 28-inch pylons were more noticeable in the curved segments.
- Double solid lines were linked to higher mean speeds, especially when combined with 28-inch pylons in the curved segments.
- Lane deviation away (i.e., shifting left) from the separators was greater with double solid lines with 24-inch pylons.
- 51% of participants reported that double solid lines were more noticeable.
- Double solid lines with 28-inch pylons resulted in shorter fixation durations.

Naturalistic Driving Study

A naturalistic driving study was conducted to examine how drivers behave in the real world on ML facilities with different separation treatments. This study utilized naturalistic driving data from ML facilities in Florida and Washington State using data collected from the Regional Integrated Transportation Information System (RITIS) and the Second Strategic Highway Research Program (SHRP2), respectively. Performance measures analyzed included lane utilization, travel speed, and lane deviation. Key findings from the naturalistic driving study include:

Lane Utilization

Left-most General Purpose Lane

- A significant difference in the lane utilization ratios was observed between all types of separators.
- Buffer-separated facilities exhibited the highest lane utilization ratio for the left-most GPL during daytime hours.
- Concrete barrier-separated ML facilities exhibited the lowest utilization, particularly during off-peak hours.
- Concrete barriers and pylon separations resulted in decreased lane utilization compared to buffer separation by 12.8% and 8.6%, respectively.

Right-most Managed Lane

- Buffer-separated and concrete barrier-separated facilities exhibited a similar lane utilization ratio during daytime hours.
- Pylon-separated ML facilities exhibited the lowest utilization, particularly during daytime hours.
- Concrete barriers resulted in a 2% increase in lane utilization compared to buffer separation.
- Pylon separations resulted in a 20% decrease in lane utilization compared to buffer separation.

Travel Speed

- Buffer separation resulted in higher average speeds on MLs, compared to pylons and concrete barriers based on pairwise comparisons.
- ML facilities with concrete barriers and pylon separation types were found to be associated with a reduction in average travel speed compared to buffer-separated ML facilities, as identified through model analysis.

Lane Deviation

- Drivers in the ML adjacent to the separator tend to drive away from the separator for all separation types.
- The magnitude of lane deviation was greater on buffer-separated ML facilities compared to concrete barrier or wide buffer separation types.
- Drivers in the leftmost GPL tend to drive towards the separator and away from the adjacent GPLs.
- Significance tests confirmed that mean lane deviation values were different for all separation types for vehicles traveling in the ML adjacent to the separator.
- There were no significant differences in the mean lane deviation values between wide buffer and concrete barrier separation types for vehicles traveling in the inside lane of the GPLs.

This research provides FDOT and other transportation agencies with a better understanding of the effects of different ML separation treatments on driver behavior. The findings will also enable the FDOT and local agencies to make informed decisions on appropriate separation treatments between the MLs and GPLs aimed at improving safety and mobility on ML facilities.

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LIST OF ACRONYMS/ABBREVIATIONS

ANOVA	Analysis of Variances
AOI	Area of Interest
Caltrans	California Department of Transportation
CI	Confidence Interval
DAQ	Data Acquisition
DSRI	Driving Safety Research Institute
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FIU	Florida International University
GLM	Generalized Linear Model
GPL	General-purpose Lane
HOT	High Occupancy Toll
HOV	High Occupancy Vehicle
IRB	Institutional Review Board
ISAT	Interactive Scenario Authoring Tool
LIFE	Learning Institute for Elders
LLRN	Learning Longevity Research Network
LOS	Level of Service
ML	Managed Lane
MMNL	Mixed Multinomial Logit
MnDOT	Minnesota Department of Transportation
MSE	Mean Squared Error
MUTCD	Manual on Uniform Traffic Control Devices
NADS	National Advanced Driving Simulator
RITIS	Regional Integrated Transportation Information System
SHRP2	Second Strategic Highway Research Program
SS	Simulation Sickness
TMT	Tile Mosaic Tool
TOD	Time of Day
TTFN	Time to First Notice
UCF	University of Central Florida
VTTI	Virginia Tech Transportation Institute
WSDOT	Washington State Department of Transportation

CHAPTER 1
INTRODUCTION

1.1 Background

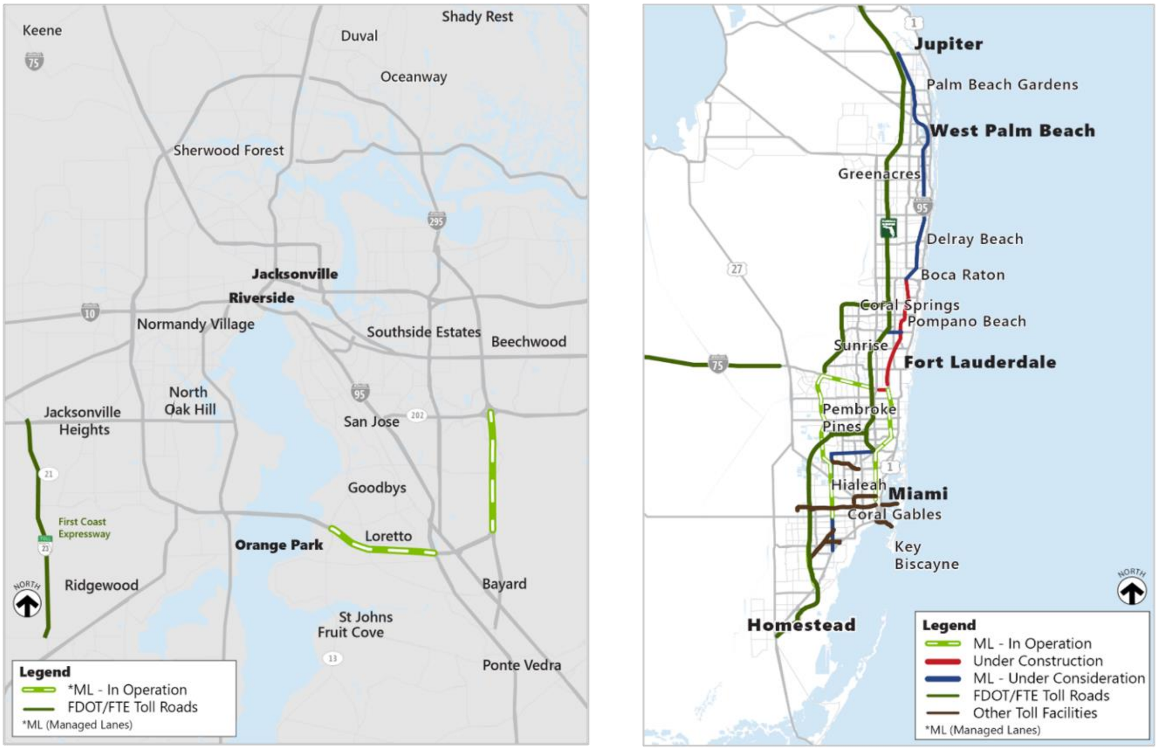
Managed lanes are “highway lanes where operational strategies are proactively implemented and managed in response to changing traffic conditions” (FHWA, 2008). Managed lanes (MLs) are commonly constructed adjacent to general-purpose lanes (GPLs) and offer various benefits, such as additional travel lanes for longer, more regional trips around congested urban areas, improved transit services, hurricane and emergency evacuation assistance, and better system connectivity between critical limited access facilities (Perez et al., 2012).

In Florida, MLs are increasingly being constructed to relieve congestion through congestion pricing strategies and vehicle restrictions. The Florida Department of Transportation (FDOT) implements and operates MLs to maximize the movement of people and goods by utilizing any combination of vehicle eligibility, transit, access control, tolling, and other applicable techniques (FDOT, 2023). MLs may be operated as reversible flow or bi-directional facilities to meet peak demands. FDOT has several managed lane facilities in operation, under construction, or in the planning phase, located in four major regions/FDOT Districts: Northeast Florida (D2), Central Florida (D5), West Central Florida (D7), and Southeast Florida (D4 and D6), as presented in Figure 1.1.

The geometry of managed lanes varies for different facilities. Since managed lanes are often built within existing freeway facilities, in many cases, right-of-way limitations and roadway constraints may make it difficult to meet all desirable design standards and may compromise the facilities' safety. The type of separation between the MLs and the GPLs is one major geometric feature that influences the safety performance of the managed lane facilities. Common separation treatments include barrier separation, buffer separation with pylons (i.e., tubular markers), buffer separation with pavement marking, wide buffer separation, and grade separation. These separation treatments have varying impacts on the managed lane facilities' overall safety and operational performance.

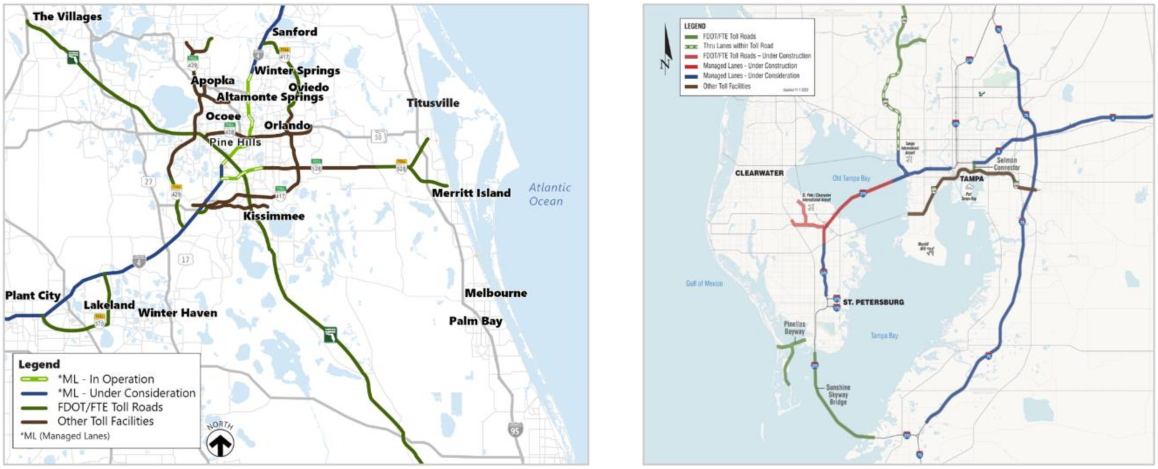
Questions related to driving behavior cannot be answered using traditional crash data analysis and, therefore, require a human factors approach. This research employed two types of human factors analyses, one using the naturalistic driving data and the other using the driving simulator with eye-tracking equipment. The focus of the two studies was to understand how separation type affects driver behavior on managed lane facilities and to determine the safety performance of buffer separation versus pylons separation and buffer separation versus concrete barrier separation through comparative analyses.

This research provides FDOT and other transportation agencies with a better understanding of the effects of different ML separation treatments on driver behavior. The findings will also enable the FDOT and local agencies to make informed decisions on appropriate separation treatments between the MLs and GPLs aimed at improving safety and mobility on ML facilities.



a) Northeast Florida (D2)

b) Southeast Florida (D4 & D6)



c) Central Florida (D5)

d) West Central Florida (D7)

Figure 1.1: Managed Lanes Facilities in Florida

1.2 Research Goal and Objectives

The objective of this research was to conduct a human factors study to understand driver behavior on managed lane facilities, specifically pertaining to the type of separation between the MLs and the GPLs. Specific objectives included:

1. Conduct a naturalistic driving study to understand how drivers behave in the real world in managed lane facilities with different separation treatments.
2. Conduct a driving simulation study to supplement the drivers' behaviors that are difficult to collect in real-world situations.

1.3 Report Organization

This report is organized as follows:

- Chapter 1 provides a brief introduction to managed lanes (MLs) and the goal and objectives of this research effort.
- Chapter 2 discusses findings from a literature review of MLs, separation types between MLs and general-purpose lanes (GPLs), existing guidelines, human factors, and driver behavior, as well as a review of previous driving simulation studies.
- Chapter 3 discusses the driving simulator study.
- Chapter 4 discusses the naturalistic driving study.
- Chapter 5 presents the conclusions of this research effort.

CHAPTER 2
LITERATURE REVIEW

This chapter discusses findings from a comprehensive literature review conducted to identify and review the human factors and driver behavior on managed lanes facilities, with respect to separation treatments. The emphasis was placed on human factors and how they influence behavior and safety on managed lanes facilities with different separation types.

2.1 Background

Managed lanes are highway lanes where operational strategies are proactively implemented and managed in response to changing traffic conditions. They are commonly built next to general-purpose lanes and offer various benefits, such as extra travel lanes for longer regional trips, improved transit services, hurricane and emergency evacuations assistance, and better system connectivity between critical limited access facilities (Perez et al., 2012). Figure 2.1 presents additional advantages of managed lanes. In Florida, managed lanes are being increasingly constructed to alleviate congestion through congestion pricing and vehicle restrictions. These lanes may be operated as reversible flow or bi-directional facilities to meet peak demands. FDOT has several managed lane facilities in operation, under construction, or in the planning phase, located in four major regions/FDOT Districts: Northeast Florida (D2), Central Florida (D5), West Central Florida (D7), and Southeast Florida (D4 and D6).

Figure 2.1: Benefits of Priced Managed Lanes (Perez et al., 2012)

The Federal Highway Administration (FHWA) defines managed lanes using three management strategies: pricing, vehicle eligibility, and access control, as shown in Figure 2.2. These lane management strategies may vary, depending on the project objective, whether the strategy is deployed on a new facility or an existing facility, the availability of right-of-way, current operational characteristics along the corridor, and environmental and societal concerns. Managed lanes strategies can be used independently or blended into two or more to effectively manage the flow of traffic along a specific facility (FHWA, 2008). The list of facilities that can fall within the definition of managed lanes continues to increase as new combinations of management strategies are employed (Neudorff et al., 2011). The following are examples of facility types that can be considered managed lanes:

- High Occupancy Vehicle (HOV) lanes
- High Occupancy Toll (HOT) lanes
- Express lanes (ELs)
- Dynamic shoulder lanes
- Truck lanes
- Interchange bypass lanes (usually, transit, HOV, or truck only)
- Dual roadways in which at least one of the roadways is managed, etc.

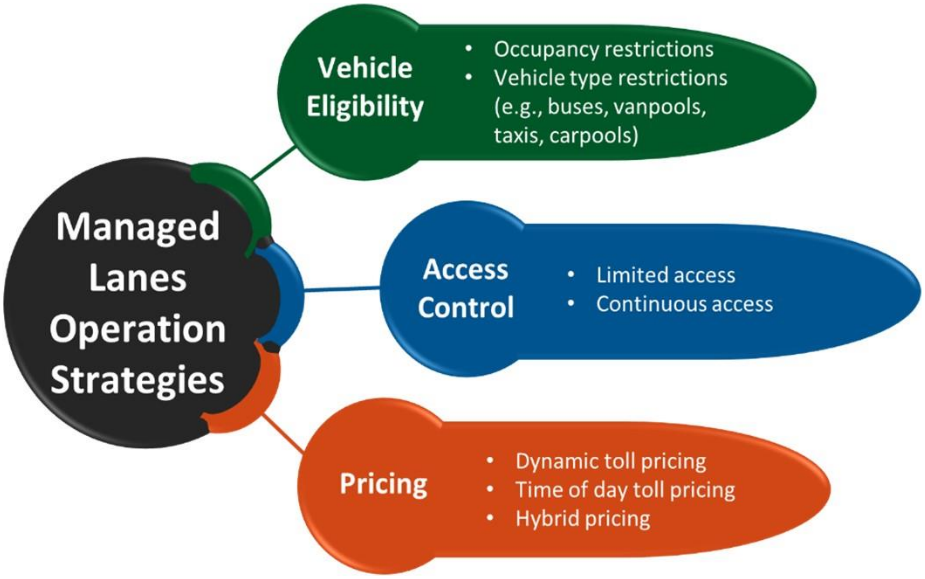


Figure 2.2: Managed Lanes Operation Control Strategies

2.2 Managed Lanes Separation Types

Managed lanes are intentionally separated from general-purpose lanes to provide a controlled and optimized use of the lanes (Kuchangi et al., 2013; Neudorff et al., 2011; Wang et al., 2012). By separating these lanes, transportation agencies can implement specific strategies to alleviate congestion, enhance overall traffic flow, or meet other intended objectives. Managed lanes often involve various management techniques such as tolling, dynamic pricing, and access control, allowing agencies to actively regulate the number of vehicles using these lanes. This separation not only encourages the adoption of carpooling for HOT lanes but also provides a reliable option for travelers willing to pay a premium for a faster and more predictable journey. Moreover, the separation ensures that managed lanes remain effective in maintaining a steady traffic flow, contributing to reduced congestion and improved overall transportation efficiency.

The earliest priced managed lanes facilities implemented in the U.S. all featured continuous concrete barriers. However, the success of the I-394 MnPASS lanes, which opened in 2005 and featured eight miles of painted buffers, has led to several new projects that do not have barrier separation. For example, the I-35W managed lanes, opened in Minneapolis in 2010, use a near-continuous access policy with skip striping to designate access, while the I-85 express lane facility in Atlanta incorporates a camera-based "virtual barrier system" to discourage weaving. The I-95 express lanes in South Florida had initially installed flexible delineators, spaced at 20 ft center to center, but later reduced the delineator spacing to 10 ft centers since numerous vehicles were weaving in and out of the 20 ft spaced delineators (Kuchangi et al., 2013).

Since concrete barriers provide a physical barrier between the managed lanes and the general-purpose lanes, they have been shown to reduce violations, especially regarding entering and exiting at undesignated locations (Perez et al., 2002). Barrier separation is typically more expensive than buffer separation but guarantees low toll violation rates and eliminates potential weaving movements between managed and the general-purpose lanes. Unlike concrete barriers, pylons have been proven to be less expensive to install, require less right-of-way, and allow emergency and maintenance vehicles to traverse between the managed and the general-purpose lanes (Perez et al., 2002). Because of being traversable, pylons encourage risky behavior commonly referred to as *lane diving*, where traffic moves in and out of the managed lanes at undesignated locations. This behavior increases the cost of maintaining the pylons and imposes a safety threat to both the managed lane and the general-purpose lane traffic.

While concrete barriers and pylons provide some form of physical barrier between the managed lanes and the general-purpose lanes, double solid white lines only provide a psychological barrier between the two types of lanes. The absence of a physical barrier on roadways with managed lanes separated by double solid white lines may encourage lane diving, especially when managed lanes are underutilized and when there is a significant variation in speed between the express lanes and the general-purpose lanes (Srinivasan et al., 2015). Wide buffers, on the other hand, offer less opportunity for sideswipes and create a substantial sense of separation, but emergency vehicle access may be difficult, especially with soft grassed buffers. Additional right-of-way is also needed when wide buffers are used (Michael, 2011). Table 2.1 provides a summary comparison of separation types for managed lanes.

Table 2.1: Pros and Cons of Different Managed Lanes Separation Types (Michael, 2011)

		Barrier Separation	Pylon Separation	Buffer Separation (Pavement Marking)	Wide Buffer Separation
Safety • Incident Avoidance • Incident Management • Lane Clearance	Pros	• Reduces GPL and ML sideswipes • MLs traffic is separated from incidents in GPLs	• Easier access for emergency vehicles since pylons can be driven over	• Easy access for emergency vehicles since there is no physical separation • Easy for MLs traffic to vacate the lanes in case of an emergency or incident	• Less opportunity for sideswipes • Wide buffers create a substantial sense of separation
	Cons	• Access to lanes is restricted - Incident Management response may take longer • The impact on MLs traffic is high in case of an incident • More difficult to vacate lanes in case of an emergency or incident	• Can create roadway debris when plugged off • Vehicles in the GPLs are not physically separated from MLs if an incident does occur	• More opportunity for GPL and ML sideswipes • Vehicles in the GPLs are not physically separated from MLs if an incident does occur	• Emergency vehicles access may be difficult especially with soft grassed buffers
Right-of-way Right-of-way in addition to the space needed for the device placement.	Pros	None	• No right-of-way typically needed for installation	• No right-of-way typically needed for installation	None
	Cons	• Extra right-of-way typically needed for access points installation • Right-of-way typically needed for shoulders	None	None	• Extra right-of-way is needed
Cost • Initial installation • Maintenance	Pros	• Low maintenance • Allows for overhead sign structure uprights to be placed within the barrier, which reduces sign structure spans	• Easy installation • Low installation cost	• Easy installation • Low installation cost	• Easy installation • Low installation cost
	Cons	• Higher cost for installation than other at-grade separation methods	• High maintenance costs due to frequent replacement of unplugged pylons • No location for overhead sign structure uprights within area separating GPLs and MLs, which results in longer sign structure spans	• No location for overhead sign structure uprights within area separating GPLs and MLs, which results in longer sign structure spans	• May require longer overhead sign structures spans

Note: ML = Managed Lane; GPL = General-purpose Lane.

Table 2.1: Pros and Cons of Different Managed Lanes Separation Types (continued)

		Barrier Separation	Pylon Separation	Buffer Separation (Pavement Marking)	Wide Buffer Separation
Features and Operational Characteristics - Concurrent flow - Mixed mode - Level of service	Pros	- Allows for higher operating speeds in concurrent flow operations - Reduces toll avoidance - Better enforcement areas due to limited access points	- Provides some physical separation which can help reduce toll avoidance - Reduces illegal lane changes	- Easy to operate in mixed mode during non-peak times	- Easy to operate in mixed mode during non-peak times - Reduces illegal lane changes
	Cons	- When installed within existing roadway cross-sections, design constraints may be involved - Mixed-mode operations in non-peak times are not applicable - Special openings or devices may be needed for emergency vehicles during incident responses	- Hard to operate in mixed mode during non-peak times - Easily traversed - Hard to establish enforcement areas - Operating speeds may be lower than posted because of limited physical separation - Frequent maintenance on pylons replacements	- Illegal lane changes are not deterred - Hard to enforce illegal maneuvers and other infractions because enforcement areas are hard to establish - Operating speeds within MLs are typically lower than posted during congested times because of no physical separation	- Some illegal maneuvers and other infractions may occur because of limited physical separation
Access Points	Pros	- Access points are controlled by physical separation making them easier to enforce and limits violators	- Easy adjustment of access points after initial installation - Access points are controlled by visual /soft separation limiting violators	- Easy adjustment of access points after initial installation	- Easy adjustment of access points after initial installation
	Cons	- Possible flyovers or extra ramps required for GPL exits	- GPL traffic may have to merge with MLs traffic for left exits	- GPL traffic may have to merge with MLs traffic for left exits	- GPL traffic may have to merge with MLs traffic for left exits

Note: ML = Managed Lane; GPL = General-purpose Lane.

Multiple factors contribute to the selection of separation types for managed lanes, encompassing aspects such as design specifications, costs, access, operations, enforcement, public perception, and safety (Michael, 2011). Given that managed lanes are often built within existing freeway facilities, in many cases, right-of-way limitations and roadway constraints may hinder the attainment of all desired design standards, potentially compromising facility safety. To illustrate, research indicates that wider lanes on managed lane facilities correlate with reduced crash frequency (Fitzpatrick & Avelar, 2016). Studies have demonstrated a notable link between the safety of managed lane facilities and cross-section, the type of separation utilized (whether it's a buffer or a barrier), and the design of access points for the managed lanes (Eisele et al., 2006; Fitzpatrick & Avelar, 2016). This underscores the necessity for a meticulous and informed selection of the appropriate separation type in managed lane implementations, considering the various factors at play to ensure optimal safety and functionality.

FDOT considers several managed lanes separation types, including grade separation, barrier separation (concrete), buffer separation with pavement marking, buffer separation with tubular markers (i.e., pylons), and wide buffer separation (FDOT, 2023). Examples of separation types used for managed lanes in Florida are shown in Figure 2.3, and include:

a) Barrier - a concrete barrier separates managed lanes from general-purpose lanes,
b) Pylons - pylons separate managed lanes from general-purpose lanes,
c) Buffer - only pavement markings (e.g., double dotted lines or double solid lines) separate managed lanes from general-purpose lanes, and
d) Wide Buffer – a wide buffer (e.g., median) separates managed lanes from general-purpose lanes.

For buffer separation, the FHWA Manual on Uniform Traffic Control Devices (MUTCD) Version 11, Chapter 3E (FHWA, 2009) recommends using one of the following provisions (see Figure 2.4):

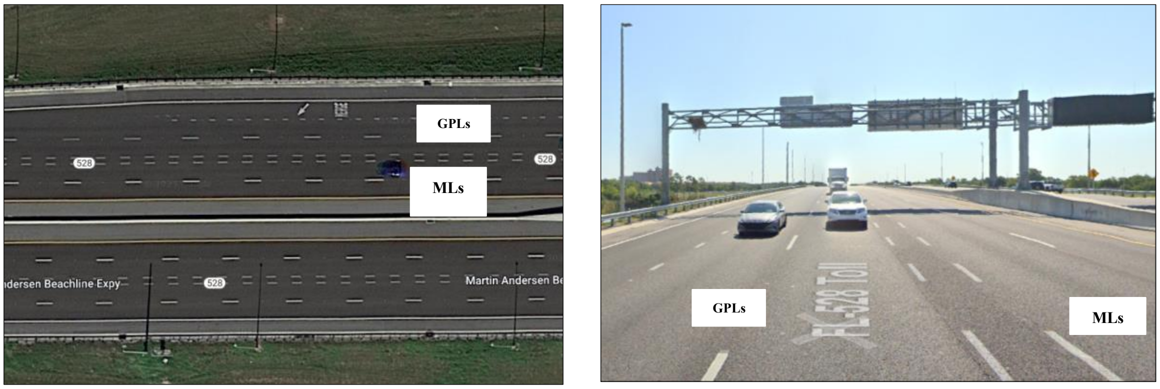
i) The buffer separation preferential lanes which consists of solid double white lane lines on each side of the buffer space, or

ii) Contiguous preferential lanes which consists solid single white lane lines where the enter/exit movement to preferential lanes is prohibited.

FDOT uses both techniques on a case-by-case basis and prefer to use delineators with both the above provisions. FHWA and FDOT recommend/use height of delineators on a straight roadway is 36". On curved roadways, FHWA recommends using at least 28", while FDOT Traffic Engineering Manual (TEM) recommends 24".

(a) Concrete Barrier Separation on I-595

(b) Pylons on I-295



(c) Buffer Separation with Pavement Marking on Beachline Expressway

(d) Wide Buffer Separation on I-75

Note: ML = Managed Lane; GPL = General-purpose Lane.

Figure 2.3: Managed Lanes Separation Types in Florida

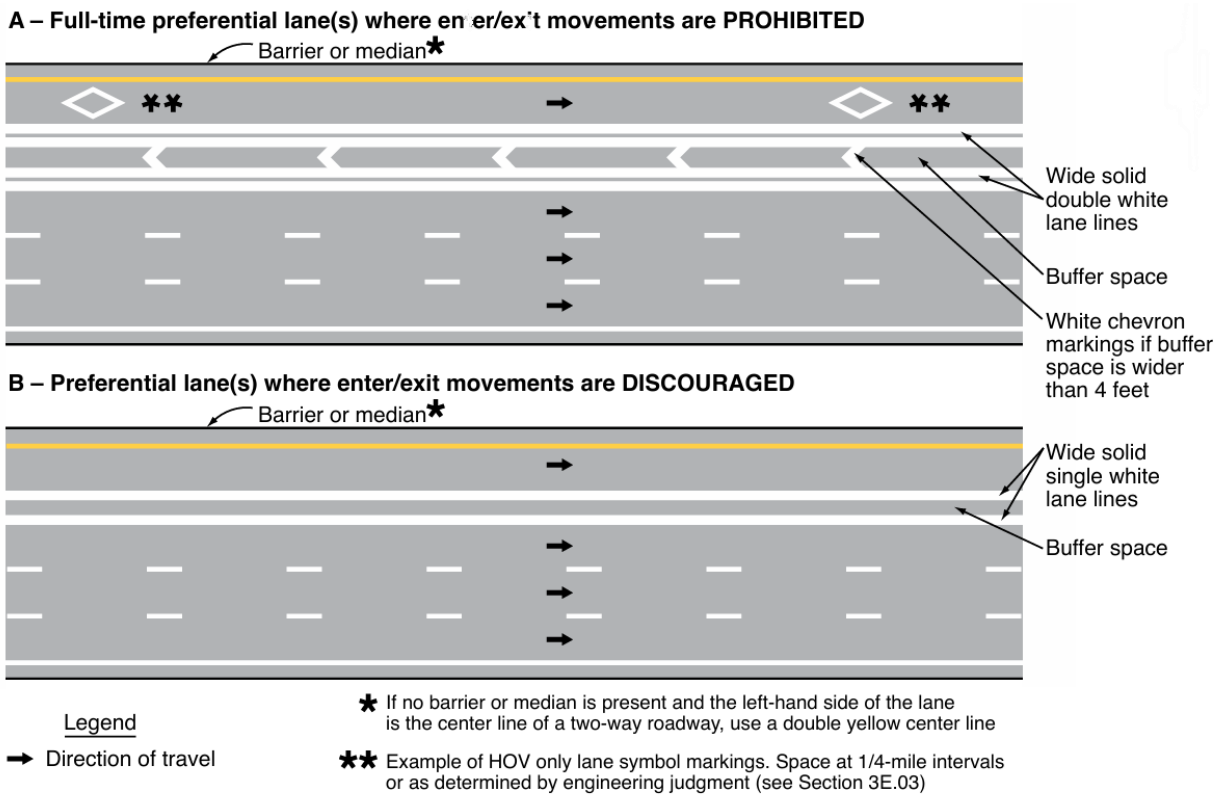


Figure 2.4: Markings for Buffer-separated Preferential Lanes (FHWA, 2023)

2.3 Existing Guidelines

2.3.1 Guidelines Specific to Separation Types

Research has established that the primary safety concern on facilities with managed lanes revolves around the speed differentials existing between the managed lanes and the general-purpose lanes (Neudorff et al., 2011). The authors contend that although safety guidelines have traditionally favored employing barrier separation between concurrent traffic streams as the safest approach, research findings on crash rates fail to fully support this stance. The FHWA furnishes design standards and guidelines for a majority of the managed lanes components. In addition, various states have established their own design requirements for managed lanes, such as the *HOV Guidelines for Planning, Design, and Operations, the Traffic Operations Policy Directive* by California Department of Transportation (Caltrans), and the *MnPASS Lanes Design and Implementation Guidelines* by Minnesota Department of Transportation (MnDOT). Further insights into guidelines on managed lanes separation types, derived from pertinent literature, are provided in the following sections.

2.3.2 Pylons

Pylons, also known as tubular markers or tubular delineators, can be used in buffer separated managed lanes as a series of highly visible, reflective, lightweight plastic tubes. Two primary types of pylons have been used in managed lanes facilities: pylons affixed to a mountable plastic raised curb, and individual plastic pylons attached to the roadway with adhesive, as shown in Figure 2.5(a) and Figure 2.5(b), respectively. Other than deciding whether to use a curb-mounted pylon or a pavement mounted assembly, key considerations in deploying pylons as a managed lanes separation treatment include:

- pylon spacing,
- buffer width,
- pylon height,
- pylon color and retro-reflectivity for nighttime visibility, and
- running length (mostly for freeway ramp to frontage road installations).

Considerations extracted from the *Guidance for effective use of pylons for lane separation on preferential lanes and freeway ramps* report by Kuchangi et al., (2013) are summarized in the following subsections.

(a) Mountable Raised Curb Pylon Separation on the I-95 Express

(b) Individual Pylon Separation on the SR-91 Express Lanes

Figure 2.5: Types of Pylons (Tubular Delineators) (Perez et al., 2012)

2.3.2.1 Longitudinal Pylon Spacing

On roadway segments with a history of a high number of crashes or a high rate of violations, a spacing of 10 ft is recommended. On roadway segments where strict enforcement is provided and violations are minimal, a larger pylon spacing of up to 20 ft may be considered. Near the entry and exit access locations on managed lanes, a minimum of 10 ft spacing is recommended. The first few pylons at access locations on managed lanes are the ones most hit by motorists. For freeway ramp-frontage road lane separation or access restriction applications, a pylon spacing of 6 ft is acceptable in most cases. The spacing of 3 ft may be used to provide a more restrictive barrier configuration to deter motorists from crossing the pylons. When curb-mounted pylons are used, drainage requirements at a specific site may influence the minimum spacing between the pylon units.

2.3.2.2 Buffer Width

Placement of pylons resulting in a 4 ft to 8 ft distance from pylon to the edge of travel lane should be avoided. Providing 4 ft to 8 ft of the shoulder is discouraged, as a vehicle taking refuge on a shoulder of that width partially encroaches on the adjacent travel lane, but not so much as to slow vehicle speeds in the travel lane. When buffer width is more than 10 ft on one side of the pylons, it may be confused as a travel lane. If geometry allows, larger buffer width on curves is recommended, with an unbalanced buffer provided as needed for more encroachment space on curves (e.g., buffer on the right side of a curve when the curve is to the left and pylons are on the right; or buffer on the left side of a curve when the curve is to the right and pylons are on the left).

2.3.2.3 Pylon Height and Color

The MUTCD states that the tubular markers shall not be less than 28 inches in height when used on freeways or other high-speed facilities (FHWA, 2009). Agencies were found to commonly use 36-inch, 42-inch, and 48-inch pylons for lane separation applications. Florida recommends the use of 24-inch at locations where stopping sight distance criteria cannot be met with markers that are 36 inches in height (FDOT, 2023). White, yellow, and orange pylon posts have been typically used for lane separation and channelization applications on roadways.

2.3.3 Concrete Barrier Separation

Barrier separation involves separating the managed lanes from the general-purpose lanes using a rigid barrier, such as a concrete barrier. Shoulders are provided on both sides of the barrier. Physical barriers are preferred for priced managed lanes, as they provide better access control and are more effective at reducing violations. They include continuous concrete barrier walls or movable barrier walls separating the managed lanes from the general-purpose lanes (FDOT, 2023).

Concrete barrier separations, unlike buffers, require extra shoulder space to allow for the removal of incapacitated vehicles, the passage of emergency vehicles, and the clearance of incidents from the general flow (Michael, 2011). Hlavacek et al., (2007) suggest that, among delineation techniques, barriers have a unique property, in that they are unaffected by speed differentials. Because errant drivers cannot simply cross the barrier at any time, users of the managed lanes are likely to feel much more comfortable with a higher speed differential. Barriers are, therefore, the delineation technique of choice for congested freeways. Barrier-separated lanes need to have a sufficient cross-section to allow drivers to get out of the way of an incident. For barrier-separated facilities, 18 ft is suggested as an absolute minimum, amounting to a 12-ft lane, a 4-ft shoulder on one side, and a 2-ft shoulder on the other. A range of 22 ft to 26 ft is considered ideal: 12-ft main lane, one 8-ft shoulder, and one 2-ft shoulder (Hlavacek et al., 2007). If this amount of space is available, the barrier is the preferred delineation technique. The FHWA's *A Guide for HOT Lane Development* suggests that 18 ft, consisting of a 12-ft travel lane, 4-ft shoulder, and 2-ft barrier, is the minimum amount of room needed for a barrier-delineated facility. The guide adopts the NCHRP 414 and several managed lanes current practices nationwide. Figure 2.6 shows the typical cross-section for express lanes in Florida (FDOT, 2018).

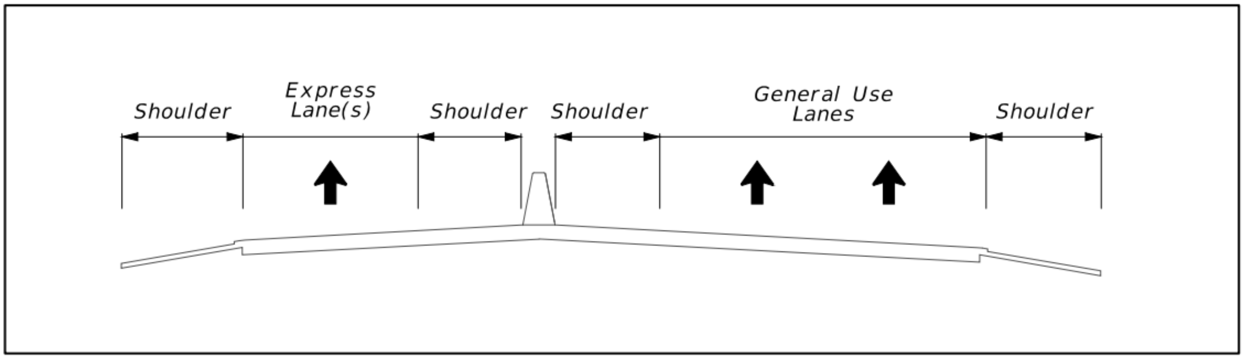


Figure 2.6: Express Lanes Barrier Separation Typical Section (FDOT, 2018)

2.3.4 Pavement Marking

Pavement markings are simple to install, inexpensive, and blend well aesthetically with the markings between other lanes (Hlavacek et al., 2007). FDOT's *Managed Lanes Guidebook* (FDOT, 2023) mentions that the references available to assist in the design of express lane pavement markings are the MUTCD, the FDOT TEM, *Turnpike Plans Preparation and Practices Handbook* (TPPPH) guide drawings, and FDOT's Design Standards. Within the MUTCD, express lanes are referred to as priced managed lanes, and pavement marking guidelines are categorized under Chapter 3D – *Markings for Preferential Lanes*. When a general-use lane transitions directly into an express lane, it is recommended that pavement messages reading "EXPRESS" and "ONLY" be placed in advance of express lane access points. These messages should be placed with overhead advance guide signs.

2.4 Human Factors and Driver Behavior

Human factors and driver behavior represent integral components in the realm of transportation and road safety, exerting profound influence on various aspects. From design perspectives, considering human factors ensures that transportation systems are user-centric, accommodating human capabilities and limitations (Sajan & Ray, 2012; Stanton et al., 2005). Meanwhile, driver behavior plays a pivotal role in determining road safety outcomes (Abbas et al., 2012). Adhering to safe practices such as following traffic rules, maintaining proper distances, and avoiding distractions significantly reduces crash risks. Conversely, risky behaviors such as aggressive driving and impaired driving escalate these risks (Kelley-Baker et al., 2021). Human cognitive factors, including attention, memory, and decision-making, shape how drivers interact with their environment (Sajan & Ray, 2012). Social influences and technological interfaces further affect driver choices (Carter et al., 2017; Young et al., 2017). Recognizing the significance of human factors and driver behavior is essential for fostering safer roadways and more effective transportation systems.

Human factors encompass a wide array of psychological, physiological, and cognitive attributes that influence how individuals interact with their driving environment (Jin et al., 2021). These factors range from perceptual processes and decision-making to attention allocation and situational awareness. Driver behavior, on the other hand, refers to the actions, choices, and reactions of individuals behind the wheel, influenced by a complex interplay of human factors and external stimuli (Jin et al., 2021; Sajan & Ray, 2012). Understanding the dynamic relationship between human factors and driver behavior is crucial for designing roadways, vehicles, and traffic management systems that align with the cognitive and perceptual capacities of drivers. Moreover, insights into how human factors shape driver behavior contribute to the development of effective interventions, policies, and technologies aimed at enhancing road safety, optimizing traffic flow, and creating a more harmonious and secure driving experience for all road users (Carter et al., 2017).

Human factors and driver behavior are closely intertwined concepts within the field of transportation and road safety, yet they have distinct focuses and functions. Human factors directly influence driver behavior. Factors such as attention, perception, memory, decision-making, and stress response all impact how a driver behaves on the road (Jin et al., 2021). For example, a driver's ability to perceive road signs, react to unexpected events, and manage distractions is heavily influenced by their cognitive processes, which fall under the domain of human factors (AASHTO, 2010). Driver behavior, in turn, is the observable actions, choices, and responses of individuals while driving. It encompasses how drivers follow traffic rules, make lane changes, merge onto highways, and interact with other road users. Driver behavior is the practical manifestation of the underlying human factors at play. If a driver is fatigued (a human factor), their behavior might include slower reaction times or an increased likelihood of drowsy driving (AASHTO, 2010; Abbas et al., 2012; Jin et al., 2021).

On their differences, human factors primarily delve into the psychological and physiological aspects of drivers, studying how human limitations and capabilities interact with the driving task, while driver behavior focuses on the observable actions and decisions of drivers, examining how they interact with the road and other vehicles (Abbas et al., 2012; Sajan & Ray, 2012). Human factors extend beyond just driving behavior, encompassing broader aspects of human-machine interaction and designing interfaces that accommodate human limitations (e.g., designing dashboard displays for optimal clarity), while driver behavior specifically pertains to actions related to operating a vehicle within a traffic environment (Young et al., 2017). Human factors research informs the design of vehicles, roadways, and traffic management systems to ensure they are user-friendly and aligned with human capabilities. Insights from driver behavior studies can lead to interventions, policies, and technologies aimed at improving road safety, such as campaigns against distracted driving or implementing adaptive cruise control systems (Abbas et al., 2012). As outlined in Figure 2.7, human factors include aspects such as cognitive processes, perception, decision-making, attention, workload, ergonomics, and user experience (Inman et al., 2017).

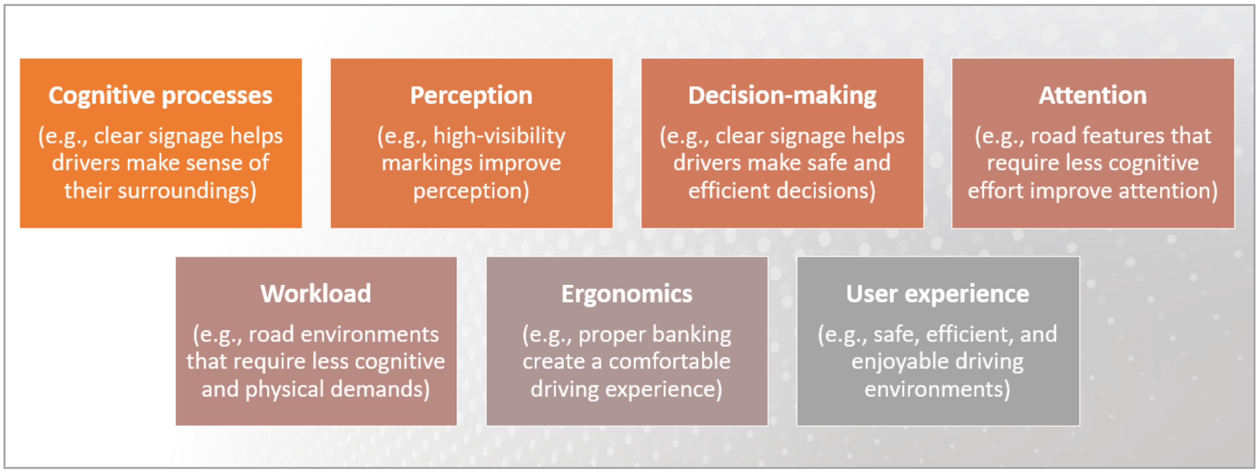


Figure 2.7: Human Factors

Driver behavior focuses specifically on how individuals operate vehicles within the context of traffic and road conditions. It involves studying the actions, choices, and responses of drivers while driving, including how they adapt to changing situations, follow traffic rules, and interact with other road users. Driver behavior encompasses a range of factors, such as speed choice, lane changing, following distance, reaction to unexpected events, use of signals, adherence to traffic laws, and risk-taking tendencies. Research on driver behavior aims to understand why drivers of all ages make certain decisions and how those decisions impact road safety and traffic flow. For example, studying driver behavior can help identify patterns of aggressive driving, distracted driving, or other risky behaviors that might contribute to crashes or congestion (Abbas et al., 2012; Kelley-Baker et al., 2021). Figure 2.8 lists examples of driver behavior.

Figure 2.8: Driver Behavior

In the dynamic realm of facilities with managed lanes, a sophisticated interplay between human factors and driver behavior takes center stage, underlining their paramount significance in the realms of design, operation, and safety (Abou-Senna et al., 2019; Kuchangi et al., 2013). These controlled lanes, featuring a range of lane types and access options, necessitate a deep understanding of how human cognition, perception, and decision-making patterns influence the actions of drivers. Simultaneously, the observed driver behavior within managed lanes provides invaluable insights into the real-world application of human factor principles, guiding the optimization of operational procedures and safety measures. Recognizing the intricate connection between human factors and driver behavior is essential for crafting managed lane systems that seamlessly accommodate human capabilities, mitigate potential risks, and ultimately foster a safer and more efficient driving experience for all.

The subsequent sections delve into specific components of human factors and driver behavior that have undergone investigation within the context of managed lane facilities. The literature review is presented through the exploration of three distinct facility types:

a) Facilities with pavement marking separation: This section scrutinizes the effects of pavement marking separation (e.g., double solid lines buffer) between managed lanes and general-purpose lanes on driver behavior. By investigating how this design feature impacts compliance, merging, and overall traffic flow, a comprehensive understanding of the human factors at play in these environments emerges. The analysis sheds light on the decisions made by drivers when presented with buffer-separated managed lanes, contributing to the broader conversation on optimizing design for enhanced safety and efficiency.

b) Facilities with pylons separation: Within this section, the focus shifts to the influence of pylons as separation treatment in managed lane facilities. By studying human factors and driver behavior in the presence of pylons, valuable insights can be gained regarding the effectiveness of visual delineators in shaping driver behavior and optimizing managed lane operation.

c) Facilities with concrete barrier separation: The third section delves into the intricate relationship between human factors and driver behavior in managed lane facilities featuring concrete barrier separation.

Through these three distinct sections, the literature review systematically explores the multifaceted interactions between human factors and driver behavior in managed lane facilities, offering valuable insights into the complexities of design, operation, and safety considerations.

2.4.1 Facilities with Pavement Marking Separation (Buffer)

2.4.1.1 Non-compliance with Pavement Markings

Non-compliance with pavement markings behavior in managed lane facilities presents a compelling case study within the broader realm of human factors and driver behavior. These facilities, designed to optimize traffic flow and enhance transportation efficiency, often incorporate pavement markings that denote lane types, access points, and regulations. The phenomenon of non-compliance, where drivers deviate from these designated markings, underscores the intricate interplay between human cognitive processes, situational awareness, and decision-making in dynamic driving environments. Non-compliance with pavement markings can manifest in various ways, such as unauthorized lane changes, illegal lane usage, or failure to adhere to specific access points. This behavior may stem from a range of factors rooted in human factors. Cognitive load, for instance, can impact a driver's ability to process and follow intricate pavement markings, particularly in congested or rapidly changing traffic conditions. Inadequate comprehension of the significance of specific markings, perhaps due to insufficient road user education, can also contribute to non-compliance.

Additionally, the presence of other drivers, cognitive biases, and perceived time pressure can influence driver behavior, potentially leading to deviations from pavement markings (Guin et al., 2008). Non-compliance may result from risk perception or social factors, where drivers perceive an advantage in disregarding markings to reach their destination faster or avoid congestion (Corey & Hallenbeck, 2011). Understanding the drivers non-compliance with pavement markings requires a comprehensive analysis of human factors and their impact on driver decision-making. It necessitates consideration of how visual perception, attention allocation, and cognitive processes interact with the design and layout of managed lane facilities. Mitigating non-compliance entails optimizing pavement marking visibility, implementing effective driver education, and employing traffic management strategies that align with human capabilities and tendencies.

An observational study in Texas on limited intermediate access to buffer-separated HOV and HOT lanes, discussed how drivers comply with the pavement markings when doing maneuvers (Fitzpatrick et al., 2008). The study revealed that approximately 9% of those moving into the HOV lane and 8% of those moving out of the HOV lane crossed the solid white markings (i.e., were not in compliance with the pavement markings). The percentage of non-compliance increased to about 15% during periods with low speeds (less than 40 mph) and high speeds (greater than 60 mph). The percentage of maneuvers in compliance with the pavement markings varied by the length of the intermediate access opening. The compliance rate was greater for the more extended access opening length (1500 ft) as compared to the 1160 ft access opening length.

Surprisingly, many maneuvers at the intermediate access openings involved vehicles passing slower-moving vehicles. Over 7% of all maneuvers involved a passing vehicle. At the two sites with more data, between 40% and 80% of the passing vehicles involved a vehicle leaving the HOV lane to pass a slower vehicle in the HOV lane. The proportion of passing maneuvers was statistically related to the 5-minute HOV lane volume count. As the HOV lane volume increases, the proportion of passing maneuvers initiated from general-purpose lanes decreases. Depending upon a site's characteristics, providing a passing lane within a one-lane managed-lane facility could improve service.

Non-compliance with pavement markings in managed lane facilities carries significant consequences that impact both individual drivers and the broader transportation ecosystem. Deliberate or inadvertent deviations from designated markings can disrupt the intended traffic flow, increase the risk of collisions, and undermine the overall safety of the facility. This behavior can lead to erratic lane changes, unpredictable merging patterns, and potential conflicts among vehicles. Furthermore, non-compliance may result in reduced operational efficiency, congestion, and delays, negating the intended benefits of managed lane systems. Addressing non-compliance becomes crucial to ensure smooth traffic operations, enhance road safety, and optimize the effectiveness of these specialized facilities.

A review of 1,150 crash reports from two buffer-separated HOV lanes in Texas unveiled distinct patterns of crash characteristics that shed light on the ramifications of non-compliance with pavement markings. The analysis highlighted key trends involving crashes between the HOV lane and the adjacent general-purpose lane (Lane 1) (Cothron et al., 2004):

- Instances were observed where vehicles on Lane 1, seeking to avoid suddenly stopped general-purpose traffic, hastily maneuvered into the HOV lane. This swift lane change led to collisions with fast-moving vehicles in the HOV lane, resulting in potentially severe crashes.
- A significant trend emerged as vehicles made sudden transitions from the HOV lane to Lane 1, only to be met with rear-end collisions from vehicles in Lane 1 unable to decelerate in time. The failure to adhere to designated markings, compounded by the velocity differential between the two lanes, contributed to these incidents.
- The study uncovered cases of illicit lane changes, characterized by drivers crossing the double white line, occurring outside proper access points. These unauthorized maneuvers triggered both rear-end and sideswipe collisions, emphasizing the peril of non-compliance with delineated markings.
- Particularly in densely congested scenarios, vehicles navigating Lane 1 endeavored to ingress into the HOV lane while maintaining lower speeds. However, these attempts to merge at dissimilar velocities led to collisions with faster-moving vehicles in the HOV lane, underlining the potential hazards of non-compliance, especially in high-traffic situations.

These findings underscore the far-reaching consequences of disregarding pavement markings in managed lane facilities. The scenarios depicted in this case study offer compelling evidence of the profound impact that non-compliance can have on traffic flow, collision rates, and overall road safety within these specialized environments.

2.4.1.2 Vehicle Position Within a Lane

In managed lane facilities, drivers may shift their vehicle position for a variety of reasons. Visibility and sight lines remain crucial, particularly when navigating unique lane configurations or access points. Based upon the findings from a single site, a study conducted in Texas revealed that vehicles appeared to be shifting their position within the HOV lane and the lane adjacent to the HOV lane in response to the pavement markings (Fitzpatrick et al., 2008). Figure 2.9 illustrates the findings for the condition when only passenger cars are present. The dot and its associated distance value provide the average lane position for the edge of the vehicle. For example, at Location 1, vehicles in Lane 3 are an average of 2.60 ft from the lane line. The error bars extending from the dot represent one standard deviation of the data. The study found that vehicles in the lane next to the HOV lane shifted towards the buffer pavement marking by an average of 1.15 ft from the first line of pavement markings (Location 2). In the HOV lane, vehicles shifted away from the buffer pavement marking by an average of 2.08 ft from the edge of the pavement marking (Location 2).

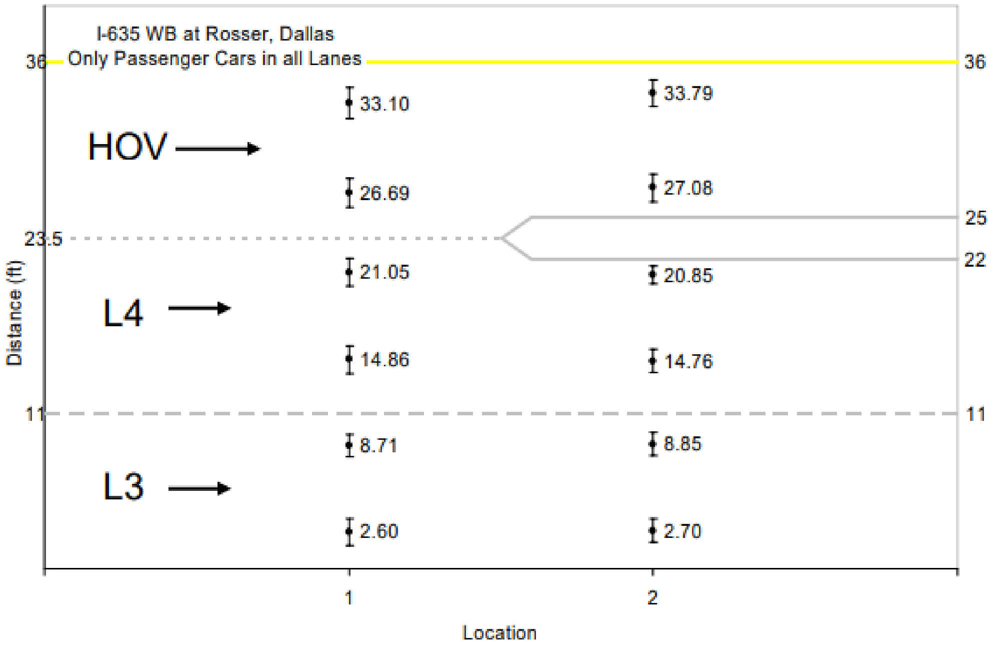


Figure 2.9: Vehicle Position Within a Lane (Fitzpatrick et al., 2008)

2.4.1.3 Occupancy Requirement Violation

Occupancy requirement violations within facilities with managed lanes provide a vivid illustration of driver behavior. When drivers intentionally or inadvertently breach occupancy requirements, which stipulate the minimum number of occupants needed to access lanes, their actions are influenced by human factors such as perceived convenience, time-saving incentives, and social norms. The decision to violate occupancy requirements is a manifestation of driver behavior that reflects the evaluation of personal benefits against potential risks, all of which are rooted in underlying cognitive and psychological processes. As such, the analysis of occupancy requirement violations offers a nuanced understanding of how human factors shape driver decisions and influence their compliance with designated lane use regulations in managed lane facilities.

A study conducted in Tennessee revealed an alarming 84% rate of occupancy violations on HOV lanes, indicating a prevalent misuse of these lanes by single occupancy vehicles (SOVs). The study highlighted the inefficacy of the HOV lanes in the Nashville region, attributing it to factors such as inadequate enforcement (Chimba & Camp, 2018). The reasons behind drivers flouting occupancy requirements in HOV lanes are diverse. Some seek convenience and time-saving benefits, while others may be unaware of the regulations or aim to evade penalties. In regions with lenient enforcement, drivers might take risks by disregarding the rules. The adoption of deceptive strategies like employing dummy passengers further compounds the issue. Factors such as a lack of awareness, a perceived low risk of detection, and unexpected emergencies can all contribute to this behavior. To rectify the situation, it is imperative to institute robust enforcement measures and launch comprehensive public awareness initiatives. These actions are vital for upholding the intended purpose and efficiency of HOV lanes (Chimba & Camp, 2023).

2.4.1.4 Decision Distance

In the realm of transportation research, the concept of decision distance has garnered significant attention due to its profound impact on driver behavior and overall road safety. This aspect intersects the domains of human factors and driver behavior, making it a focal point in the design and operation of managed lanes. Whether short or extended, the decision distance is a pivotal factor directly influenced by human cognitive processes. Research has consistently demonstrated that shorter decision distances tend to induce rushed decision-making and erratic behaviors, potentially compromising road safety. Conversely, longer decision distances afford drivers more time to process information, make calculated decisions, and execute maneuvers with a higher degree of control. This intricate interplay between human factors and driver behavior within the context of decision distances underscores its significance in the design of managed lanes. By ensuring appropriate decision distances, transportation planners and policymakers can mitigate the risks associated with abrupt lane changes, missed exits, and potential collisions, thus creating safer and more efficient road networks (Machumu et al., 2017).

In a field study conducted in Texas, researchers observed vehicles weaving across all general-purpose lanes and merging into the HOV lane from a ramp located just upstream of the intermediate access lane. The access opening began approximately 100 feet beyond the end of the ramp gore. A vehicle would have to make five lane changes of approximately 250 feet per lane to enter the HOV lane near the end of the access opening, which is a distance much less than the values currently recommended in design guides. The study also found that 2.5% of ramp vehicles failed to enter the HOV lane, and many drivers who attempted the ramp-to-HOV lane maneuver crossed buffer pavement markings.

2.4.1.5 Speed Choice and Differential

The speed differential in managed lanes, where vehicles within these lanes often travel at higher speeds compared to adjacent general-purpose lanes, can be attributed to several factors. This disparity in speeds can be attributed to various factors, including the specialized nature of managed lanes (e.g., occupancy requirement, toll), the incentives for using them, and the differing traffic compositions. While speed differential is commonly expected due to the desire to maintain a better level of service in managed lanes (Buckeye, 2014), studies have shown that, it rarely exceeds 20 mph (Guin et al., 2008). Figure 2.10 gives the first indication of a limit to the speed difference at which HOV drivers are willing to travel with their neighboring lanes. However, balancing speed differentials and ensuring safe travel remains a critical consideration for managing managed lane systems.

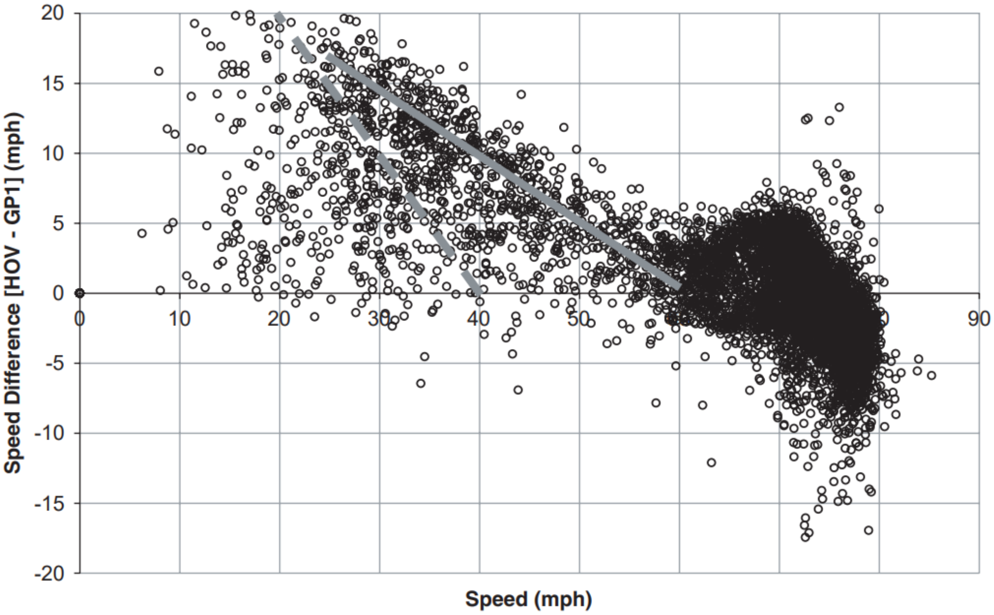


Figure 2.10: Speed Difference Between HOV Lane and GP1 Lane Versus GP1 Lane Speed (Guin et al., 2008)

One significant aspect, a human factor and driver behavior, is the perceived advantage of using managed lanes for quicker travel, encouraging some drivers to exceed speed limits in these lanes. Research has shown that drivers might interpret managed lanes as providing an opportunity to save time, leading to a tendency of speeding. This behavior is reinforced by the notion that managed lanes offer a premium, high-speed travel experience for which drivers are willing to pay or meet specific occupancy requirements (FHWA, 2008).

2.4.2 Facilities with Pylons Separation

2.4.2.1 Color of Pylons

Pylons are an integral component of transportation infrastructure, strategically positioned to separate managed and general-purpose lanes. While their primary function revolves around functional delineation, the color of these pylons significantly taps into the realm of human factors, substantially influencing driver behavior and yielding noteworthy implications for traffic management and road safety (Abou-Senna et al., 2019). The selection of pylon color emerges as an influential determinant of driver behavior, profoundly enhancing lane recognition and swift comprehension of distinct traffic flows. Through the use of a distinctive and consistent color palette for pylons, drivers swiftly discern the transition into lanes with unique features. This heightened visual prompt empowers drivers to intuitively adapt their choices to specific circumstances. A well-defined and instantly recognizable color scheme on these pylons serves as an authoritative guide during lane changes. This promotes smoother and safer transitions, mitigating the potential for abrupt maneuvers that might otherwise disrupt traffic flow and compromise road safety. It's important to acknowledge that the impact of color goes beyond behavior; it pertains to fundamental human perceptual processes. Thoughtful consideration is imperative, ensuring that chosen colors harmonize with established standards. Suboptimal color decisions could lead to confusion, lane encroachments, and heightened on-road risks.

A study in Florida showed that white was the optimal and most significant color for driver awareness, performance, and notice of the express lane markers, in both the objective and subjective tests, followed by yellow, with black being the least desirable (Abou-Senna et al., 2019). Based on the parameters, the results indicated that most drivers noticed the white pylons consistently before entering the express lanes. The highest miss rates were for the black markers. The results showed that black markers consistently showed high significance and low optimality. White and yellow markers consistently had high significance and high optimality among all the models, with white always outperforming yellow except in the case of lane deviation. Purple and orange markers only appeared to be effective occasionally (Abou-Senna et al., 2019).

2.4.2.2 Vehicle Position Within a Lane

In the context of express lanes in Florida, an intriguing pattern emerges in how drivers of different age groups position themselves within the lane. Notably, as drivers make their entry into express lanes, a distinct trend becomes apparent: they tend to be farthest from the white and yellow pylons, signifying a heightened sense of awareness and attention. This observation underscores the impact of visual cues on driver behavior, with these vibrant colors potentially serving as attention-grabbing markers that encourage drivers to position themselves in a manner that aligns with the intended use of the express lane. Furthermore, a closer examination of driver behavior reveals an interesting nuance among different age groups. Specifically, the 18-39 age group tends to position themselves closer to the center of the lane when compared to other age cohorts. This observation suggests a potential difference in driving habits and perceptions based on the driver’s age. Whether influenced by a desire to maintain a central lane position or other underlying factors, this behavioral tendency among younger drivers highlights the intricate interplay between age, perceptual cues, and lane utilization strategies (Abou-Senna et al., 2019).

Table 2.2 shows the mean and standard deviations of the vehicle’s lateral position for each of the age groups and lane configurations. From a design standpoint, the driver’s chosen position within a lane is one of the most crucial factors to be considered. Lane deviations beyond 3 feet in either direction (positive or negative) reflect a condition where the vehicle is outside of its lane markings and beginning to exhibit unsafe behavior. Drivers that position themselves too far to the right (positive lane deviation) are approaching or overrunning either the pylons or the adjacent traffic stream. The findings presented in Table 2.2 reveal noteworthy disparities in the lateral positioning behavior of vehicles, shedding light on age group distinctions and variations between single and double lane configurations, both at the entry (beginning) and midpoint of the express lanes. Across all scenarios, the mean lateral position consistently leans towards the left side of the lane (negative lane deviation), indicating a tendency for vehicles to position farther from pylons. The age-related distinctions are evident, with younger drivers (18-39 age group) exhibiting a comparatively smaller negative mean lateral position, suggesting a preference for slightly center-oriented positioning. Conversely, middle-aged drivers (40-64 age group) show a more pronounced leftward bias in their vehicle positioning. Furthermore, the choice between single and double lanes influences lateral placement, with vehicles in single lanes tending to position farther leftward than those in double lanes. These findings are crucial for informed road design and safety measures, as they underscore the need for tailored approaches considering age group and lane configuration differences to enhance road safety and prevent vehicles from veering beyond lane boundaries.

Table 2.2: Lateral Lane Position (Tice et al., 2020)

Age Group	Statistic	Single Lane		Double Lane	
		Beginning	Midpoint	Beginning	Midpoint
Overall (n = 681)	Mean	-1.50909	-1.52992	-0.25441	-0.16787
	SD	1.641672	1.383731	1.389386	1.267266
18-39 (n = 252)	Mean	-1.16217	-1.41355	-0.25871	-0.29903
	SD	1.225611	1.448099	1.353638	1.23979
40-64 (n = 223)	Mean	-1.53657	-1.75691	-0.39677	-0.06937
	SD	1.213262	1.170598	1.47819	1.233898
65+ (n = 206)	Mean	-1.90373	-1.42656	-0.09505	-0.11406
	SD	2.274791	1.482578	1.314276	1.321412

Note: All values shown are in feet.

These findings shed light on the multi-faceted nature of driver behavior within the context of express lanes. The inclination of drivers to position themselves differently based on age and their responsiveness to the visual cues provided by pylons underscores the dynamic interplay between human factors, visual stimuli, and decision-making on the road. This insight is not only relevant for optimizing express lane operations but also emphasizes the broader implications for road safety and traffic management, further underscoring the importance of understanding and accommodating the diverse factors that influence driver behavior.

2.4.2.3 Lane Diving

In managed lane facilities with pylons, "lane diving" refers to the behavior where drivers cut through pylons to move between managed and general-purpose lanes, often to take advantage of specific benefits or avoid certain conditions or tolls. Research has established that the motivations behind lane diving can vary widely and are often rooted in individual preferences, needs, and perceptions. For instance, a driver might dive into an express lane to take advantage of higher speed or bypass congestion. Similarly, lane diving could involve entering just after the tolling point and exiting before the next tolling point to avoid paying the toll. This decision-making process is influenced by cognitive factors, such as risk perception, time-saving incentives, and social norms, all of which contribute to the ultimate choice to engage in lane diving behavior.

The implications of lane diving on safety cannot be overstated. Abrupt lane changes and maneuvers contribute to an increased risk of collisions, disruptions in traffic flow, and compromised road safety. The unpredictable nature of lane diving introduces an element of unpredictability that can lead to rear-end collisions, sideswipes, or other traffic incidents. For example, lane diving risky behavior has led to numerous arrests and fatal crashes in Florida (WLRN, 2015). The March 5, 2011, fatal crash underscored concerns about the design and safety of the I-95 express lanes, particularly the narrow shoulder and the challenges of enforcing regulations and preventing dangerous driving behaviors. The author reported that some are discouraged from riding next to the pylons if they are in the express lane (WLRN, 2015).

2.4.2.4 Speed Choice and Differential

Facilities with pylons have observed a speed differential between vehicles in those lanes and adjacent general-purpose lanes. This disparity has accelerated lane diving, a dangerous driving behavior, according to a report. Master Trooper William Smith stated that lane diving is particularly hazardous when one set of lanes is moving quickly, and others are not. Before the express lanes and pylons, I-95 had one HOV lane separated by a strip of paint, avoiding the dangerous differences in speed (WLRN, 2015).

2.4.2.5 Older Drivers

Research has also documented the human limitations of aging drivers related to a decline in depth perception, contrast sensitivity, and phoria in managed lane facilities with pylons. One study in Florida delved into the challenges faced by older drivers when navigating express lanes separated from general-purpose lanes by pylons, highlighting the gradual perceptual changes that come with age and their consequential impact on driving behavior (Tice et al., 2020). The study revealed that older drivers (65 years and older), who often experience gradual perceptual declines, exhibit slower speeds and increased lane deviations in express lanes. It highlighted the need for design adaptations in areas with a high population of older drivers, such as Florida. These adaptations include widening single lanes and increasing buffer widths to accommodate age-related cognitive and perceptual limitations. The study recommended incorporating these design considerations, so the safety of single-lane express lanes could be improved for older drivers. It also recommended expanding buffer areas between lanes and pylons to mitigate potential crashes. In essence, the research underscored the critical importance of accounting for the unique characteristics of older drivers in the design and implementation of express lanes to ensure their safety and optimize their driving experience (Tice et al., 2020).

2.4.2.6 Occupancy Requirement Violation

Similarly, occupancy requirement violations occur in managed lanes separated from general-purpose lanes by pylons, as seen in the SR-91 Express Lanes in California. The violation rates along this facility range approximately 8%, with variations depending on the time of day and season. On the 91 Express Lanes, visual enforcement is performed at three locations where the median was widened to accommodate a vehicle. Pylons separate the Express Lanes from the SR-91 mainline lanes, with no intermediate access locations between the eastern and western entry points of the facility. The entry points have a dedicated HOV3+ lane and an Express Lane. Only eligible HOV3+ vehicles can enter the HOV3+ lane; these vehicles are charged a half-toll (Sas et al., 2007).

2.4.3 Facilities with Concrete Barrier Separation

2.4.3.1 Lane Diving

Research has established that concrete barriers provide better access control and are more effective at reducing violations, such as lane diving (Michael, 2011). They include continuous concrete barrier walls or movable barrier walls separating the managed lanes from the general-purpose lanes (FDOT, 2023).

2.4.3.2 Speed Choice and Differential

Speed differential is always expected in facilities with adjacent managed lanes, even those with concrete barriers. However, drivers tend to speed, as seen on I-4, resulting in an alarming number of crashes. In the initial days of the newly opened I-4 express lanes, officials reported no crashes, but they are concerned about some drivers excessively speeding, treating the lanes like a racetrack. Speeds as high as the 90s and even 101 mph in a 60-mph zone have been observed, including during the daytime. The Florida Highway Patrol issued 77 speeding tickets over the weekend following the opening of the lanes. Despite being called "express lanes," drivers are reminded that they still need to adhere to the posted speed limit of 60 mph for most of the 21-mile express lane stretch. Many drivers ticketed claimed they believed they could drive faster in these lanes. Lt. Kim Montes emphasized that drivers caught exceeding the speed limit by 30 mph or more would be required to appear before a judge who would determine the fine (Feiner, 2022).

2.4.3.3 Occupancy Requirement Violation

Similarly, occupancy requirement violations occur in managed lanes separated from general-purpose lanes by a concrete barrier, as seen in the I-15 Express Lanes in California. The violation rates along this facility range between 5% and 15%, with variations depending on the time of day and season. The I-15 Express Lanes is a reversible flow HOT lane that was expanded from an 8-mile facility to a 20-mile facility with multiple access points. However, the extended segment posed a major challenge for shoulder enforcement due to limited roadway geometry and restricted shoulders. To address this, more mobile enforcement capabilities and supporting reader technologies in mobile units were necessary for effective enforcement (Sas et al., 2007).

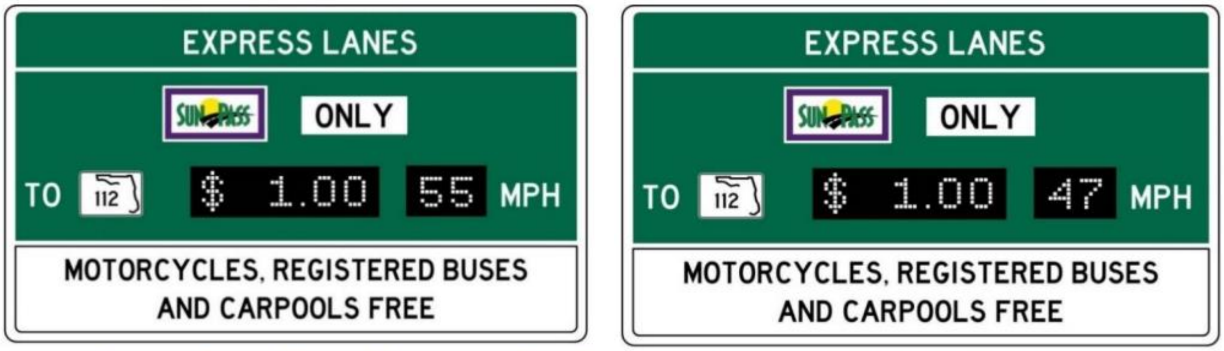
2.4.4 All Types of Managed Lane Facilities

2.4.4.1 Human Factor Considerations for Priced Managed Lane Traveler Information Systems

Navigating priced managed lanes can be challenging for travelers who have unique informational requirements. These needs often relate to specific managed lane features, such as access points and toll prices, as well as information about major traffic incidents and lane closures. Traditional roadway signage is not always sufficient to accommodate these needs, as it can overload and distract drivers, and some drivers may not comprehend the intention of the signs (Alluri et al., 2017). With traditional roadway signage, drivers require the needed information to navigate facilities with express lanes. Information overload can pose significant risks, as it overwhelms drivers with an abundance of data, reducing their attention, increasing cognitive load, inducing stress, and ultimately compromising safety (Chrysler & Nelson, 2009). The constant stream of information, such as dynamic pricing, lane-specific rules, and traffic updates, can lead to confusion, distraction, and reduced situational awareness, if presented in an unclear and overwhelmingly. This, in turn, can result in suboptimal decision-making, erratic driving behavior, and a higher likelihood of crashes. To mitigate these issues, it's essential for transportation authorities to design clear and concise information systems and promote driver education to help motorists navigate express lanes more safely and efficiently (Alluri et al., 2017).

As an example, transportation agencies often display travel time or average speed to help drivers decide whether to choose express lanes. A focus group study in Florida suggested that using average speed instead of travel time could provide better information for drivers to assess traffic conditions. Unlike travel time, which depends on distance and is only known to local drivers, average speed has a fixed range that is independent of distance. It is clear to all drivers that a low average speed on an express lane facility implies congestion, while a high average speed implies the opposite (Alluri et al., 2017).

However, the study revealed that some drivers misinterpret the average speed as the speed limit. About 61.2% of participants thought that 55 MPH was the speed limit on the express lanes, while only 34.7% correctly identified it as the average speed (Alternative A, Figure 2.11(a)). When the displayed average speed was not a multiple of five, the percentage of correct answers increased to 55.1% (Alternative B, Figure 2.11(b)). The study recommended using non-multiple-of-five average speeds to avoid confusion. Although the percentage of participants who misunderstood the speed values was considered high in both cases, it is expected that with time and driver education, the level of misinterpretation will decrease significantly (Alluri et al., 2017).

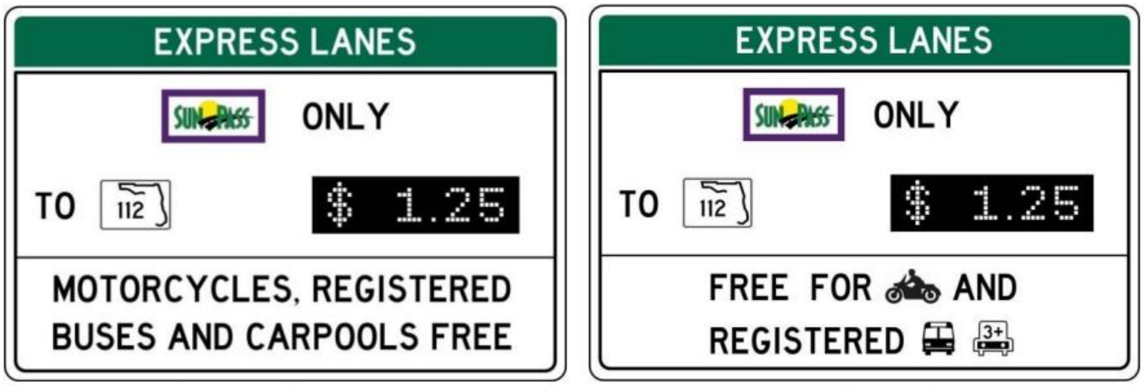


(a) Express Lanes Sign with Average Speed in Multiples of Five

(b) Express Lanes Sign with Average Speed not in Multiples of Five

Figure 2.11: Average Speed Information on Express Lanes Signs (Alluri et al., 2017)

According to a study on drivers' comprehension of toll-exempt vehicles on express lanes, 49% (24) of participants preferred Alternative A, while 51% (25) preferred Alternative B (Figure 2.12). The participants found Alternative A easy to understand, but it had too much information to read. Alternative B, on the other hand, could be recognized faster, but the symbols were difficult to understand, especially if they were small. The participants generally preferred the word "FREE" to be placed at the start of the sentence rather than at the end. Figure 2.12 shows the two sign alternatives for displaying toll-exempt vehicles on express lanes. Alternative A, which is an existing sign on the 95 Express, displays toll-exempt vehicles using words alone. Alternative B, the proposed alternative, displays this information using a combination of words and symbols.



(a) Alternative A (b) Alternative B

Figure 2.12: Sign Alternatives Displaying Toll-exempt Vehicles (Alluri et al., 2017)

The aforementioned instances emphasize the crucial role that clear signage and driver education play in improving the functionality and safety of express lanes.

In addition to signage, transportation agencies have leveraged technologies to furnish traveler information. The 2017 national review of practices revealed that many agencies have varying online availability of real-time traveler information. From a human factor perspective, a survey of 866 Texas-based respondents indicated that drivers prioritize information about traffic incidents and lane closures over toll price data. A higher share of respondents wanted to receive travel time and incident alerts on in-vehicle devices compared to destination and toll rate information on roadway signs. Most respondents use smartphone applications and mapping websites for pre-trip planning purposes, compared to TV and radio reports (Figure 2.13). Five years earlier, radio was found to be a highly influential media in influencing behavior. This study suggested that agencies adopt a flexible approach for sharing essential data with third-party entities, based on the general transit-feed specification used for transit. This will help travelers navigate priced managed lanes more efficiently and safely (Wood et al., 2018).

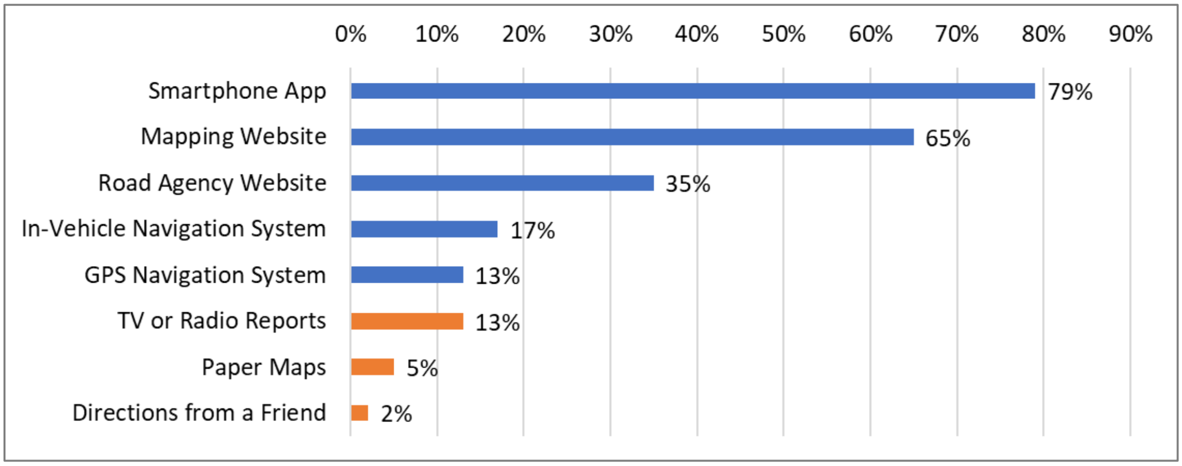


Figure 2.13: Use of Traveler Information (Wood et al., 2018)

2.4.4.2 Comparison Summary

Table 2.3 offers a comprehensive overview of the influence of human factors and driver behavior across various managed lane separation types. This summary reveals several noteworthy trends. First, occupancy requirement violations are a significant concern in all separation types, albeit to varying degrees. Lane diving and other illegal maneuvers affect driver behavior in managed lane facilities with pavement marking and pylons separations but are notably absent in concrete barrier. Additionally, driver behavior in terms of vehicle positioning within a lane is influenced by buffer pavement markings and pylons. Speed-related issues, particularly speeding problems and speed differentials are pervasive concerns across all separation types, with the exception of speed differentials not impacting risky driving behavior in concrete barrier separation. Moreover, optimal decision distances are deemed crucial for reducing risky driving behavior in all managed lane separation types. Lastly, the color of pylons is a noteworthy factor, with white being the preferred color for pylons. This comprehensive analysis equips transportation planners and policymakers with valuable insights for enhancing road safety and efficiency in managed lanes.

Table 2.3: Human Factors and Driver Behavior on Different Managed Lanes Separation Types

Human Factor/ Driver Behavior	Pavement Marking / Buffer Separation	Pylon Separation	Concrete Barrier Separation
Occupancy requirement violation, if HOV or HOT	• Highly affected by occupancy requirement violation	• Affected by occupancy requirement violation	• Affected by occupancy requirement violation
Lane diving	• Affected by lane diving and other illegal maneuvers and infractions	• Affected by lane diving and other illegal maneuvers and infractions	• Not affected by lane diving and other illegal maneuvers and infractions
Vehicle position within lane	• Vehicles in managed lanes shift away from the buffer pavement markings	• Vehicles in managed lanes shift away from the buffer pavement markings	• Not available
Speed choice and differential	• Speeding problem • Speed differential influences risky driving behavior	• Speeding problem • Speed differential influences risky driving behavior	• Speeding problem • Speed differential does not influence risky driving behavior
Decision distance	• Need optimum decision distance to reduce risky driving behavior	• Need optimum decision distance to reduce risky driving behavior	• Need optimum decision distance to reduce risky driving behavior
Color of pylons	• NA	• White is the optimal, followed by yellow and orange	• NA

Note: NA = Not applicable; HOV = High Occupancy Vehicle; HOT = High Occupancy Toll.

2.5 Driving Simulation

Driving simulators are a crucial tool in studying human factors and driver behavior in various road environments, including those with managed lanes. Since human factors research covers a range of topics, including visual attention to traffic control devices; distraction sources external to the vehicle; road signs and other traffic control devices' legibility, conspicuity, and comprehension; it becomes apparent that these datasets are hard to collect in the real world. Instead, numerous studies have been conducted using driving simulators to collect such rich data.

In managed lanes, by using driving simulators, researchers can study how drivers respond to the unique challenges posed by managed lanes, including lane changing, merging, and interacting with other vehicles. Simulators allow for the manipulation of different variables such as separation treatments, and traffic densities, facilitating an in-depth analysis of their impact on driver behavior. Additionally, driving simulator research provides insights into cognitive aspects such as driver workload, attention allocation, and risk perception within managed lane settings. Simulators allow for the observation of driver responses to sudden events or unexpected situations, shedding light on how well drivers adapt to the dynamic nature of managed lanes. Listed below are examples of studies that have shown the usefulness of driving simulators in different subjects of managed lanes:

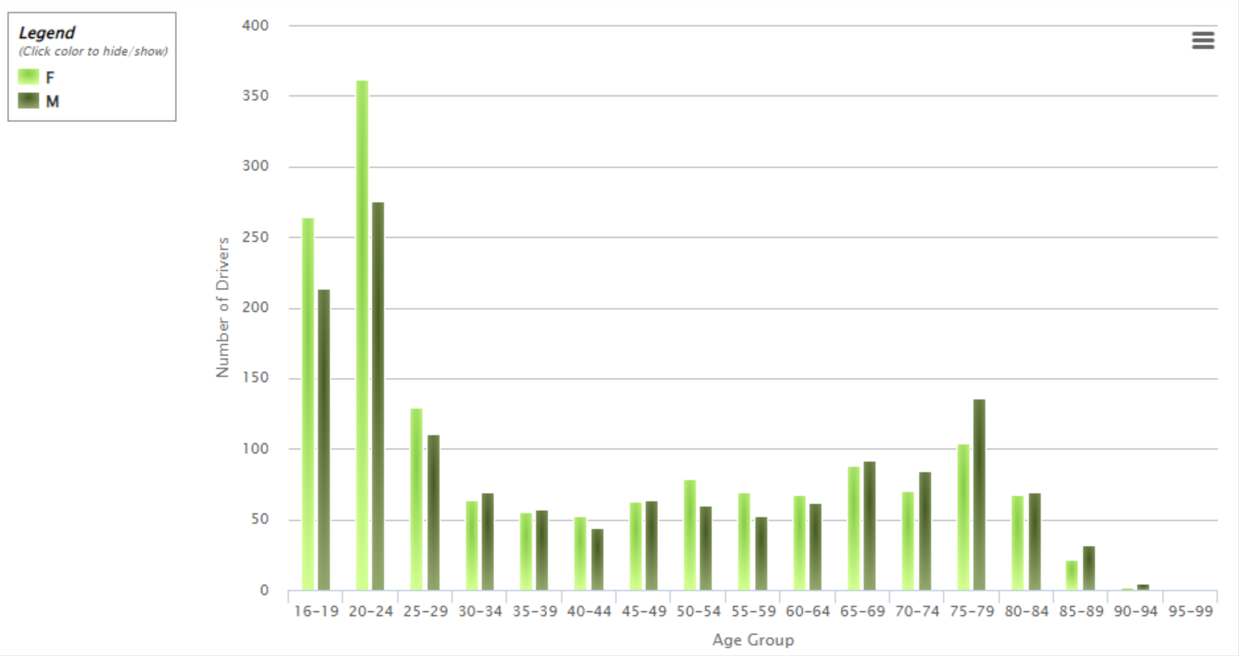
- Human factors study on the use of colors for express lane delineators (Abou-Senna et al., 2019)
- Analysis of driving behavior at expressway toll plazas using driving simulator (Saad et al., 2019)
- A driving simulator study to evaluate the effects of different types of median separation on driving behavior on 2 + 1 roads (Calvi et al., 2023)
- Car-following behavioral adaptation when driving next to automated vehicles on a dedicated lane on motorways: A driving simulator study in the Netherlands (Schoenmakers et al., 2021)
- Aging drivers and post delineated express lanes: Threading the needle at 70 miles per hour (Tice et al., 2020)

With these examples, driving simulators have played an even greater role in refining the understanding of human factors and driver behavior within managed lane facilities. Ongoing research can leverage driving simulators to delve deeper into nuanced aspects of managed lane interactions, such as exploring interventions to mitigate unsafe behaviors. Additionally, efforts to bridge the gap between simulator studies and real-world findings could enhance the applicability of simulator-based insights to practical road safety enhancements. By employing driving simulators as a powerful tool in transportation research, we can collectively strive towards safer and more efficient managed lane systems that cater to the intricacies of human behavior and contribute to the overall advancement of road safety.

2.6 SHRP2 NDS Data

The Second Strategic Highway Research Program Naturalistic Driving Study (SHRP2 NDS) is a comprehensive research initiative that involved collecting and analyzing real-world driving data to gain insights into driver behavior, decision-making, and interactions with the road environment (SHRP2, 2013). The goal of the study was to improve road safety and transportation system effectiveness by understanding how drivers behave in various driving scenarios and identifying factors that contribute to crashes and near-crash incidents (Campbell, 2012). The SHRP2 NDS collects its data using naturalistic driving methods, which involve equipping participating vehicles with specialized sensors, cameras, and recording equipment. These systems continuously capture a wide range of information, including vehicle speed, acceleration, braking, steering angle, road geometry, weather conditions, and driver actions (Campbell, 2012). This approach allows researchers to obtain a detailed and unbiased view of how drivers respond to different situations, without relying on participants' self-reporting.

The SHRP2 NDS dataset comprises data from more than 3,000 participants in six states: Florida, Indiana, North Carolina, New York, Pennsylvania, and Washington. This dataset includes non-identifying time series data, such as profiles of speed, acceleration, steering, distance and relative speed to other objects, and Global Positioning System (GPS) data on certain road segments (Campbell, 2012). Analyzing this dataset provided invaluable insights into driver behavior on managed lane facilities with different separation treatments. Participant distribution by age group and gender is presented in Figure 2.14.



Note: F = Female; M =Male

Figure 2.14: Drivers by Age Group and Gender

The collected data can then be analyzed to identify patterns, risk factors, and critical events that contribute to road crashes. This information helps researchers and policymakers make informed decisions about road design, traffic management, driver education, and vehicle technology enhancements. Insights from the SHRP2 NDS data contribute to the development of strategies to mitigate crash risks, improve road safety infrastructure, and enhance driver behavior through targeted interventions. The insights derived from this initiative have the potential to shape transportation policies and practices to reduce crashes and improve overall road safety.

The wealth of data from the SHRP2 NDS has been instrumental in conducting comprehensive research across a spectrum of critical dimensions concerning driver performance and behavior within the realm of traffic safety. This dataset has served as a cornerstone for investigations that delve into intricate details of how drivers engage with the road environment, make decisions, and respond to an array of dynamic driving scenarios. Researchers have harnessed this data to dissect driver behavior, scrutinizing factors like acceleration, braking, lane changes, and interactions with other vehicles, unraveling insights that contribute to a nuanced comprehension of how drivers navigate complex traffic situations. Moreover, the dataset offers a window into pivotal driver performance metrics, encompassing reaction times, adherence to traffic rules, and following distances, allowing researchers to not only evaluate the efficacy of various driver actions but also to pinpoint risky behaviors that can compromise road safety. In essence, the SHRP2 NDS data has provided an invaluable foundation upon which to build a robust understanding of the intricate interplay between driver behavior, performance, and the overarching landscape of traffic safety. Below are a few studies that demonstrate the usefulness of the datasets:

- Safer glances, driver inattention, and crash risk: an investigation using the SHRP 2 Naturalistic Driving Study (Victor et al., 2014)
- Assessing the relationship between driver, roadway, environmental, and vehicle factors and lane departures on rural two-lane curves: An investigation using the SHRP 2 Naturalistic Driving Study (Hallmark & Mcgehee, 2013)
- Evaluation of offset left-turn lanes: an investigation using the SHRP 2 Naturalistic Driving Study (Hallmark & Mcgehee, 2013)
- Car following, driver distraction, and capacity-reducing crashes on congested freeways: an investigation using the SHRP 2 Naturalistic Driving Study (Hallmark & Mcgehee, 2013)
- Visual Sensory and Visual-Cognitive Function and Rate of Crash and Near-Crash Involvement Among Older Drivers Using Naturalistic Driving Data (Huisingh et al., 2017)

2.7 Summary and Discussion

This chapter discusses findings from a comprehensive literature review conducted to identify and review the human factors and driver behavior on managed lanes facilities, with respect to separation treatments. The emphasis was placed on human factors and how they influence behavior and safety on managed lanes facilities with different separation types. Previous studies on managed lane separation types, including existing guidelines specific to separation treatments were reviewed. The focus was on three separation types: pylons, buffer, and concrete barrier. Available literature on human factors and driver behavior related to the three separation types was also reviewed, along with general information on all types of managed lane facilities. Studies and available information on driving simulation were also reviewed.

Driver behavior is the practical manifestation of the underlying human factors associated with operating a vehicle. For example, if a driver is fatigued (a human factor), their behavior might include slower reaction times or an increased likelihood of drowsy driving. Previous studies have established that human factors and driver behavior represent an integral component and a potential profound influence on various aspects of transportation and road safety. However, gaps in research, with respect to driver behavior and managed lane separation types, exist among available literature. Some of the research questions that remain sparse in the literature include:

- Do drivers look at the top or bottom of the pylons (i.e., tubular markers)?
- Does the effect of managed lane separation type vary across different age groups of drivers?”
- Do drivers avoid the inside lane of the general-purpose lanes (i.e., the general-purpose lane adjacent to the managed lane)?

- Is driver speed affected by the managed lane separation type?
- Is the driver's lateral position affected by the managed lane separation type?

These questions cannot be answered using traditional crash data analysis and require human factors approaches. As such, this research conducted two types of analyses, one using naturalistic driving data and the other using a driving simulator with eye-tracking equipment.

CHAPTER 3
DRIVING SIMULATOR STUDY

This chapter discusses the driving simulator study conducted to examine driver behavior for different managed lane separation types. The purpose of the driving simulator study was to understand how different age groups of drivers, including younger (18-34), middle-aged (35-64), and older (65+), behave on managed lane facilities with various combinations of delineator (pylon) heights and separation pavement markings in a controlled setting using a driving simulator and eye tracking device. A one-page summary of the experiment is provided in Appendix F.

3.1 Study Procedures and Protocols

This section discusses the procedures and protocols used to design the driving simulator experiment to evaluate driver behavior on managed lanes with various combinations of pylon heights (36” for straight road sections and 24” or 28” for the curves) and separation pavement markings (single solid lines versus double solid lines on each edge of the separation). The experiment was conducted at the Intelligent Transport Systems lab at the University of Central Florida (UCF). It should be noted that all research involving human participants conducted by UCF and Florida International University (FIU) requires review and approval by the Institutional Review Board (IRB), prior to beginning, to ensure compliance with all ethical principles and guidelines for human subject protection. The IRB approval letters for UCF and FIU are provided in Appendix A and B, respectively, of this report.

3.1.1 Equipment

3.1.1.1 Driving Simulator

Figure 3.1 shows the driving simulator used for the experiment and data collection. Located at UCF in Orlando, Florida, the simulator is a compact, customizable version (miniSim^{TM}) of the National Advanced Driving Simulator (NADS) developed by the Driving Safety Research Institute (DSRI) at the University of Iowa. The miniSim^{TM} provides a high-fidelity driving testing environment, utilizing the technical sophistication of the NADS-1 simulator (DSRI, 2025).

The simulator includes a visual system (three 42” flat panel displays), a quarter-cab of actual vehicle hardware from a real vehicle, including a steering wheel, pedals, adjustable seat, and shifter, a digital sound simulation system, and a central console. The data sampling frequency reaches 60 Hz along with a recording system. The simulator is also equipped with four recording cameras to ensure the subjects’ safety and to capture the participants’ performance while driving in the simulator. One camera is pointed directly at the participant’s feet to record their gas and brake-pedal usage. Another camera is directed towards their face to record head movements, and another camera is pointed towards their hands. The fourth recording device is located behind the participant, recording the monitors and where they direct the simulated vehicle.

Figure 3.1: UCF miniSim^{TM} Driving Simulator

3.1.1.2 Eye Tracking System (FOVIO Eye Tracking Device)

An eye tracking system was also utilized in this study. Eye movements were recorded using a FOVIO infrared seeing machine with a 60-Hz system, as shown in Figure 3.2. The eye tracker is lightweight, with an accuracy of 0.87 degrees (Mean) and 0.59 (Std. Dev.) angular error. It has one-step (5-point) calibration via the EyeWorks software suite. The software output provides fixation-based metrics for cognitive and emotional states such as a pattern of multiple, short-duration gazes and other area of interest (AOI) based metrics, including dwell time and other metrics.

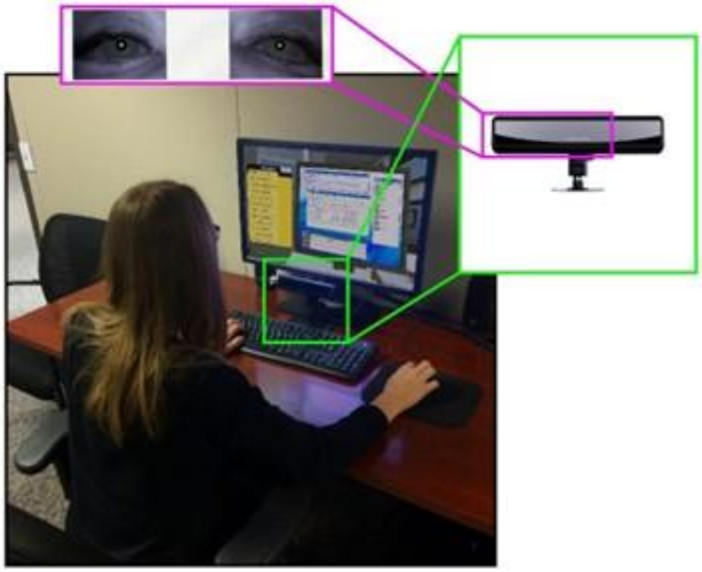


Figure 3.2: FOVIO Eye Tracker

3.1.2 Participants

The target number of participants for the experiment was at least 60 drivers with a valid driver license. The ages of the subjects ranged from age 18 to over 65. Since most of the variables of interest in this study are based on the participants' demographics, an even distribution was needed to ensure unbiased results. Therefore, a variety of subjects with varying ages, gender, education, ethnicities, and backgrounds were recruited. Participation in running the simulations was strictly voluntary, and participants were free to withdraw from the simulation at any time and from partaking in the study for any reason. The target distribution of the participants' age and gender is shown in Table 3.1.

Table 3.1: Driving Simulator Study Participant Demographics

Age Group	Gender	
	Male	Female
18 - 34	10	10
35 - 64	10	10
65+	10	10
Total	30	30

3.1.3 Recruitment Process

Identifying potential participants was not a difficult task because the main requirements were to be at least 18 years old with a valid driver's license. Also, participants who violated the traffic rules on purpose were excluded. A monetary incentive of $50 was provided to each participant, provided that they finished all the scenarios. The UCF Psychology Research Participation System (SONA Systems) was utilized in the recruitment of participants, allowing students to earn extra credits in their coursework or choose to receive the $50.

Family and friends of the researchers were also recruited by word of mouth or by e-mail. Older adults (65+) were recruited through the Learning Longevity Research Network via e-mail. Faculty and staff at UCF were also recruited by word of mouth or by e-mail. An email was distributed to all potential participants explaining the basis of the research. In addition, flyers were sent out to off-campus area companies, as well as religious institutions in the Orlando area. These flyers were also posted on social media to help advertise the study. The advertisement is provided in Appendix C.

3.1.3.1 SONA Systems

SONA Systems is UCF's online research participation system for the Psychology Department at the University. This system provides undergraduate UCF psychology students a way to easily view and sign up for studies within, or partnering with, the psychology department. In return for volunteering their time participating in a study registered on SONA Systems, individuals typically receive extra credit in one of their Psychology courses. However, other means of payment can be used instead of course credit as determined by the researcher.

3.1.3.2 Learning Longevity Research Network (LLRN)

The Learning Longevity Research Network (LLRN) is a database comprised of contact information for older adults in the greater Orlando area who are interested in participating in research conducted at UCF. This network allows researchers at UCF to email older adults in the database about research participation opportunities that may be of interest to the individual.

3.1.4 Experiment Protocol

Upon arrival, all participants were asked to read and sign an informed consent form required by the IRB to ensure that each participant understood what to expect. Then, each participant was asked to take a demographic survey, including questions on the variables of interest (age, gender, etc.), before they entered the driving simulator room. The demographic survey is included in Appendix D.

Driving simulator systems may induce a variety of simulation/virtual reality sickness symptoms (e.g., nausea, dizziness, and disorientation) because of system exposure and/or longer exposure durations, especially for older adults who may be more susceptible to simulation sickness (SS) than their younger counterparts. In the case of SS occurrence, experimental protocols were adjusted accordingly to reduce the effects of SS symptoms.

Before starting the driving simulator scenarios, each participant was given a short training session, including traffic regulation education, a safety notice, and familiarity training. In the traffic regulation education session, all participants were advised to drive, follow traffic rules, and behave as they normally do in real driving situations. In addition, participants were not informed about the changes in separation types before the experiment. In the safety notice session, each participant was informed that they could quit the experiment at any time if they have any motion sickness symptoms or any kind of discomfort. In the familiarity training session, each participant was given about 10 minutes of training to familiarize them with the driving simulator operation, such as straight driving, acceleration, deceleration, left/right turns, and other basic driving behaviors.

After completing the short training session, participants began the formal experiment, with the 16 scenarios presented in a random sequence to eliminate any time order effects. The duration of each scenario was at least five minutes. In addition, all participants were encouraged to rest for about three minutes between each scenario.

After completing all the scenarios, each participant was asked to complete an exit survey to determine whether they noticed the change in separation lines and pylon heights and to gather their opinion on the most noticeable separation type. The exit survey is provided in Appendix E. Table 3.2 summarizes the experiment procedure, showing an approximate time duration of two hours for each participant.

Table 3.2: Driving Simulator Study Procedure Summary

SN	Procedure	Time Duration (per participant)
1	Fill in the demographic survey	10 mins
2	Training session (Traffic regulation education, safety notice, and familiarity training)	10 mins
3	Formal experiment (without breaks), minimum	90 mins
4	Exit survey	10 mins
Total Duration (minimum)		120 mins

Note: SN = Serial Number.

3.1.5 Experiment Design

3.1.5.1 Scenario Matrix

In many scientific investigations, the concern is to optimize the system. Experimentation is one of the popular activities used to understand and/or improve a system. This can be achieved by simultaneously studying the effects of two or more factors on the response at two or more values known as "levels" or settings. This type of standard experiment is known as factorial design. Cost and practical constraints must be considered in choosing factors and levels. Therefore, two-level factorial designs are common for factor screening in industrial applications. However, if a non-standard model is required to adequately explain the response or the model contains a mix of factors with different levels, the experiment results in an enormous number of runs. In this study, the parameters consisted of five (5) two-level factors. The standard number of the full factorial design needed to cover all cases would amount to 32 runs, resulting in the whole procedure taking at least 3 hours and 5 minutes (without any rest time) for each applicant. For 60 applicants, the total runs would be 1,920. However, the main challenge with the full factorial design is the required time for each experiment, as participants may not want to remain in the experiment for a lengthy duration of time and may also experience motion sickness. Under such conditions, optimal custom designs are the recommended design approach which requires choosing an optimality criterion to select the design points.

Optimal designs fall under two main categories. One is optimized with respect to the regression coefficients (D-Optimality Criteria), and the other is optimized with respect to the prediction variance of the response (l-Optimality Criteria). D-Optimal designs are more appropriate for screening experiments because the optimality criterion focuses on estimating the coefficients precisely. The D-optimal design criterion minimizes the volume of the simultaneous confidence region of the regression coefficients when selecting the design points. This is achieved by maximizing the determinant of X'X over all possible designs with the specific number of runs. Since the volume of the confidence region is related to the accuracy of the regression coefficients, a smaller confidence region means more precise estimates even for the same level of confidence. Therefore, this experiment utilized the D-Optimal design. Table 3.3 provides the layout of the scenario matrix, which describes the experimental plan in terms of the study factors.

Table 3.3: Scenario Matrix (D-Optimal Design)

No.	TOD	Traffic Density	Visibility	Separation Height	Separation Width
1	Night	High	Low	Delineator (24")	Double Solid Line (6")
2	Day	High	High	Delineator (28")	Single Solid Line (8")
3	Day	Low	High	Delineator (24")	Single Solid Line (8")
4	Night	High	Low	Delineator (28")	Single Solid Line (8")
5	Day	Low	Low	Delineator (28")	Single Solid Line (8")
6	Day	Low	High	Delineator (28")	Double Solid Line (6")
7	Night	Low	High	Delineator (28")	Single Solid Line (8")
8	Night	High	High	Delineator (28")	Double Solid Line (6")
9	Night	Low	High	Delineator (24")	Double Solid Line (6")
10	Night	High	High	Delineator (24")	Single Solid Line (8")
11	Day	High	High	Delineator (24")	Double Solid Line (6")
12	Day	High	Low	Delineator (24")	Single Solid Line (8")
13	Day	Low	Low	Delineator (24")	Double Solid Line (6")
14	Day	High	Low	Delineator (28")	Double Solid Line (6")
15	Night	Low	Low	Delineator (28")	Double Solid Line (6")
16	Night	Low	Low	Delineator (24")	Single Solid Line (8")

Note: TOD = Time of Day.

It should be noted that separation height variations were applied exclusively to the curved sections, as the study aimed to evaluate the effects of 24-inch and 28-inch delineators on driver behavior. These two height configurations were treated as a two-level factor within the D-optimal experimental design. Accordingly, all scenarios included the straight section utilizing a standard 36-inch delineator, with the delineator height transitioning to either 24 or 28 inches upon entering the curved section. Each of the 60 participants completed the 16 scenarios for a total of 960 runs. Each row of Table 3.3 represents one set of experimental conditions that produced a value of the response variable once the scenario was completed.

The response variable entailed bio-behavioral measures consisting of the drivers' attention responses, driving performance accuracy, and eye movements. These measures were recorded in a series of simulated driving environments, where vehicle speed, deceleration, steering angles, and lane changing behavior were extracted from the driving simulator. First fixation time, perception-reaction time, and average blink duration were identified from the eye tracking device.

3.1.5.2 Driving Simulator Scenarios

The driving simulator miniSim$^{\text{TM}}$ and software tools, including the tile mosaic tool (TMT) and the interactive scenario authoring tool (ISAT), were used to create driving scenarios within virtual traffic environments and virtual road networks. The models and tiles were developed by the NADS staff at the University of Iowa DSRI.

The model included three static objects representing flexible lane delineator posts (i.e., pylons) of different heights. Straight sections contained 36-inch pylons, while curved sections contained 24-inch or 28-inch pylons. The pylons are equipped with a white retroreflective sheeting requirement of 30 square inches (3” diameter × 10” length) omni-directional single wrap around the post. The top of the sheeting is 1.5 inches below the top of the post, and the spacing between the posts is five feet.

In addition, six (6) tile models were constructed with 12-foot lanes, consistent in appearance with existing NADS Tile Library models. These tiles contain features consistent with an urban environment with a center barrier median, straight section, curved section, and transition sections. Each tile is 0.5 miles in length (4 × 660-foot tile units). Longer road sections can be constructed using the NADS TMT by placing additional tiles adjacent to each other in the TMT workspace. Each road tile incorporates multiple switches for toggling between various options, as these options contain different pavement markings, including 8-inch single solid lines on each edge of the separation or 6-inch double solid lines on each edge of the separation typical for express lanes. The developed roadway type consisted of an asphalt surface. Snapshots of the driving simulator model with varying combinations of delineator heights, pavement markings, and overhead guide signs are depicted in Figure 3.4.

The model consisted of a 4-lane section with a transitioning taper to a 5-lane section containing a single-lane entrance to the express lane (i.e., 4 GPLs + 1 ML). The 4-lane section length was 1.25 miles to account for advance guide signs for the point of entry to the express lane, in accordance with the FDOT Traffic Engineering Manual (TEM), Express Lanes Signing section. Sequential overhead guide signs were located at half mile, one mile, and at the express lane point of entry, as shown in Figure 3.3. The express lane consisted of a straight section as well as a curved section. The total length of the one-lane express lane (i.e., managed lane) section was 1.5 miles, which then transitioned into the GPL for another 1.0 mile to account for another set of advance signs to another ML point of entry. The second ML entry was for a 2-lane expressway with a 2-lane entrance (i.e., 3 GPLs + 2 MLs), which extended 1.5 miles with a straight and curved section before exiting into the GPL over a length of 0.25 miles. The total length of the scenario was around six miles. A schematic diagram of the lane configurations in the model is shown in Figure 3.3.

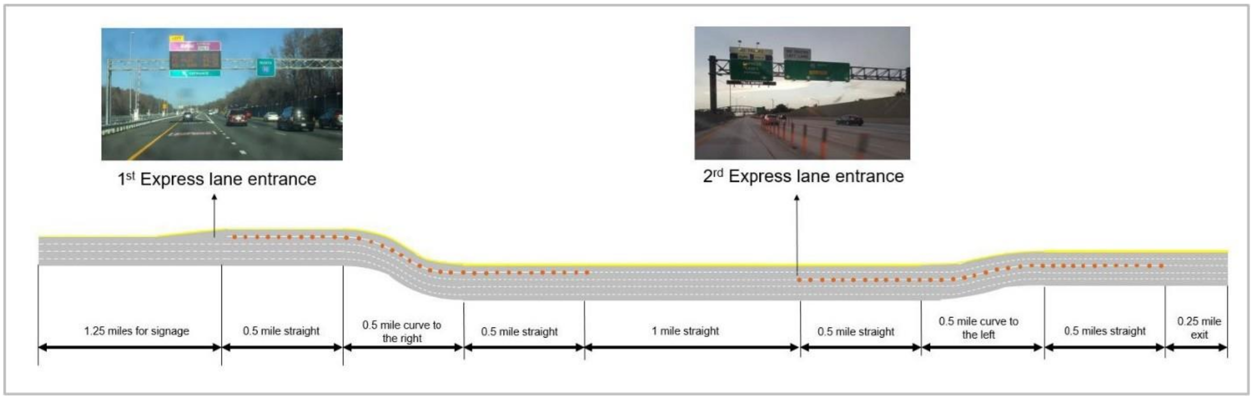


Figure 3.3: Model Lane Configurations

Each participant was asked to drive the total length of the scenario to experience all conditions (straight, curved, one-lane expressway, and 2-lane expressway). The speed limit was 70 mph. The driving speed of the participants depended on the traffic density. Each scenario required approximately five to seven minutes to finish.

a) Managed Lane entrance with single solid line

b) Nighttime scenario with 36” pylons and double solid lines

c) Curved section with 24” pylons and double solid lines

d) Curved section with 28” pylons and single solid lines

e) Daytime scenario with low visibility

f) Nighttime scenario with low visibility

Figure 3.4: Driving Simulator Experiment Scenarios

In addition to separation types, three other factors that can influence the driving behavior, were included in the experimental design. These factors include time of day, traffic density, and visibility. Time of day included daytime and nighttime, and traffic density refers to low and high traffic densities ranging from 5 to 30 vehicles per lane per mile. Visibility factors included good weather with clear skies and bad weather with moderate to heavy rains.

The data was examined at several locations or areas to evaluate the driving behavior. As shown in Figure 3.5, the locations were before the participant entered the one-lane expressway, at the curved section, and after exiting the express lanes. Data collection also included the experiment sampling time, vehicle speed, acceleration, deceleration, lane changes, vehicle position, and steering angle. Also collected data on eye movement included time to first fixation, and areas of attention. Each response variable was analyzed comprehensively.

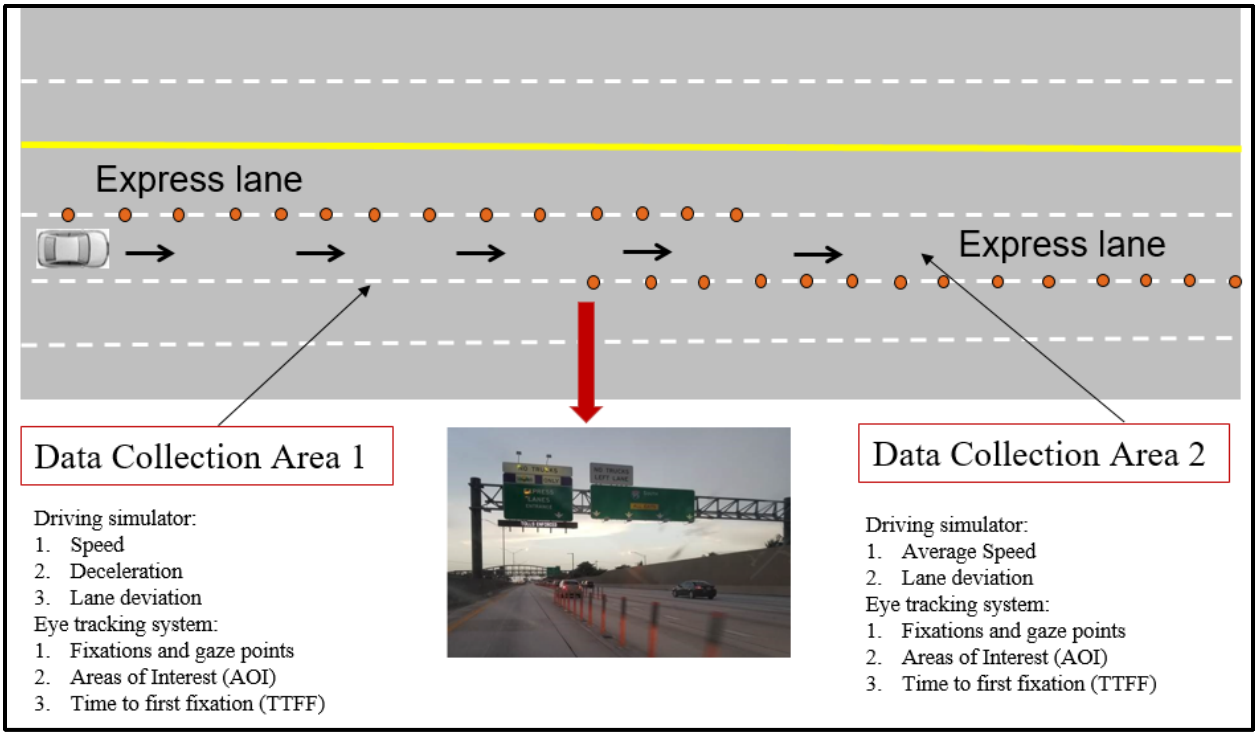


Figure 3.5: Data Collection Locations

3.2 Data Collection

3.2.1 Participant Recruitment

Sixty-four (64) participants from three age groups: young (18–34), middle-aged (35–64), and older (65+) were recruited for the study through various sources, including UCF SONA student recruitment, the Learning Longevity Research Network (LLRN), the Learning Institute for Elders (LIFE), social media, fliers, and personal connections. Each participant was required to have a normal vision and be over 18 years of age. All participants were briefed on the experiment and then asked to sign a consent form and complete a demographics survey.

Summarized in Table 3.4, two (2) of the 63 originally recruited participants experienced dizziness and could not complete the experiment, and one (1) participant did not attend. As a result, the experiment included 60 participants that completed the experiment. However, following a review of the data, one participant's data was excluded from the analysis due to significant deviation from the driving rules (see Section 3.2.4). To maintain the target number of participants (60), an additional participant was recruited to replace the individual whose data was deemed unsatisfactory. In total, 64 participants were recruited and data from 60 participants was included in the analysis.

Table 3.4: Study Participants

Participants Recruited	Number
Did not attend	1
Experienced motion sickness after the first few scenarios and could not continue	2
Completed the experiment	61
Data later excluded from the analysis	1
Total included in the analysis	60

3.2.2 Eye Tracking Calibration Process

Before the experiment, the eye tracker was calibrated for each participant. Participants were asked to sit and adjust their seats for comfort. Once seated, the eye tracker was positioned to ensure a clear view of the participant's eyes. The participants were then asked to follow a red dot that appeared on a white background on the screen. The dot moved across five points on the screen, as shown in Figure 3.6.

After the eye tracking calibration was completed, it was cross-checked to ensure that the eye tracking was accurate. An additional calibration was also conducted midway through the study to ensure accurate eye tracking.

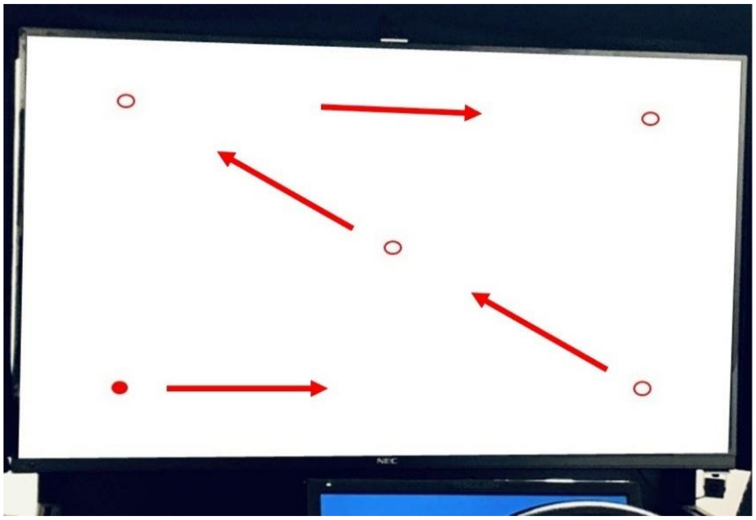


Figure 3.6: Eye Tracking On-Screen Calibration

3.2.3 Calibration Challenges

The calibration duration varied for each participant. There were a few challenges related to some participants wearing highly reflective glasses and glasses of various sizes. When the glasses covered the entire eye, the glare was uniform and made the calibration easier. However, with small frames, parts of the eye would be exposed while other parts were covered by glasses. This issue was resolved by turning off the room lights to eliminate unnecessary glare. Multiple calibrations were conducted for participants wearing glasses to ensure eye tracking accuracy.

3.2.4 Driving Simulator Experiment

Once the eye tracker was calibrated, the participants were given two practice scenarios: a daytime scenario and a nighttime with low visibility scenario. The practice scenarios were designed to familiarize the participants with the simulator. The researcher explained the rules for practice scenarios as well as the simulator controls, including the start button, gear buttons, and windshield wipers. Participants were then allowed to drive for an allotted time of three to five minutes, adhering to all traffic laws.

Scenarios used in the experiment included various conditions, such as time of day (TOD), weather-related visibility (low and high), traffic density (low and high), separation width (i.e., type of pavement marking), and separation height (i.e., delineator height). There were 16 scenarios in total, with each of the separation width and separation height tested in eight scenarios encompassing both low and high traffic density conditions (see Table 3.3). Snapshots of the driving simulator experiment scenarios are shown in Figure 3.4. Low traffic density was defined as 11 vehicles per mile per lane (veh/mile/lane), reflecting a level of service (LOS) B', while high traffic density was defined as 26 veh/mile/lane, corresponding to a LOS 'D'. LOS is a qualitative measure used to describe the operating conditions of a roadway based on factors such as speed, density, travel time, maneuverability, delay, and safety. The levels of service range from A to F, with A representing the best operating conditions and F the worst.

The study was divided into two sessions: eight scenarios in the first session and eight scenarios in the second session. Between the two sessions, there was a 5-min to 10-min break allotted depending on the participant's condition. Participants were also allowed to take breaks in the middle of each session if needed, particularly drivers aged 65 years and older. After each break, the eye tracker was recalibrated, and participants resumed driving through the remaining scenarios, which were presented in random order. Once the participants finished the experiment, they completed an exit survey (see Appendix E).

Each participant's data was reviewed after the experiment to determine whether it was satisfactory. Data was considered unsatisfactory if it showed excessive deviation from regular driving rules. One participant's data was found to be unsatisfactory due to significant deviation, as the participant struggled to control the vehicle in the driving simulator while entering the managed lanes (MLs). Consequently, this participant and all associated scenario files were excluded from the study. However, an additional participant was recruited (see Section 3.2.1), providing a total of 60 participants with usable data included in the analysis.

3.2.5 Simulator Data Extraction

The miniSim^{TM} generates both a data acquisition (DAQ) file and a text file for each scenario run. The text file contains records of general variables, such as mean speed, lane deviation, and headway. In contrast, the DAQ file holds detailed records of various simulator data variables, including speed, steering rate, lane deviation, and brake pedal force. To capture these variables, specific data collection points must be established. In the miniSim^{TM}, these points are defined within scenario files and are referred to as events. These events are crucial for segmenting simulator data into meaningful sections. The segmentation of these sections is achieved using log streams, which serve as data markers within the DAQ files. Typically, up to 10 log streams are utilized to mark specific occurrences in the data, such as the beginning of an event, during a subsection of an event, or at the event's conclusion. For example, log stream-1 might be set to a specific value to indicate the start of an event and then reset (often to ‘0’) at the end of the event. This approach helps to filter and separate data, ensuring that only relevant sections are analyzed.

In this study, each scenario included two ML sections. The first section represented a single-lane ML facility, while the second section represented a 2-lane ML facility. For data analysis, including both the driving simulator and frame-by-frame analysis, the two ML sections were divided into six segments for analysis, labeled 1A, 1-C, 1B, 2A, 2-C, and 2B, as shown in Figure 3.7 and described in Table 3.5. The four straight sections (1A, 1B, 2A, and 2B) were separated from the general-purpose lanes (GPLs) using 36-inch delineators, while the two curved sections (1-C and 2-C), were separated using either 24-inch or 28-inch delineators.

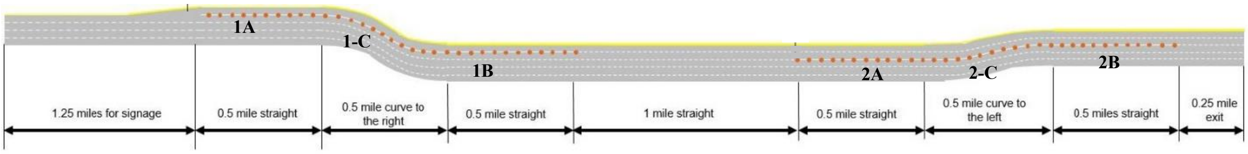


Figure 3.7: Managed Lane (ML) Study Segments

Table 3.5: Managed Lane Analysis Segments

Section	Description
1A	First straight section with 36” delineators separating the one-lane ML
1-C	Curved section with 24”/28” delineators separating the one-lane ML
1B	Second straight section with 36” delineators separating the one-lane ML
2A	First straight section with 36” delineators separating the two-lane MLs
2-C	Curved section with 24”/28” delineators separating the two-lane MLs
2B	Second straight section with 36” delineators separating the two-lane MLs

The simulator data was extracted into a tabulated format at a time-step of 1/60 seconds using the miniSim^{TM} DaqViewer and nDaqTools scripts. The tabulated data were then processed into useful driving parameters using a custom MATLAB script developed at UCF. The following four driving parameters were examined:

1. Mean speed within critical sections of the delineated lanes.
2. Lane deviation measurements within critical sections of the delineated lanes.
3. Steering angle rate within critical sections of the delineated lanes.
4. Deceleration rate at the entrance or starting point of the critical sections of the delineated lanes.

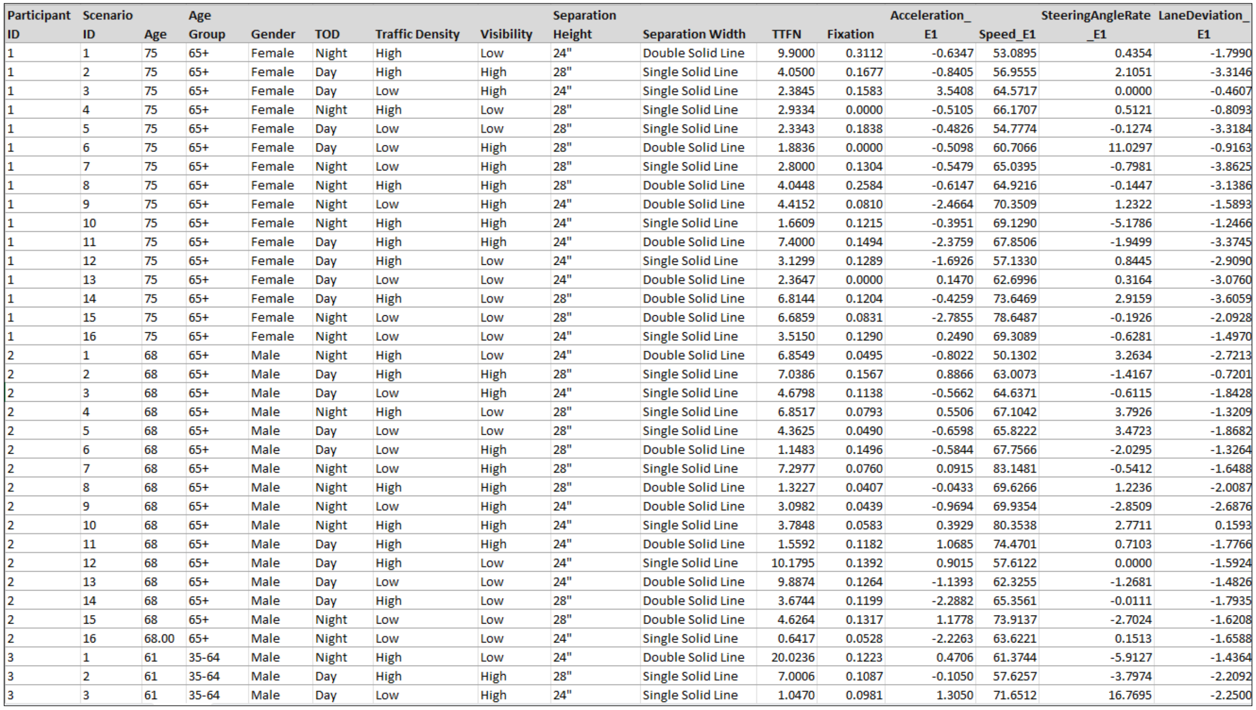
3.2.6 Eye Tracking Data Extraction

The eye tracking data was extracted using the EyeWorks software provided with the eye tracking device. The eye tracker generates both a video file and a data file, with the data file containing gaze coordinates recorded every 1/60th of a second. However, since the raw data lacks a reference point within the visual scenes, each video file was manually reviewed for data extraction. A reference point representing the first onset to see the MLs, set at 325 feet before the first ML entry point begins, was used to synchronize the data. The start time for each participant was marked when they crossed this reference point, and the end time was marked when they exited the second ML. Two key parameters were examined from the eye tracking data:

- Time to First Notice (TTFN): The time it took participants to first notice the separation treatment after passing the reference point
- Fixation Duration: The length of time participants' eyes remained fixed for each time they looked at the separation treatment.

The driving data and eye tracking data were then combined into a single Microsoft Excel file to analyze driving behavior within the MLs. Table 3.6 provides a sample of the driving and eye tracking data used in the statistical analysis, along with participant ID, gender, age group, and the various driving conditions in each scenario.

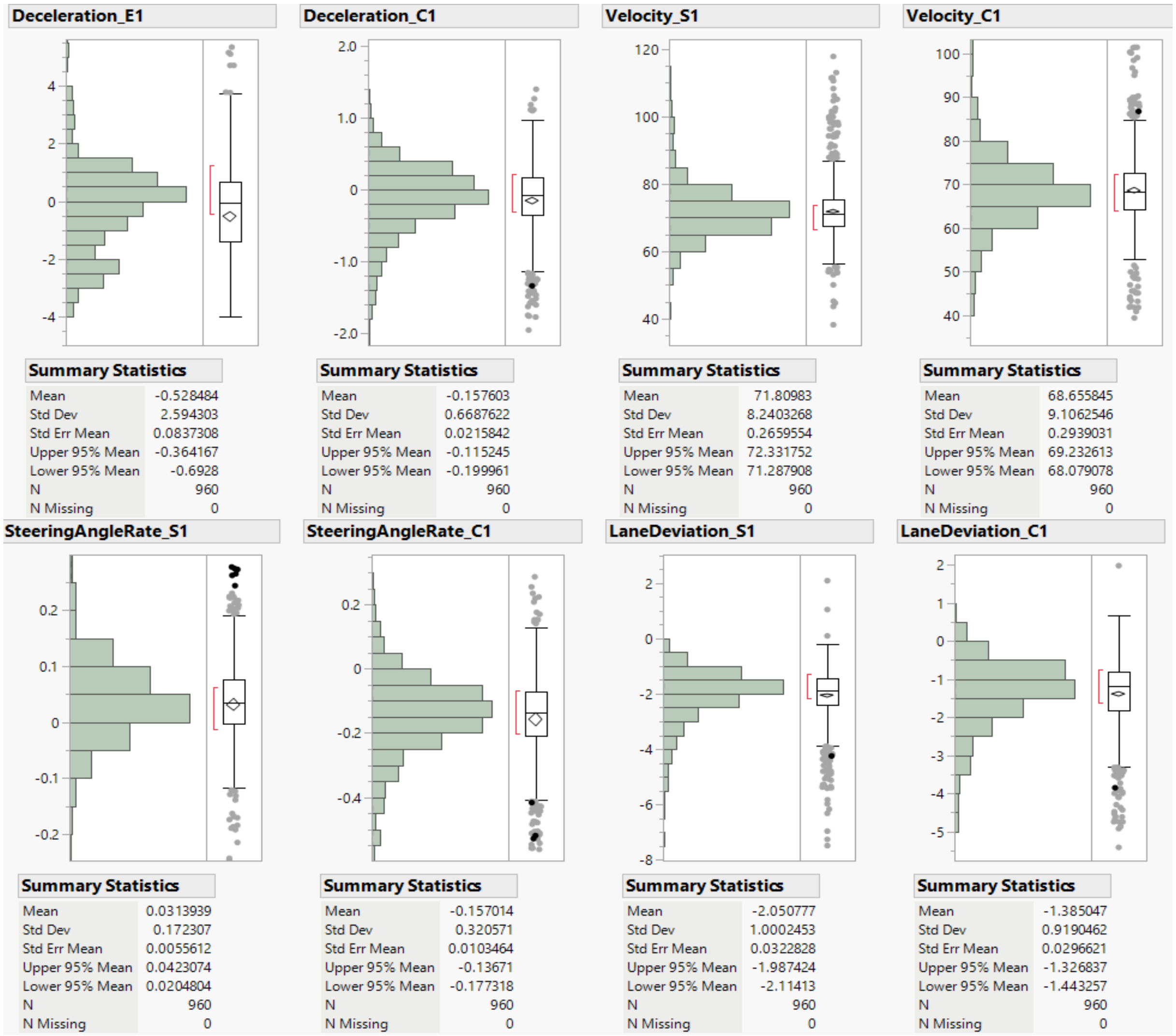
Table 3.6: Driving and Eye Tracking Data Sample



Participant ID	Scenario ID	Age	Age Group	Gender	TOD	Traffic Density	Visibility	Separation Height	Separation Width	TTFN	Fixation	Acceleration_ E1	Speed_E1	SteeringAngleRate _E1	LaneDeviation_ E1
1	1	75	65+	Female	Night	High	Low	24"	Double Solid Line	9.9000	0.3112	-0.6347	53.0895	0.4354	-1.7990
1	2	75	65+	Female	Day	High	High	28"	Single Solid Line	4.0500	0.1677	-0.8405	56.9555	2.1051	-3.3146
1	3	75	65+	Female	Day	Low	High	24"	Single Solid Line	2.3845	0.1583	3.5408	64.5717	0.0000	-0.4607
1	4	75	65+	Female	Night	High	Low	28"	Single Solid Line	2.9334	0.0000	-0.5105	66.1707	0.5121	-0.8093
1	5	75	65+	Female	Day	Low	Low	28"	Single Solid Line	2.3343	0.1838	-0.4826	54.7774	-0.1274	-3.3184
1	6	75	65+	Female	Day	Low	High	28"	Double Solid Line	1.8836	0.0000	-0.5098	60.7066	11.0297	-0.9163
1	7	75	65+	Female	Night	Low	High	28"	Single Solid Line	2.8000	0.1304	-0.5479	65.0395	-0.7981	-3.8625
1	8	75	65+	Female	Night	High	High	28"	Double Solid Line	4.0448	0.2584	-0.6147	64.9216	-0.1447	-3.1386
1	9	75	65+	Female	Night	Low	High	24"	Double Solid Line	4.4152	0.0810	-2.4664	70.3509	1.2322	-1.5893
1	10	75	65+	Female	Night	High	High	24"	Single Solid Line	1.6609	0.1215	-0.3951	69.1290	-5.1786	-1.2466
1	11	75	65+	Female	Day	High	High	24"	Double Solid Line	7.4000	0.1494	-2.3759	67.8506	-1.9499	-3.3745
1	12	75	65+	Female	Day	High	Low	24"	Single Solid Line	3.1299	0.1289	-1.6926	57.1330	0.8445	-2.9090
1	13	75	65+	Female	Day	Low	Low	24"	Double Solid Line	2.3647	0.0000	0.1470	62.6996	0.3164	-3.0760
1	14	75	65+	Female	Day	High	Low	28"	Double Solid Line	6.8144	0.1204	-0.4259	73.6469	2.9159	-3.6059
1	15	75	65+	Female	Night	Low	Low	28"	Double Solid Line	6.6859	0.0831	-2.7855	78.6487	-0.1926	-2.0928
1	16	75	65+	Female	Night	Low	Low	24"	Single Solid Line	3.5150	0.1290	0.2490	69.3089	-0.6281	-1.4970
2	1	68	65+	Male	Night	High	Low	24"	Double Solid Line	6.8549	0.0495	-0.8022	50.1302	3.2634	-2.7213
2	2	68	65+	Male	Day	High	High	28"	Single Solid Line	7.0386	0.1567	0.8866	63.0073	-1.4167	-0.7201
2	3	68	65+	Male	Day	Low	High	24"	Single Solid Line	4.6798	0.1138	-0.5662	64.6371	-0.6115	-1.8428
2	4	68	65+	Male	Night	High	Low	28"	Single Solid Line	6.8517	0.0793	0.5506	67.1042	3.7926	-1.3209
2	5	68	65+	Male	Day	Low	Low	28"	Single Solid Line	4.3625	0.0490	-0.6598	65.8222	3.4723	-1.8682
2	6	68	65+	Male	Day	Low	High	28"	Double Solid Line	1.1483	0.1496	-0.5844	67.7566	-2.0295	-1.3264
2	7	68	65+	Male	Night	Low	High	28"	Single Solid Line	7.2977	0.0760	0.0915	83.1481	-0.5412	-1.6488
2	8	68	65+	Male	Night	High	High	28"	Double Solid Line	1.3227	0.0407	-0.0433	69.6266	1.2236	-2.0087
2	9	68	65+	Male	Night	Low	High	24"	Double Solid Line	3.0982	0.0439	-0.9694	69.9354	-2.8509	-2.6876
2	10	68	65+	Male	Night	High	High	24"	Single Solid Line	3.7848	0.0583	0.3929	80.3538	2.7711	0.1593
2	11	68	65+	Male	Day	High	High	24"	Double Solid Line	1.5592	0.1182	1.0685	74.4701	0.7103	-1.7766
2	12	68	65+	Male	Day	High	Low	24"	Single Solid Line	10.1795	0.1392	0.9015	57.6122	0.0000	-1.5924
2	13	68	65+	Male	Day	Low	Low	24"	Double Solid Line	9.8874	0.1264	-1.1393	62.3255	-1.2681	-1.4826
2	14	68	65+	Male	Day	High	Low	28"	Double Solid Line	3.6744	0.1199	-2.2882	65.3561	-0.0111	-1.7935
2	15	68	65+	Male	Night	Low	Low	28"	Double Solid Line	4.6264	0.1317	1.1778	73.9137	-2.7024	-1.6208
2	16	68.00	65+	Male	Night	Low	Low	24"	Single Solid Line	0.6417	0.0528	-2.2263	63.6221	0.1513	-1.6588
3	1	61	35-64	Male	Night	High	Low	24"	Double Solid Line	20.0236	0.1223	0.4706	61.3744	-5.9127	-1.4364
3	2	61	35-64	Male	Day	High	High	28"	Single Solid Line	7.0006	0.1087	-0.1050	57.6257	-3.7974	-2.2092
3	3	61	35-64	Male	Day	Low	High	24"	Single Solid Line	1.0470	0.0981	1.3050	71.6512	16.7695	-2.2500

3.2.7 Distributions of Driving Performance Factors

Figure 3.8 illustrates the distribution of driving performance factors for the single-lane ML across all driving scenarios. The performance factors include deceleration at the ML entry and start of curves (E/C, where E = ML entrance point, C = starting point of the curves), as well as speed, steering angle rate, and lane deviation in both straight (S) sections and curved (C) sections. The summary statistics show that the average deceleration rate was higher at the entrance likely due to the need to assess and adjust the speed to safely enter the ML, compared to the beginning of the curved sections where they may already be accustomed to the lane. As for the speeding behavior, the mean speed was higher on straight sections. This result was expected since drivers generally tend to reduce speed in curved sections to focus on staying in their lane. In both straight and curved sections, the negative mean lane deviation indicates that drivers tend to position themselves closer to the shoulder line and away from the ML separation treatment. The lesser deviation in the curved sections can be attributed to the direction of the curves and their efforts to stay centered in the lane while managing the curve's direction.



Deceleration_E1

Summary Statistics	
Mean	-0.528484
Std Dev	2.594303
Std Err Mean	0.0837308
Upper 95% Mean	-0.364167
Lower 95% Mean	-0.6928
N	960
N Missing	0

Deceleration_C1

Summary Statistics	
Mean	-0.157603
Std Dev	0.6687622
Std Err Mean	0.0215842
Upper 95% Mean	-0.115245
Lower 95% Mean	-0.199961
N	960
N Missing	0

Velocity_S1

Summary Statistics	
Mean	71.80983
Std Dev	8.2403268
Std Err Mean	0.2659554
Upper 95% Mean	72.331752
Lower 95% Mean	71.287908
N	960
N Missing	0

Velocity_C1

Summary Statistics	
Mean	68.655845
Std Dev	9.1062546
Std Err Mean	0.2939031
Upper 95% Mean	69.232613
Lower 95% Mean	68.079078
N	960
N Missing	0

SteeringAngleRate_S1

Summary Statistics	
Mean	0.0313939
Std Dev	0.172307
Std Err Mean	0.0055612
Upper 95% Mean	0.0423074
Lower 95% Mean	0.0204804
N	960
N Missing	0

SteeringAngleRate_C1

Summary Statistics	
Mean	-0.157014
Std Dev	0.320571
Std Err Mean	0.0103464
Upper 95% Mean	-0.13671
Lower 95% Mean	-0.177318
N	960
N Missing	0

LaneDeviation_S1

Summary Statistics	
Mean	-2.050777
Std Dev	1.0002453
Std Err Mean	0.0322828
Upper 95% Mean	-1.987424
Lower 95% Mean	-2.11413
N	960
N Missing	0

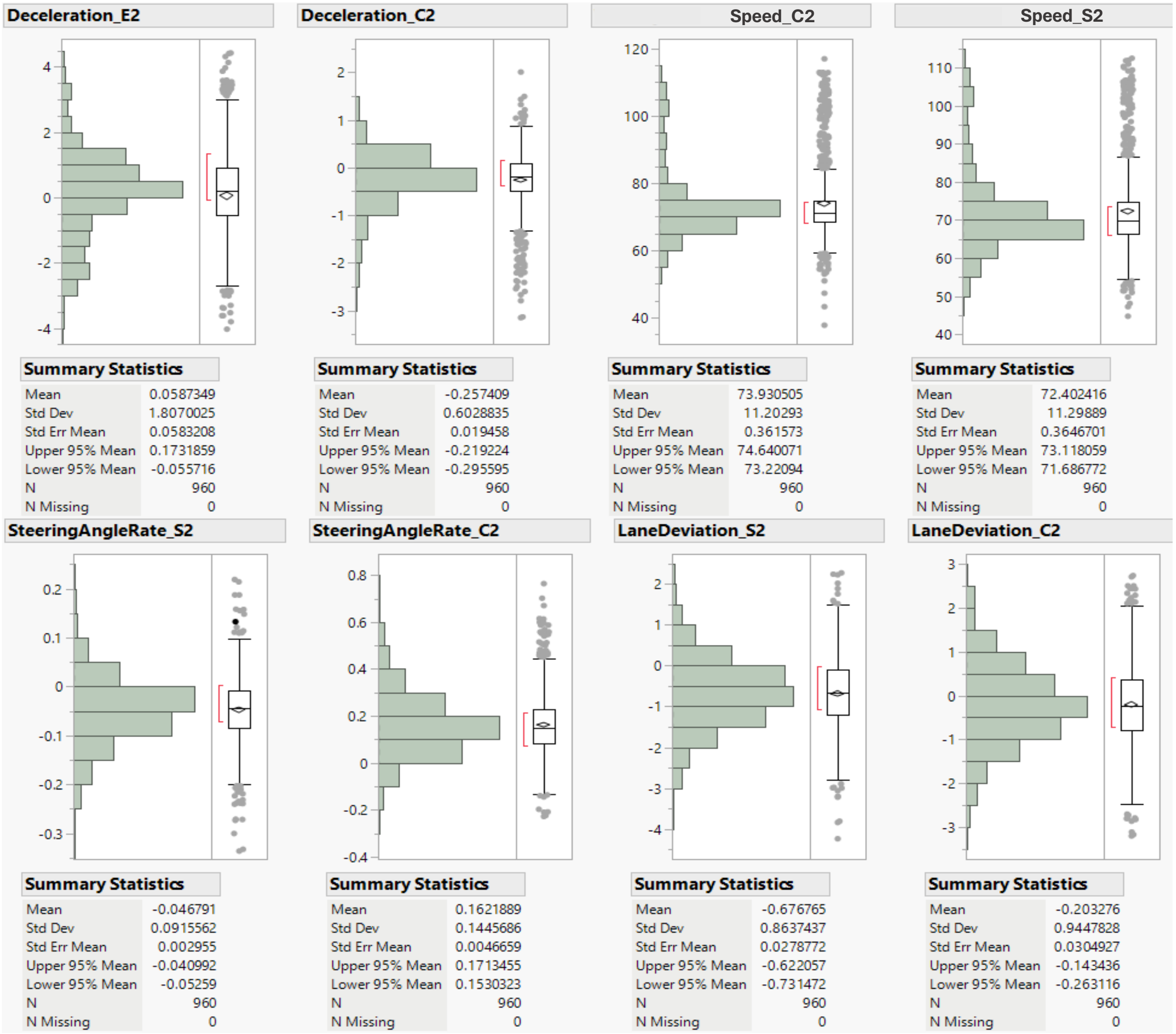
LaneDeviation_C1

Summary Statistics	
Mean	-1.385047
Std Dev	0.9190462
Std Err Mean	0.0296621
Upper 95% Mean	-1.326837
Lower 95% Mean	-1.443257
N	960
N Missing	0

Note: E/C/S = entrance/curved/straight subsections; 1 = one lane.

Figure 3.8: Summary Statistics of Performance Factors – Single-lane ML

As indicated in Figure 3.9, the distribution of performance factors for two-lane MLs is notably different than the single-lane MLs. The deceleration rate at the entrance of two-lane MLs is lower and more sparsely distributed compared to the start of the curves. The mean speed is nearly identical between straight and curved sections, indicating that drivers maintained a consistent pace despite the change in road geometry. In addition, the mean lane deviation is closer to zero, which could be attributed to the reduced sense of space constraints in a two-lane configuration. With more room to maneuver, drivers feel less restricted, leading to more stable and centered lane positioning throughout the MLs. This behavior underscores how the availability of additional lane space in two-lane MLs influences driver comfort and performance.



Deceleration_E2

Summary Statistics	
Mean	0.0587349
Std Dev	1.8070025
Std Err Mean	0.0583208
Upper 95% Mean	0.1731859
Lower 95% Mean	-0.055716
N	960
N Missing	0

Deceleration_C2

Summary Statistics	
Mean	-0.257409
Std Dev	0.6028835
Std Err Mean	0.019458
Upper 95% Mean	-0.219224
Lower 95% Mean	-0.295595
N	960
N Missing	0

Speed_C2

Summary Statistics	
Mean	73.930505
Std Dev	11.20293
Std Err Mean	0.361573
Upper 95% Mean	74.640071
Lower 95% Mean	73.22094
N	960
N Missing	0

Speed_S2

Summary Statistics	
Mean	72.402416
Std Dev	11.29889
Std Err Mean	0.3646701
Upper 95% Mean	73.118059
Lower 95% Mean	71.686772
N	960
N Missing	0

SteeringAngleRate_S2

Summary Statistics	
Mean	-0.046791
Std Dev	0.0915562
Std Err Mean	0.002955
Upper 95% Mean	-0.040992
Lower 95% Mean	-0.05259
N	960
N Missing	0

SteeringAngleRate_C2

Summary Statistics	
Mean	0.1621889
Std Dev	0.1445686
Std Err Mean	0.0046659
Upper 95% Mean	0.1713455
Lower 95% Mean	0.1530323
N	960
N Missing	0

LaneDeviation_S2

Summary Statistics	
Mean	-0.676765
Std Dev	0.8637437
Std Err Mean	0.0278772
Upper 95% Mean	-0.622057
Lower 95% Mean	-0.731472
N	960
N Missing	0

LaneDeviation_C2

Summary Statistics	
Mean	-0.203276
Std Dev	0.9447828
Std Err Mean	0.0304927
Upper 95% Mean	-0.143436
Lower 95% Mean	-0.263116
N	960
N Missing	0

Note: E/C/S = entrance/curved/straight subsections; 2 = two lane.

Figure 3.9: Summary Statistics of Performance Factors – Two-lane ML

3.3 Statistical Analysis and Results

Statistical analysis was conducted using JMP software (pronounced “Jump”, www.jmp.com) with a mixed model approach. All main effects and interactions were considered as candidate effects, following the principle of effect hierarchy. Mixed effects models (also known as multilevel models) are effective for handling variable inclusion issues when dealing with a large number of variables, especially in data with repeated measures or hierarchical structures. This approach allows for the inclusion of both fixed and random effects, enabling a more accurate representation of the data. The model construction involves testing and selecting independent variables based on their statistical significance while accounting for variability within the data.

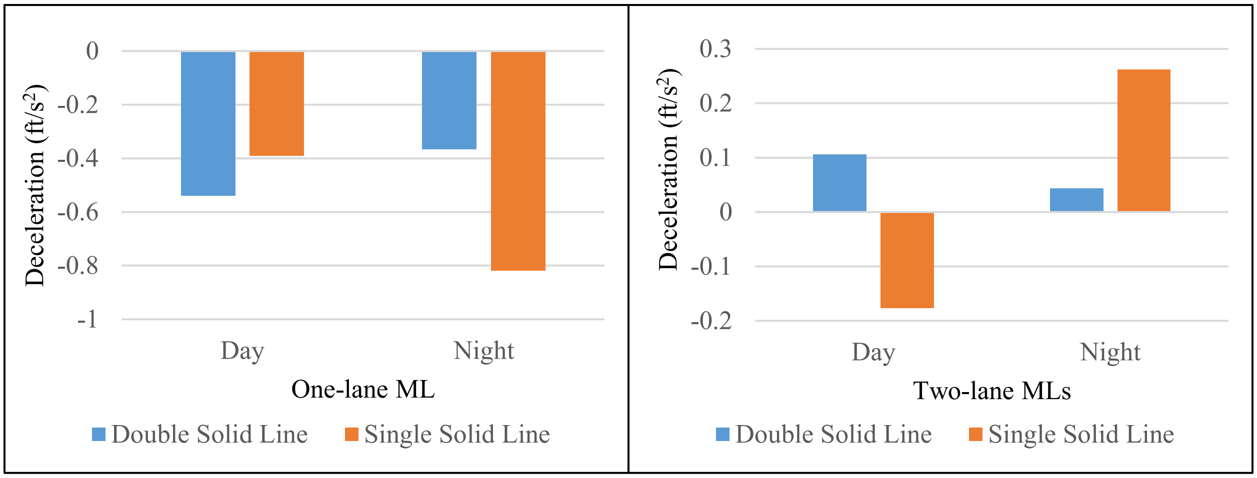
3.3.1 Effect of Separation Width on Driving Behavior

3.3.1.1 Deceleration

Figures 3.10 and 3.11 present a comparison of participants' deceleration during the entry of MLs for straight and curved sections, with different separation widths (i.e., single- or double-solid pavement lines on each edge of the separation), during daytime and nighttime conditions. It is important to note that deceleration is inherently negative; thus, a more negative estimate indicates a greater likelihood of deceleration, while a positive estimate refers to an increased likelihood of acceleration. Deceleration is generally expected as drivers adjust their speed to safely enter the MLs. However, excessive or abrupt deceleration indicates over-caution or a lack of confidence, potentially disrupting traffic flow and reducing the efficiency of the MLs. Figure 3.10(a) illustrates that during the daytime, drivers exhibit a moderate response when entering the single-lane ML, with mean deceleration rates remaining below 0.60 ft/s^2. The data shows that the deceleration rate for double solid lines is slightly higher than for single solid lines. At night, the deceleration rate for double solid lines remains relatively consistent with daytime values. However, for single solid lines, there is a significant increase in deceleration at night, nearly doubling the rate observed with double solid lines.

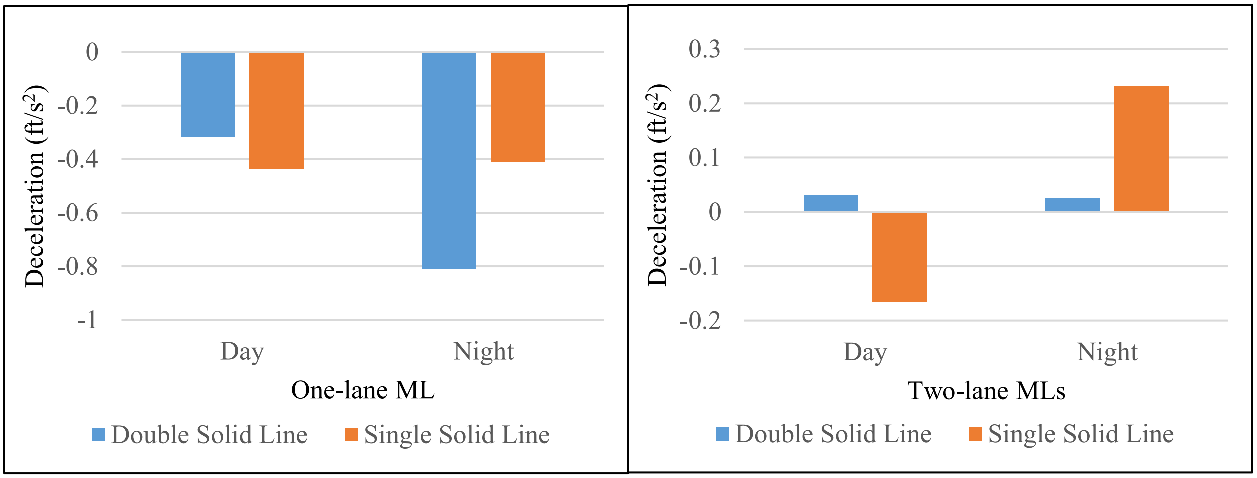
For two-lane MLs, drivers tend to accelerate as they enter the ML facility, as shown in Figure 3.10(b). This difference in deceleration/acceleration behavior can be attributed to the reduced space constraints provided by the additional lane. The double solid lines exhibit a relatively consistent acceleration rate, while the single solid lines display a contrasting response, with significant differences between daytime and nighttime behavior.

On curved sections, drivers exhibit consistent behavior in single-lane MLs with single solid lines during both daytime and nighttime. However, for double solid lines, driver responses are less consistent, with the nighttime deceleration rate more than doubled compared to daytime, as indicated in Figure 3.11(a). On the other hand, Figure 3.11(b) shows that driver responses in the curved section for the two-lane ML facility closely mirror those in the two-lane straight section (see Figure 3.10(b)).



(a) (b)

Figure 3.10: Deceleration/Acceleration Rate at ML Entrances



(a) (b)

Figure 3.11: Deceleration/Acceleration Rate at ML Curved Sections

Given the distinct deceleration behaviors observed at the entry points of straight and curved sections, two separate deceleration models were developed. These models also considered demographics and external factors to better understand their impact, with outliers removed for accuracy. The analysis shows that as drivers enter the MLs, they are more likely to decelerate especially during daytime when double solid lines are present (see Table 3.7). Specifically, the interaction between daytime and double solid lines had an estimate of -0.0986 (p-value = 0.06) in the straight section model, indicating a significant increase in deceleration at the entry point prompting drivers to slow down. In contrast, a positive estimate of 0.1090 (p-value = 0.04) for the interaction in curved sections explains that drivers are less likely to decelerate when approaching the curves in the double solid line scenarios. This indicates that the double solid lines improved the drivers' sense of safety around lane boundaries at curves, encouraging them to maintain or even increase their speed compared to the single solid line. Furthermore, it was found that the random effect of separation width in the deceleration model for the curved sections, was also significant (std. dev = 0.3940, p-value = 0.0173) (see *Deceleration (Curve)* in Table 3.7). This finding indicates that the impact of separation width on deceleration behavior varies across different drivers or conditions. In other words, while separation width generally influences how much drivers decelerate, the degree of this influence is not uniform across all participants or scenarios.

Furthermore, traffic density was found to significantly influence deceleration behavior (β=0.1029, p-value=0.06 for straight sections and β=0.1375, p-value=0.04 for curved sections). As expected, higher traffic density typically results in steady average speeds, and so the rate of speed changes was low. The JMP prediction profiles in Figure 3.12 dynamically illustrate the predicted deceleration rates based on the different age groups, gender, and separation widths. For instance, young male drivers (18-34 years) appear to exhibit lower deceleration rates compared to middle-aged (35-64 years) female drivers and older drivers (65+ years).

Table 3.7: Model Estimations for Deceleration

Response/Parameter	Parameter Effect	Estimate	Std Error	Prob>|t|
Deceleration (Entrance)	Intercept	-0.2496	0.0602	0.0001***
	(standard deviation)	*(-)*	*(-)*	*(-)*
Age Group	Age (18-34)	0.1929	0.0853	0.0277**
	Age (35-64)	-0.0651	0.0852	0.4482
Gender	Female	-0.1198	0.0602	0.0514*
Traffic Density	High Density	0.1029	0.0602	0.0928*
	(standard deviation)	*(0.4269)*	*(0.0850)*	*(0.0322)***
Separation Width	Double Solid Line	-0.0433	0.0539	0.4247
	(standard deviation)	*(-)*	*(-)*	*(-)*
TOD x Separation Width	Day x Double Solid Line	-0.0986	0.0529	0.0632*
Deceleration (Curve)	Intercept	-0.2681	0.0704	0.0003***
	(standard deviation)	*(0.3580)*	*(0.0668)*	*(0.0551)**
Traffic Density	High Density	0.1375	0.0476	0.0055***
	(standard deviation)	*(-)*	*(-)*	*(-)*
Separation Width	Double Solid Line	-0.0206	0.0456	0.6528
	(standard deviation)	*(0.3940)*	*(0.0652)*	*(0.0173)***
TOD x Separation Width	Day x Double Solid Line	0.1091	0.0404	0.008***

Note: TOD = Time of Day; *(-)* = standard deviation is not significant at 90% confidence intervals; * = Significant at 90% confidence interval; ** = Significant at 95% confidence interval; *** = Significant at 99% confidence interval; "×" denotes an interaction effect, indicating that the impact of one variable depends on the level of another variable.

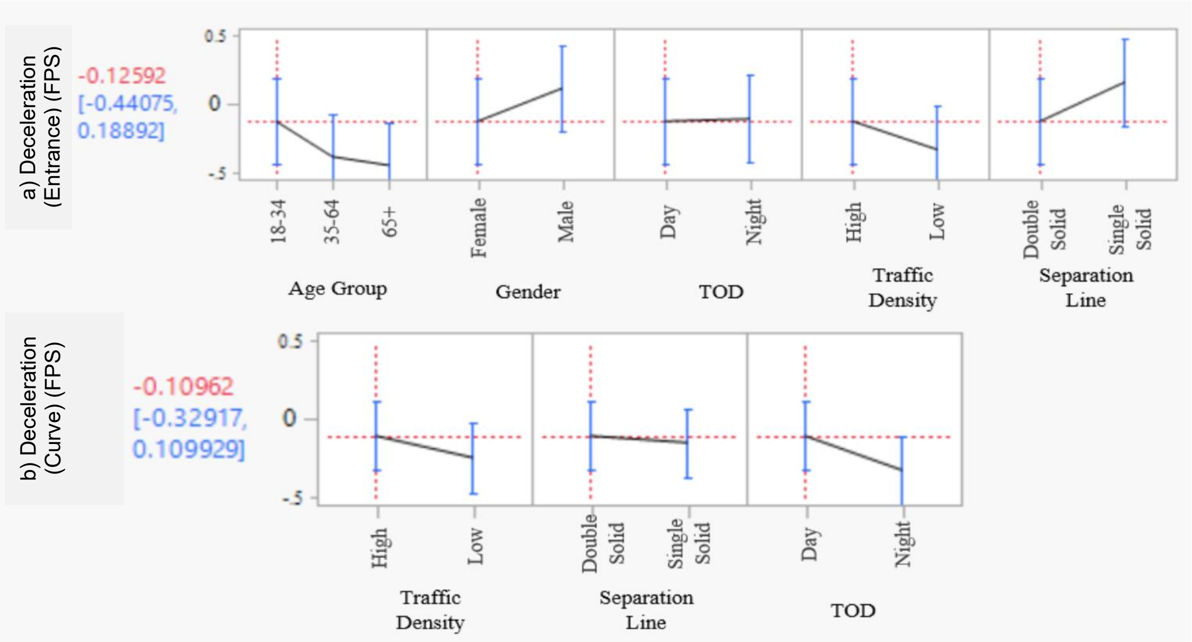


Figure 3.12: Predicted Deceleration Profiles

3.3.1.2 Speed

Driver speeding behavior was analyzed by examining the mean speed across various sections of the ML road segments. As previously mentioned, the study road was divided into four distinct sections: a straight section and a curved section for both the one-lane and two-lane MLs.

Straight Sections

Figures 3.13 and 3.14 demonstrate that separation width has a notable impact on driving behavior, as the mean speed is higher when double solid lines are present. This trend is consistent across various conditions, including different times of day (day and night), varying traffic densities (high and low), and different visibility levels (high and low). Moreover, the influence of other factors on drivers' speeding behavior is also evident. For instance, mean speed tends to be closer to 70 mph, the set speed limit, during daytime, under high traffic conditions, and in scenarios with high visibility.

Curved Sections

A similar speeding trend is observed in the curved sections as in the straight sections (see Figures 3.15 and 3.16). Although the mean speed in the curved sections is lower compared to the straight sections, it remains higher in MLs separated by double solid lines treatment.

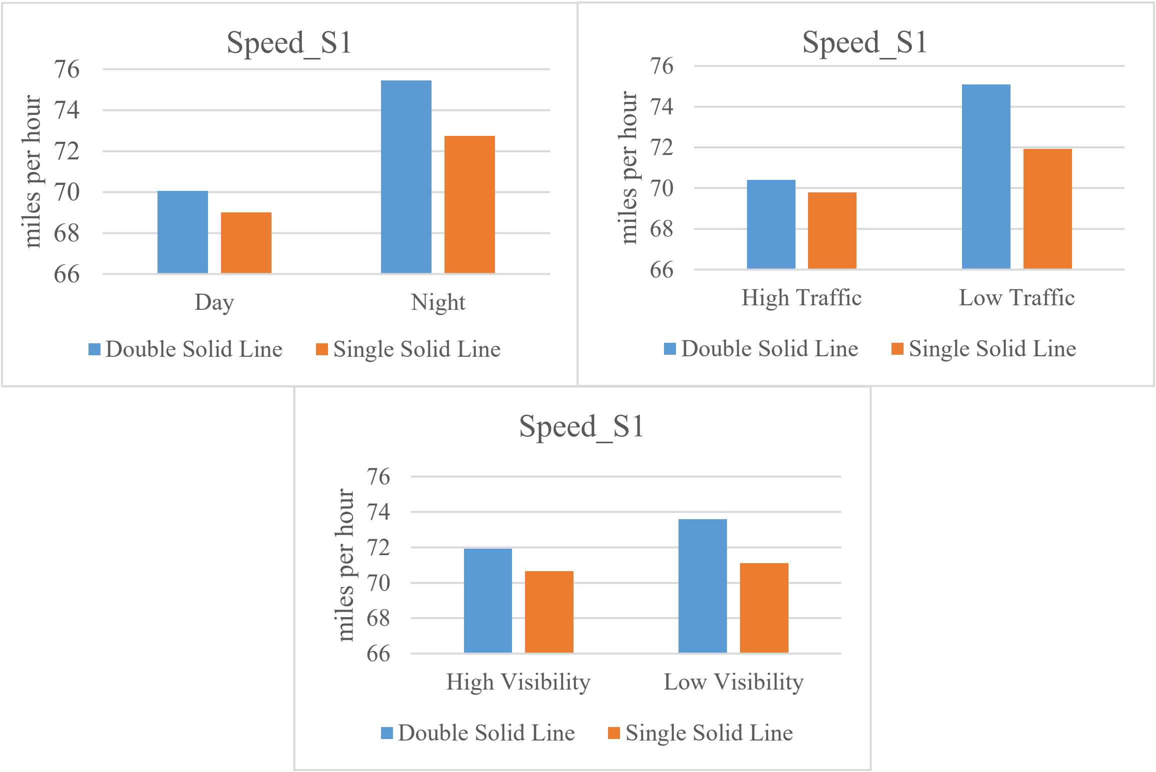


Figure 3.13: Effect of Separation Width on Speed in One-lane ML Straight Sections

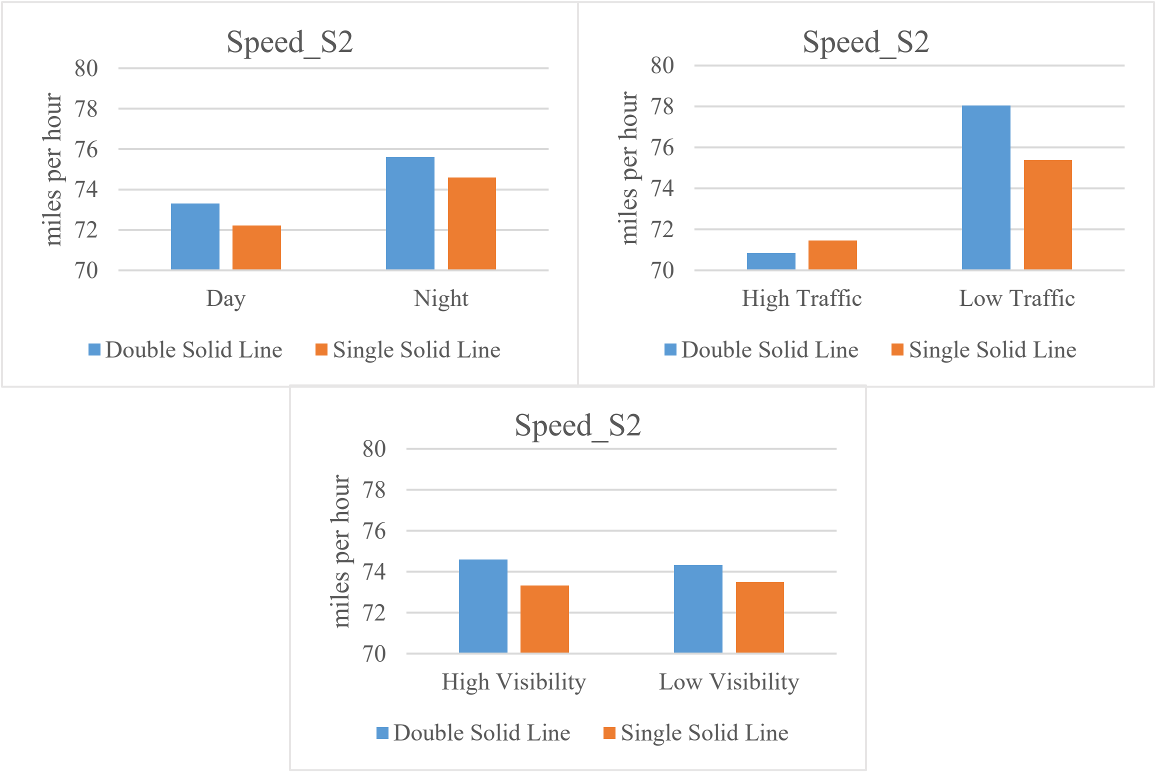


Figure 3.14: Effect of Separation Width on Speed in Two-lane ML Straight Sections

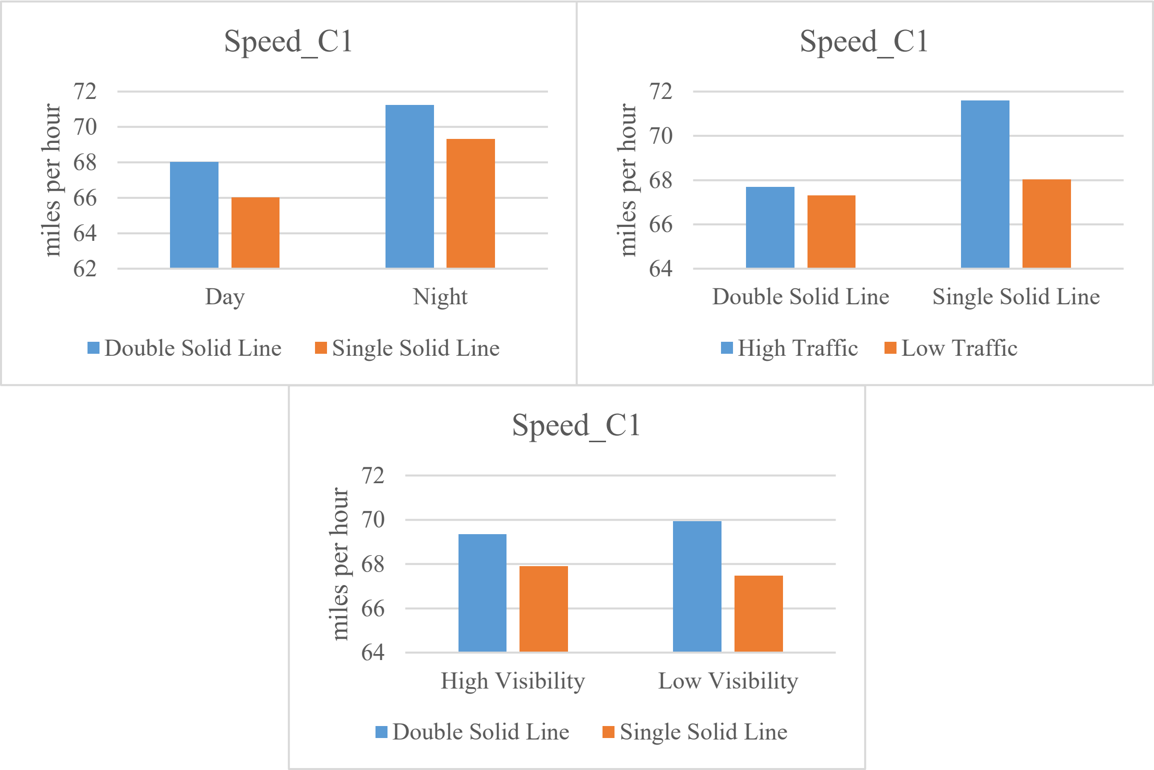


Figure 3.15: Effect of Separation Width on Speed in One-lane ML Curved Sections

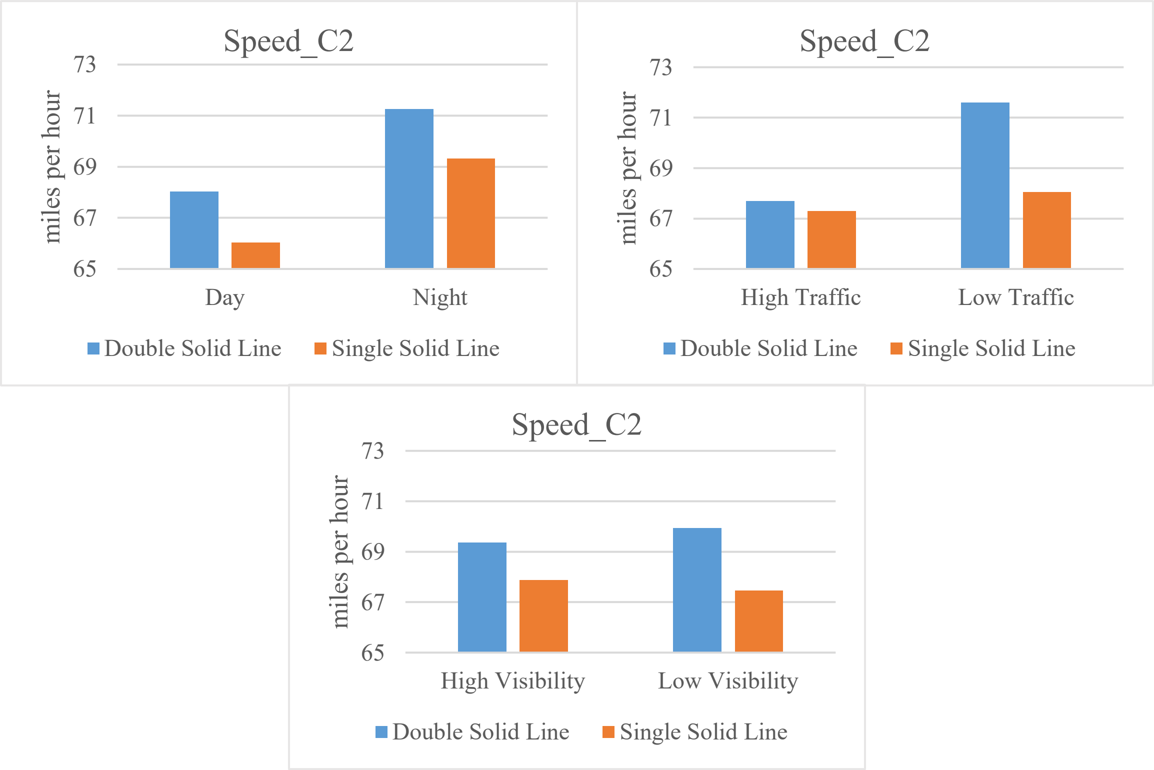


Figure 3.16: Effect of Separation Width on Speed in Two-lane ML Curved Sections

Speed Models

Three speed models were developed: (a) mean speed for straight sections, (b) mean speed for curved sections, and (c) speed differential (the difference between straight and curved sections, where a positive value indicates that the speed in curves is higher than in straight sections). Table 3.8 shows the model estimations for the speed.

Table 3.8: Model Estimations for Speed

Response/Parameter	Parameter Effect	Estimate	Std Error	Prob>|t|
Speed (Straight Sections)	Intercept	71.1993	0.3499	<.0001***
	(standard deviation)	*(2.2873)*	*(1.4927)*	*(0.0005)****
Age Group	Age (18-34)	1.6206	0.4952	0.0018***
	Age (35-64)	0.5989	0.4969	0.2331
TOD	Day	-1.5553	0.1364	<.0001***
	(standard deviation)	*(-)*	*(-)*	*(-)*
Traffic Density	High Density	-0.7889	0.1863	<.0001***
	(standard deviation)	*(1.874)*	*(0.9741)*	*(0.0003)****
Separation Width	Double Solid Line	0.3065	0.1136	0.0093***
	(standard deviation)	*(-)*	*(-)*	*(-)*
Speed (Curved Sections)	Intercept	68.2343	0.408	<.0001***
	(standard deviation)	*(2.3488)*	*(5.5167)*	*(0.0083)****
TOD	Day	-0.9875	0.1844	<.0001***
	(standard deviation)	*(1.3074)*	*(1.7092)*	*(0.051)**
Traffic Density	High Density	-0.3433	0.2113	0.11
	(standard deviation)	*(1.7224)*	*(2.9665)*	*(0.0078)****
Separation Width	Double Solid Line	0.4519	0.149	0.0037***
	(standard deviation)	*(1.7539)*	*(3.076)*	*(0.0029)****
Speed Differential	Intercept	-2.9577	0.3775	<.0001***
	(standard deviation)	*(2.5091)*	*(1.7575)*	*(0.0003)****
Age Group	Age (18-34)	-1.5608	0.534	0.005***
	Age (35-64)	-0.3525	0.5338	0.5118
TOD	Day	0.6107	0.1648	0.0005***
	(standard deviation)	*(-)*	*(-)*	*(-)*
Traffic Density	High Density	0.342	0.189	0.0755*
	(standard deviation)	*(-)*	*(-)*	*(-)*
Separation Width	Double Solid Line	0.1376	0.171	0.4245
	(standard deviation)	*(-)*	*(-)*	*(-)*
TOD x Separation Width	Day x Double Solid Line	0.4376	0.1635	0.0076***

Note: TOD = Time of day; “×” denotes an interaction effect, indicating that the impact of one variable depends on the level of another variable; *(-)* = standard deviation is not significant at 90% confidence intervals; * = Significant at 90% confidence interval; ** = Significant at 95% confidence interval; *** = Significant at 99% confidence interval.

For both straight and curved sections, double solid lines were found to positively impact mean speed (β = 0.3065, p-value = 0.0093 and β = 0.45193, p-value = 0.0037). To gain deeper insight into the impact of separation width on speed, predicted speed was also analyzed, which allows a more accurate assessment on how variations in separation width influence driving speed under different conditions. The analysis shows that the predicted average speed is closer to the 70-mph speed limit when double solid lines are present (see Figure 3.17). This supports the purpose of the ML, where maintaining speeds close to the speed limit is crucial for operational efficiency. Driving significantly below the speed limit in the ML is not expected, as it would hinder the lane's effectiveness. A significant negative relationship was also observed between age and speed, indicating that younger drivers tend to exhibit higher mean speeds compared to other age groups.

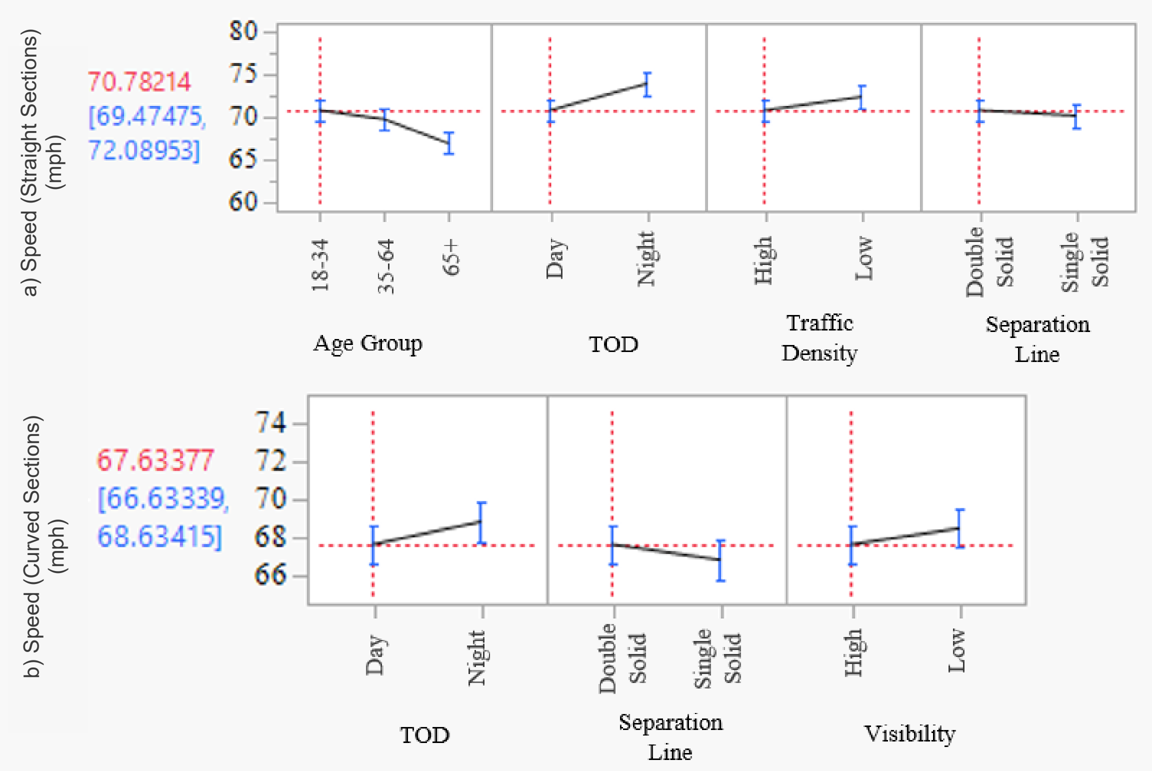
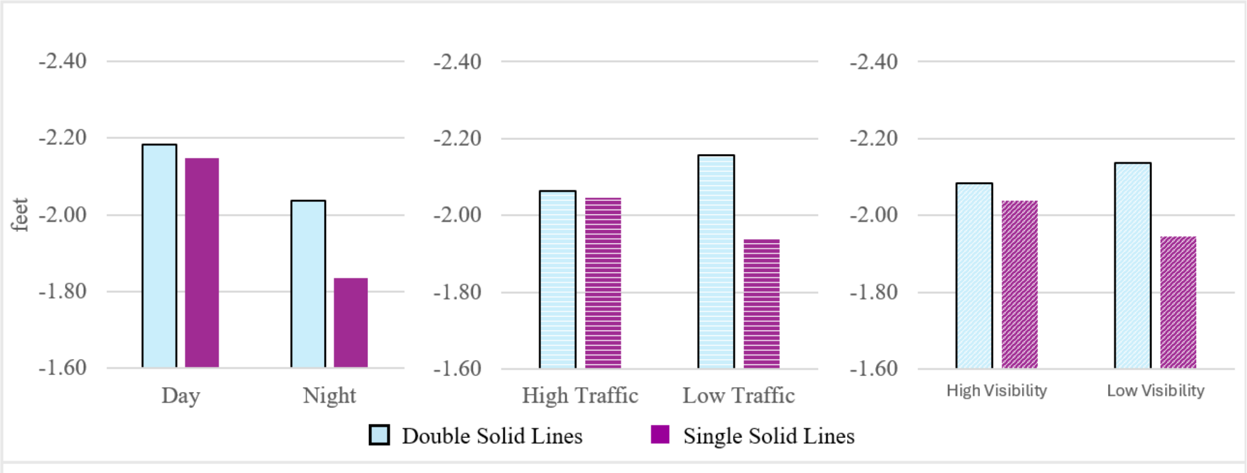


Figure 3.17: Predicted Speed Profiles

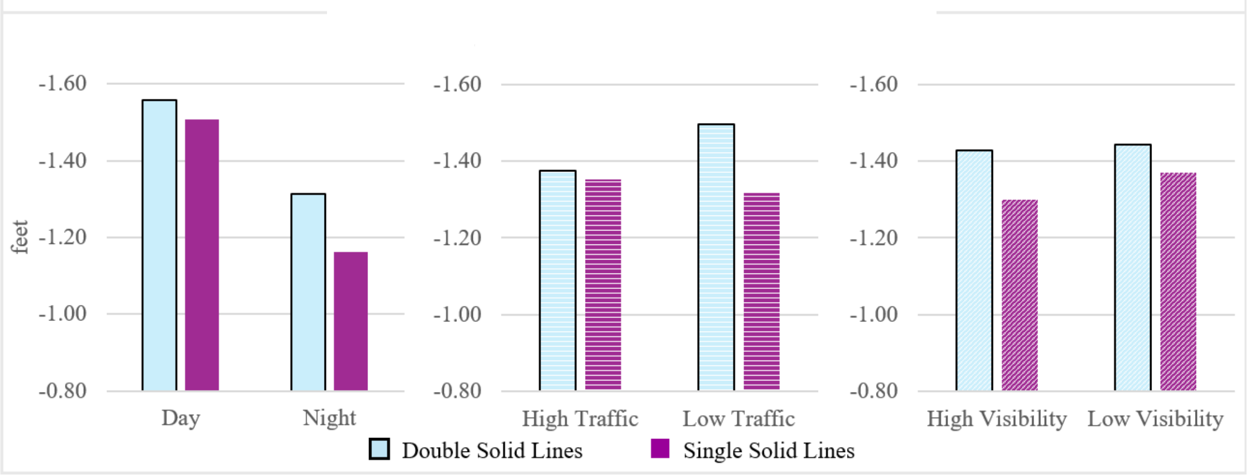
3.3.1.3 Lane Deviation

Lane deviation measures the vehicle position within the ML, whether to the left of the lane's center (further from the delineators) or to the right of the lane's center (closer to the delineators). The influence of separation width on lane deviation is depicted in Figures 3.18 and 3.19.

The analysis results of lane deviation, shown in Table 3.9, reveal that drivers are more likely to steer left, away from the double solid lines ($\beta = -0.0636$, $p = 0.0007$ and $\beta = -0.0504$, $p = 0.0097$). This tendency can be attributed to the increased visibility of the double solid lines, which aligns with the subjective findings, as participants reported that these lines were more noticeable. This observation was expected, as double solid lines signal a wider lane separation, prompting drivers to position themselves closer to their left lane boundaries. Moreover, the analysis revealed that traffic density, visibility, and separation lines significantly impact lane positioning. Under high traffic density and good visibility conditions, drivers tend to stay closer to the double solid lines. Figure 3.20 illustrates the marginal effects of significant parameters on lane deviation.

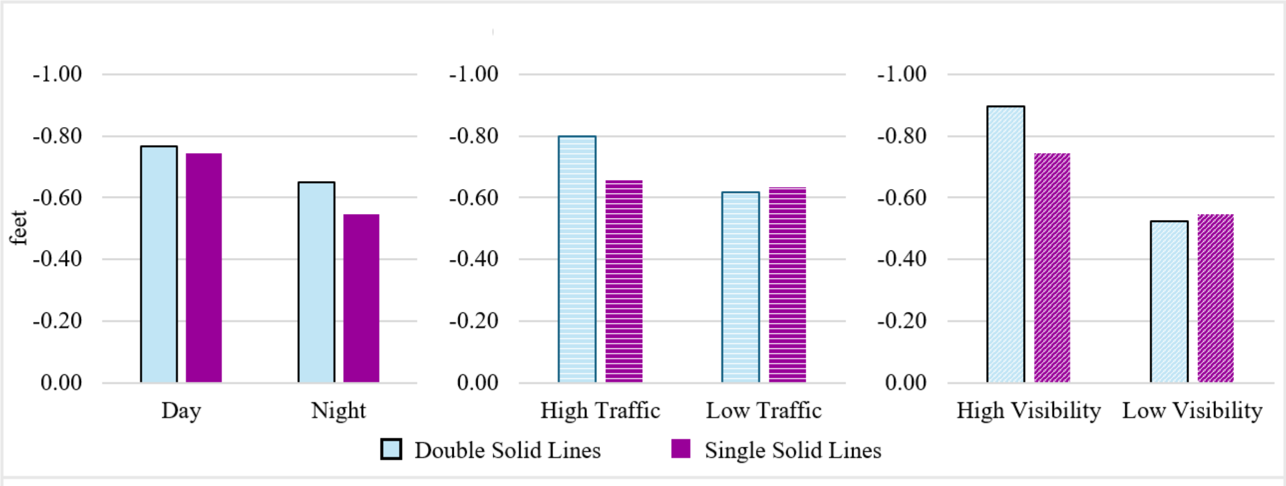


(a) Lane Deviation (Straight Section)

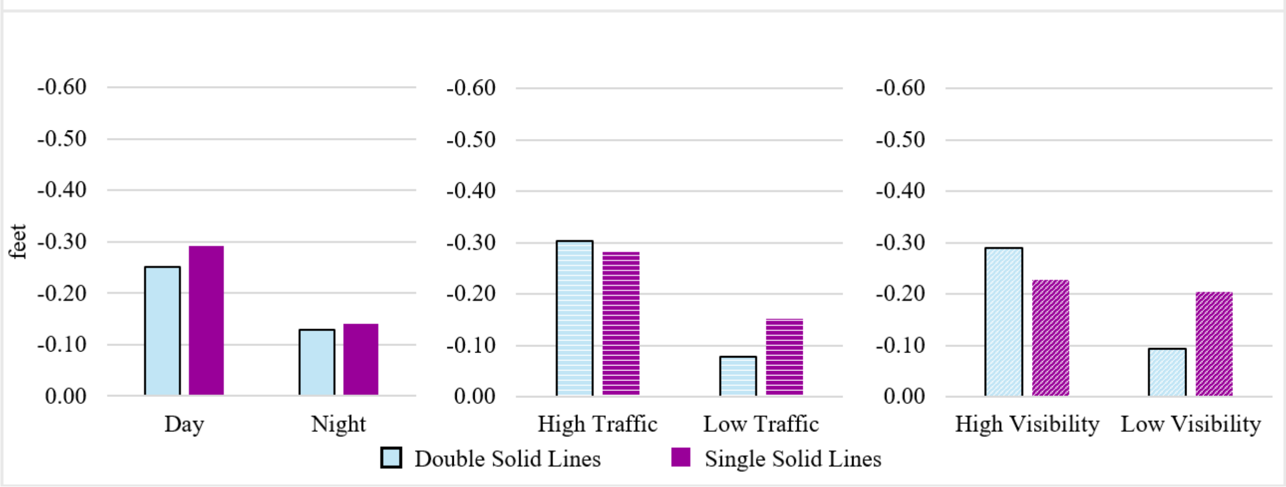


(b) Lane Deviation (Curved Section)

Figure 3.18: Effect of Separation Width on Lane Deviation – One-lane ML



(a) Lane Deviation (Straight Section)



(b) Lane Deviation (Curved Section)

Figure 3.19: Effect of Separation Width on Lane Deviation – Two-lane ML

Table 3.9: Model Estimations for Lane Deviation

Response/Parameter	Parameter Effect	Estimate	Std Error	Prob>|t|
Lane Deviation (Straight Section)	Intercept	-2.0101	0.0858	<.0001***
	(standard deviation)	*(0.6279)*	*(0.0844)*	*(<.0001)* ***
TOD	Day	-0.1058	0.0232	<.0001***
	(standard deviation)	*(-)*	*(-)*	*(-)*
Separation Width	Double Solid Line	-0.0636	0.0177	0.0007***
	(standard deviation)	*(-)*	*(-)*	*(-)*
Traffic Density x Separation Width	High Density x Double Solid Line	0.0504	0.0143	0.0010***
Visibility x Separation Width	High Visibility x Double Solid Line	0.0419	0.0161	0.0119**
Lane Deviation (Curved Section)	Intercept	-1.385	0.09	<.0001***
	(standard deviation)	*(0.6666)*	*(0.0901)*	*(<.0001)* ***
TOD	Day	-0.1481	0.0258	<.0001***
	(standard deviation)	*(0.1779)*	*(0.0152)*	*(0.0374)* **
Separation Width	Double Solid Line	-0.0504	0.0189	0.0097***
	(standard deviation)	*(-)*	*(-)*	*(-)*

Note: TOD = Time of day; “×” denotes an interaction effect, indicating that the impact of one variable depends on the level of another variable; *(-)* = standard deviation is not significant at 90% confidence intervals; * = Significant at 90% confidence interval; ** = Significant at 95% confidence interval; *** = Significant at 99% confidence interval.

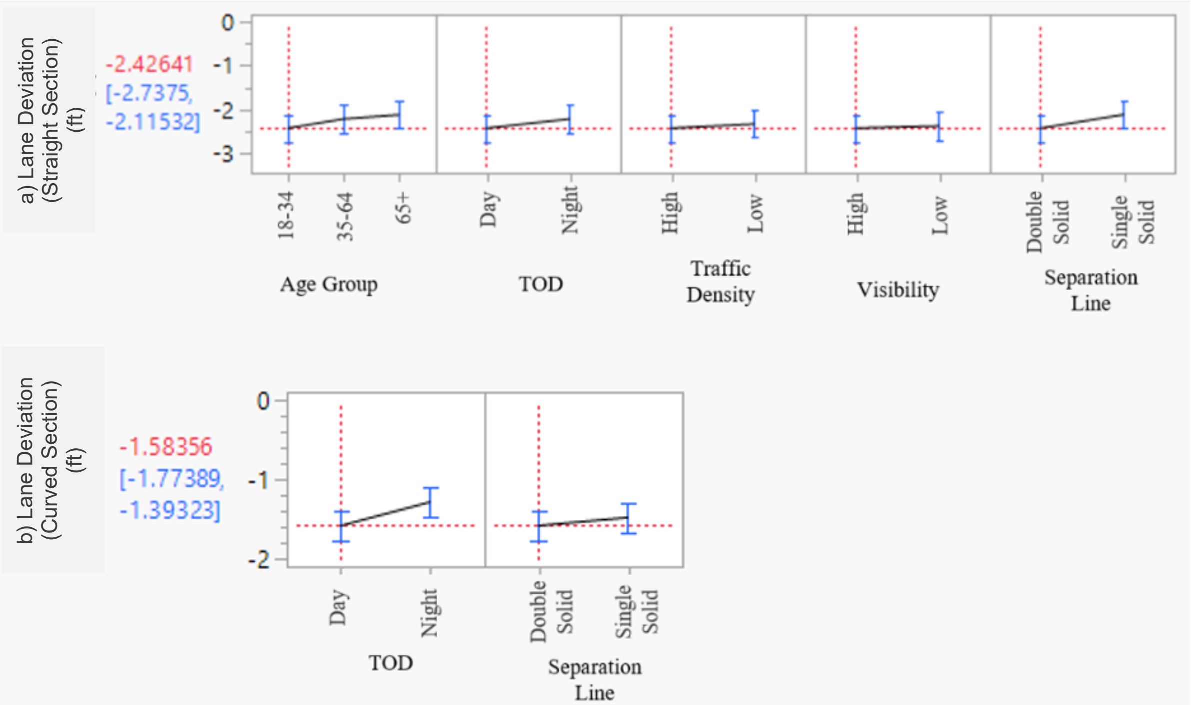


Figure 3.20: Predicted Lane Deviation Profiles

3.3.1.4 *Visual Attention*

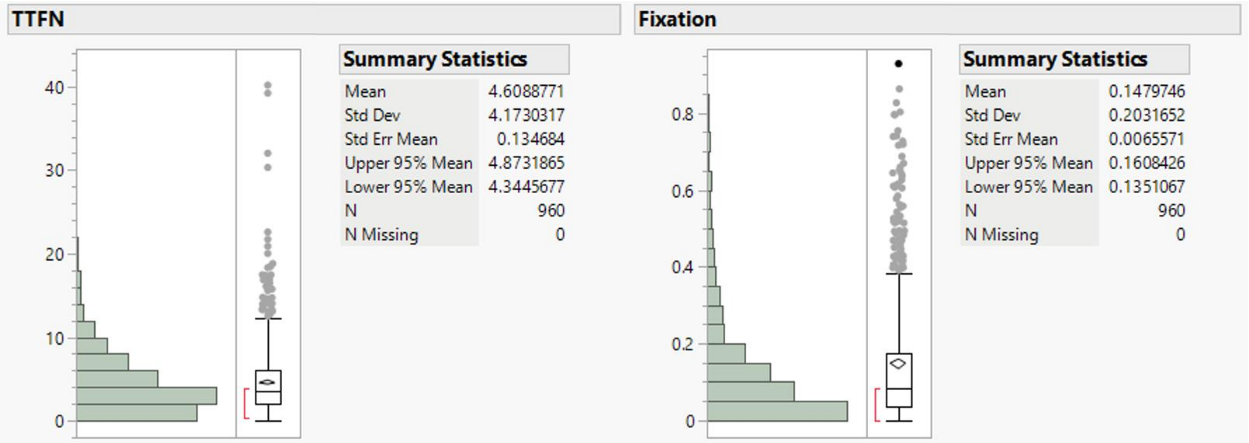
The eye tracking process focused on visual attention measures and was divided into two components: time to first notice (TTFN) and fixation duration. Eye tracking data and video data were analyzed frame by frame to determine these two metrics. To measure the TTFN, a reference point was set at 325 feet before the ML entrance, marked by the second lamppost as shown in Figure 3.21. Each video data point was manually reviewed to record the time duration as drivers crossed the second lamppost, and was later used as the start time for the calculation of the TTFN and fixation duration, with the end time set to when drivers exited the second ML.

Figure 3.21: Location and Distance for Estimating Visual Attention Measures

The FOVIO eye tracker operates at a frame rate of 60 Hz, which means it captures 60 frames per second. This allows for precise tracking of eye movements, providing detailed data on where and how long a participant is looking at specific points in their field of view.

The TTFN analysis focused on one key question: how long did it take for participants to first notice the separation treatment? To determine this, a specific region was defined as the area of interest (AOI). The TTFN was then calculated by subtracting the timestamp when the driver crossed the reference point from the timestamp when the participant's gaze first landed on the AOI. Figure 3.22 presents the distribution of the eye tracking metric. The distribution shows that both TTFN and fixation durations are right-skewed. To better understand the impact of separation width on these visual attention measures, the logarithmic transformation of the two metrics was analyzed, allowing for a more accurate assessment of the underlying effects.

As shown in Table 3.10, the logarithmic analysis of TTFN identified age, time of day (TOD), traffic density, and visibility as the main significant factors. Younger drivers tend to notice separation lines more quickly from a distance, which is expected given that visual ability declines with age, causing older drivers to take longer and requiring them to be closer to the ML entry to notice the separation lines. Additionally, TTFN is significantly shorter during the day and in high visibility conditions, whereas high traffic density increases detection time, indicating that congestion makes it more challenging for drivers to quickly notice the separation lines. Regarding separation width, Figure 3.23 shows that double solid lines have shorter TTFN; however, there is insufficient statistical evidence to confirm this effect.



TTFN

Summary Statistics	
Mean	4.6088771
Std Dev	4.1730317
Std Err Mean	0.134684
Upper 95% Mean	4.8731865
Lower 95% Mean	4.3445677
N	960
N Missing	0

Fixation

Summary Statistics	
Mean	0.1479746
Std Dev	0.2031652
Std Err Mean	0.0065571
Upper 95% Mean	0.1608426
Lower 95% Mean	0.1351067
N	960
N Missing	0

Figure 3.22: Distribution of Eye Tracking Metrics

Table 3.10: Model Estimations for Log (TTFN) and Log (Fixation)

Response/Parameter	Parameter Effect	Estimate	Std Error	Prob>|t|
Log (TTFN)	Intercept	1.2274	0.0373	<.0001***
	(standard deviation)	*(0.1935)*	*(0.0218)*	*(0.0853)* *
Age Group	Age (18-34)	-0.108	0.0528	0.0455**
	Age (35-64)	0.0369	0.0527	0.4869
TOD	Day	-0.0802	0.0236	0.0013***
	(standard deviation)	*(-)*	*(-)*	*(-)*
Traffic Density	High Density	0.3368	0.0244	<.0001***
	(standard deviation)	*(-)*	*(-)*	*(-)*
Visibility	High Visibility	-0.0418	0.0247	0.0957*
	(standard deviation)	*(-)*	*(-)*	*(-)*
Separation Width	Double Solid Line	-0.0283	0.0231	0.2246
	(standard deviation)	*(-)*	*(-)*	*(-)*
Log (Fixation)	Intercept	-2.4745	0.1098	<.0001***
	(standard deviation)	*(0.7944)*	*(0.1365)*	*(<.0001)* ***
Age Group	Age Group [18-34]	0.3723	0.1552	0.0198**
	Age Group [35-64]	-0.0663	0.1552	0.6709
TOD	Day	0.0702	0.0343	0.0453**
	(standard deviation)	*(0.2932)*	*(0.028)*	*(0.0022)****
Separation Width	Double Solid Line	-0.029	0.0259	0.267
	(standard deviation)	*(0.1744)*	*(0.0155)*	*(0.05)* ***

Note: TTFN = Time to First Notice; TOD = Time of day; *(-)* = standard deviation is not significant at 90% confidence intervals; * = Significant at 90% confidence interval; ** = Significant at 95% confidence interval; *** = Significant at 99% confidence interval.

The analysis of fixation duration shows that younger drivers tend to have longer fixations compared to other age groups. Time of day also significantly influences gaze duration, with longer fixations occurring during the day (β = 0.0702, p = 0.0453). As with TTFN, there was no clear evidence that separation lines significantly affect fixation duration. However, there is a marginally significant variability in fixation duration associated with separation lines (std. dev. = 0.1744, p = 0.05). The effect of separation lines is random on participants' fixation responses, as the influence of these lines on duration of their fixations varied for each individual. Figure 3.23 presents the predicted outcome for fixation duration, showing that double solid lines have a lower fixation rate compared to single solid lines. Furthermore, older drivers tend to concentrate less on separation markings and focus more on their surroundings.

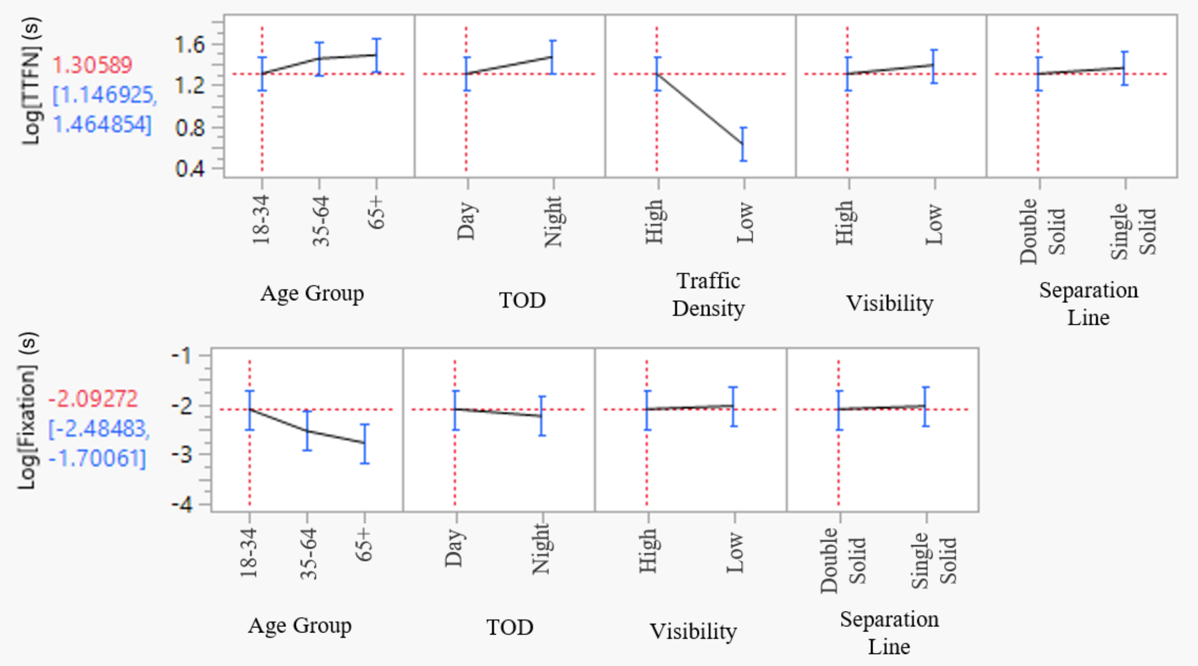


Figure 3.23: Predicted TTFN and Fixation Duration Profiles

3.3.2 Effect of Separation Height on Driving Behavior

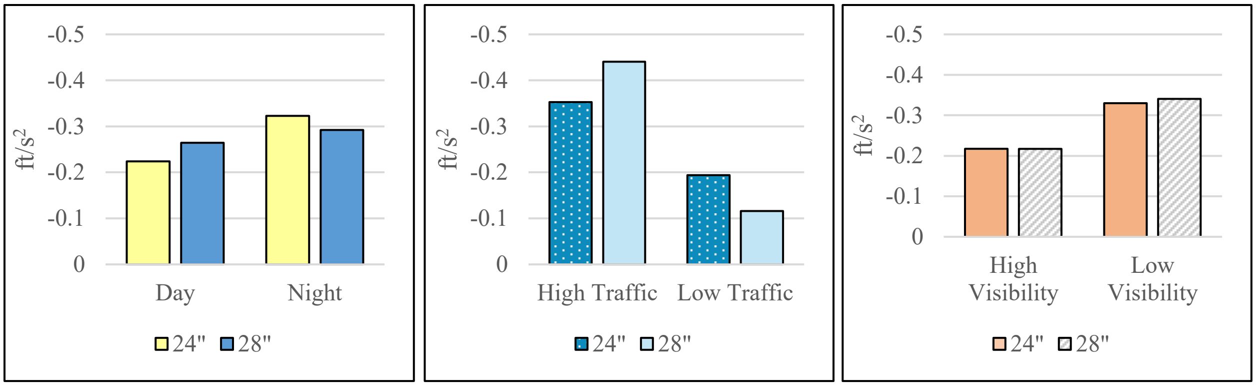
Speed patterns and vehicle positioning are two critical factors in assessing the safety performance of MLs, especially in curved sections. To evaluate the impact of separation height (i.e., height of delineators) on driving behavior, deceleration and mean speed were analyzed within speed patterns for curved sections. Lane deviation and steering angle rate were considered for vehicle positioning in curved sections. Note that, in this study, delineator height varied only in the curved sections (e.g., 24-inch or 28-inch); therefore, only ML curved sections were included in analyses related to separation height. The analysis in this section focused only on the one-lane ML curve to allow for a better assessment of the direct effects of delineator height on driver performance. While comparing separation heights, the 28-inch delineator was used as the base level for comparison.

3.3.2.1 Speed Patterns

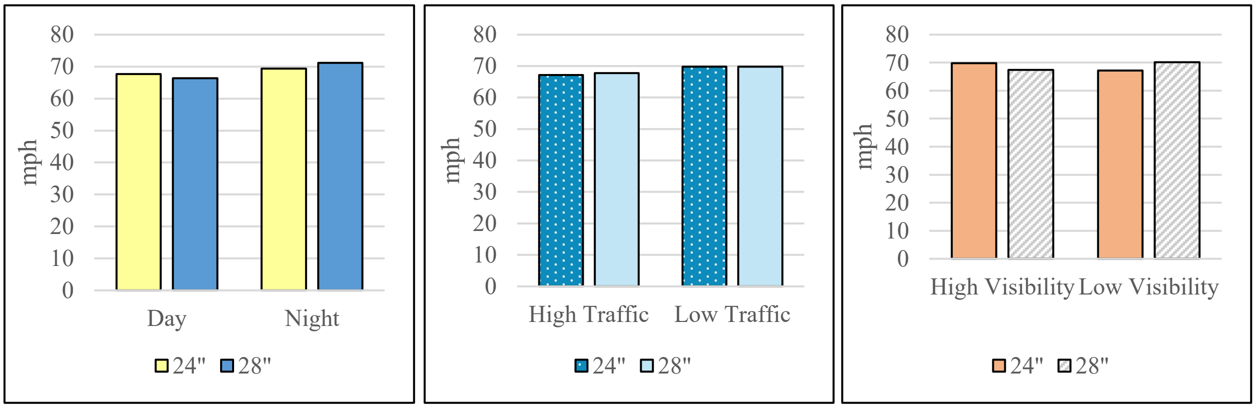
A mixed response was observed for the effects of separation height on deceleration in a one-lane ML curve. For instance, from Figure 3.24(a) it can be observed that in nighttime and low traffic conditions, the mean deceleration rate is higher for the 24-inch delineators, while in different weather conditions, the deceleration rate is nearly the same for both 24-inch and 28-inch delineators. These results imply that separation height does not significantly influence deceleration behavior as drivers approached the curved section. The mixed effects model further supports this finding, showing no significant fixed effect of separation height on deceleration. However, the model identified a significant random effect of separation height on deceleration behavior (std. dev = 0.3259, p-value = 0.0152), indicating that its impact varies across drivers. This variability refers to the uneven influence of separation height across drivers, indicating that its effect, instead, depends on individual driver characteristics or other factors. This finding aligns with the exit survey results since more than one-third of the participants (38%) could not notice the changes in separation height, and so the effect of separation height on the drivers' deceleration behavior varied between drivers. The deceleration profiles in Figure 3.24(a) show that the deceleration rate is predicted to be higher for the 28-inch delineators. This may be attributed to the higher visibility of 28-inch delineators, as participants who noticed the changes in separation heights reported that these delineators were more noticeable than the 24-inch delineators. Another possible reason behind the higher deceleration rate could be the relation between delineator height and the perception of a curve, as previous studies found that taller delineators can enhance the perception of curve steepness (Nygårdhs et al., 2014). As a result, drivers decelerate more as a natural response to taller delineators. In the case of other factors, traffic density was found to have an influence on deceleration behavior. In high-traffic conditions, drivers are more likely to adjust their speed dynamically, often cruising, then accelerating to keep pace with the flow of traffic.

Similar to deceleration, no definite pattern was identified in participants' mean speed that can lead to a relationship between separation height and speeding behavior. The mean speed ranged from 66 MPH to 71 MPH for scenarios with 28-inch delineators, while for the 24-inch delineators, the mean speed ranged from 67 MPH to 70 MPH. The Speed analysis, shown in Table 3.11, did not find that separation height affects speed because the p-value (0.5418) is greater than 0.1 (90% confidence). Other factors such as age, daytime, and high traffic density were found to have a consistent effect on the mean speed at the curve.

However, marginal profiles shown in Figure 3.25(b) show a reduction in drivers' mean speed associated with the 24-inch delineators since they are more prevalent on the curves. Taller delineators can provide clearer demarcation of lanes, allowing drivers to have a better understanding of the lane alignment and increase perception of safety. The improved perception of safety can lead to higher confidence, and consequently, higher speeds. However, the analysis did not find statistical evidence to prove this assumption, as shown in Table 3.11. Additionally, a negative relationship between mean speed and both age and time of day was observed, indicating that older drivers tend to reduce their speed around curves, and all drivers exhibit increased carefulness during daytime conditions.



a) Deceleration (ft/s^2)



b) Speed (mph)

Figure 3.24: Effects of Separation Heights on Speed in ML Curve (One-lane)

Table 3.11: Mixed-effects Model Estimates for Separation Height on Deceleration & Speed

Metrices	Parameters	Estimate	Std. Error	Prob>|t|
Deceleration (ft/s^2)	Intercept	-0.1329	0.0196	<.0001***
TOD	Day	0.0337	0.0391	0.3923
Traffic Density	High Density	0.1234	0.0509	0.0187**
Separation Height	24-inch Delineators	0.0017	0.0580	0.9772
	(standard deviation)	*(0.4647)*	*(0.0889)*	*(0.0152)***
Speed (mph)	Intercept	71.8489	1.2788	<.0001***
	(standard deviation)	*(0.4647)*	*(0.0889)*	*(0.0004)****
Age	Age	-0.0673	0.0248	0.0078***
TOD	Day	-1.6302	0.2764	<.0001***
Traffic Density	High Density	-1.1642	0.4944	0.0208**
	(standard deviation)	*(0.4647)*	*(0.0889)*	*(0.0045)****
Separation Height	24-inch Delineators	-0.1236	0.2013	0.5418

Note: TOD = Time of day; * = Significant at 90% confidence interval; ** = Significant at 95% confidence interval; *** = Significant at 99% confidence interval. Results represent the analysis of one-lane ML curved section.

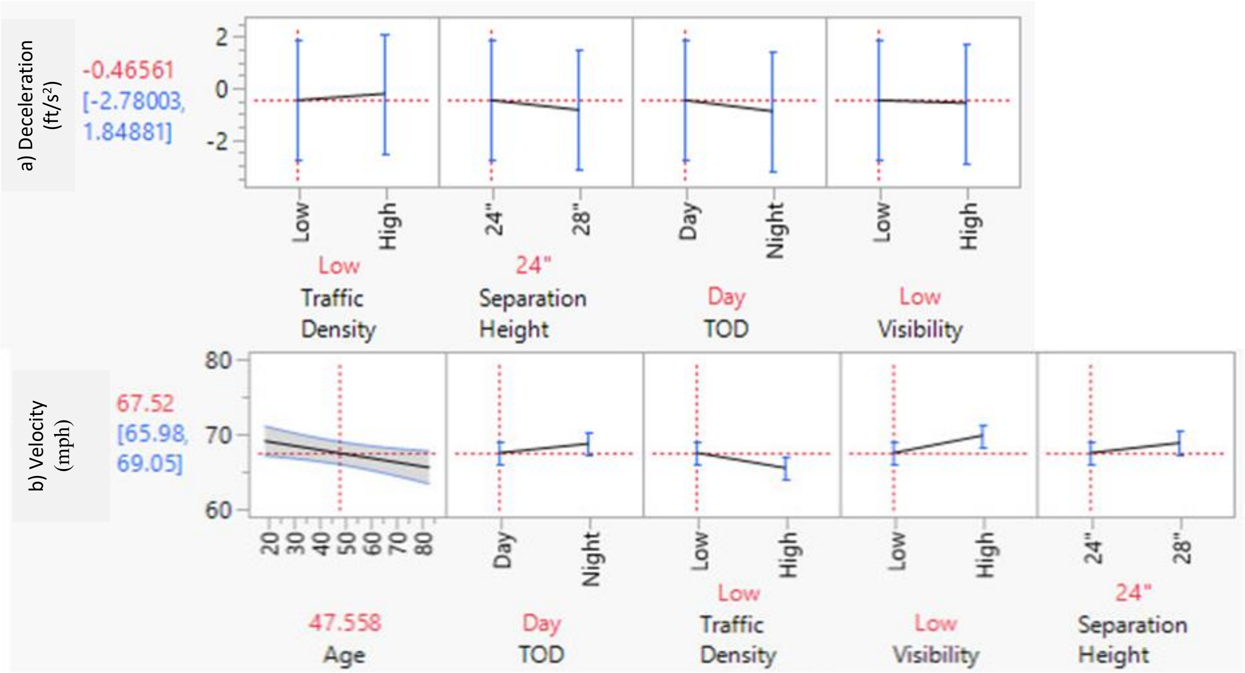
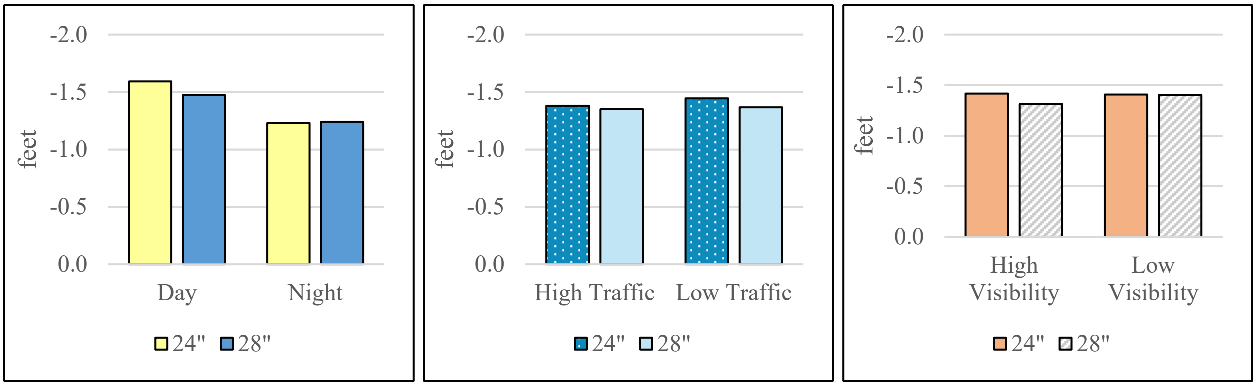


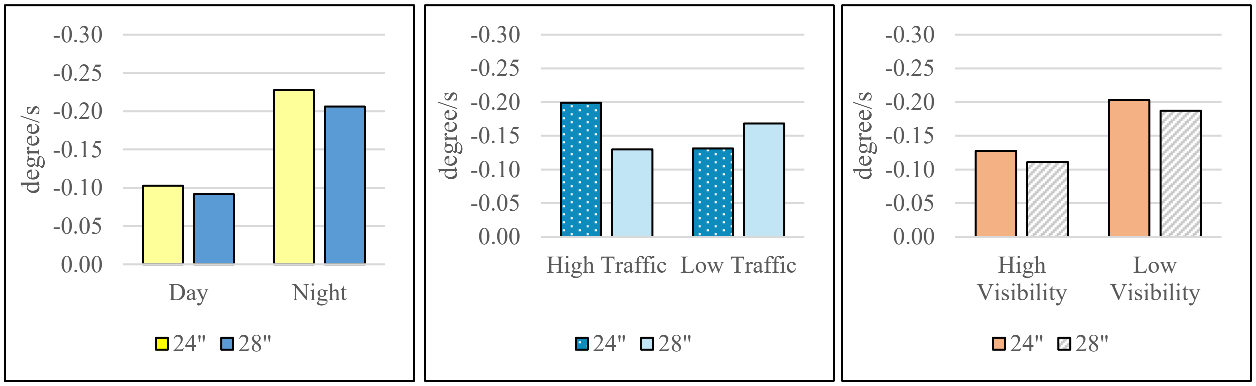
Figure 3.25: Predicted Speed Behavior Profiles

3.3.2.2 Vehicle Positioning

Lane deviation measures the lateral position of the vehicle within the lane in the curved section of the ML, with negative values indicating that the vehicle is positioned to the left side of the lane, and positive values indicating a position to the right side. The magnitude of the lane deviation indicates how far the position is from the center of the lane. The steering angle rate reflects the speed and direction of steering adjustments made by the driver. It reflects how quickly and aggressively the driver is changing the vehicle's direction. A negative value typically represents turning the steering toward left directions and vice versa. Figure 3.26 shows the average lane deviation and steering rate observed in the one-lane curve under different driving conditions and delineator heights.



a) Lane Deviation (ft)



b) Steering Angle Rate (degree/s)

Figure 3.26: Effects of Separation Height on Vehicle positioning (One-lane Curve)

The most prominent effect on lane deviation was found to be between time of day and separation height, as shown in Table 3.12. Also, age was found to have an impact on lane deviation, but with lesser significance. For separation height, drivers showed a tendency to drive closer to the left shoulder with shorter delineators in the curve ($\beta = -0.0326$, $p = 0.065$). Figure 3.27 illustrates the marginal effects of significant parameters on predicted vehicle positioning, highlighting the intensity of the impact of these parameters on lane deviation and steering angle rate. The profiles in Figure 3.27 also show that the intensity of the separation height effect is not substantial. This could be attributed to the minimal difference in height between the 24-inch and 28-inch delineators perceived while driving. The negative estimate ($\beta = -0.1532$) for daytime indicates that vehicles tend to be positioned more to the left during the day, while younger drivers tend to drive closer to the center of the lane ($\beta = 0.0076$).

As indicated in Table 3.12, the analysis of the steering angle rate reveals a similar driving tendency, showing a highly significant association with 24-inch delineators and a higher steering rate towards the left when approaching the curved section of the ML ($\beta = -0.0164$, $p < 0.0001$). It also refers to the dependency on the left lane boundary lines while navigating the curved section with 24-inch delineators. Age was positively associated with steering angle rate, revealing better control over the steering wheel with an increase in age. Daytime and high visibility conditions also enhance steering control, leading to a reduction in steering angle rate at the curves.

Table 3.12: Mixed-effects Model for Separation Height on Lane Deviation & Steering Angle

Metrices	Parameters	Estimate	Std. Error	Prob>|t|
Lane Deviation (ft)	Intercept	-1.7257	0.1669	<.0001***
	(standard deviation)	(0.6470)	(0.0877)	(<.0001) ***
Age	Age	0.0073	0.0042	0.0876*
TOD	Day	-0.1481	0.0272	<.0001***
	(standard deviation)	(0.2284)	(0.0169)	(0.0027)***
Separation Height	24-inch delineators	-0.0390	0.0181	0.0317**
Steering Angle (degree/s)	Intercept	-0.1698	0.0104	<.0001***
	(standard deviation)	(0.0262)	(0.0003)	(0.0661) *
Age	Age	0.0005	0.0002	0.0227**
TOD	Day	0.0479	0.0040	<.0001***
Traffic Density	High Density	-0.0179	0.0036	<.0001***
Visibility	High Visibility	0.0261	0.0039	<.0001***
Separation Height	24-inch	-0.0164	0.0036	<.0001***

Note: TOD = Time of day; * = Significant at 90% confidence interval; ** = Significant at 95% confidence interval; *** = Significant at 99% confidence interval. Results represent the analysis of one-lane ML curved section.

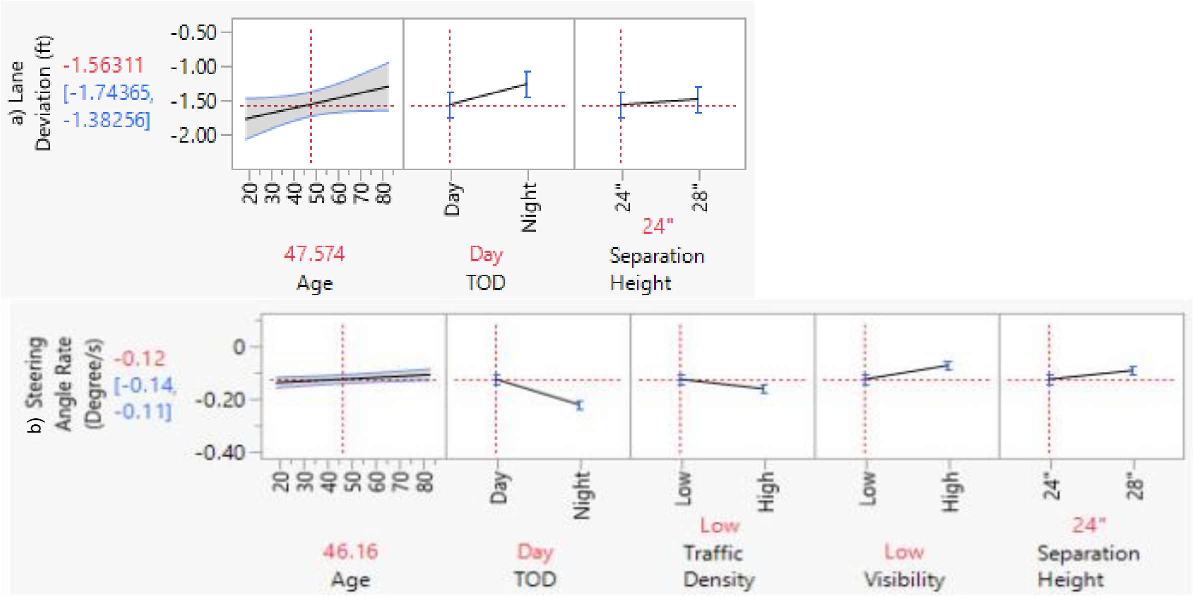


Figure 3.27: Predicted Vehicle Positioning Profiles

3.3.2.3 Fixation

Fixation duration was investigated to understand the impact of separation height on drivers' attention. A fixation is when the eye briefly pauses on a specific area or object during a task, with fixation duration referring to the average time spent on each pause (Holmqvist et al., 2011; Tullis & Albert, 2013). Fixation duration can be sensitive to several factors. For instance, the amount of attention directed onto a fixated location, memory load or the amount of information a working memory can hold, and information processing time can increase fixation duration (Henderson & Hollingworth, 1999; Irwin, 2004; Just & Carpenter, 1980; McCarley et al., 2006; Salthouse & Ellis, 1980). However, driving experience can lead to shorter fixation durations (Crundall & Underwood, 2011). Given that the fixation data were highly skewed to the right, the log function was applied to normalize the distribution for the analysis. This approach allows for more accurate information. The analysis of log(fixation) in Table 3.13 shows a positive association between 24-inch delineators and fixation duration (β = 0.0376). Although this association is statistically significant at the 90% confidence level (p-value = 0.070 > 0.05), Figure 3.28 shows that the difference in predicted effects of separation heights is relatively small. The exit survey results also showed that drivers found the 24-inch delineators less noticeable. Therefore, it cannot be concluded that either the 24-inch or 28-inch delineator has a dominant influence on driver attention, as the separation height showed a weaker association with fixation duration. The exit survey results further support this finding, as many drivers (38%) could not differentiate the change in delineator heights at the curved sections (see Section 4.3 for exit survey results).

Conversely, there is a strong correlation between fixation duration and demographic factors, such as age and gender, as indicated in Table 3.13 and Figure 3.28. Results show that as age increases, fixation duration decreases, suggesting that younger drivers, particularly those aged 18 to 34, tend to fixate more on the delineators while navigating curves. Female drivers also showed higher fixation times (β = 0.2738, p = 0.0004), which can be attributed to increased attention to delineators and scanning behavior. Based on the exit survey, the number of female participants who noticed the change in separation height was higher than male participants. Low visibility was also associated with higher fixation duration at the curves.

Table 3.13: Mixed-effects Model Estimates for Separation Height on Fixation Duration

Metrices	Parameters	Estimate	Std. Error	Prob>|t|
Log [Fixation] (s)	Intercept	-1.7444	0.2598	<.0001***
	(standard deviation)	(0.7268)	0.115	(<.0001) ***
Age	Age	-0.0151	0.0050	0.0040***
Gender	Female	0.2722	0.1009	0.0091***
Visibility	Low Visibility	0.0414	0.0207	0.0461**
Separation Height	24-inch delineators	0.0376	0.0207	0.0701*

Note: * = Significant at 90% confidence interval; ** = Significant at 95% confidence interval; *** = Significant at 99% confidence interval.

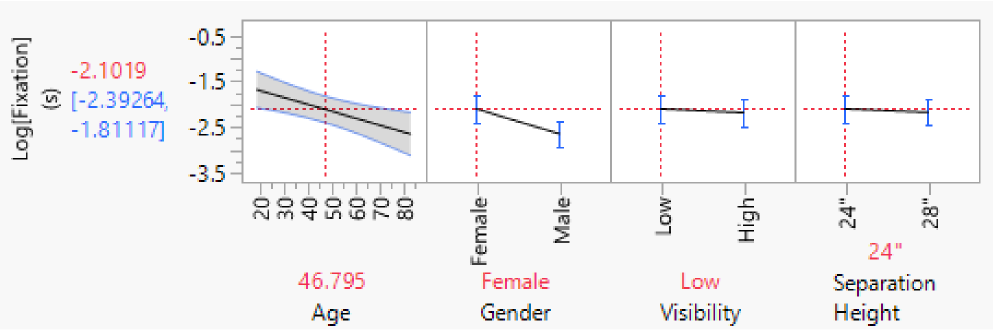


Figure 3.28: Predicted Fixation Duration Profiles

3.3.3 Combined Effect of Separation Width and Height on Driving Behavior

To further understand how different combinations of separation height and width influence driver behavior, the interaction effect of combinations was examined on the curved sections of the MLs. Each performance factor was analyzed, incorporating separation height, width, and their interaction effects to capture the combined impact on driving behavior. Performance factors were then examined by the age group, and the results were compared with the full model. Before conducting these analyses, outliers were eliminated to ensure accuracy. Additionally, a stepwise regression was employed to identify other potential influences on each performance factor beyond the target effects. Lastly, mixed-effects modeling techniques were applied to account for both fixed and random effects, providing a comprehensive understanding of the factors influencing driving behavior across different age groups.

3.3.3.1 Deceleration

The analysis of deceleration reveals a combined effect of separation width and height on driver behavior. Specifically, the interaction between 24-inch delineators and double solid lines is inversely associated with deceleration, meaning that drivers tend to decelerate less when entering curves where both 24-inch delineators and double solid lines are present. The mixed-effect estimates in Table 3.14 show that this trend is consistent across both the full model and the age group-specific models. However, the interaction effect is not significant for all age groups, except for the middle-aged group, which was significant ($\beta = 0.210$, p-value = 0.038). In the full model, the interaction effect is significant at the 90% confidence level ($\beta = 0.086$, p-value = 0.098), suggesting that while there is some impact on deceleration behavior, it is not particularly strong across all drivers, regardless of age. The marginal effects of separation height and width (see Figure 3.30) indicate that both 24-inch delineators and double solid lines have a lesser effect on the deceleration rate. Overall, Figure 3.29 shows that the deceleration rate is the highest for the double solid lines with 28-inch delineators, followed by single solid lines with 24-inch delineators, and the single solid lines with 28-inch delineators.

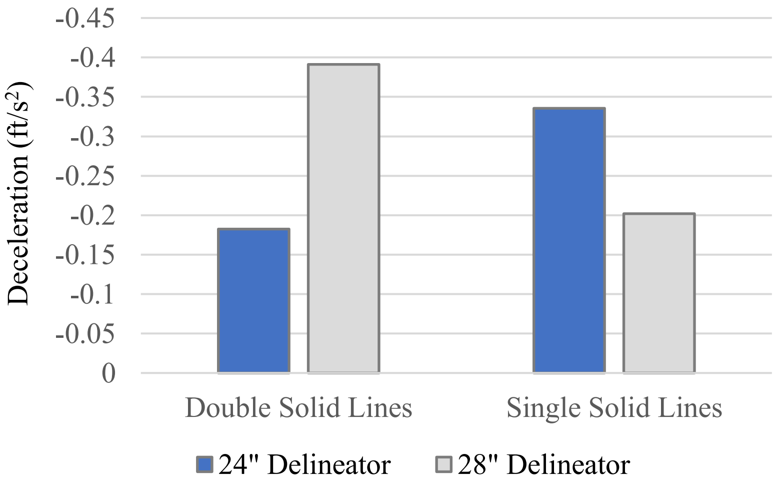


Figure 3.29: Deceleration Rate by Separation Height and Width

The effect of age on deceleration behavior was also observed in both younger and older age groups, where the tendency to decelerate while entering a curve increased with age. However, middle-aged drivers showed no significant influence on their deceleration tendencies, indicating more uniform behavior within this group. High traffic density influences the deceleration rate, as the increased number of cars on the road limits the space available for speeding, leading to a generally lower deceleration rate, as shown in Figure 3.30. From Table 3.14, this effect was not specific to any particular age group but instead reflects a broader tendency among drivers.

Table 3.14: Mixed-effects Estimates for Separation Height and Width on Deceleration

		Full Model		Age (18 -34)		Age (35-64)		Age (65+)	
Response/ Parameter	Parameter Effects	Est.	Prob>|t|	Est.	Prob>|t|	Est.	Prob>|t|	Est.	Prob>|t|
Deceleration	Intercept	-0.407	0.030**	1.320	0.106	-0.439	0.516	2.536	0.058*
Age	Age	0.003	0.453	-0.065	0.038**	0.004	0.806	-0.038	0.043**
TOD	Day	0.016	0.729	-0.035	0.663	0.144	0.116	-0.046	0.440
Traffic Density	High Density	0.112	0.028**	0.155	0.123	0.129	0.194	0.035	0.548
SH	24”	0.017	0.738	0.115	0.257	-0.106	0.287	0.022	0.712
SW	Double Solid	-0.014	0.787	-0.037	0.711	0.062	0.534	-0.053	0.379
SH * SW	24” * Double	0.086	0.098*	0.046	0.645	0.21	0.038**	0.018	0.770

Note: SH = Separation Height; SW =Separation Width; DSL = Double Solid Line; “×” denotes an interaction effect, indicating that the impact of one variable depends on the level of another variable; * = Significant at 90% confidence interval; ** = Significant at 95% confidence interval; *** = Significant at 99% confidence interval.

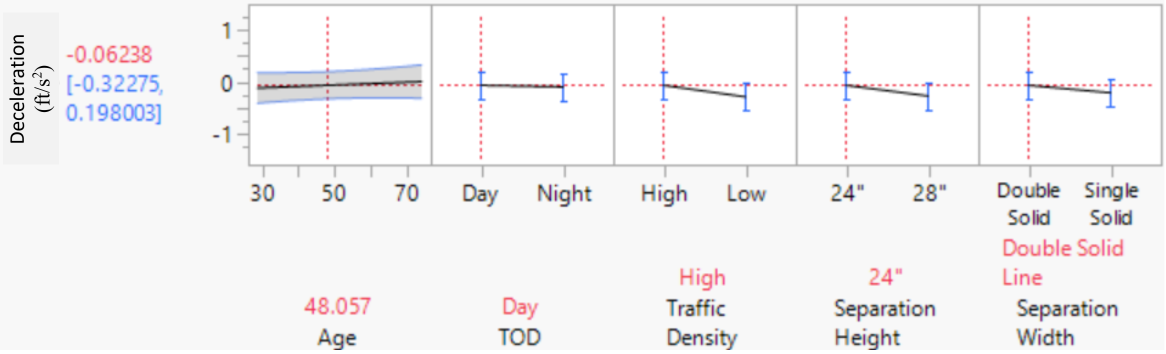


Figure 3.30: Predicted Deceleration Profiles for Separation Height and Width

3.3.3.2 Speed

Both separation width and height can impact drivers' speeding behavior. From the model estimates in Table 3.15, the interaction between 24-inch delineators and double solid lines appears to reduce mean speed (β = -0.698, p-value = 0.002). The magnitude of effect varies across different age groups, with a particularly strong impact on older drivers, who show a more noticeable tendency to reduce speed (β = -1.510, p-value = 0.0002). Conversely, the presence of double solid lines alone is associated with an increase in mean speed at curves.

As shown in Figure 3.31, double solid lines result in higher mean speed compared to single solid lines, but when combined with 24-inch delineators, the mean speed was lower than with 28-inch delineators. Interestingly, when considered independently, separation height does not have a significant association with mean speed. However, both the model estimates (see Table 3.15) and the marginal effects profiles (see Figure 3.32) indicate that under certain conditions, such as daytime and high visibility, the presence of 24-inch delineators on managed lane curves results in higher mean speeds. Notably, this interaction affects all age groups similarly, with strong positive associations observed across different age demographics.

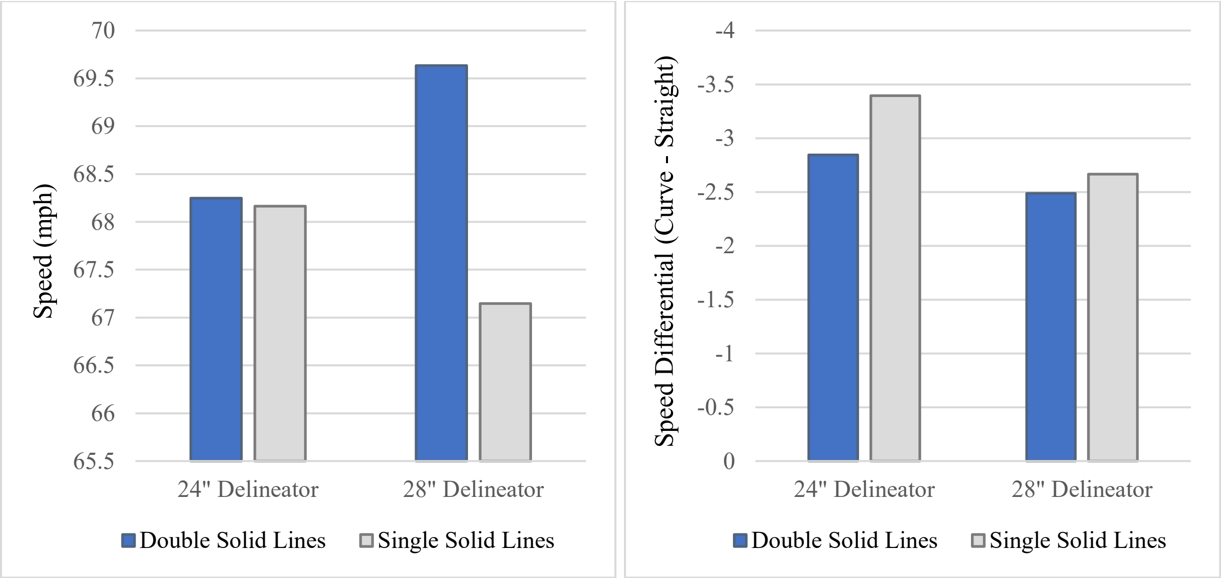


Figure 3.31: Mean Speed by Separation Height and Width

Speed differential is a crucial metric for assessing the efficiency of MLs, as a higher or more positive speed differential typically signifies more effective lane use. The analysis of speed differential (speed at curve – speed at straight section) in Table 3.15 indicates that, among the factors of separation height and width, only separation height has an association with speed differential. With 24-inch delineators, the speed differential tends to be lower ($\beta = -0.272$, p-value = 0.076). Additionally, the interaction effect between 24-inch delineators and double solid lines was found to be significant only for younger age groups, indicating that this combination can increase the speed differential among the young drivers.

Table 3.15: Mixed-effects Model Estimates for Separation Height and Width on Speed

Response/ Parameter	Parameter Effects	Full Model		Age (18 -34)		Age (35-64)		Age (65+)	
		Est.	Prob>|t|	Est.	Prob>|t|	Est.	Prob>|t|	Est.	Prob>|t|
Speed	Intercept	70.609	<.0001***	78.323	<.0001***	75.638	<.0001***	86.727	<.0001***
Age	Age	-0.048	0.087*	-0.365	0.156***	-0.154	0.195	-0.267	0.061*
TOD	Day	-1.276	<.0001***	-1.015	0.019**	-1.927	0.0002***	-0.880	0.032**
Traffic Density	High Density	-0.794	0.004***	-1.401	0.002***	-1.224	0.036**	0.178	0.602
Visibility	High Visibility	-0.129	0.515	-0.455	0.089*	0.215	0.573	-0.140	0.716
SH	24”	-0.114	0.486	0.209	0.340	-0.429	0.181	-0.111	0.720
SW	DSL	0.682	0.0004***	0.722	0.037**	0.710	0.038**	0.665	0.049**
TOD x SH	Day x 24”	0.776	<.0001***	0.467	0.164	1.039	0.004***	0.797	0.012**
Visibility x SH	High Visibility x 24”	1.042	<.0001***	1.452	0.001***	1.195	0.002***	0.496	0.124
SH x SW	24” x DSL	-0.698	0.002***	-0.083	0.825	-0.449	0.221	-1.510	0.0002***
Speed Differential	Intercept	-6.202	<.0001***	7.758	0.176	-8.747	0.005***	2.949	0.520
Age	Age	0.068	0.001***	-0.466	0.037**	0.122	0.060*	-0.056	0.381
Gender	Female	0.305	0.425	0.581	0.497	0.217	0.701	-0.123	0.736
TOD	Day	0.585	0.001***	0.670	0.015**	0.662	0.084*	0.497	0.052*
SH	24”	-0.272	0.076*	-0.376	0.182	-0.193	0.478	-0.224	0.380
SW	DSL	0.105	0.512	0.425	0.131	-0.249	0.501	0.084	0.718
TOD x SH	Day x 24”	0.497	0.004***	0.261	0.485	0.877	0.001***	0.353	0.167
SH x SW	24” x DSL	0.063	0.709	0.541	0.082*	-0.196	0.532	-0.126	0.616

Note: SH = Separation Height; SW =Separation Width; DSL = Double Solid Line; “×” denotes an interaction effect, indicating that the impact of one variable depends on the level of another variable; * = Significant at 90% confidence interval; ** = Significant at 95% confidence interval; *** = Significant at 99% confidence interval.

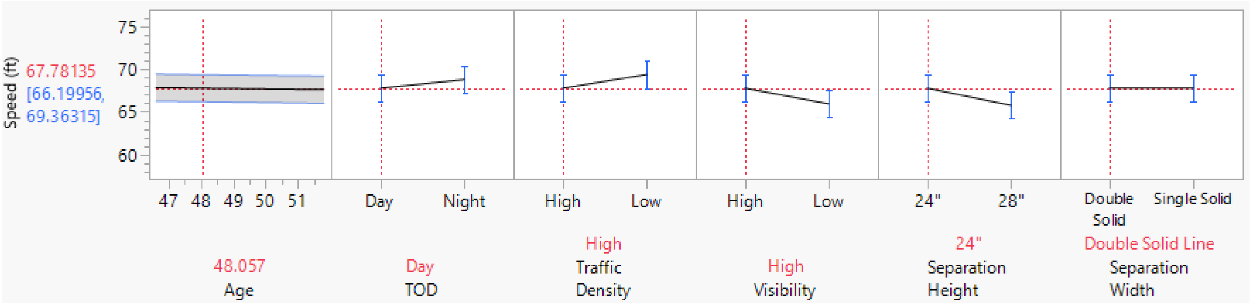


Figure 3.32: Predicted Speed Profiles for Separation Height and Width

3.3.3.3 Lane deviation

The effect of lane positioning was also investigated for both separation height and width. From Figure 3.33, the lane deviation can be observed to be higher for both double solid lines and 24-inch delineators. The full model, as shown in Table 3.16, also identified a negative association of lane positioning with 24-inch delineators and double solid lines. It should be noted that the negative estimates refer to the tendency to keep the vehicle away from the ML separation treatment, while the positive value refers to keeping the vehicle closer to the ML separation treatment. Both double solid lines and 24-inch delineators were found to cause drivers to shift more to the left side from the center of the lane ($\beta_{\text{double solid line}} = -0.44$, p-value = 0.0169, and $\beta_{24”} = -1.510$, p-value = 0.0375). However, their interaction effect on lane positioning is not significant at 90% confidence ($\beta_{24”, \text{double solid line}} = 0.029$, p-value > 0.1). Figure 3.34 further supports this observation, showing that the marginal effects of separation height and width on lane deviation are similar when considered in the same model setting. Furthermore, no significant effect is present in any of the age groups, indicating that the effect of separation width and height can be more general than age specific.

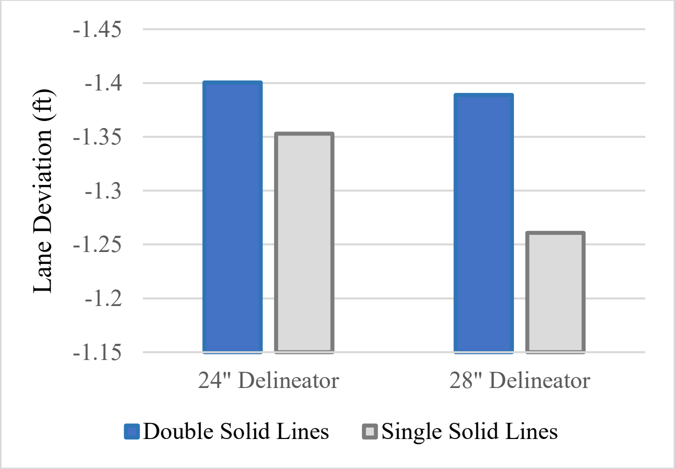


Figure 3.33: Lane Deviation by Separation Height and Width

Time of day is another significant factor influencing lane positioning. During daytime, drivers tend to position themselves more to the left and closer to the shoulder line in a single-lane ML facility when visibility is better. Lane deviation is also linked to age and gender, particularly among young drivers. Young female drivers tend to drive closer to the left than the male drivers. Lane deviation to the left of the lane’s center was found to increase with age for young drivers aged between 18 to 34. However, these demographic factors do not affect other age groups in the same way.

Table 3.16: Mixed-effects Estimates for Separation Height and Width on Lane Deviation

Response/ Parameter	Parameter Effects	Full Model		Age (18 -34)		Age (35-64)		Age (65+)	
		Est.	Prob>|t|	Est.	Prob>|t|	Est.	Prob>|t|	Est.	Prob>|t|
Lane Deviation	Intercept	-1.714	<.0001***	0.205	0.819	-1.530	0.0551*	-1.288	0.5057
Age	Age	0.007	0.0988*	-0.066	0.0619*	0.002	0.9124	0.002	0.9378
Gender	Female	-0.080	0.3477	-0.330	0.0252**	0.061	0.6904	-0.029	0.851
TOD	Day	-0.148	<.0001***	-0.171	0.0046***	-0.156	0.0025***	-0.117	0.0153**
SH	24”	-0.039	0.0375**	-0.098	0.0018***	-0.021	0.5534	0.001	0.9667
SW	DSL	-0.044	0.0169**	-0.050	0.1179	-0.048	0.1125	-0.036	0.329
SH x SW	24” x DSLe	0.029	0.108	0.002	0.9403	0.045	0.1381	0.040	0.2104

Note: SH = Separation Height; SW =Separation Width; DSL = Double Solid Line; “×” denotes an interaction effect, indicating that the impact of one variable depends on the level of another variable; * = Significant at 90% confidence interval; ** = Significant at 95% confidence interval; *** = Significant at 99% confidence interval.

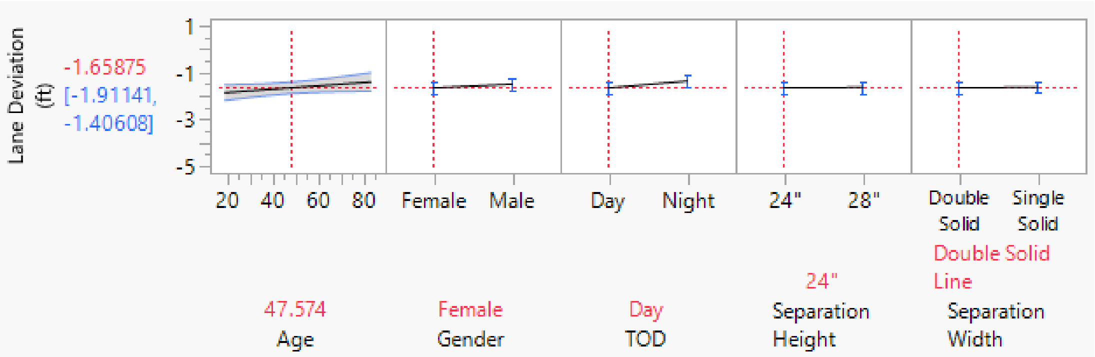


Figure 3.34: Predicted Lane Deviation for Separation Height and Width

3.3.3.4 Fixation

Fixation refers to the duration a driver's gaze remains focused on a specific point or region, often used as an indicator of visual workload. A longer fixation duration indicates a higher visual workload, meaning the driver requires more time and cognitive effort to process the visual information. In contrast, shorter fixation durations indicate a lower visual workload, allowing the driver to quickly recognize and interpret visual cues, such as lane separation treatments. For the operational efficiency of MLs, lower fixation duration on separation treatments is crucial, as it signifies quicker recognition and less demand on the driver's attention.

The fixation analysis reveals that double solid lines result in relatively shorter fixation durations compared to single solid lines, particularly among older drivers, as shown in Figure 3.34 and Table 3.17. However, for young drivers, the analysis shows a significant impact of separation height on fixation duration. Specifically, both marginal effects (see Figure 3.36) and model results (see Table 3.17) indicate that the presence of 24-inch delineators on ML curves leads to longer fixation durations compared to 28-inch delineators (β = -0.062, p-value = 0.0809). This effect is further amplified when combined with double solid lines, resulting in even longer fixation durations (β = -0.053, p-value = 0.0191).

Furthermore, analysis of the interaction effect of the separation line and height on fixation duration found no significant difference, while double solid lines tend to reduce fixation duration. As for gender, fixation duration varies between males and females. Female drivers are more likely to have higher fixation duration than males (β=0.285, p-value=0.007). Overall, Figure 3.35 highlights significant differences in the marginal effects of age and gender, with young female drivers showing a higher effect on fixation duration, while the marginal effects of other factors are minimal.

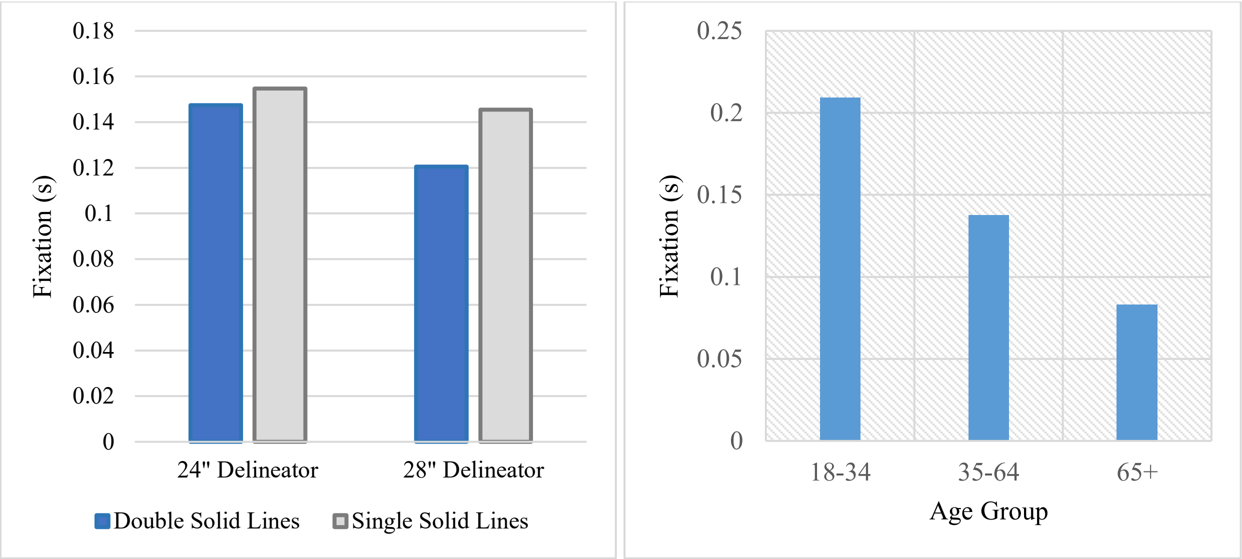


Figure 3.35: Fixation Duration by Separation Height and Width and Age Group

Table 3.17: Mixed-effects Model Estimates for Separation Height and Width on Fixation

<table>
<tr><th rowspan="2">Response/ Parameter</th><th rowspan="2">Parameter Effects</th><th colspan="2">Full Model</th><th colspan="2">Age (18 -34)</th><th colspan="2">Age (35-64)</th><th colspan="2">Age (65+)</th></tr>
<tr><th>Est.</th><th>Prob>|t|</th><th>Est.</th><th>Prob>|t|</th><th>Est.</th><th>Prob>|t|</th><th>Est.</th><th>Prob>|t|</th></tr>
<tr><td><i>Log (Fixation)</i></td><td>Intercept</td><td>-1.790</td><td><.0001***</td><td>-1.072</td><td>0.3998</td><td>-1.954</td><td>0.0713*</td><td>-1.411</td><td>0.4555</td></tr>
<tr><td>Age</td><td>Age</td><td>-0.014</td><td>0.0065***</td><td>-0.039</td><td>0.4128</td><td>-0.013</td><td>0.5646</td><td>-0.019</td><td>0.4654</td></tr>
<tr><td>Gender</td><td>Female</td><td>0.285</td><td>0.007***</td><td>0.519</td><td>0.0138**</td><td>0.117</td><td>0.5787</td><td>0.207</td><td>0.1785</td></tr>
<tr><td>TOD</td><td>Day</td><td>0.080</td><td>0.0382**</td><td>0.151</td><td>0.0323**</td><td>0.106</td><td>0.1626</td><td>-0.015</td><td>0.7798</td></tr>
<tr><td>SH</td><td>24”</td><td>0.033</td><td>0.1115</td><td>0.062</td><td>0.0809*</td><td>0.027</td><td>0.4678</td><td>0.011</td><td>0.7609</td></tr>
<tr><td>SW</td><td>DSL</td><td>-0.039</td><td>0.0921*</td><td>-0.010</td><td>0.7949</td><td>-0.057</td><td>0.3015</td><td>-0.049</td><td>0.0555*</td></tr>
<tr><td>SH x SW</td><td>24” x DSL</td><td>0.023</td><td>0.1505</td><td>0.053</td><td>0.0191**</td><td>0.041</td><td>0.1627</td><td>-0.021</td><td>0.5102</td></tr>
</table>

Note: SH = Separation Height; SW =Separation Width; DSL = Double Solid Line; “×” denotes an interaction effect, indicating that the impact of one variable depends on the level of another variable; * = Significant at 90% confidence interval; ** = Significant at 95% confidence interval; *** = Significant at 99% confidence interval.

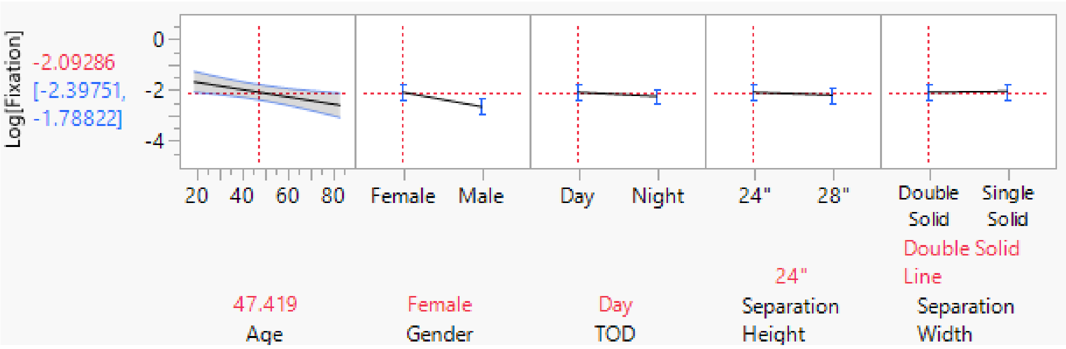


Figure 3.36: Predicted Fixation Duration Profiles

3.3.4 Frequency Analysis

A frequency analysis was also conducted for participants who noticed the changes in separation width and height (Figure 3.37). Out of the 60 participants, 45 participants across all age groups noticed the change in separation width. Specifically, 58% reported that double solid lines were more noticeable during daytime, with this percentage increasing to 64% under nighttime and rainy conditions. Additionally, 51% of the 45 participants reported that double solid lines were more noticeable than single solid lines in high-traffic conditions.

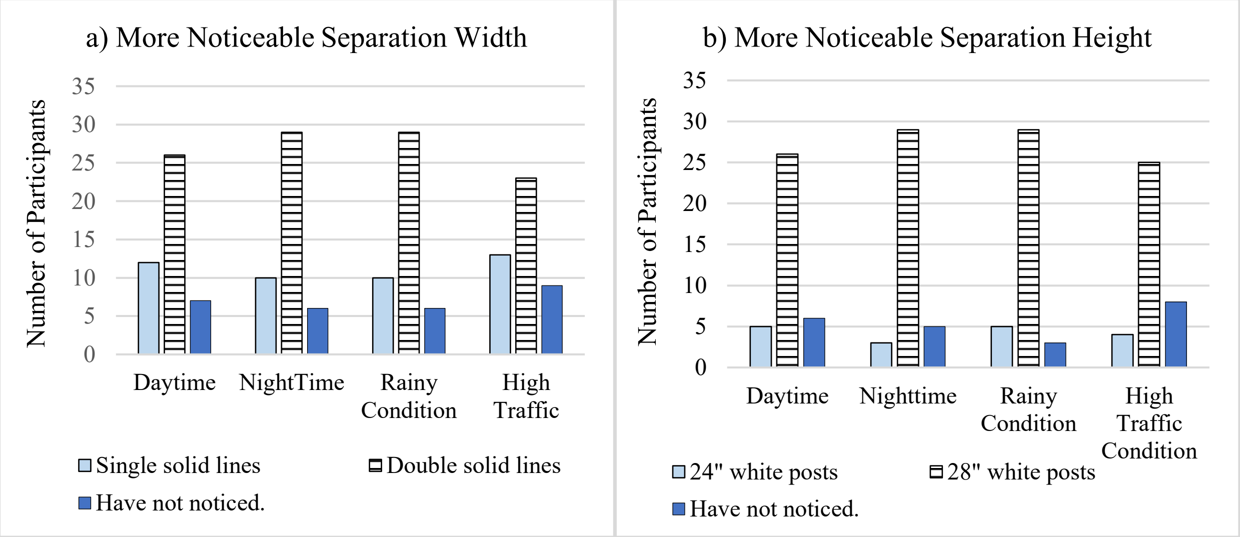


Figure 3.37: Frequency Analysis of Participant Responses on Separation Height/Width

For the separation height, 37 participants across all age groups noticed the difference. Of these, 70% found the 28-inch delineators to be more noticeable during daytime, with this percentage increasing to 78% during nighttime and rainy conditions. Furthermore, 67.5% of participants reported that the 28-inch delineators were more noticeable than the 24-inch delineators in high traffic conditions.

3.4 Exit Survey

At the end of the experiment, participants were asked a number of questions about the noticeability of separation height and width, including the following:

1. Did you notice the change in the separation height/width while driving in ML?
2. Which separation height/width appeared more prominent at the curves in daytime?
3. Which separation height/width was more noticeable at night?
4. Which separation height/width was more noticeable in rainy conditions?

Figure 3.38 shows the percentage of participants who noticed the changes in separation width and height, and Table 3.18 illustrates the frequency distribution by age groups and gender.

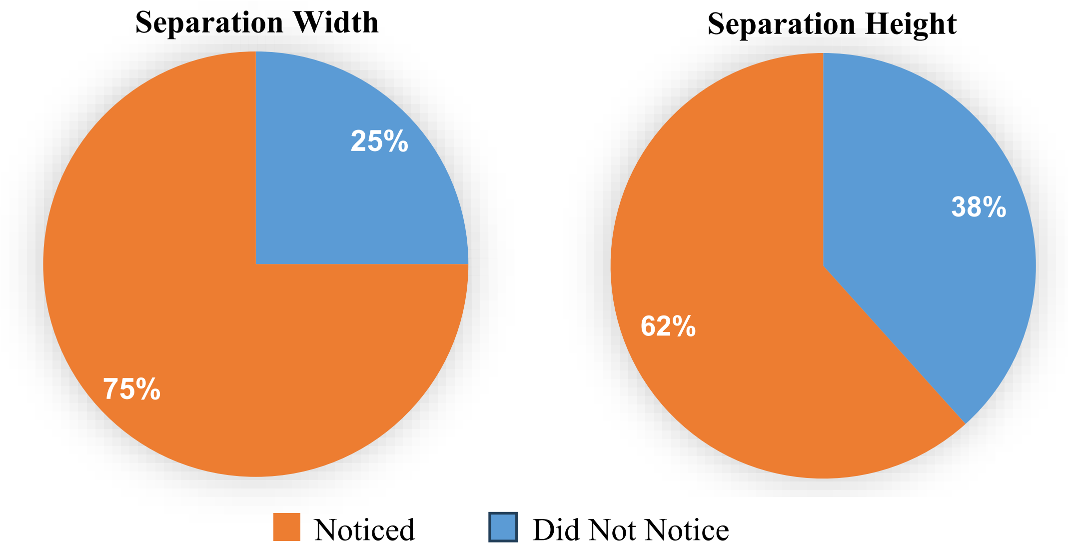


Figure 3.38: Exit Survey Responses

According to the survey, approximately 38% of participants did not notice any change in the delineator's height at the curve, while 25% did not observe a difference in the separation width. The majority of those who did notice changes in both separation width and height were from the middle-aged group (35 to 64 years), whereas participants aged 65+ did not notice these changes (see Table 3.18).

Table 3.18: Distribution of Exit Survey Responses by Age and Gender

Participant Age / Gender	**Separation Width**		**Separation Height**	
	Noticed	Did not notice	Noticed	Did not notice
18-34	**18**	**2**	**12**	**8**
Female	9	1	6	4
Male	9	1	6	4
35-64	**17**	**3**	**14**	**6**
Female	9	1	8	2
Male	8	2	6	4
65+	**10**	**10**	**11**	**9**
Female	6	4	5	5
Male	4	6	6	4
Total	**45**	**15**	**37**	**23**

3.5 Summary

This research aimed to analyze the impact and noticeability of different separation treatments on driver behavior by examining behavioral data from a driving simulator, visual attention data from an eye-tracking device, and participants' subjective survey responses. The study was conducted using the driving simulator at the Intelligent Transport Systems lab at UCF, where various demographics groups were tested under different separation heights, widths, and driving conditions. The analysis incorporated scenario parameters such as time of day, traffic density, visibility conditions, age, gender, separation height, and separation width to develop comprehensive evaluation models. The models were designed to simultaneously assess the effects of all significant parameters, providing insights into how these factors influence driver behavior and performance on managed lane facilities.

A total of 64 participants were initially recruited through various channels, including student recruitment via the UCF SONA System, the Learning Longevity Research Network, the Learning Institute for Elders (LIFE), social media outreach, fliers, and personal connections. To participate, individuals were required to have a valid driver's license and be over the age of 18. Out of the 64 participants, 60 successfully completed the experiment with usable data. The remaining participants were either unable to finish due to motion sickness or chose not to attend. Additionally, one participant's data was excluded from the analysis due to significant deviation from the driving rules.

A comprehensive analysis was performed, utilizing data from a driving simulator, eye-tracking, demographic information, and exit surveys to assess the effects of varying separation heights and widths across different age groups. Instead of relying on basic linear regression models, mixed effects models (also known as multilevel models) were used to account for both fixed and random effects. These models are particularly effective when there are repeated observations (scenarios) per subject, as they allow for the inclusion of random effects to account for differences among group (scenario) means. The effects of separation width and height were analyzed individually, as well as their combined effect. The focus of the simulation for this project was based on a comparison of two separation widths and markings and two pylon heights.

The key findings from the evaluation models on the performance factors include the following:

- **Deceleration:** The analysis of the deceleration parameter revealed that separation treatment with double solid lines resulted in higher deceleration rates at the ML entry section. Interestingly, drivers tended to slow down less when approaching curves with double solid lines. This behavior indicated that drivers exhibited more caution when entering the ML and improved their speed performance along the curved sections with double solid lines. At night, the deceleration rate for double solid lines remained relatively consistent with daytime values. However, for single solid lines, there was a significant increase in deceleration at night, nearly doubling the rate observed with double solid lines. Conversely, separation height did not have a significant fixed effect on the deceleration rate as it did not similarly affect deceleration rates for drivers across all age groups, rather the effect of deceleration rate varied for different drivers. The results matched the subjective responses reported by participants, that they did not notice the differences in separation height while driving in the curved sections. When considering the combined effect of separation width and height, the combination of double solid lines and 28-inch delineators lead to a smoother deceleration rate along the curves. Furthermore, it was found that the double solid lines had better visibility than single solid lines.

- **Speed:** The type of separation treatment significantly impacted driving speed, with double solid lines linked to higher mean speeds. Although the mean speed in the curved section was lower than the straight section, it remained high in MLs separated by double solid lines treatment. This was especially important for maintaining the 70-mph speed limit in MLs, which was key to their operational efficiency. While separation height did not greatly affect the speed overall, 24-inch delineators were associated with higher speeds during the daytime and in good visibility conditions. However, when combined with double solid lines, the shorter delineators lead to a reduction in average speed at curves, compared to the 28-inch delineators. Overall, the double solid lines with 28-inch delineators resulted in higher speeds at the curves.

- **Speed differential:** The analysis revealed that the 24-inch delineators were negatively associated with speed differential, indicating that drivers reduced their speed when transitioning from straight to curved sections within MLs, compared to 28-inch delineators. Conversely, during the daytime, double solid lines were linked to a low-speed differential, suggesting less reduction in speed as drivers navigate curves. Maintaining the operational efficiency of MLs is crucial, and any significant reduction in speed within these lanes could compromise their intended purpose of ensuring smooth and efficient traffic flow.

- **Lane Deviation and Steering Angle:** The study also highlighted the impact of separation width and height on lane deviation and steering behavior. Drivers were consistently driving away from the separation treatment, especially with double solid lines and 24-inch delineators, indicating a preference for maintaining distance from the separation treatment. Additionally, steering adjustments were more frequent with shorter delineators, reflecting a conscious effort by drivers to maintain proper lane positioning. This was attributed to the visibility of the double solid lines which supported the subjective analysis as participants found double solid lines caught their attention more than single solid lines. This outcome showed that double solid lines may signal a wider lane separation, leading drivers closer to their left lane boundaries. However, under high traffic density, drivers showed a tendency to drive closer to the double solid lines indicating better lane guidance and demarcation, helping drivers maintain their lane position more precisely in dense traffic. Additionally, under good visibility conditions, the double solid lines were easily seen and followed by drivers, further contributing to improved lane discipline.

- **Visual Attention:** Visual attention metrics, such as fixation duration, were found to be influenced by both separation width and height. Double solid lines generally resulted in shorter fixation durations, indicating that they were easier for drivers to notice and required less visual workload. In contrast, 24-inch delineators were associated with longer fixation times, especially among young drivers. The association of double solid lines and 28-inch delineators with shorter fixation duration highlights their higher visibility compared to single solid lines and 24-inch delineators.

According to the exit survey responses from 60 participants, 45 participants (75% of the total) across all age groups noticed the change in separation treatment, with over half of these participants finding double solid lines more noticeable across various conditions. Regarding separation height, 37 participants (62%) could distinguish difference under different conditions, with the majority indicating that 28-inch delineators appeared more noticeable. The findings from the driving simulator matched the exit survey as it showed that separation treatment has a substantial impact on driving behavior, with double solid lines being more visible. The results also showed that the

28-inch delineators improved the driving performance in terms of speed, lane positioning and steering angle rate.

An overarching study, with a wider range of separation widths and vertical separation devices, would provide a better approach to determine which treatments are best overall. With only two alternatives in this study, this effort only provides a relative comparison of alternatives.

CHAPTER 4
NATURALISTIC DRIVING STUDY

This chapter discusses the naturalistic driving study conducted to better understand driver behavior on managed lanes (MLs). A naturalistic driving study is a research method used to investigate the driving behavior of individuals in their natural driving environment using unobtrusive data collection techniques. Unlike traditional driving studies that use driving simulators or controlled experiments in specific settings, naturalistic driving studies observe and record the drivers' behaviors under real-world conditions without being influenced by the presence of researchers. This approach provides a more accurate picture of how drivers interact with their vehicle, the road, other road users, and the environment during their everyday driving tasks.

4.1 Research Approach

4.1.1 Study Objective

The objective of this human factors study was to examine how drivers behave in the real world on ML facilities with different separation treatments. Naturalistic driving data was used to analyze human factors and driver behavior on different ML separation types. The ML separation types analyzed included delineators (pylons), concrete barriers, and buffer separation, while only delineators were analyzed in the driving simulation study (see Chapter 3 of this report).

4.1.2 Methodology

The study utilized naturalistic driving data from ML facilities in two states: Florida and Washington. The data sources included the Regional Integrated Transportation Information System (RITIS) and the Second Strategic Highway Research Program (SHRP2) (see Appendix F). The impact of ML separation types was examined by focusing on vehicles traveling in lanes adjacent to the separators. The research approach included pairwise comparisons of facilities with different separation types, as well as the application of inferential statistics using various modeling techniques.

Several performance metrics were considered to analyze how human factors and driver behavior are affected by the separation types for the MLs. Summarized in Table 4.1 and Appendix F, the performance measures considered in the study include lane utilization, travel speed, and lane deviation.

Table 4.1: Naturalistic Driving Study Performance Measures

Performance Measure	Research Objective
Lane Utilization	To investigate whether drivers avoid the managed lane (ML) adjacent to the general-purpose lanes (GPLs), i.e., the rightmost ML. To investigate whether drivers avoid the inside lane of the general-purpose lanes, i.e., the GPL adjacent to the ML.
Travel Speed	To investigate whether travel speed is affected by the ML separation type.
Lane Deviation	To investigate whether the driver's lateral position is affected by the ML separation type.

4.2 Lane Utilization

Understanding lane utilization on freeways is crucial for transportation planners, policymakers, and traffic engineers. The significance of studying lane utilization lies in the need to optimize traffic flow, ensure safety, and improve the overall efficiency of freeways. By analyzing lane utilization, transportation authorities can make informed decisions regarding lane management, such as lane widening or lane restrictions.

Lane utilization can be referred to as the distribution of traffic across the available lanes on a freeway section. Lane utilization, an important component of highway efficiency, is influenced by a multitude of factors. Among these factors, traffic conditions, such as congestion levels and varying traffic volumes, influence lane utilization dynamics (Wang & Liu, 2005).

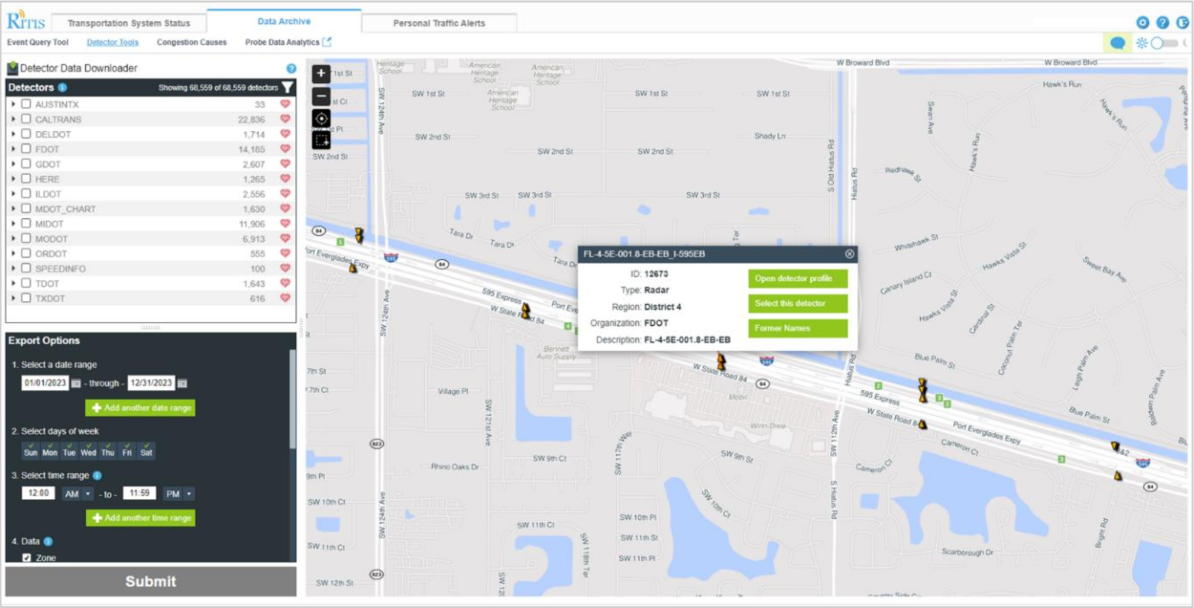
Lane choice is a driver behavior and can be affected by a myriad of factors, including:

- Geometric characteristics: lane width, lane type, and managed lane separation type
- Traffic conditions: congestion level, travel speed, etc.
- Driver preferences: aggressiveness and complacency
- Vehicle characteristics: vehicle type
- Other factors, such as environmental factors

The lane utilization factor represents the proportion of vehicles that use a particular lane. It provides insights into driver behavior and lane preferences during different traffic conditions. Identifying lanes with a higher utilization factor can help transportation authorities distribute traffic more evenly and potentially alleviate congestion by encouraging drivers to use underutilized lanes.

4.2.1 Data

The analysis used traffic volume data sourced from the Regional Integrated Transportation Information System (RITIS), which serves as a comprehensive transportation data platform integrating real-time information from multiple transportation agencies and sources. RITIS offers a wealth of traffic data, including speed and volume information collected from various sensors and detectors positioned along the roadway network. Figure 4.1 presents the user interface from RITIS software showing detector information. The data was collected for a 12-month study period, from January 1, 2023, to December 31, 2023. All detectors utilized in this study were located in Florida.



Detectors — Showing 68,559 of 68,559 detectors

☐ AUSTINTX	33
☐ CALTRANS	22,836
☐ DELDOT	1,714
☐ FDOT	14,185
☐ GDOT	2,607
☐ HERE	1,265
☐ ILDOT	2,556
☐ MDOT_CHART	1,630
☐ MIDOT	11,906
☐ MODOT	6,913
☐ ORDOT	555
☐ SPEEDINFO	100
☐ TDOT	1,643
☐ TXDOT	616

Export Options

1. Select a date range: 01/01/2023 - through - 12/31/2023
2. Select days of week: ✓ Sun ✓ Mon ✓ Tue ✓ Wed ✓ Thu ✓ Fri ✓ Sat
3. Select time range: 12:00 AM - to - 11:59 PM
4. Data: ☑ Zone

FL-4-5E-001.8-EB-EB_I-595EB

ID: 12673
Type: Radar
Region: District 4
Organization: FDOT
Description: FL-4-5E-001.8-EB-EB

Figure 4.1: Excerpt from RITIS Website

Volume data was collected at 15-minute intervals for weekdays and weekend days during peak hours and off-peak hours. This approach allowed for a thorough analysis of lane utilization under diverse traffic scenarios. Furthermore, the volume and speed data were collected for each lane. Note that the lanes of interest were those closest to the separation type, i.e., the rightmost ML and the leftmost general-purpose lane (GPL), as demonstrated in Figure 4.2.

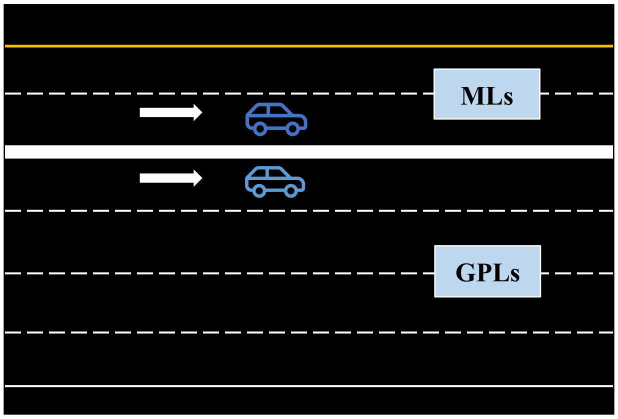


Figure 4.2: Site Characteristics Diagram

The dataset utilized for analysis consisted of comparison points for sites with buffer separation, concrete separation, and pylon separation. These comparison points were carefully selected to provide meaningful insights into the lane utilization patterns and the overall impact of the managed lanes. By leveraging the extensive data available through RITIS and incorporating various traffic scenarios, the analysis offers a robust and comprehensive evaluation of how the managed lane separation types affect the traffic flow in the inside lanes for both MLs and GPLs.

4.2.2 Study Areas

Study sites selected to analyze lane utilization included segments along Florida freeways with managed lanes. The segments were carefully chosen to be comparable in terms of both traffic and geometric characteristics. Key features used in selecting the comparison sites included:

a) Number of lanes: The comparison sites were selected to have an equal number of lanes for both GPLs and MLs. This criterion allows for a direct comparison of lane utilization between the two locations, considering the same lane capacity.

b) Traffic volume: The Average Annual Daily Traffic (AADT) on the comparison site was restricted to within 30% of the AADT observed at the selected managed lane sections. This criterion aims to minimize the impact of significant traffic volume differences between the comparison sites.

c) Separation type: The comparison sites were selected based on the separation types. Separation types included concrete barriers, buffer separation, and pylon separation.

A total of seven segments were selected for the analysis. Two study segments contain one ML and three GPLs with different separation types, as shown in Figures 4.3 and 4.4. Three study segments contain two MLs and three GPLs with different separation types, as shown in Figures 4.6 through 4.8, and two study segments contain three MLs and three GPLs with concrete barrier separation (Figures 4.5 and 4.9).

Roadway	FL-528
Configuration	3 GPLs, 1 ML
Detector No. (RITIS)	528-007_2-WB-LNK & 528-007_2-EB-LNK 528-007-2EB-LNK & 528-007-2WB-LNK
AADT	99,300 vpd

Figure 4.3: Site 1 – Buffer Separation (Single ML) Link-Buffer

Roadway	FL-589 – Veterans Expressway
Configuration	3 GPLs, 1 ML
Detector No. (RITIS)	589-003-1SB-LNK & 589-003-1NB-LNK
AADT	88,900 vpd (GPL) & 3,400 vpd (ML)

Figure 4.4: Site 2 – Pylon Separation (Single ML) Link-Pylons

Roadway	I-595
Configuration	3 GPL, 3 ML
Detector No. (RITIS)	FL-4-5E-001.8-EB-EB_I-595EB & FL-4-5E-001.8-ER/WB-EB_I-595 REV
AADT	117,000 vpd (GPL) & 16,400 vpd (ML)

Figure 4.5: Site 3 – Concrete Barrier Separation (Three MLs) Link-Concrete

Roadway	FL-528
Configuration	3 GPLs, 2 MLs
Detector No. (RITIS)	528-002_4-WB-LNK & 528-002_4-EB-LNK
AADT	108,500 vpd

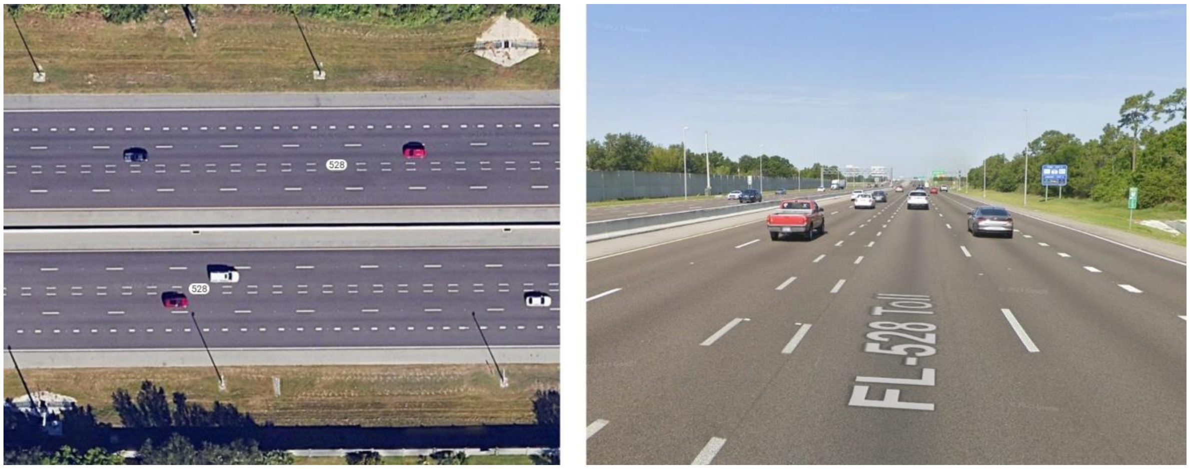


Figure 4.6: Site 4 – Buffer Separation (Two MLs) Link-Buffer(b)

Roadway	I-95
Configuration	3 GPLs, 2 MLs
Detector No. (RITIS)	FLD4DOT095035.8-DS-EL & FLD4095NB035.8
AADT	181,000 vpd (GPL) & 11,000 vpd (ML)

Figure 4.7: Site 5 – Pylon Separation (Two MLs) Link-Pylons(b)

Roadway	I-4
Configuration	3 GPL, 2 ML
Detector No. (RITIS)	I-4 EB @ MM 076.2-EL
AADT	174,500 vpd (GPL) & 15,000 vpd E (ML) 9,200 vpd W (ML)

Figure 4.8: Site 6 – Concrete Barrier Separation (Two MLs) Link-Concrete(b)

Roadway	I-595
Configuration	3 GPL, 3 ML
Detector No. (RITIS)	FL-4-5E-001.4-EB-EB_I-595EB & FL-4-5E-001.4-ER/WB-EB_I-595 REV
AADT	129,500 vpd (GPL) & 18,000 vpd (ML)

Figure 4.9: Site 7 – Concrete Barrier Separation (Three MLs) Link-Concrete(c)

4.2.3 Methodology

A comparative cross-sectional approach was employed to assess lane utilization on specific sites with express lanes by comparing them to carefully selected comparison sites based on separation type. The comparison sites were chosen to have relatively similar features in terms of the number of lanes and other relevant geometric and traffic characteristics. The objective was to analyze the differences in lane utilization of the lanes adjacent to the separator in managed lane facilities with different separation types.

The study was designed to be conducted with simultaneous data collection at both comparison sites during the same period to ensure comparability. Capturing data from both locations at a single point in time provides a snapshot of lane utilization patterns under similar traffic conditions.

Using a comparative cross-sectional approach allowed for the identification of any distinct lane utilization patterns associated with the presence of specific separation types. This information is valuable for transportation planners and policymakers seeking to optimize traffic flow and improve overall freeway efficiency.

The pairwise analysis conducted to examine lane utilization for the three ML separation types (pylons, buffer, and concrete barrier) examined the following comparisons:

a) Buffer separation vs. Pylon separation
b) Buffer separation vs. Concrete barrier separation
c) Concrete barrier separation vs. Pylon separation

4.2.3.1 Pairwise Comparison

To analyze lane choice behavior, the degree of lane utilization for each lane at every detector point was calculated. The lane utilization ratio represents the proportion of traffic volume in a specific lane to the total traffic volume in the entire lane group, as shown in Equation 4.1. The ratio provides a numerical representation of how much a particular lane contributes to the overall traffic flow within its lane group.

$$\mathrm{R_{LU,i}} = \frac{\mathrm{V_i}}{\sum_{\mathrm{i=1}}^{\mathrm{i=n}} \mathrm{V_i}} \tag{4.1}$$

where,

$R_{LU,i}$ = lane utilization ratio of lane i,
V_i = traffic volume of lane i, and
n = number of lanes in lane group.

The lane utilization ratio was calculated for each lane of interest at 15-minute intervals, considering both the peak 15-minute period and overall traffic conditions. These values were used for the following analyses.

- Determine whether the differences in lane utilization ratios across various separation types are statistically significant.
- Assess whether, for each separation type, the lane utilization ratio of the lane of interest significantly deviates from the balanced lane utilization factor.

The balanced lane utilization factor was calculated based on the number of lanes in each facility under the assumption that, in an optimal scenario, all lanes would have equal utilization. Specifically, the balanced lane utilization factor was determined as the reciprocal of the total number of lanes (see Equation 4.2). This calculation was used to evaluate whether the lane utilization ratio for the lane of interest under each separation type significantly deviated from this balanced value. By comparing each lane's utilization to the balanced lane utilization factor, transportation planners can identify lanes that experience higher or lower traffic volumes and determine if any lane shows significantly higher utilization than others. This information is valuable in understanding lane preference among drivers and potential bottlenecks on the freeway.

$$\mathrm{f}_{bal,\mathrm{j}} = \frac{1}{\mathrm{n_j}} \tag{4.2}$$

where,

$f_{bal,j}$ = balanced lane utilization factor for facility j, and

n_j = number of lanes for facility j.

Analyzing lane utilization during peak 15-minute periods and overall traffic conditions was crucial for understanding how traffic flow evolves during periods of congestion and normal traffic flow. It helps identify if certain lanes experience more significant changes in utilization during peak hours and whether drivers exhibit consistent lane preference irrespective of traffic conditions. Such insights can lead to the development of targeted strategies to improve traffic management and reduce congestion during peak periods.

4.2.3.2 Hypothesis Testing

Hypothesis testing was used to compare the utilization ratios of the lanes in facilities with express lanes with different separation types and determine if there was a significant statistical difference between the two datasets. The t-test was conducted at a 95% confidence level to determine whether to reject or fail to reject the null hypothesis. The null and alternative hypotheses for each objective were specified as follows:

a) Objective: Determine whether the differences in lane utilization ratios across various separation types are statistically significant.

- $H_0: M = 0$ (The difference between the means of the lane utilization ratios of the two datasets is equal to zero)
- $H_a: M \neq 0$ (The difference between the means of the lane utilization ratios of the two datasets is not equal to zero)

b) Objective: Assess whether, for each separation type, the lane utilization ratio of the lane of interest significantly deviates from the balanced lane utilization factor.

- $H_0: \mathrm{R_{LU,i}} = \mathrm{f_{bal,j}}$ (The difference between the means of the lane utilization ratio and the balanced lane utilization factor is equal to zero)

- H_a: $\mathrm{R}_{\mathrm{LU,i}} \neq \mathrm{f}_{\mathrm{bal,j}}$ (The difference between the means of the lane utilization ratio and the balanced lane utilization factor is not equal to zero)

Welch's t-test (unequal variance t-test) was used to determine if there is a statistically significant difference in the left lane utilization ratios. This test is a modification of the student's t-test to determine if two sample means are significantly different. Welch's t-test is recommended over the student's t-test because it does not assume equal variances between the two datasets. It modifies the degree of freedom used for the student's t-test, and therefore, increases the test power for samples with unequal variances. Equation 4.3 shows the Welch's t-test statistic, and Equation 4.4 denotes the degree of freedom for Welch's t-test (Liu & Wang, 2021).

$$\mathrm{t} = \frac{(\overline{\mathrm{x}_1} - \overline{\mathrm{x}_2})}{\sqrt{\frac{\mathrm{S}_1^2}{\mathrm{n}_1} + \frac{\mathrm{S}_2^2}{\mathrm{n}_2}}} \tag{4.3}$$

$$\text{Degree of freedom} = \frac{\left(\frac{\mathrm{S}_1^2}{\mathrm{n}_1} + \frac{\mathrm{S}_2^2}{\mathrm{n}_2}\right)^2}{\left(\frac{\mathrm{S}_1^4}{\mathrm{n}_1{}^2 v_1} + \frac{\mathrm{S}_2^4}{\mathrm{n}_2{}^2 v_2}\right)} \tag{4.4}$$

where,

$\overline{x_1}$ and $\overline{x_2}$ = sample means,
S_1 and S_2 = sample variance,
n_1 and n_2 = sample size for the first and second samples, and
v_1 and v_2 = degrees of freedom associated with the first and second variance estimates, respectively.

Mean Square Error (MSE) analysis was utilized to estimate the deviation of the mean utilization ratio from the balanced utilization ratio. Specifically, MSE quantifies the average squared difference between the observed mean utilization ratio and the balanced utilization ratio. The smaller the MSE value, the better it is, as this indicates that the actual lane utilization ratio is closer to the balanced lane utilization ratio.

MSE is a measure of the average squared difference between observed values (lane utilization of GPL or ML) and balanced values. The formula for calculating the MSE for each separation type is presented in Equation 4.5.

$$\mathrm{MSE} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i=1}}^{\mathrm{n}} \left(\text{Lane Utilization}_{\mathrm{GPL/ML,i}} - \text{Optimum}_{\mathrm{i}}\right)^2 \tag{4.5}$$

where,

n = the total number of observations for that specific separation type, Lane Utilization Ratio $_{\mathrm{GPL/ML},i}$ = the observed lane utilization ratio for the i-th observation in the separation type group, and

$\mathrm{Optimum}_i$ = the balanced lane utilization value for GPL for the i-th observation.

4.2.3.4 Statistical Modeling

The next step was to fit the data using a generalized linear model (GLM). The GLM is a flexible statistical framework used to analyze relationships between a dependent variable and one or more explanatory variables. Unlike traditional linear regression models, GLMs allow for dependent variables that do not follow a normal distribution, making them suitable for a wide range of data sets. The equation for the linear model can be expressed as shown in Equation 4.6 (Nayem et al., 2024).

$$y = \mathrm{X}\beta + \epsilon \tag{4.6}$$

where $\boldsymbol{\epsilon}$ is the vector of normal random errors, $\mathbf{X}$ matrix represents the set of predictors, $\mathbf{y}$ is the response (lane utilization ratio), and $\widehat{\boldsymbol{\beta}}$ is the set of estimated parameters. The complete model is constructed through a relationship shown by Equation 4.7, that is assumed between the distribution mean and the linear predictor (Myers & Montgomery, 1997).

$$E[y] \quad = \mu \ = \beta_0 + \beta_1 X_1 + \cdots + \beta_i X_i \tag{4.7}$$

The GLM differs from traditional regression models in that the response variable must have a distribution that belongs to the exponential family (Chou, 2009). Generally, the link function presented by Equation 4.8 determines the relationship between the population mean and the linear predictor (Gan & Bai, 2014).

$$h\,(\mu) = \mathrm{X}'\beta \tag{4.8}$$

where $h\,(\cdot)$ is a monotonic function.

Equation 4.9 represents the regression model, which contains the population mean as the parametric response (Myers & Montgomery, 1997).

$$\mu = h^{-1}(\mathrm{X}'\beta) \tag{4.9}$$

Equation 4.10 represents the GLM used to analyze the factors affecting the lane utilization ratio (Fitrianti et al., 2019).

$$m\,(\mu) = \ln\,(\beta_0 + \beta_1 X_1 + \cdots + \beta_i X_i + e_i) \tag{4.10}$$

where,

$m\,(\mu)$ = mean of the response variable (lane utilization ratio),

β_{i} = estimated coefficients of the respective predictors,

X_i = predictors, and
e_i = random error term.

The independent variables considered in the analysis of factors influencing lane utilization ratio included:

- Separation type
- Number of lanes - ML
- Number of lanes – GPL
- Traffic volume
- Time of the day

4.2.4 Results

This section presents the results of the lane utilization analysis. The analysis was conducted on the inside travel lane of the GPLs (i.e., the leftmost GPL adjacent to the MLs). Lane utilization was also analyzed for the inside lane of the MLs (i.e., the rightmost ML adjacent to the GPLs). The following subsections discuss the results of both analyses.

4.2.4.1 Inside Lane of the GPLs

Pairwise Comparison Results

This section presents the results of the pairwise comparison for the lane utilization analysis for the inside lane of the GPLs (i.e., the GPL closest to the separator). Sites with three GPLs (3-lane facilities) were selected for this portion of the analysis. Figures 4.10, 4.11, and 4.12 present the average traffic volume over a 24-hour period, averaged across the one-year study period, for the comparison of buffer separation against pylon separation, pylon separation against concrete barrier separation, and buffer separation against concrete barrier separation, respectively.

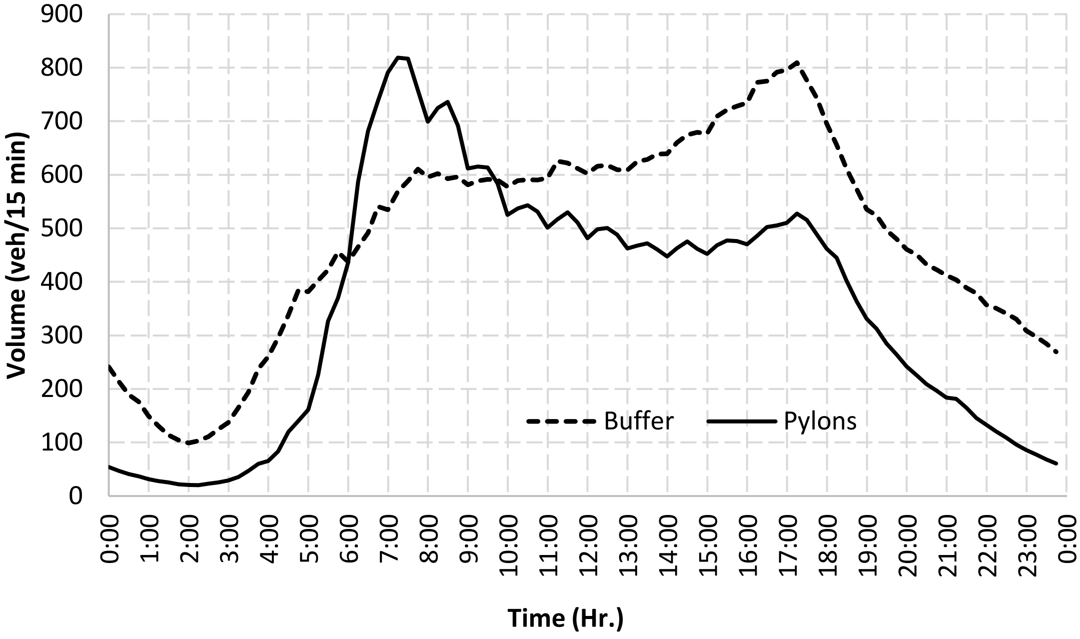


Figure 4.10: Average Traffic Volume for Buffer Against Pylons (GPL – Inside Lane)

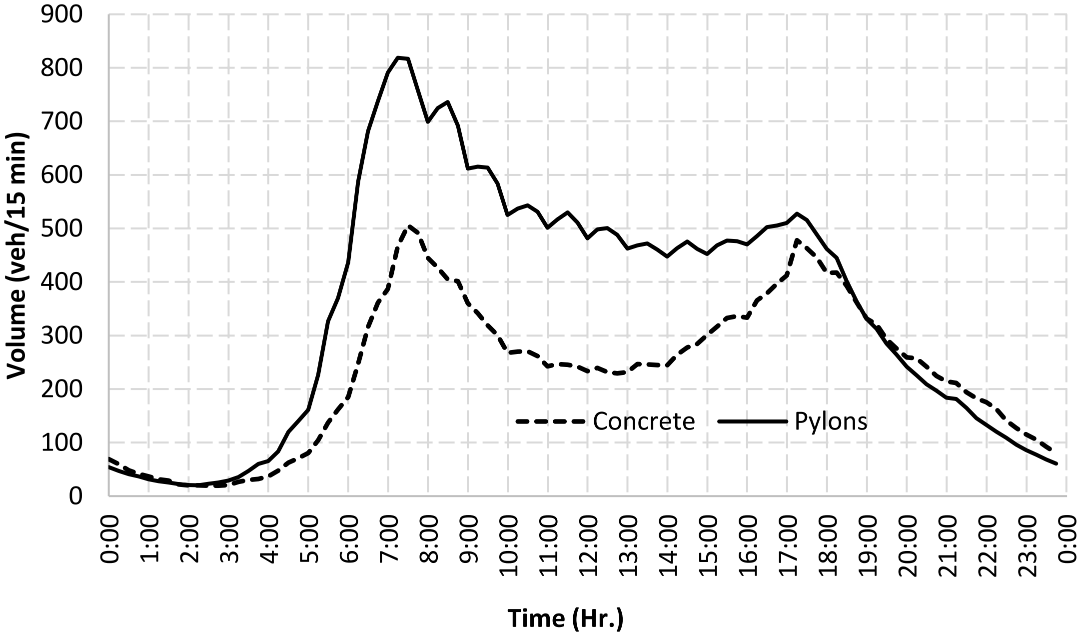


Figure 4.11: Average Traffic Volume for Pylons Against Concrete Barrier (GPL – Inside Lane)

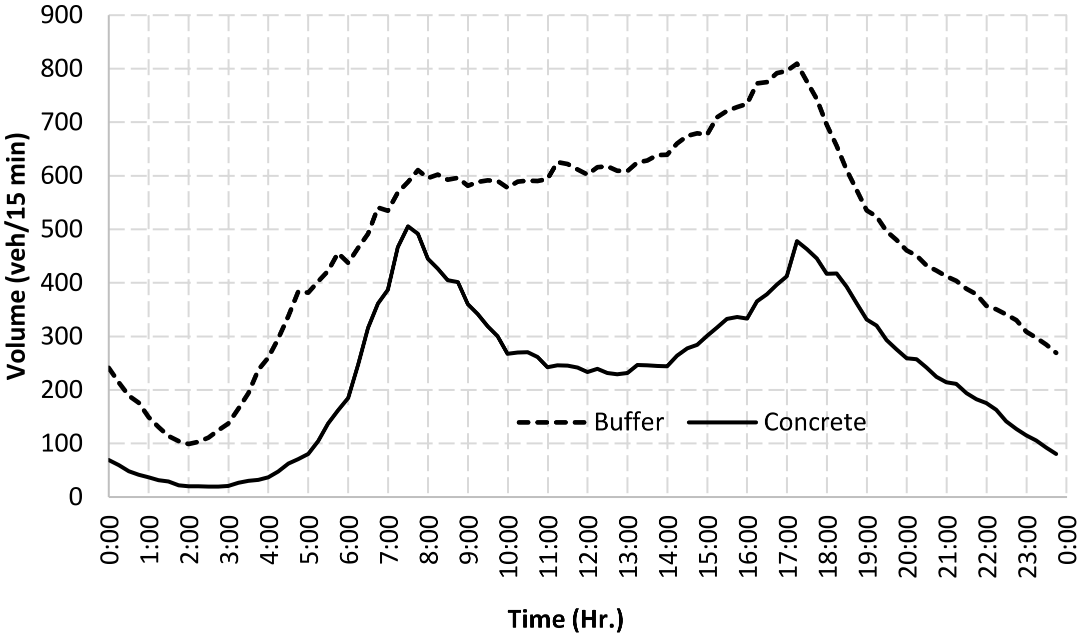


Figure 4.12: Average Traffic Volume for Buffer Against Concrete Barrier (GPL – Inside Lane)

Figures 4.13, 4.14, and 4.15 illustrate the left-lane utilization ratio over a 24-hour period for a 3-lane facility. The results indicated that the lane utilization ratio for the leftmost GPL was highest in facilities with buffer separation compared to those with concrete barriers or pylons.

The facility with buffer separation demonstrated a consistent left-lane utilization ratio of approximately 0.35 to 0.40 during daytime hours (6:00 AM to 7:00 PM), with traffic volumes ranging from 500 to 800 vehicles per 15 minutes.

When comparing pylon-separated facilities to concrete barrier-separated facilities, the left-lane utilization ratio was higher for pylons, particularly during daytime hours (6:00 AM–7:00 PM). For pylon-separated facilities, the left-lane utilization ratio remained relatively consistent at around 0.30, with the highest values observed during the AM peak hours (6:00 AM–9:00 AM), ranging from 0.33 to 0.37.

Concrete barrier-separated facilities had the lowest left-lane utilization ratios among the three separation types, with values ranging from 0.15 to 0.18 during the AM peak period (7:00 AM – 10:00 AM) and dropped to as low as 0.12 during the afternoon off-peak period. During the PM peak period (4:00 PM – 8:00 PM), the utilization values increased to a range of 0.14 to 0.20.

Overall, the differences in left-lane utilization among the separation types are most pronounced during daytime hours. However, during off-peak hours, buffer-separated and concrete barrier-separated facilities demonstrated a utilization ratio of approximately 0.30, which is closest to the balanced 0.33 for a 3-lane facility. In contrast, pylon-separated MLs exhibited lane utilization ratios as low as approximately 0.11 during the off-peak hours.

The higher utilization of the leftmost GPL of the buffer-separated facility suggests that drivers may prefer to use this lane more consistently for faster travel, as there is no physical barrier between the GPLs and MLs in buffer-separated facilities. This observation is further supported by the results from the Welch's t-test analysis presented in the next section.

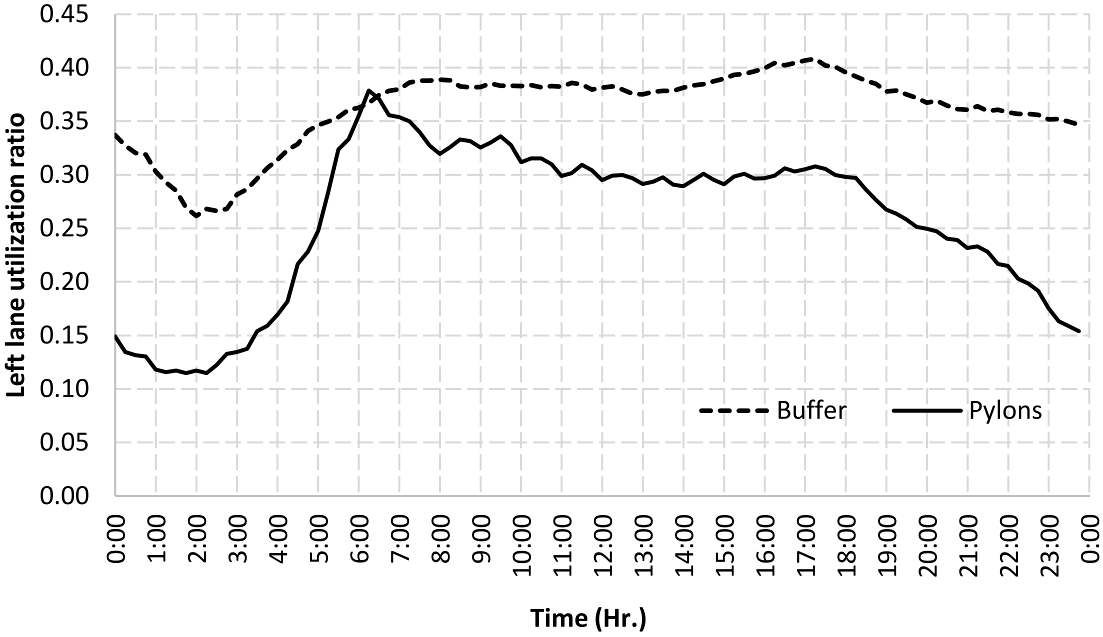


Figure 4.13: Average Lane Utilization Ratio for Buffer Against Pylons (GPL – Inside Lane)

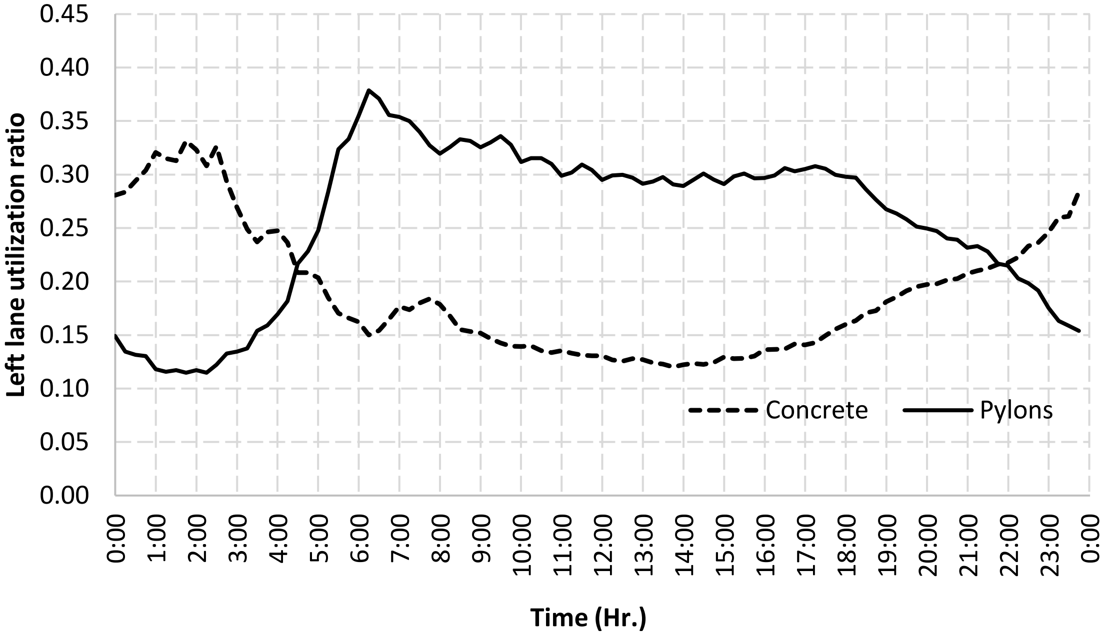


Figure 4.14: Average Lane Utilization Ratio for Concrete Barrier Against Pylons (GPL – Inside Lane)

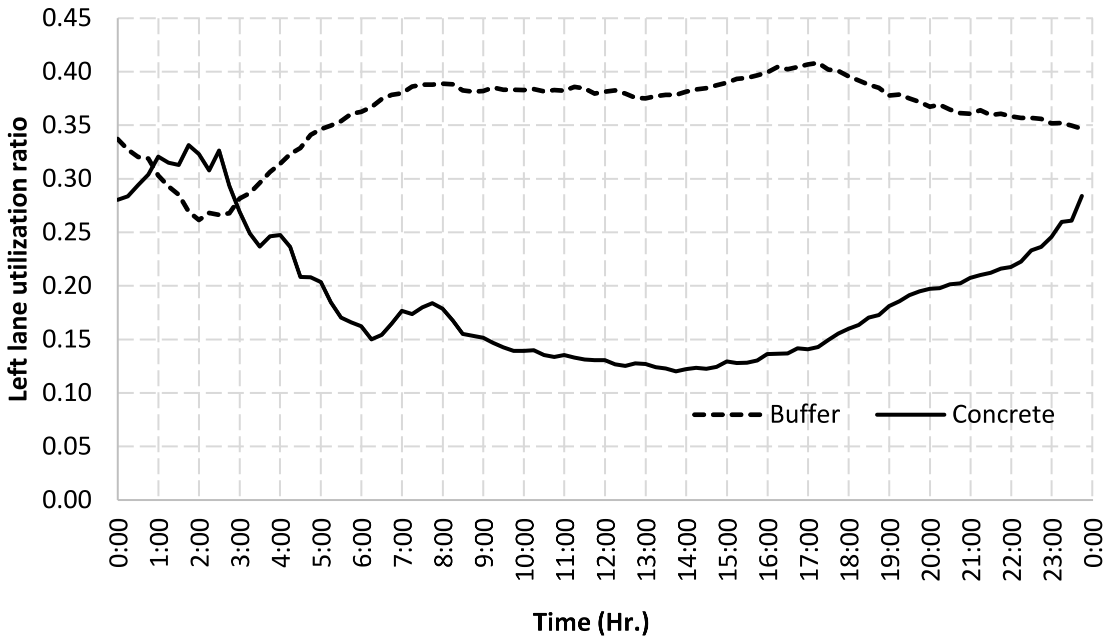


Figure 4.15: Average Lane Utilization Ratio for Buffer Against Concrete Barrier (GPL – Inside Lane)

Welch's t-Test Results

This section presents the results of the hypothesis testing using a Welch's t-test analysis. This analysis was conducted to determine whether the differences in mean utilization ratio on facilities with different separation types were statistically significant at a 95% confidence interval (CI). The null hypothesis was that the difference between the means of the lane utilization ratios of the two datasets was equal to zero. The alternate hypothesis was that the difference between the means of the lane utilization ratios of the two datasets was not equal to zero.

Table 4.2 presents the results of the Welch's t-test for all three pairwise comparisons. The results indicate that there is a statistically significant difference in the mean utilization ratio between each pair of separation types at a 95% CI.

Table 4.2: Welch's t-Test Results of Lane Utilization of the Inside GPL

Pair	Mean Difference	Welch's t-test p-value
Buffer vs. Pylons	0.105	<0.001
Buffer vs. Concrete Barrier	0.173	<0.001
Pylons vs. Concrete Barrier	0.068	<0.001

Mean Squared Error (MSE) Results

The MSE analysis was performed to assess whether, for each separation type, the lane utilization ratio of the lane of interest significantly deviated from the balanced lane utilization factor. The null hypothesis was that the difference between the means of the lane utilization ratios and the balanced lane utilization factor was equal to zero. The alternate hypothesis was that the difference between the means of the lane utilization ratios and the balanced lane utilization factor was not equal to zero. Since the number of lanes for the selected facilities was three, the balanced lane utilization factor was 0.33.

Table 4.3 presents the results of the MSE analysis. The smaller the MSE value, the closer the actual lane utilization ratio is to the balanced lane utilization ratio. As shown in Table 4.3, buffer-separated facilities had the lowest MSE value. This indicates that, on a 24-hour average, drivers on buffer-separated lanes utilize the leftmost lane of the GPLs more consistently, maintaining a utilization ratio closer to the balanced value of 0.33 for a 3-lane facility, compared to pylons and concrete barrier separation types. When considering peak hours only, pylon-separated facilities exhibited the lowest MSE values, almost similar to buffer-separated facilities. Concrete barrier-separated facilities exhibited the highest MSE value in all three scenarios.

Table 4.3: MSE Results for Lane Utilization for the Inside GPL

Separation Type	MSE 24-hr Average	MSE Peak Hours	MSE Off-Peak Hours
Buffer	0.003	0.004	0.003
Concrete Barrier	0.031	0.033	0.029
Pylons	0.013	0.003	0.018

Note: MSE = Mean Squared Error; GPL = General-purpose Lane.

Generalized Linear Model (GLM) Results

The generalized linear model was used to explore the influence of separation type on lane utilization. Table 4.4 provides the results of the GLM. The response variable was the lane utilization ratio, which was modeled as a continuous variable. The explanatory variables included separation type, traffic volume, and time of day.

As indicated in Table 4.4, all three independent variables (i.e., separation type, traffic volume, and time of the day) were significant at a 95% CI. A negative model coefficient signifies a decrease in lane utilization. On the other hand, a positive coefficient indicates an increase in the lane utilization.

Vehicles traveling on the inside lane of the GPLs on ML facilities with concrete barriers were associated with a 12.8% reduction in lane utilization compared to the buffer-separated facilities. Similarly, vehicles traveling on the inside lane of the GPLs on pylon-separated ML facilities were associated with an 8.6% decrease in lane utilization compared to the buffer-separated facilities. Regarding the time of the day, PM peak (4:00 PM – 8:00 PM) and AM peak (7:00 AM – 10:00 AM) periods were associated with a slight increase in the mean lane utilization compared to daytime off-peak periods by about 1%.

Table 4.4: GLM Results for the Inside GPL

Variable	Factors	Estimate	Std. Error	Odds Ratio	t-value	p-value
(Intercept)		**0.136**	**0.002**		**56.334**	**<0.001**
Separation Type	Buffer*					
	Concrete Barrier	**-0.137**	**0.001**	**0.872**	**-192.943**	**<0.001**
	Pylons	**-0.090**	**0.001**	**0.914**	**-140.615**	**<0.001**
Traffic Volume (veh/15 min.)		**0.034**	**0.0004**	**1.035**	**96.329**	**<0.001**
Time of the Day	Day Off -peak*					
	AM Peak (7 AM – 10 AM)	**0.017**	**0.001**	**1.017**	**19.627**	**<0.001**
	Night Off-peak	**0.033**	**0.001**	**1.034**	**43.112**	**<0.001**
	PM Peak (4 PM – 8 PM)	**0.008**	**0.001**	**1.008**	**9.666**	**<0.001**

Note: GLM = Generalized Linear Model; * = Indicates base level condition; Values in bold are significant at a 95% Confidence Interval.

4.2.4.2 Inside Lane of the MLs

Pairwise Comparison

This section presents the results of the pairwise comparison for the lane utilization analysis of MLs with different separation types. The analysis was performed on the inside lane of the MLs (i.e., the ML adjacent to the separator). Sites with two express lanes (i.e., 2-lane ML facilities) were selected for this analysis. Figures 4.16, 4.17, and 4.18 present the average traffic volume over a 24-hour period, averaged across the one-year study period, for the buffer separation against pylon separation, pylon separation against concrete barrier separation, and buffer separation against concrete barrier separation, respectively. The traffic volume refers to the total volume on the managed lanes.

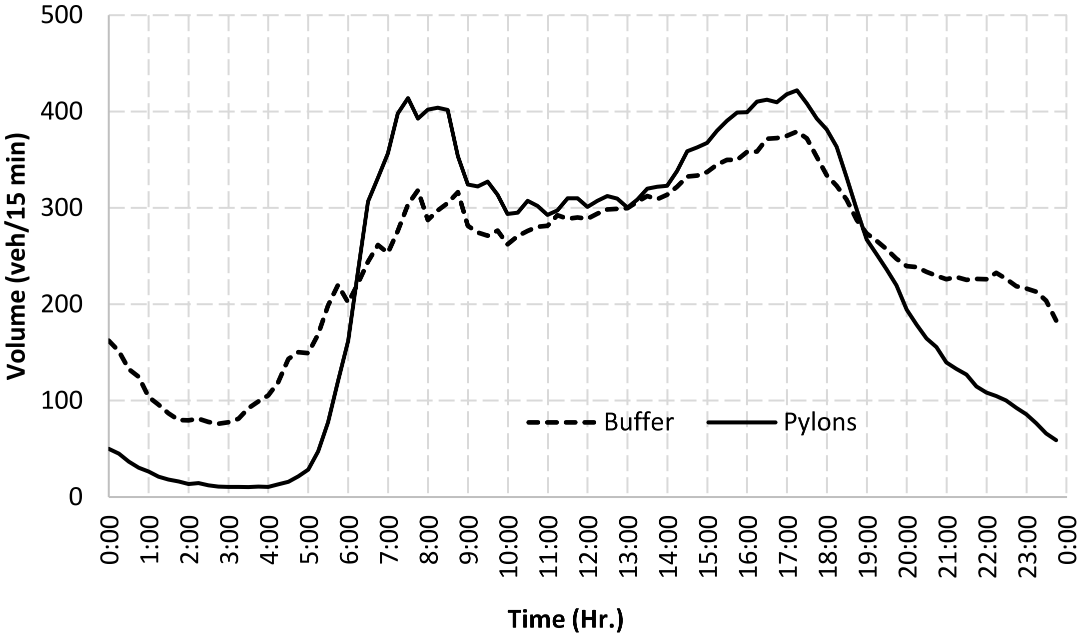


Figure 4.16: Average Traffic Volume for Buffer Against Pylons (MLs – Inside Lane)

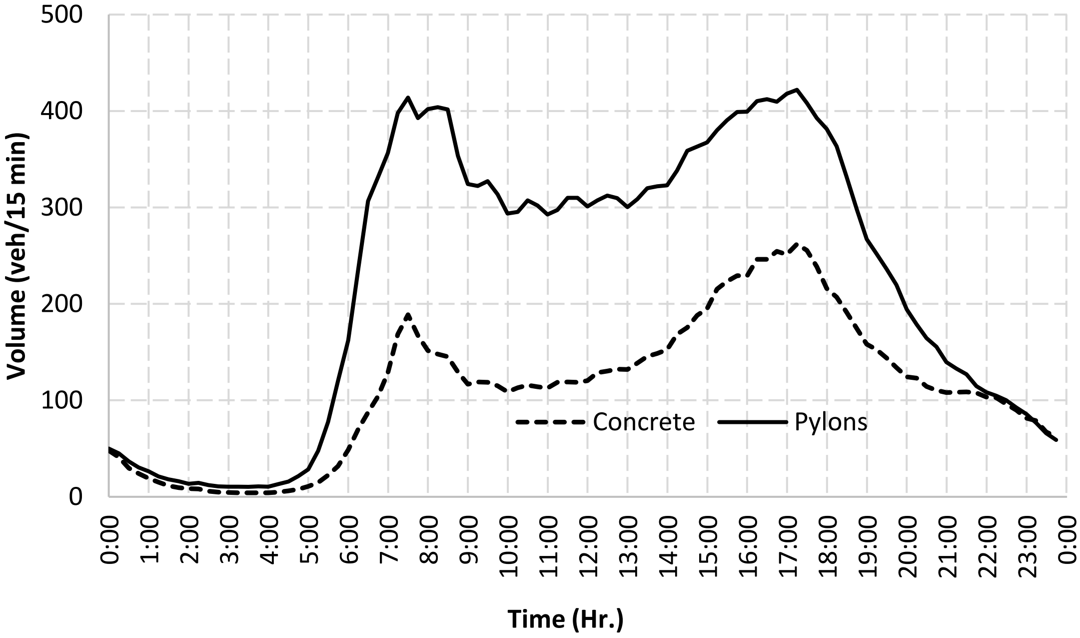


Figure 4.17: Average Traffic Volume for Pylons Against Concrete Barrier (MLs – Inside Lane)

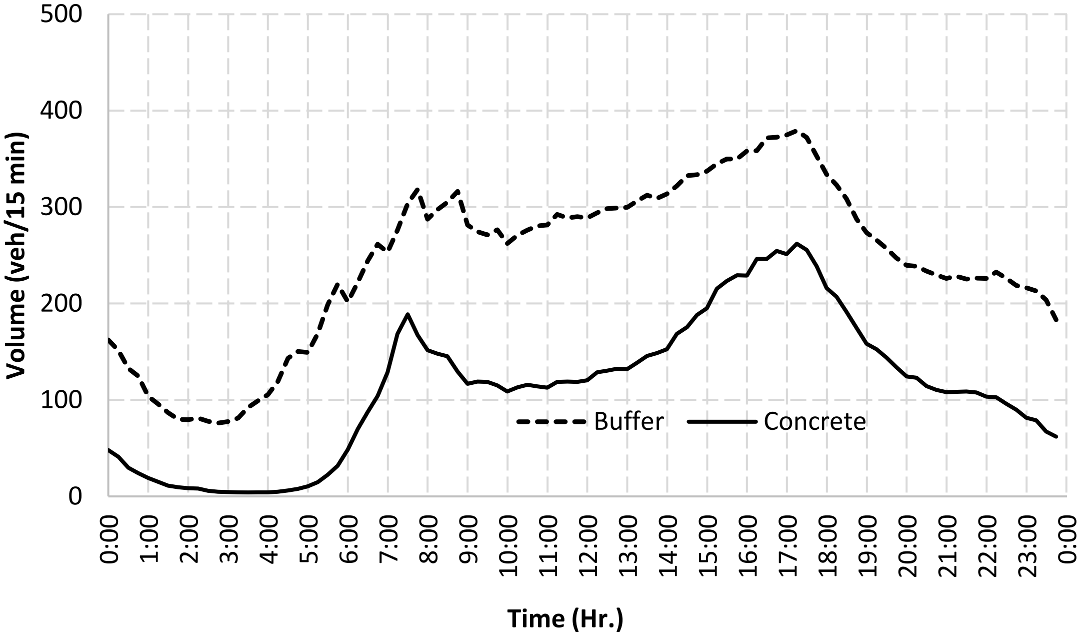


Figure 4.18: Average Traffic Volume for Buffer Against Concrete Barrier (MLs – Inside Lane)

Figures 4.19, 4.20, and 4.21 illustrate the lane utilization ratio for the inside ML (i.e., the rightmost ML adjacent to the separator) over a 24-hour period for facilities with two MLs. The results indicated that the lane utilization ratio for buffer and concrete separated facilities is consistently similar to each other throughout the day. When compared to pylon-separated ML facilities, both buffer and concrete barrier-separated ML facilities exhibited consistently higher utilization ratios.

The facility with buffer separation demonstrated a consistent lane utilization ratio throughout the day of approximately 0.60 to 0.70 during the daytime hours (6:00 AM to 7:00 PM), with traffic volumes ranging from 200 to 380 vehicles per 15 minutes. The utilization ratio was higher (0.80) for the inside ML during early morning off-peak hours (2:00 AM to 4:00 AM), where the volume was the lowest (approx. 80 vehicles per 15 minutes).

Similarly, for concrete barrier-separated MLs, the lane utilization ratio during the daytime hours (6:00 AM to 7:00 PM) was consistent throughout the day with slight dips during the AM peak (0.62) and PM peak (0.60) periods for the inside ML. The lane utilization ratio stayed fairly consistent during all other hours, between 0.60 and 0.70.

An interesting trend was observed for pylon-separated MLs, with the lane utilization ratio being the highest during both peak periods (utilization ratio = 0.50). This indicates that drivers tend not to avoid the inside ML during peak periods. The lane utilization ratio was consistently lower for off-peak periods, ranging from 0.45 (day-off peak) to 0.32 (night off-peak).

Overall, the differences in lane utilization among the separation types were most pronounced when comparing buffer against pylons and concrete barrier against pylons. When comparing buffer and concrete barrier, the difference was not as pronounced; this conclusion was also supported by results from the Welch's t-test analysis presented in the next section.

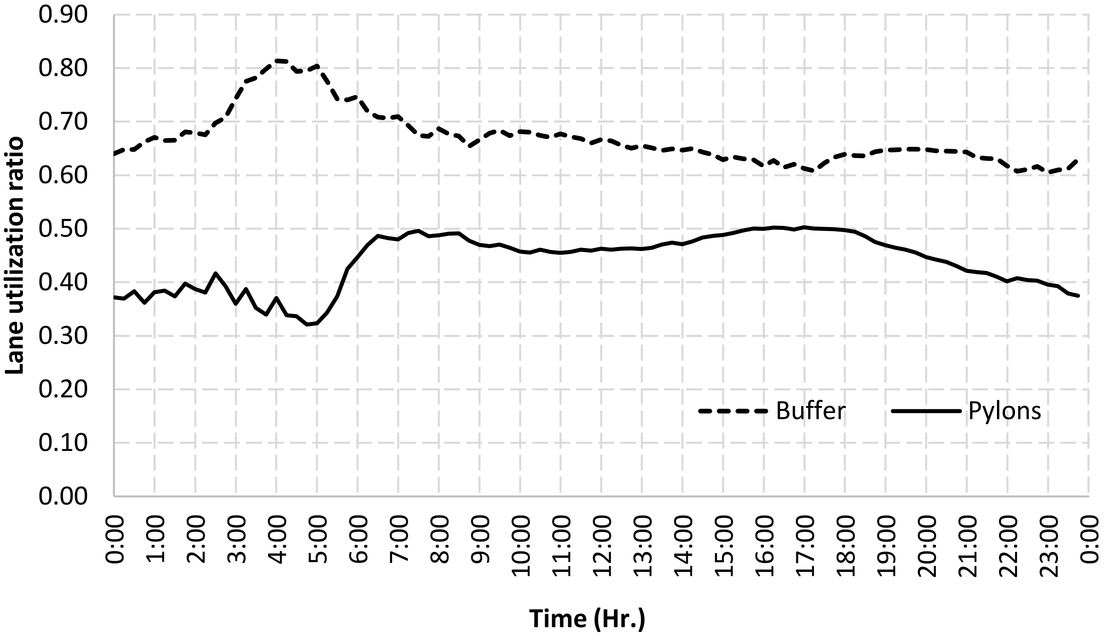


Figure 4.19: Average Lane Utilization Ratio for Buffer Against Pylons (MLs – Inside Lane)

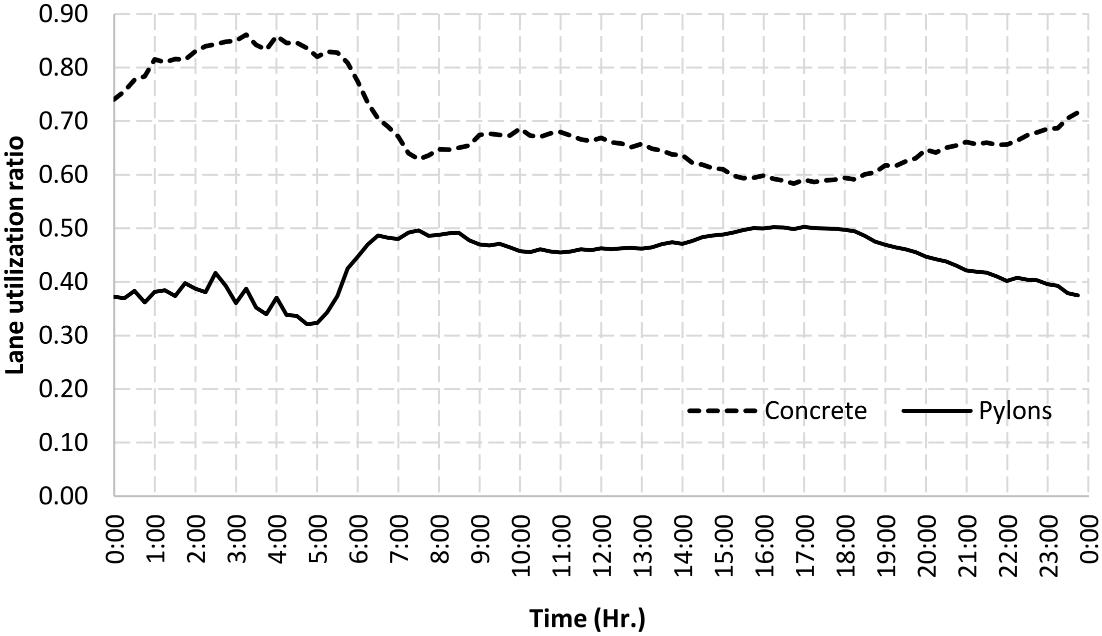


Figure 4.20: Average Lane Utilization Ratio for Concrete Barrier Against Pylons (MLs – Inside Lane)

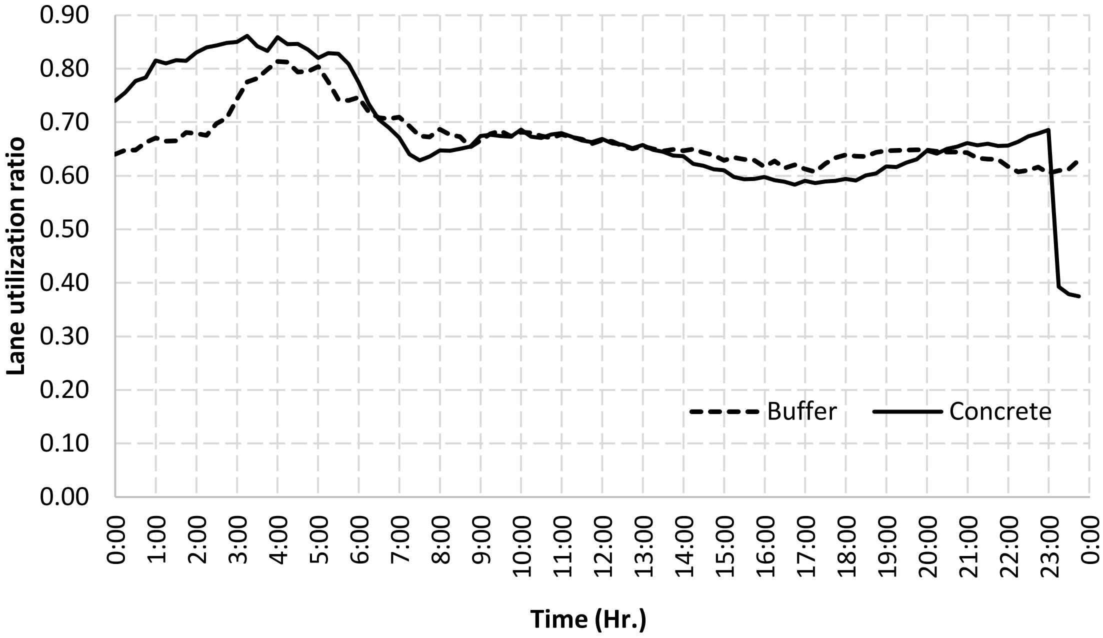


Figure 4.21: Average Lane Utilization Ratio for Buffer Against Concrete Barrier (MLs – Inside Lane)

Welch's t-Test Results

A Welch's t-test was performed to determine whether the differences in mean utilization ratio on ML facilities with different separation types were statistically significant at a 95% CI. The null hypothesis was that the difference between the means of the lane utilization ratios of the two datasets was equal to zero. The alternative hypothesis was that the difference between the means of the lane utilization ratios of the two datasets was not equal to zero.

Table 4.5 presents the results of the Welch's t-test for all three pairwise comparisons. The results show that there is a statistically significant difference in the mean utilization ratio between each pair of separation types at a 95% CI. However, the magnitude of the difference is considerably smaller when comparing buffer separated versus concrete barrier separated MLs.

Table 4.5: Welch's t-Test Results of Lane Utilization of the Inside ML

Pair	Mean Difference	Welch's t-test p-value
Buffer vs. Pylons	0.238	<0.001
Buffer vs. Concrete Barrier	-0.020	<0.001
Pylons vs. Concrete Barrier	-0.257	<0.001

Mean Squared Error (MSE) Results

The MSE analysis was performed to assess whether, for each separation type, the lane utilization ratio of the lane of interest significantly deviated from the balanced lane utilization factor. The null hypothesis was that the difference between the means of the lane utilization ratios and the balanced lane utilization factor was equal to zero. The alternative hypothesis was that the difference between the means of the lane utilization ratios and the balanced lane utilization factor was not equal to zero. Since the number of lanes for the select ML facilities was two, the balanced lane utilization factor was 0.50.

Table 4.6 presents the results of the MSE analysis. The smaller the MSE value, the closer the actual lane utilization ratio is to the balanced lane utilization ratio. As shown in Table 4.6, pylon-separated MLs had the lowest MSE value compared to the other separation types. This indicates that, on a 24-hour average and during peak and off-peak hours, drivers on pylon-separated MLs consistently utilized the inside ML (adjacent to the separator), maintaining a utilization ratio closer to the balanced value of 0.50 for a 2-lane ML facility. However, the other separation types exhibited a higher overall observed utilization ratio.

Table 4.6: MSE Results for Lane Utilization for the Inside ML

Separation Type	MSE 24-hr Average	MSE Peak Hours	MSE Off-Peak Hours
Buffer	0.034	0.026	0.037
Concrete Barrier	0.052	0.021	0.065
Pylons	0.019	0.004	0.025

Generalized Linear Model (GLM) Results

The generalized linear model was used to explore the influence of separation type on lane utilization. Table 4.7 provides the results of the GLM. The response variable was the lane utilization ratio, which was modeled as a continuous variable. The explanatory variables included the separation type, traffic volume, and the time of day.

As indicated in Table 4.7, all three independent variables (i.e., separation type, traffic volume, and time of the day) were significant at 95% CI. A negative sign of the model coefficient signifies a decrease in lane utilization. On the other hand, a positive coefficient indicates an increase in the lane utilization. Key findings from the analysis include:

- Vehicles traveling in the ML closest to the separator on concrete barrier-separated facilities were associated with a 1.4% increase in the lane utilization ratio compared to buffer-separated facilities. Conversely, vehicles traveling in the ML closest to the separator with pylon separations were associated with over a 20% decrease in the lane utilization ratio compared to those with buffer separation type.

- PM peak periods were associated with a decrease of approximately 2% in the mean lane utilization ratio compared to daytime off-peak periods, while AM peak periods were associated with an increase of about 2% in the mean lane utilization ratio compared to daytime off-peak periods.

Table 4.7: GLM Results for the Inside Lane of the ML

Variables	Factors	Estimate	Std. Error	Odds Ratio	t-value	p-value
(Intercept)		**0.685**	**0.002**		**276.490**	**<0.001**
Separation Type	Buffer*					
	Concrete Barrier	**0.040**	**0.001**	**1.014**	**14.980**	**<0.001**
	Pylons	**-0.235**	**0.001**	**0.787**	**-279.750**	**<0.001**
Traffic Volume (veh/15 min.)		**-0.004**	**0.0004**	**0.996**	**-10.260**	**<0.001**
Time of the Day	Day Off Peak*					
	AM Peak	**0.018**	**0.001**	**1.017**	**14.690**	**<0.001**
	Night Off Peak	**0.046**	**0.001**	**1.014**	**13.310**	**<0.001**
	PM Peak	**-0.019**	**0.001**	**0.985**	**-13.85**	**<0.001**

Note: GLM = Generalized Linear Model; * = Indicates base level condition; Values in bold are significant at a 95% Confidence Interval.

4.2.5 Summary

Lane utilization can be referred to as the distribution of traffic across the available lanes on a freeway segment. This section summarizes the impact of different separation types on lane utilization in ML facilities.

The analysis of the lane utilization in the leftmost GPL revealed the following key findings:

- Buffer-separated facilities exhibited the highest lane utilization ratio for the leftmost GPL (0.35 to 0.40 during daytime hours), suggesting drivers utilize this lane more for faster travel due to the absence of physical barrier.

- Pylon-separated facilities consistently exhibited a lane utilization ratio of around 0.30 during daytime hours, with a slight increase to approximately 0.37 during the AM peak hours.

- Concrete barrier-separated facilities exhibited the lowest utilization, particularly during off-peak hours, with a utilization ratio as low as 0.12 to 0.20.

- The Welch's t-test analysis results showed a significant difference in the lane utilization ratios between all types of separators, confirming that the type of lane separation impacts drivers' choice of lanes.

- Buffer-separated lanes exhibited the lowest mean squared error (MSE) value of 0.003 when comparing left-lane utilization ratios to the balanced utilization ratio. This indicates that the mean lane utilization ratio for buffer-separated lanes was the closest to the balanced ratio of 0.33 for a 3-lane facility.

- Results from the GLM showed that concrete barriers and pylon separations result in decreased lane utilization compared to buffer separation by 12.8% and 8.6%, respectively. Traffic volume and time of day also significantly affect lane utilization.

The analysis of the lane utilization in the ML lane adjacent to the separator revealed the following key findings:

- Buffer-separated and concrete barrier-separated MLs exhibited similar lane utilization patterns, with a high utilization ratio throughout the day (ranging from 0.60 to 0.70 during daytime hours).

- Pylon-separated MLs exhibited a lower lane utilization ratio compared to those of buffer-separated and concrete barrier-separated MLs, with a peak of 0.50, suggesting drivers tend to use the express lanes equally.

- The Welch's t-test analysis results showed a significant difference in the lane utilization ratios between all types of separators, confirming that the type of lane separation impacts drivers' choice of lanes. The difference was less pronounced between buffer and concrete separators.

- Pylon-separated MLs exhibited the lowest MSE value of 0.019 when comparing lane utilization ratios to the balanced utilization ratio. This indicates that the mean lane utilization ratio for pylon-separated lanes was the closest to the balanced ratio of 0.50 for a 2-lane ML facility.

- Results from the GLM showed that concrete barrier-separated ML facilities resulted in increased lane utilization by 4.1% compared to buffer-separated ML facilities, while pylon-separated ML facilities decreased lane utilization by nearly 20% compared to buffer-separated ML facilities. The impact also varied by time of the day, with the AM peak and PM peak hours showing different impacts.

4.3 Travel Speed

Managed lanes are designed to provide mobility, and speed is one of the most important mobility-focused performance measures. As such, understanding whether the separation type on ML facilities influences the speed distribution of the managed lanes and the leftmost GPL is crucial for transportation planners, policymakers, and traffic engineers.

The rationale behind studying how speed varies on managed lanes with different separators lies in the need to optimize traffic flow, ensure safety, and improve the overall efficiency of freeways. By analyzing speed distribution, transportation authorities can make informed decisions regarding the ML separation type, as far as speed management is concerned.

The variation in travel speed provides insights into the driver behavior on roadways with MLs. Identifying factors affecting the speed choice of drivers can help transportation authorities in decision-making. Ensuring that the traffic travels at designated safe speeds can help to potentially alleviate congestion. This is especially true if roadway characteristics such as separation type were found to affect the average speed.

This section analyzes whether different separation types have different impacts on the average travel speed for drivers in the managed lane closest to the separator (i.e., the inside ML). To understand the speed variation in ML facilities, the study analyzed the speed distribution at comparative sites. The analysis considered three sections; these sections featured the three types of ML separators: concrete barrier, pylons, and buffer. The study examined the mean speeds of the lane closest to the separator for these sections and compared them to ascertain if there was any significant difference in the observed mean speeds.

The analysis aimed to answer the following question: Does the managed lane adjacent to the separator exhibit different mean speeds across sections with varying separation types, and which sections, if any, show statistically significant differences?

4.3.1 Data

The analysis utilized speed data sourced from the Regional Integrated Transportation Information System (RITIS), which serves as a comprehensive transportation data platform integrating real-time information from multiple transportation agencies and sources. RITIS offers a wealth of traffic data, including speed and volume information collected from various sensors and detectors positioned along the roadway corridors. The data used in this analysis was collected at 15-minute intervals over a 12-month period, from January 1, 2023 to December 31, 2023.

The study areas for the average speed analysis were freeway segments in Florida with managed lanes. Two main criteria were used to select these areas:

a) Traffic Volume: Segments were chosen so that the lane volumes for the managed lane closest to the separator were similar. To ensure comparability, the difference in observed lane volume between selected segments was limited to within 30%.
b) Separation Type: Sites were selected based on the type of managed lane separation. The separation types included concrete barriers, buffer separation, and pylon separation.

Study sites used in this analysis included:

- FL-528 (Buffer Separation) (see Figure 4.3)
- FL-589 – Veterans Expressway (Pylons Separation) (see Figure 4.4)
- I-595 (Concrete Barrier Separation) (see Figure 4.5)

4.3.2 Methodology

Consistent with the objectives of this research to analyze whether vehicle speed is affected by managed lane separation types, the study adopted the one-way Analysis of Variance (ANOVA) test. This test aimed to analyze whether the observed difference between the mean speeds for the study sites was significant at a 95% confidence interval.

4.3.2.1 ANOVA Analysis

Analysis of Variance (ANOVA) is a statistical method used to compare the means of three or more samples to determine if at least one of the sample's mean significantly differs from the others. This method helps to identify whether the differences among group means are due to variation within the groups or due to the effect of the independent variable(s) on the dependent variable across different groups.

The basic principle behind ANOVA is to partition the total variation observed in the data into two parts: variation within groups and variation between groups. By comparing the variance (or variation) within groups to the variance between groups, ANOVA assesses whether the means of the groups are statistically significantly different from each other. Equation 4.11 presents the ANOVA formula (Chen et. al., 2018). Equation 4.12 presents the F-test formula (Gamage & Weerahandi, 1998).

Assumptions made in the ANOVA analysis include:

- Values for each level follow a normal distribution.
- Variances are the same for each level.
- Observed values are mutually independent.

$$\sum_{i=1}^{m}\sum_{j=1}^{n}(X_{ij}-\overline{X}_{\bullet\bullet})^2 = \sum_{i=1}^{m}\sum_{j=1}^{n}(X_{ij}-\overline{X}_{i\bullet})^2 + n\sum_{i=1}^{m}(\overline{X}_{i\bullet}-\overline{X}_{\bullet\bullet})^2 \qquad (4.11)$$

$$\text{SST} = \text{SSE} + \text{SS(Tr)}$$

where,

SST = Sum of Squares - Total,
SSE = Sum of Squares - Error (variance within a group), and
SS(Tr) = Sum of Squares - Treatment (variance between groups).

$$F = \frac{SS(Tr)/(m-1)}{SSE/(m(n-1)} \overset{\Delta}{=} \frac{MS(Tr)}{MSE} \sim F[m-1, m(n-1)] \qquad (4.12)$$

By employing a comparative cross-sectional analysis, insights into the differences in the average speed between the managed lanes facilities with different separation types can be gained. This approach facilitates the identification of distinct speed patterns, if any, associated with the presence of specific managed lane separation types, providing valuable information for transportation planners and policymakers to optimize traffic flow and improve overall freeway efficiency.

4.3.2.2 Hypothesis Testing

The null hypothesis (H_0) states that there are no differences in the population means of average speed across different separation types (see Equation 4.13). The alternate hypothesis states that at least two of the population means of average speed are different.

$$\mu 1 = \mu 2 = \mu 3 \tag{4.13}$$

where,

$\mu 1$ = Mean speed for Section 1 (MLs with buffer separation),
$\mu 2$ = Mean speed for Section 2 (MLs with pylon separation), and
$\mu 3$ = Mean speed for Section 3 (MLs with concrete barrier separation).

An ANOVA test was conducted at a 95% confidence level to determine whether to reject or fail to reject the null hypothesis. If the null hypothesis was not rejected, the analysis would conclude at that point, implying there are no significant differences in the mean speeds for the inside lane of the MLs. This would mean the presence or type of separator does not influence the driver's speed choice. On the other hand, if null hypothesis was rejected, the analysis would continue to the post hoc analysis stage, implying there are significant differences in the mean speeds for the inside lane of the MLs. This would mean the presence or type of separator does influence the driver's speed.

4.3.2.3 Post-Hoc Analysis

Post-hoc analysis refers to statistical analyses that are conducted after an initial analysis has been completed, aiming to find patterns, trends, or differences within the data that were not specified in the earlier study. It is often used to explore data further and test hypotheses that arise from the initial results, allowing researchers to understand the nuances and subtleties within their findings.

In this study, rejecting the null hypothesis implied that there was a difference between at least two of the mean speeds. Further analysis was warranted to identify the differences. The study adopted the Tukey range test, also known as Tukey's honest significance test (Abdi & Williams, 2010). This test compared all the possible pairs of means. It applied simultaneously to the set of all pairwise comparisons and identified any difference between two means that was greater than the expected standard error, which in this case was 5%. Equation 4.14 presents the Tukey's formula (Montgomery, 2017).

$$q_s = \frac{Y_A - Y_B}{SE} \tag{4.14}$$

where,

Y_A = the larger of the two means compared,
Y_B = the smaller of the two means compared, and
SE = standard error of the sums of the mean.

The value q_s is then compared to the value q from the studentized range distribution. The value of q is calculated using Equation 4.15 (Montgomery, 2017).

$$q = \frac{Y_{max} - Y_{min}}{S\sqrt{(2/n)}} \tag{4.15}$$

where,

Y_{max} = the largest of the sample means,
Y_{min} = the smallest of the sample means,
S = pooled sample standard deviation,
n = sample size

The degree of freedom for each mean can be calculated as N-k, where N is the total number of observations and k is the number of sub populations being compared.

4.3.2.4 Statistical Modeling

The next step was to fit the data using a generalized linear model (GLM), a flexible statistical framework for analyzing relationships between a dependent variable and one or more explanatory variables. In this performance measure, the response variable was average speed, while the explanatory variables included separation type, traffic volume, time of day, and the number of ML and GPL lanes. Refer to Section 4.2.3.4 for a detailed explanation of the principles and equations of the GLM.

4.3.3 Results

This section presents the results of the speed choice analysis. The first subsection presents the results for the pairwise comparison between ML sites with different separation types. The second subsection presents the results of the GLM model.

4.3.3.1 Pairwise Comparison

This section presents the results of the pairwise comparison for the speed analysis, focusing vehicles traveling in the inside lane of the MLs (i.e., the lane adjacent to the separator). The analysis investigated whether the average speed for vehicles traveling in this lane was affected by the separation type.

Figures 4.22, 4.23, and 4.24 present the average traffic volume over a 24-hour period, averaged across the one-year study period. Note that the traffic volume corresponds to the lane volume on the inside lane of the MLs.

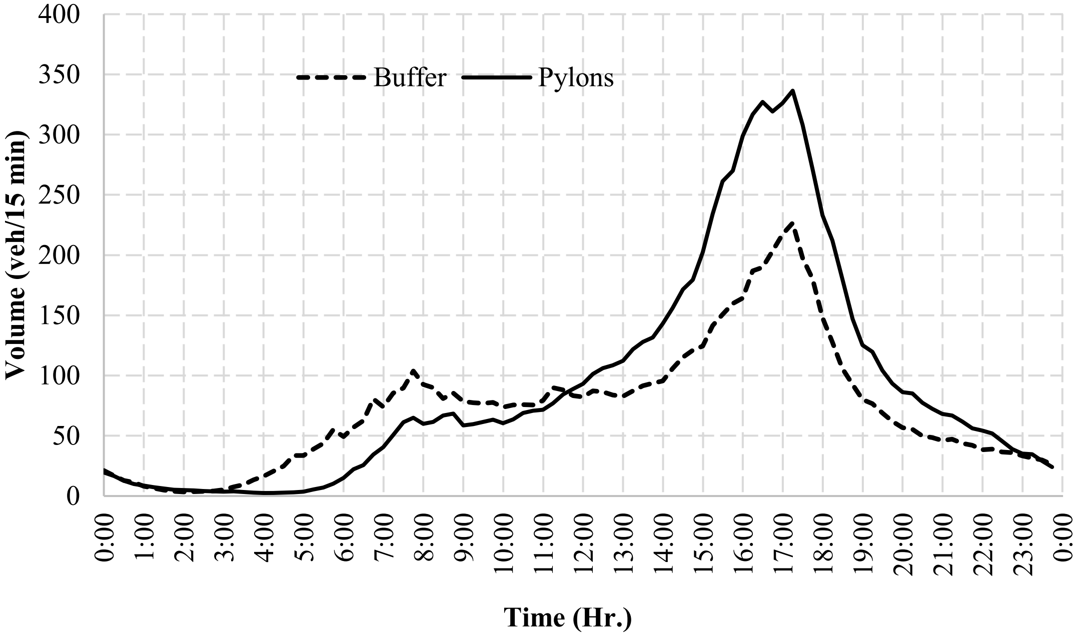


Figure 4.22: Lane Volume for Buffer Against Pylons (MLs – Inside Lane)

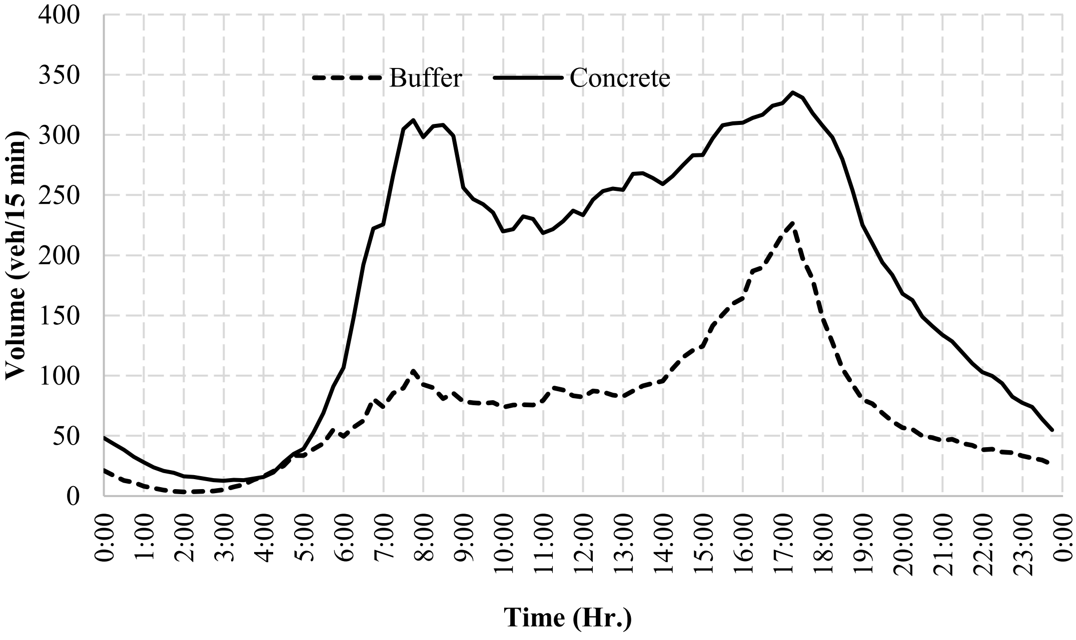


Figure 4.23: Lane Volume for Buffer Against Concrete Barrier (MLs – Inside Lane)

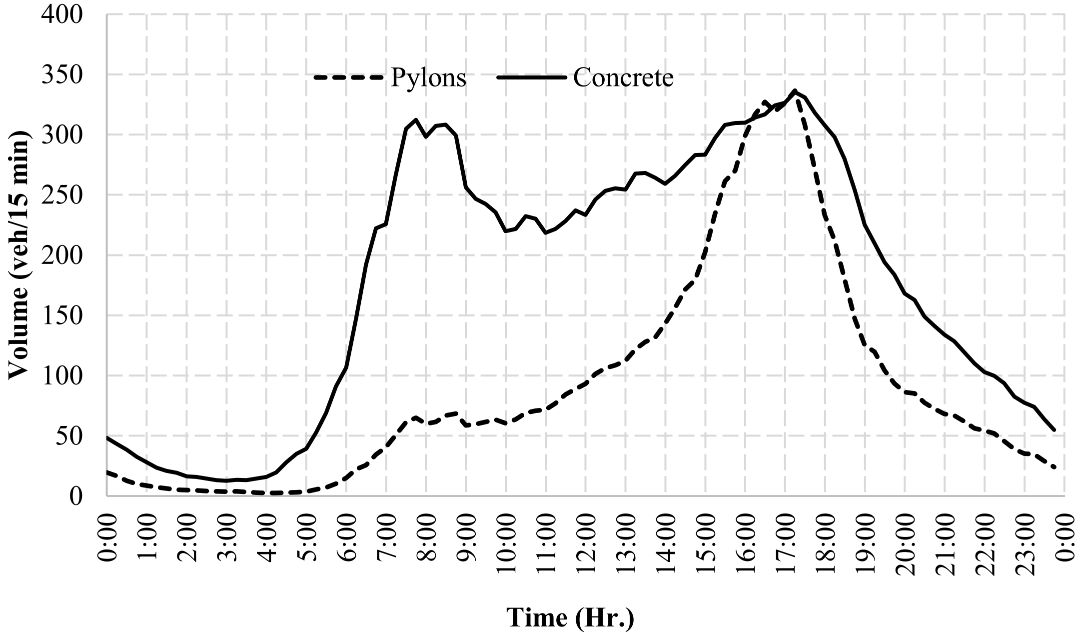


Figure 4.24: Lane Volume for Pylons Against Concrete Barrier (MLs – Inside Lane)

Figures 4.25, 4.26, and 4.27 present the graphs for average speed over a 24-hour period for ML facilities included in the travel speed analyses.

It is evident that drivers consistently travel at higher average speeds on MLs with buffer separation compared to those with pylons, with the exception of AM peak hours. Similarly, MLs with buffer separation exhibit higher average speeds compared to those with concrete barriers across all periods. Interestingly, for MLs with concrete barriers, average speeds during daytime hours surpass those observed on MLs with pylons, while the opposite pattern emerges during nighttime hours.

These observations suggest that the type of separation significantly influences driver behavior, likely due to varying perceptions of safety and comfort associated with each separation type. The consistent preference for higher speeds on buffer-separated MLs may reflect drivers' perception of greater lane stability and reduced constraints compared to pylons and concrete barriers. Conversely, the reduced speeds on MLs with pylons and concrete barriers, particularly during certain periods, may indicate a higher level of caution.

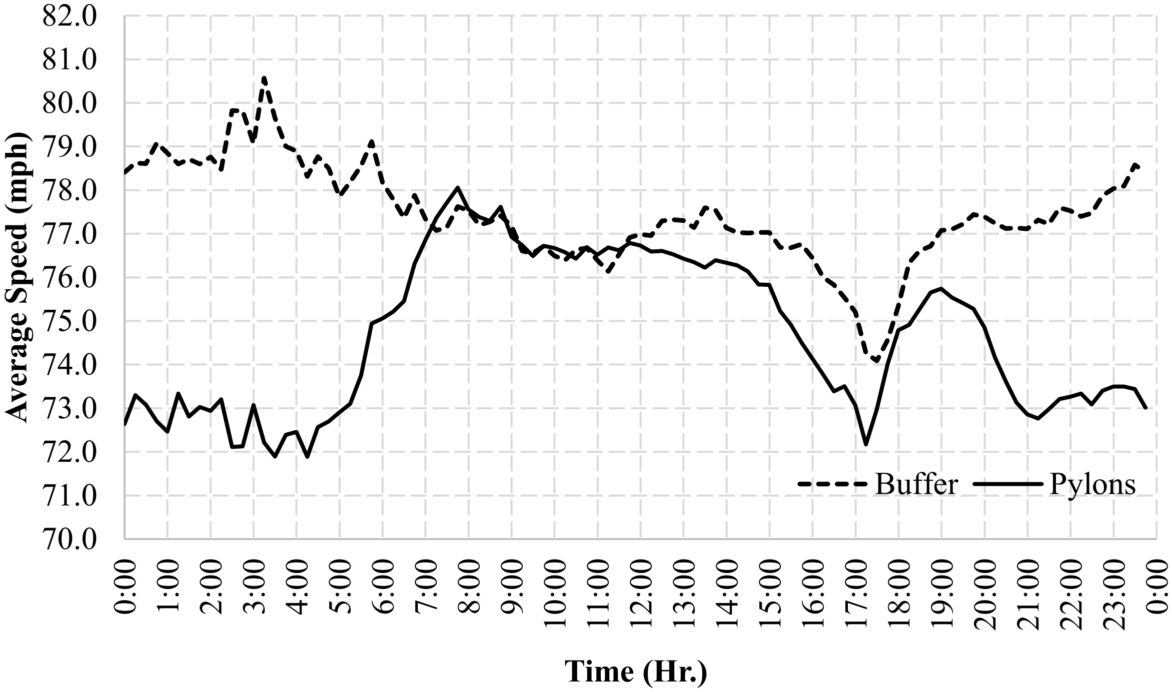


Figure 4.25: Comparison of Average Speed for Buffer Against Pylons (MLs – Inside Lane)

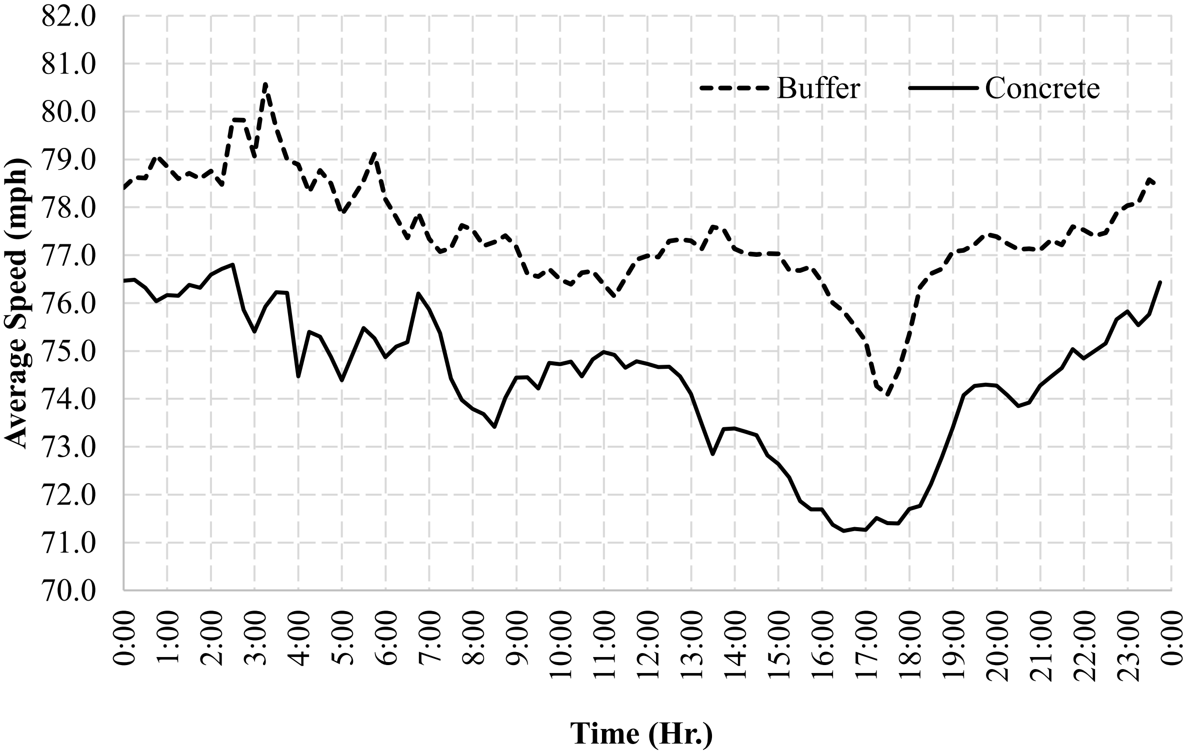


Figure 4.26: Comparison of Average Speed for Buffer Against Concrete Barrier (MLs – Inside Lane)

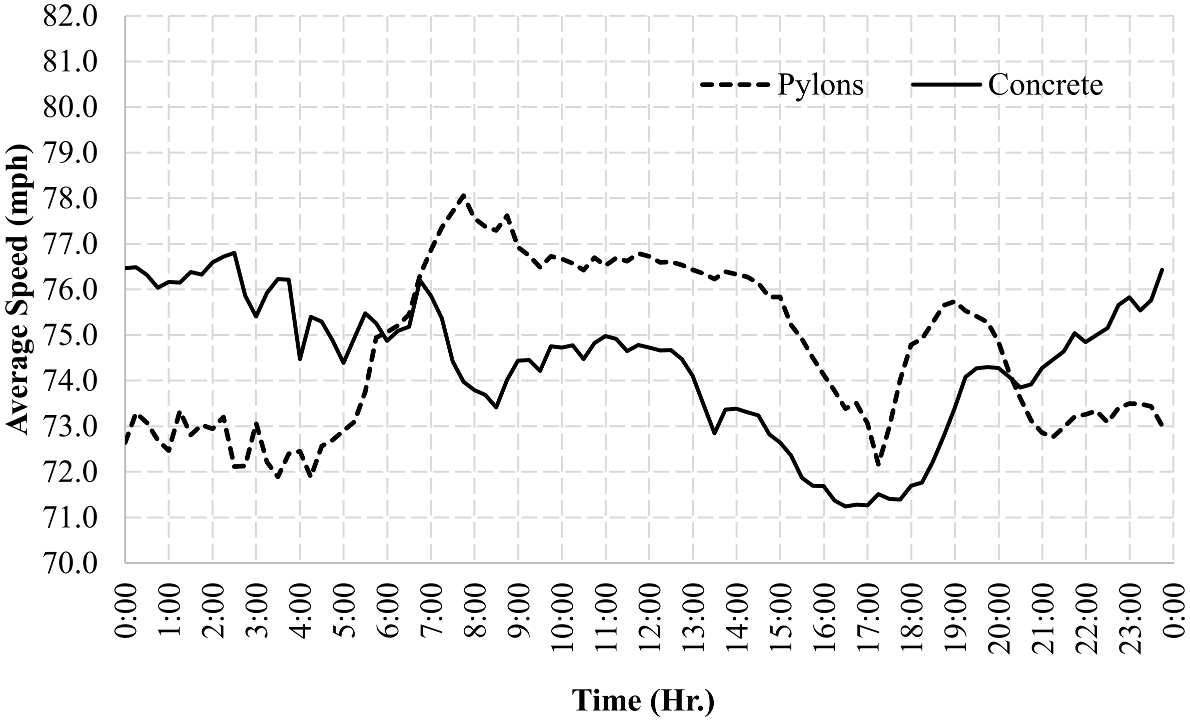


Figure 4.27: Comparison of Average Speed for Pylons Against Concrete Barrier (MLs – Inside Lane)

4.3.3.2 Significance Test Results

This section presents the results of the ANOVA analysis. The analysis examined whether the average speed of vehicles on ML facilities varied significantly by separation type at a 95% CI. Table 4.8 presents the results of the ANOVA test. Since the p-value was less than 0.05, the null hypothesis was rejected. Table 4.9 presents the results of the Tukey test analysis. As indicated in Table 4.9, there is a statistically significant difference in the average speed between ML facilities with concrete barriers and those with buffer separation, as well as between ML facilities with pylon separation and those with buffer separation, at a 95% CI. There is no significant difference in average speed between MLs with pylon separation when compared to MLs with concrete barriers, at a 95% CI.

Table 4.8: ANOVA Results for Average Speed

Factor	Df	Sum Sq	Mean Sq	F value	P value
Separation Type	2	539.7	269.86	121.5	<0.001
Residuals	285	633.2	2.22		

Note: Df = degree of freedom; Sum Sq = sum of the squares; Mean Sq = mean square value.

Table 4.9: Tukey Test of Significance Results for Average Speed

Separation Type	Difference (mph)	p-value
Concrete barrier - Buffer	-3.1	<0.001
Pylons - Buffer	-2.7	<0.001
Pylons – Concrete barrier	0.3	0.320

4.3.3.3 Generalized Linear Model (GLM) Results

The generalized linear model was used to explore the influence of separation type on the average speed. Table 4.10 provides the results of the generalized linear model. The response variable was the average speed. The average speed was modeled as a continuous variable. The explanatory variables included separation type, lane volume, and time of the day.

Table 4.10: GLM Results for Average Speed

Variable	Factors	Estimate	Std. Error	Odds Ratio	t-value	p-value
(Intercept)		**78.883**	**0.248**		**318.101**	**<0.001**
Separation Type	Buffer*					
	Concrete Barriers	**-1.896**	**0.230**	**0.15**	**-8.257**	**<0.001**
	Pylons	**-2.545**	**0.181**	**0.08**	**-14.04**	**<0.001**
Lane Volume (veh/15 min.)		**-0.011**	**0.001**	**0.99**	**-8.055**	**<0.001**
Time of the Day	Day Off Peak*					
	AM Peak	0.329	0.251	1.39	1.314	0.189
	Night Off Peak	**-1.272**	**0.250**	**0.28**	**-5.078**	**<0.001**
	PM Peak	**-0.822**	**0.240**	**0.44**	**-3.433**	**0.001**

Note: * = base level condition; Values in bold are significant at a 95% CI.

As indicated in Table 4.10, all three independent variables (i.e., separation type, lane volume, and time of the day) were significant at a 95% CI. A negative sign of the model coefficient signifies a decrease in the average speed. On the other hand, a positive coefficient indicates an increase in the average speed. Key findings include:

- Vehicles traveling on ML facilities with concrete barriers and pylon separation types were found to travel at a lower average speed compared to ML facilities with buffer separation.
- An increase in traffic volume on the inside lane of the managed lanes was associated with a slight decrease in average speed.
- PM peak periods were associated with a decrease in the average speed compared to day-off peak periods. The same observation was observed for night off-peak periods indicating a decrease in the average lane speed in low light conditions.

4.3.4 Summary

Speed is one of the most critical mobility-focused performance measures for managed lanes. Several analyses were performed to determine the impacts of the separation type on average speed on managed lane facilities, focusing on the ML adjacent to the separation type. It is important to note that the average speed analysis included drivers from all age groups.

Key findings from the analysis of the average speed in the ML adjacent to the separator include:

- On MLs with buffer separation, people consistently drive at a higher average speed compared to MLs with pylons. An exception was observed during AM peak hours.
- On MLs with buffer separation, people consistently drive at a higher average speed compared to MLs with concrete barriers.
- On MLs with concrete barriers, people consistently drive at a higher average speed compared to MLs with pylons during the day. The opposite was observed during the night hours.
- Results from the ANOVA analysis concluded that there is a statistically significant difference in the observed average travel speed on at least two separation types.
- A Tukey test of significance confirmed that MLs with buffer separators had significantly higher speeds than those with concrete barriers and pylons. There was no significant difference in the average speed between concrete barriers and pylons.
- Results from the GLM analysis showed that ML facilities with concrete barriers and pylon separation types were associated with a reduction in average travel speed compared to buffer-separated ML facilities. Regarding the time of the day, it was observed that PM peak periods were associated with significantly lower average speeds compared to daytime off-peak periods. Finally, an increase in the traffic volume in the managed lane adjacent to the separator was associated with a slight reduction in average speed.

4.4 Lane Deviation

Lane deviation is defined as an offset between the position of the vehicle's centroid and the centerline of the lane. The lane deviation values can be positive or negative depending on the relative position of the vehicle's centroid to the centerline of the lane. The lane deviation values are positive when the vehicle centroid is at the righthand side of the lane centerline. Figure 4.28 presents the graphical illustration of lane deviation analysis. The offset was calculated using the formula shown in Equation 4.16.

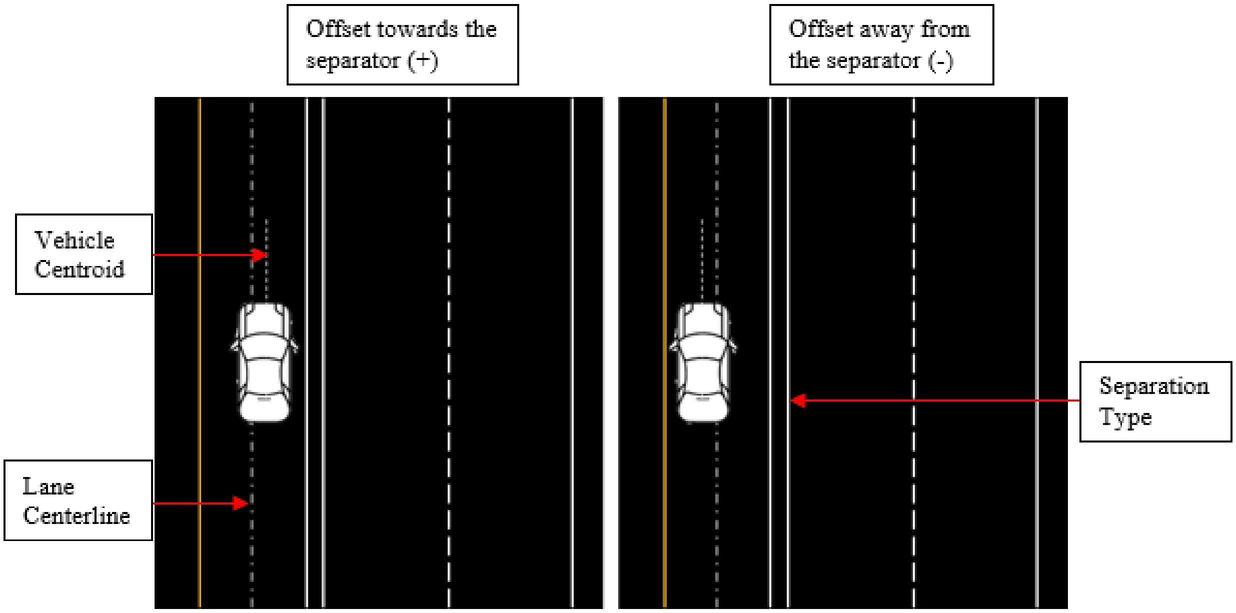


Figure 4.28: Lane Deviation – Offset

$$\text{Offset} = \text{Vehicle Centroid} - \text{Centerline} \tag{4.16}$$

Understanding lane deviation on freeways is crucial in maintaining safety on the roadway. The rationale behind studying lane deviation lies in the fact that when drivers considerably deviate from the centerline of the lane, there is an increased risk of experiencing safety issues, such as sideswipes. The premise of this analysis was to understand whether the separation types in managed lanes have any influence on the lane deviation values. By analyzing the relationship between lane deviation and separation type on managed lanes, transportation agencies can better understand driver behavior and make informed decisions regarding what separation treatment to adopt.

Lane deviations are particularly relevant in managed lanes, as any encroachment into adjacent lanes can compromise the safety of all road users. The proximity of separators often influences drivers' lane-keeping behavior, with deviations potentially linked to factors such as perceived lane width, separation type, and driver confidence. A previous study on rural two-lane curved sections concluded that in the presence of barriers, such as guardrails, resulted in drivers tendency to steer away from the barriers (Hallmark et al., 2015).

4.4.1 Data

This section presents the study area and the descriptive statistics of the data used in the lane deviation analysis. The study used naturalistic driving data (NDS) from the Strategic Highway Research Program 2 (SHRP2) to determine the impact of separation types on lane deviation along the I-5 and I-90 freeways in Seattle, Washington. The data used in this study was collected from 310 participants of the SHRP2 naturalistic study program. All of the trips analyzed in this study involved vehicles traveling either in the inside lane of the ML or in the inside lane of the GPL. For this study, the inside lane refers to the lane closest to the separator. The initial data review yielded over 8,373 trips, of which 8,051 (96%) were from Washington State. Therefore, only the data from Washington State was considered in the analysis. Figures 4.29, 4.30, and 4.31 present the maps showing the spatial distribution of the trips.

Figure 4.291: U.S. Map Showing SHRP2 Trips

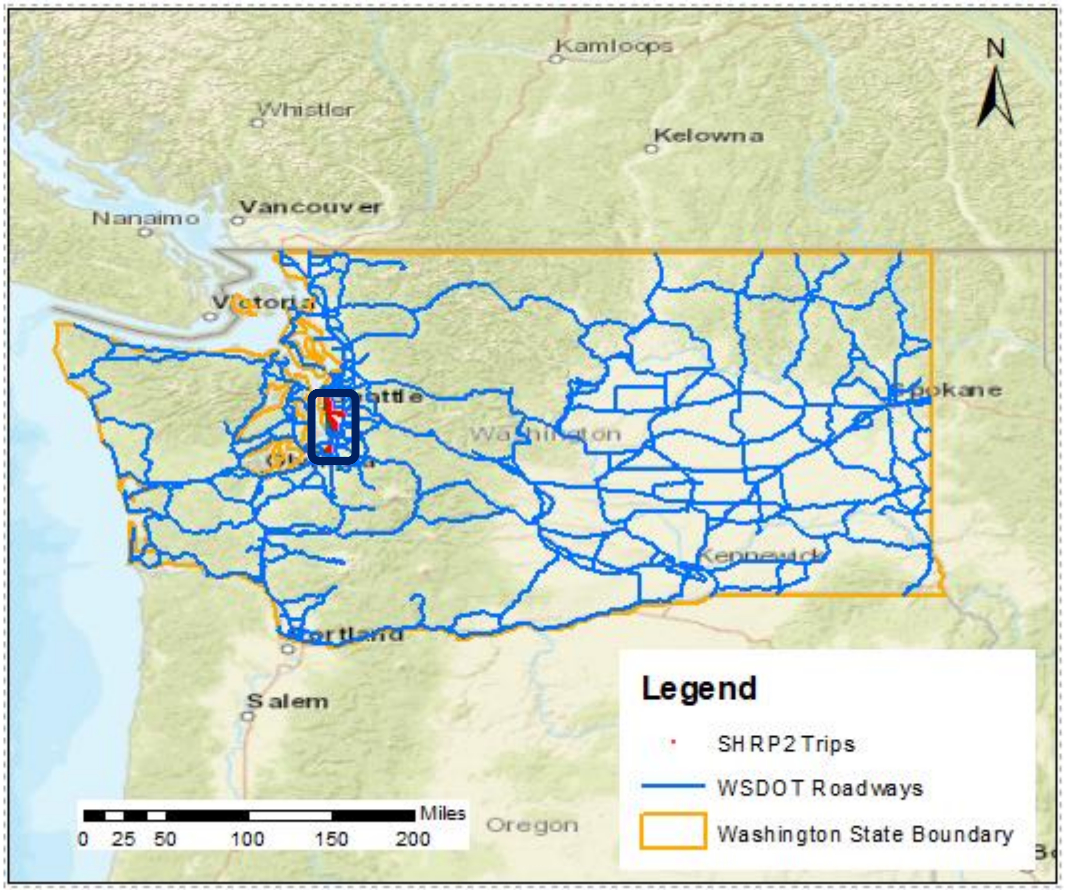


Figure 4.30: Washington State Map Showing SHRP2 Trip Location

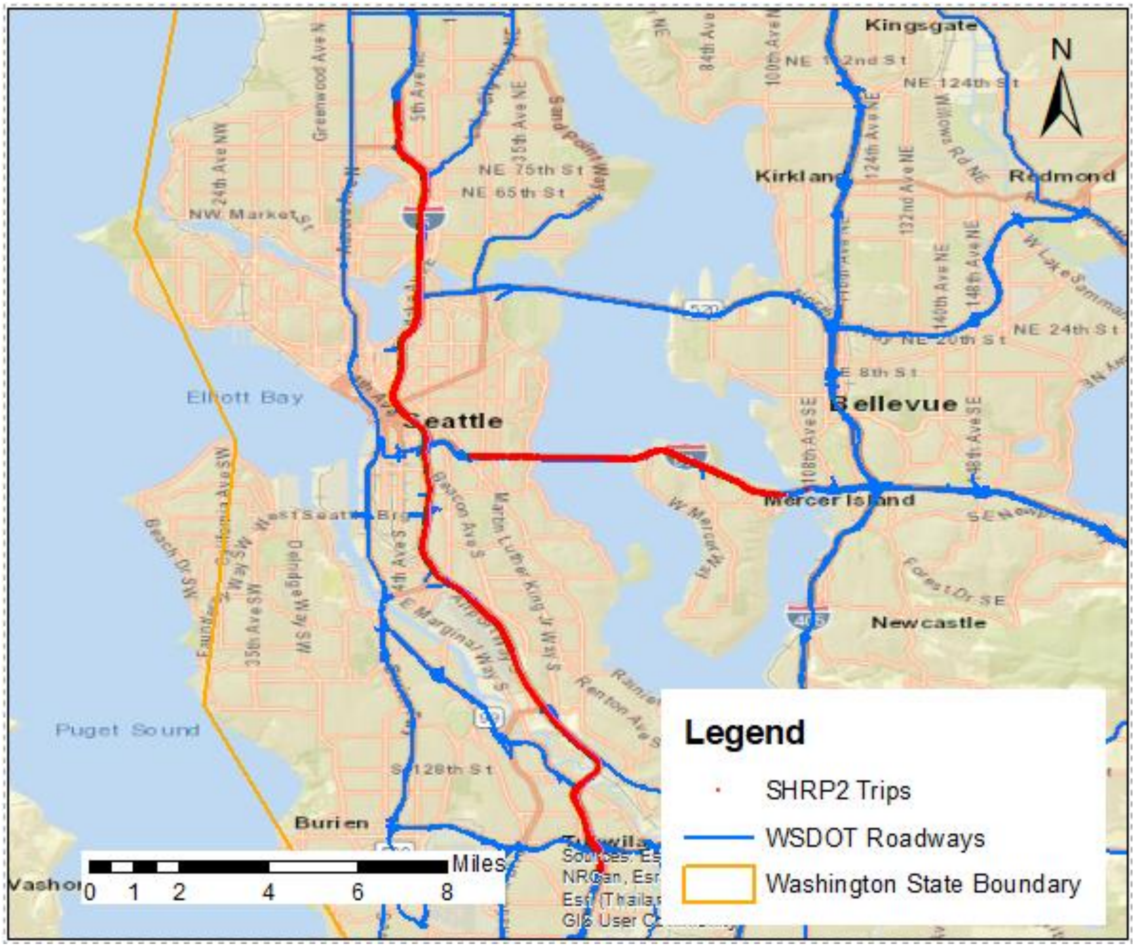


Figure 4.31: Close-up View of the Trip Locations on I-5 and I-90 Roadways

The next process was the data cleanup. The primary variable in this analysis was the lane deviation values, which were retrieved from the SHRP2 data using the variable "distance lane off center". In the data cleaning process, all trips with missing data and those with faulty lane deviation values were removed. The lane deviation values were considered faulty when the values exceeded ± 7 feet.

Additional data, such as roadway characteristics data, including AADT and speed limit, were also collected. AADT data were retrieved from the Washington State Department of Transportation (WSDOT) Geospatial shapefiles. Data on geometric characteristics were collected from the images from the SHRP2 data from the Virginia Tech Transportation Institute (VTTI), the Geographic Information System database, and Google Maps. The Google Earth Pro software imagery tool was used to verify the geometric characteristics of the study corridors. The SHRP2 data also contained information on demographic, driver, and vehicle characteristics. The variables considered include vehicle type, driver age group, vision acuity and peripheral vision, miles driven in the past year, etc.

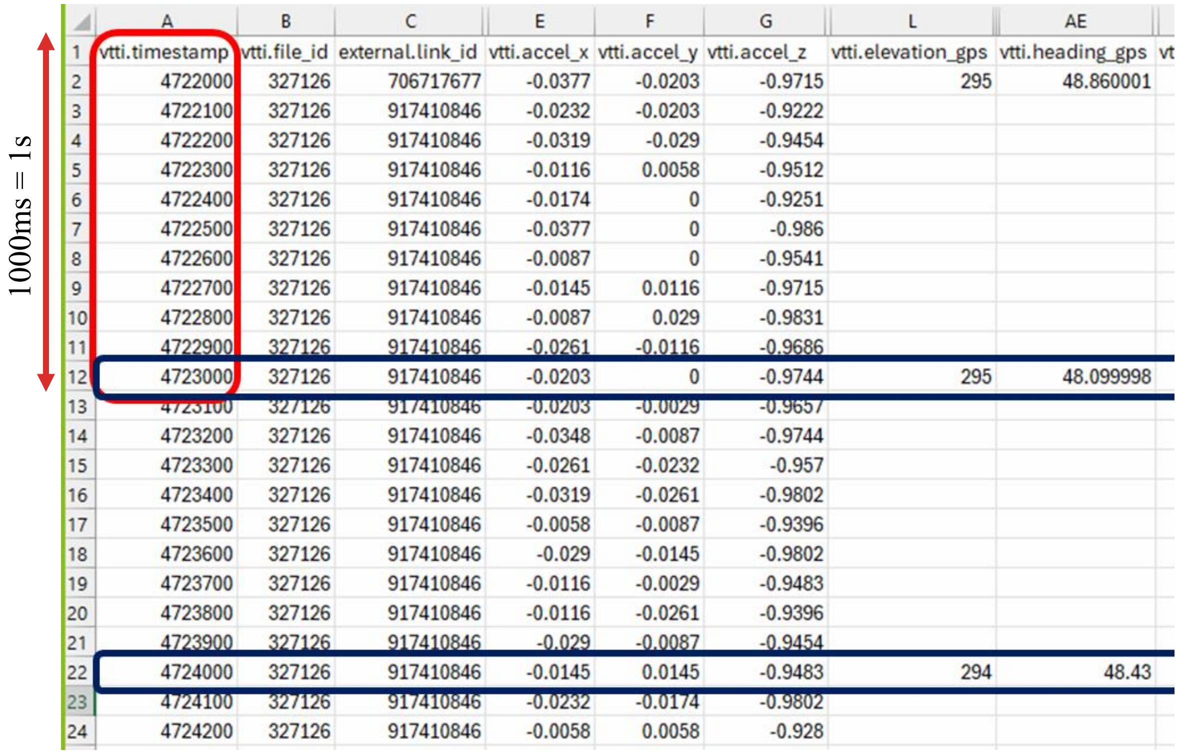
4.4.1.1 Descriptive Statistics

Lane deviation was the response variable for this study. As explained earlier, the lane deviation values were collected from SHRP2 data. The values are either positive or negative based on the location of the vehicle relative to the center of the lane. The data analysis was conducted separately for trips in which the vehicle was traveling in the ML closest to the separator and those traveling in the leftmost lane of the GPL. Therefore, the following two different research objectives were investigated:

- Effect of the ML separation types on the lane deviation values for vehicles traveling in the inside lane of the ML.
- Effect of the ML separation types on the lane deviation values for vehicles traveling in the inside lane of the GPL.

Inside Lane of the MLs

A total of 5,976 trips included a vehicle traveling in the inside lane of the ML, of which 261,359 data points were collected. Note that, for each trip, a data point corresponds to the time series data recorded every second (1s) of the vehicles' travel within the trip. Figure 4.32 presents an excerpt of the time series data.



	A	B	C	E	F	G	L	AE	
1	vtti.timestamp	vtti.file_id	external.link_id	vtti.accel_x	vtti.accel_y	vtti.accel_z	vtti.elevation_gps	vtti.heading_gps	vt
2	4722000	327126	706717677	-0.0377	-0.0203	-0.9715	295	48.860001	
3	4722100	327126	917410846	-0.0232	-0.0203	-0.9222			
4	4722200	327126	917410846	-0.0319	-0.029	-0.9454			
5	4722300	327126	917410846	-0.0116	0.0058	-0.9512			
6	4722400	327126	917410846	-0.0174	0	-0.9251			
7	4722500	327126	917410846	-0.0377	0	-0.986			
8	4722600	327126	917410846	-0.0087	0	-0.9541			
9	4722700	327126	917410846	-0.0145	0.0116	-0.9715			
10	4722800	327126	917410846	-0.0087	0.029	-0.9831			
11	4722900	327126	917410846	-0.0261	-0.0116	-0.9686			
12	4723000	327126	917410846	-0.0203	0	-0.9744	295	48.099998	
13	4723100	327126	917410846	-0.0203	-0.0029	-0.9657			
14	4723200	327126	917410846	-0.0348	-0.0087	-0.9744			
15	4723300	327126	917410846	-0.0261	-0.0232	-0.957			
16	4723400	327126	917410846	-0.0319	-0.0261	-0.9802			
17	4723500	327126	917410846	-0.0058	-0.0087	-0.9396			
18	4723600	327126	917410846	-0.029	-0.0145	-0.9802			
19	4723700	327126	917410846	-0.0116	-0.0029	-0.9483			
20	4723800	327126	917410846	-0.0116	-0.0261	-0.9396			
21	4723900	327126	917410846	-0.029	-0.0087	-0.9454			
22	4724000	327126	917410846	-0.0145	0.0145	-0.9483	294	48.43	
23	4724100	327126	917410846	-0.0232	-0.0174	-0.9802			
24	4724200	327126	917410846	-0.0058	0.0058	-0.928			

Figure 4.32: Excerpt from the Time Series Data

Table 4.11 presents a descriptive summary of the lane deviation values for the trips in which the vehicle was traveling in the inside lane of the ML. The total trips for single-lane and multi-lane MLs exceed that of all MLs combined because some trips span both types, drivers may travel through single-lane ML sections and then transition to multi-lane ML segments within the same trip or vice versa. In other words, a single trip ID may be associated with observations in both single-lane and multi-lane MLs. There were only three types of ML separation in the study areas: buffer, concrete barriers, and wide buffer separation.

Figures 4.33, 4.34, and 4.35 present the graphical representation of the mean and standard deviation for different separation types. Based on Figure 4.33, on average, the drivers in the ML tend to move away from the separator for all separation types, as observed by the negative values of the mean lane deviation. However, the magnitude varies across the separation types, with drivers on wide buffer-separated MLs tending to drive further away from the separator than with a concrete barrier or buffer separation. Similar results were observed for multi-lane facilities when analyzed separately. When considering only single-lane ML facilities, drivers on concrete barrier-separated lanes tended to drive further away from the separator than with buffer-separated or wide buffer separation types.

Table 4.11: Lane Deviation Mean and Standard Deviation for ML Vehicles (Inside Lane)

Facility Type	Separation Type	Trips	Observations	Lane Deviation	
				Mean (ft)	SD (ft)
All MLs	Buffer	3,362	120,542	-0.445	1.33
	Concrete barrier	502	99,482	-0.237	1.34
	Wide buffer	2,112	41,335	-0.532	1.46
	Total	**5,976**	**261,359**		
Single-lane MLs	Buffer	3,362	120,542	-0.445	1.33
	Concrete barrier	124	750	-0.627	1.32
	Wide buffer	1,343	22,188	-0.626	1.52
	Total	**4,829**	**143,480**		
Multi-lane MLs	Buffer	-	-	-	-
	Concrete barrier	396	98,732	-0.231	1.34
	Wide buffer	1,091	19,147	-0.417	1.38
	Total	**1,487**	**117,879**		

Note: SD = Standard Deviation; ML = Managed Lane.

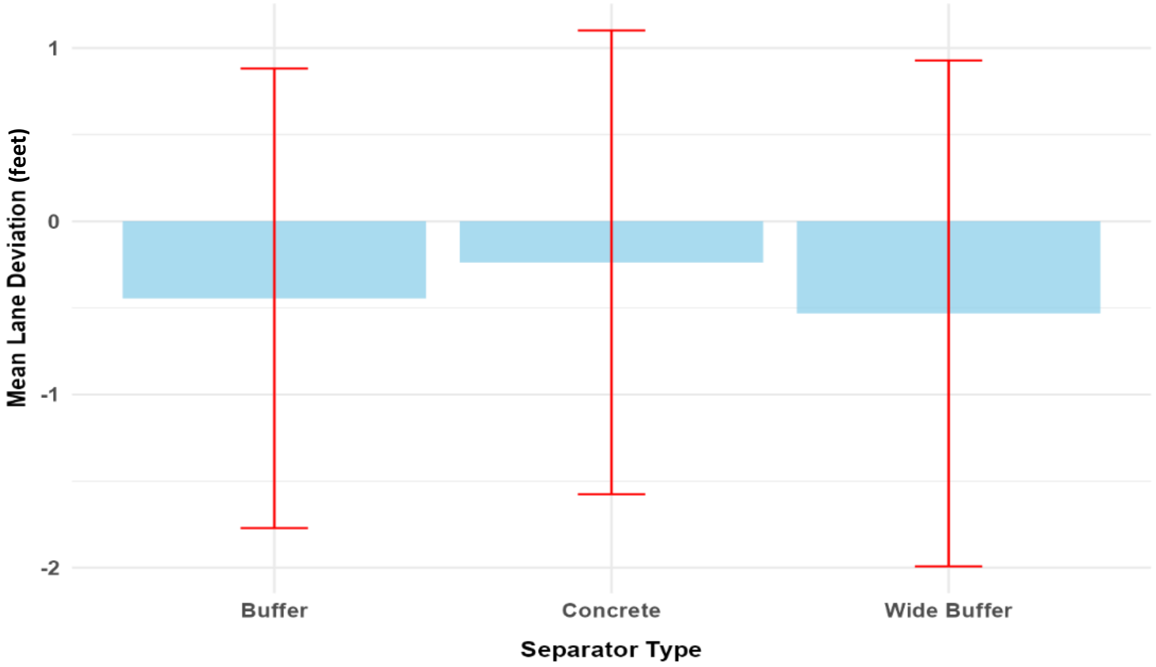


Figure 4.33: Mean Lane Deviation by Separation Type for All MLs

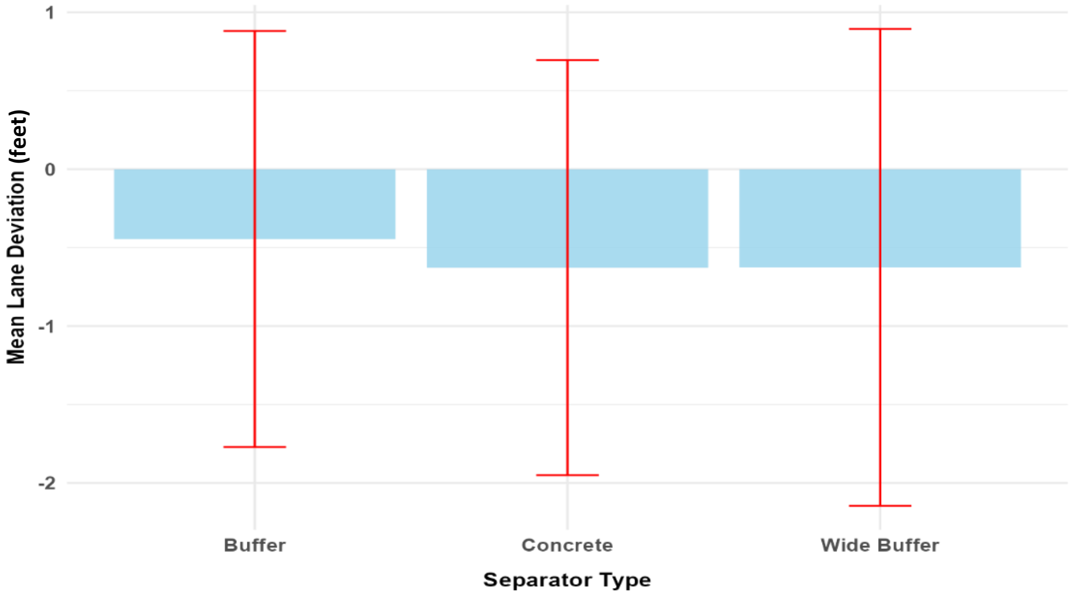


Figure 4.34: Mean Lane Deviation by Separation Type for Single-lane MLs

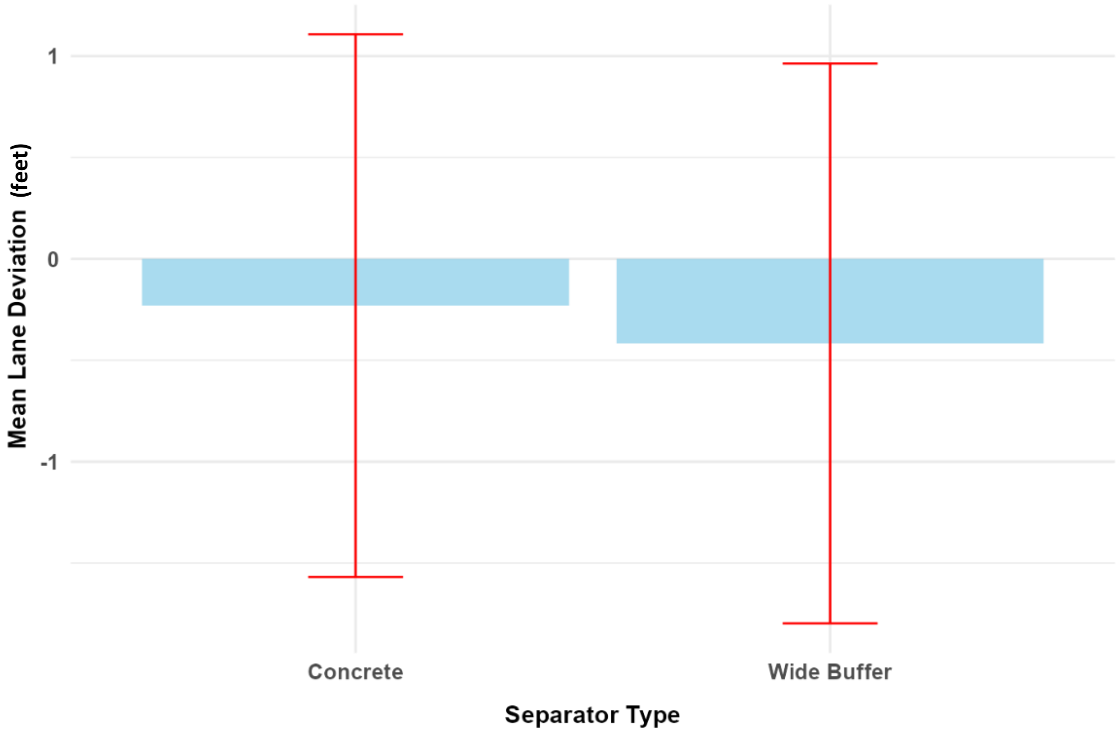


Figure 4.352: Mean Lane Deviation by Separation Type for Multi-lane MLs

Figures 4.36, 4.37, and 4.38 present boxplot diagrams for all MLs, single-lane MLs, and multi-lane MLs, respectively. These boxplots illustrate the distribution of lane deviation, highlighting key statistical metrics such as the median (represented by the central line) and the interquartile range (the box spanning the 25th to 75th percentiles). Additionally, the plots depict the extreme values of lane deviation, corresponding to data points outside the interquartile range beyond the 25th and 75th percentiles.

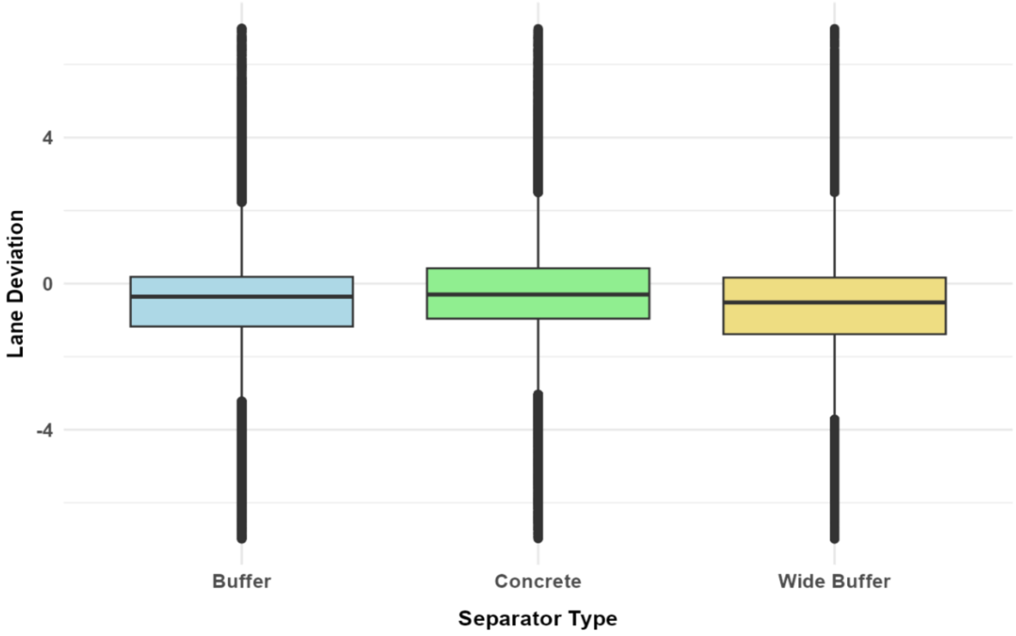


Figure 4.36: Boxplot Diagram for All MLs

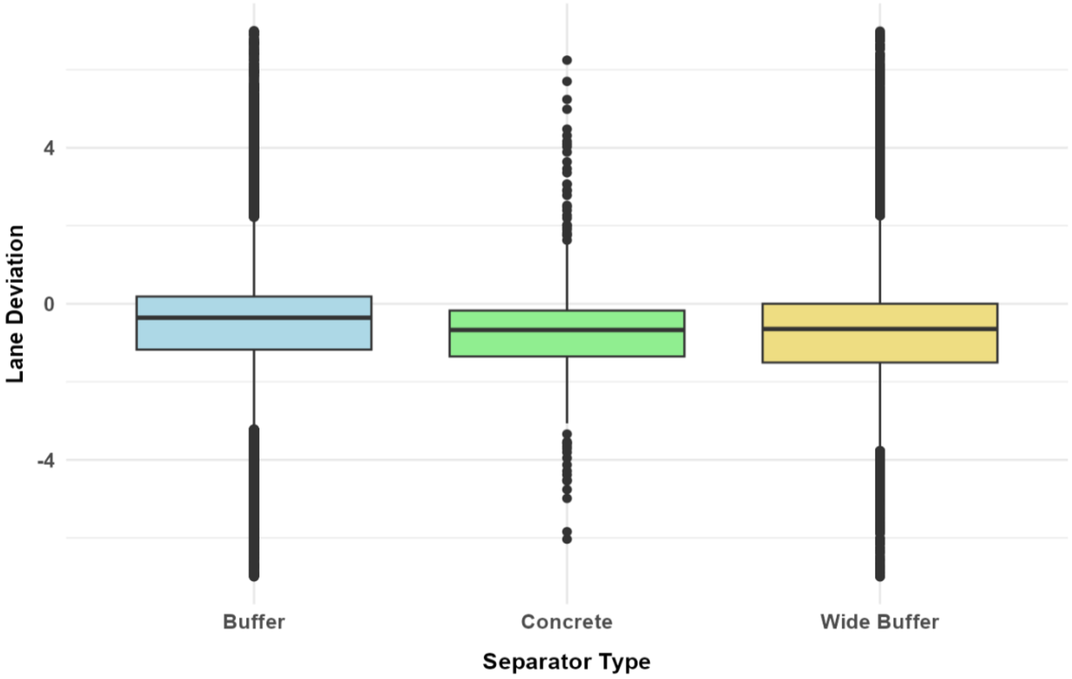


Figure 4.37: Boxplot Diagram for Single-Lane MLs

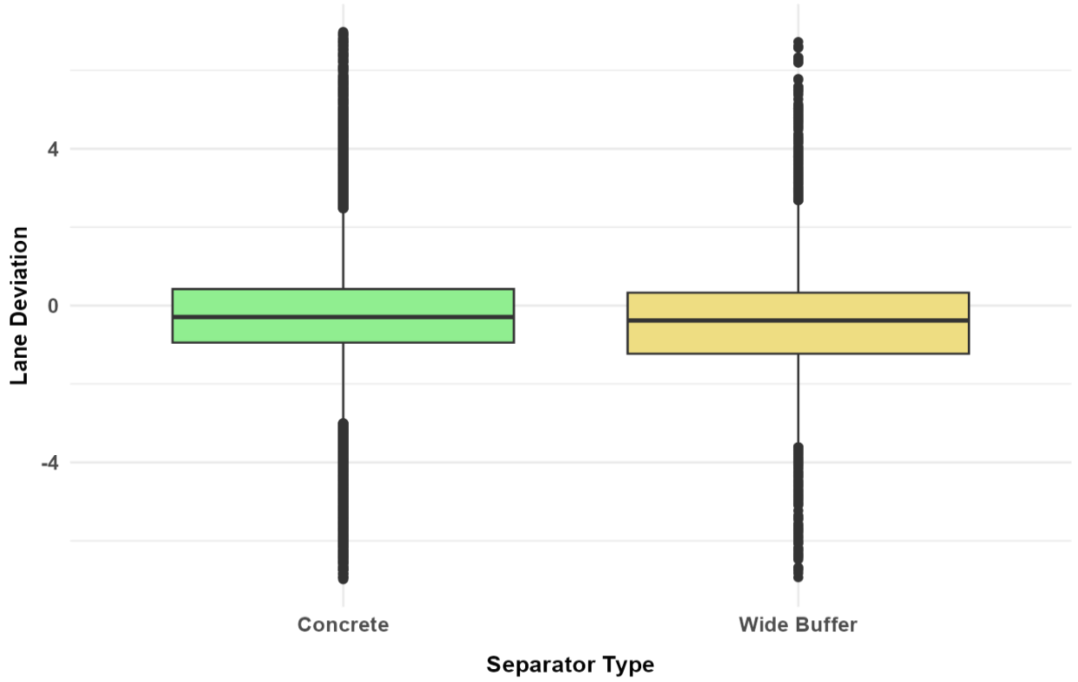


Figure 4.38: Boxplot Diagram for Multi-Lane MLs

Inside Lane of the GPLs

A total of 2,752 trips included a vehicle traveling in the inside lane of the GPLs, of which 149,173 data points were collected. Note that, for each trip, a data point corresponds to the time series data recorded every second (1s) of the vehicles' travel within the trip.

Table 4.12 presents a descriptive summary of the lane deviation values for the trips in which the vehicle was traveling in the inside lane of the GPLs. There were only three types of ML separation in the study areas: buffer, concrete barriers, and wide buffer separation.

Table 4.12: Lane Deviation Mean and Standard Deviation for GPL Vehicles (Inside Lane)

Facility Type	Separation Type	Trips	Observations	Lane Deviation	
				Mean (ft)	SD (ft)
All GPLs	Buffer	2,222	89,008	-0.631	1.11
	Concrete barrier	269	43,443	-0.644	1.55
	Wide buffer	261	16,722	-0.701	1.79
	Total	**2,752**	**149,173**		

Figure 4.39 presents the graphical representation of the mean and standard deviation for different separation types. Based on Figure 4.39, on average, the drivers traveling in the leftmost lane of the GPLs tended to drive closer the separator and away from adjacent GPLs, as observed by the negative values of the mean lane deviation. Note that a negative mean value indicates that the vehicle's centroid is left of the lane's center and closer to the separator for vehicles traveling in the inside lane of the GPLs. Buffer and concrete barrier separation have almost similar average

lane deviations. The other observation is that drivers on facilities with buffer separators showed the lowest variability in the mean lane deviation values than drivers on facilities with the other separation types.

Figure 4.40 presents the boxplot diagram for the lane deviation values for the vehicles traveling in the inside lane of the GPLs. The boxplot illustrates the distribution of lane deviation, highlighting key statistical metrics such as the median (represented by the central line) and the interquartile range (the box spanning the 25th to 75th percentiles). Additionally, the plot also depicts the extreme values of lane deviation, corresponding to data points outside the interquartile range, beyond the 25th and 75th percentiles.

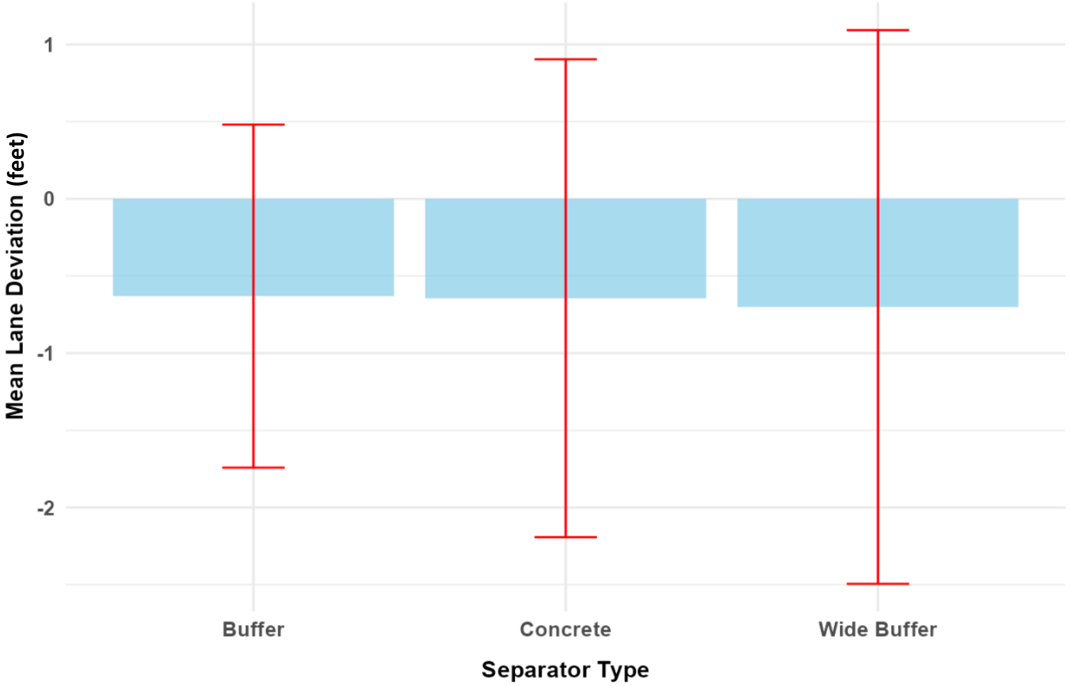


Figure 4.39: Mean Lane Deviation by Separation Type for GPLs

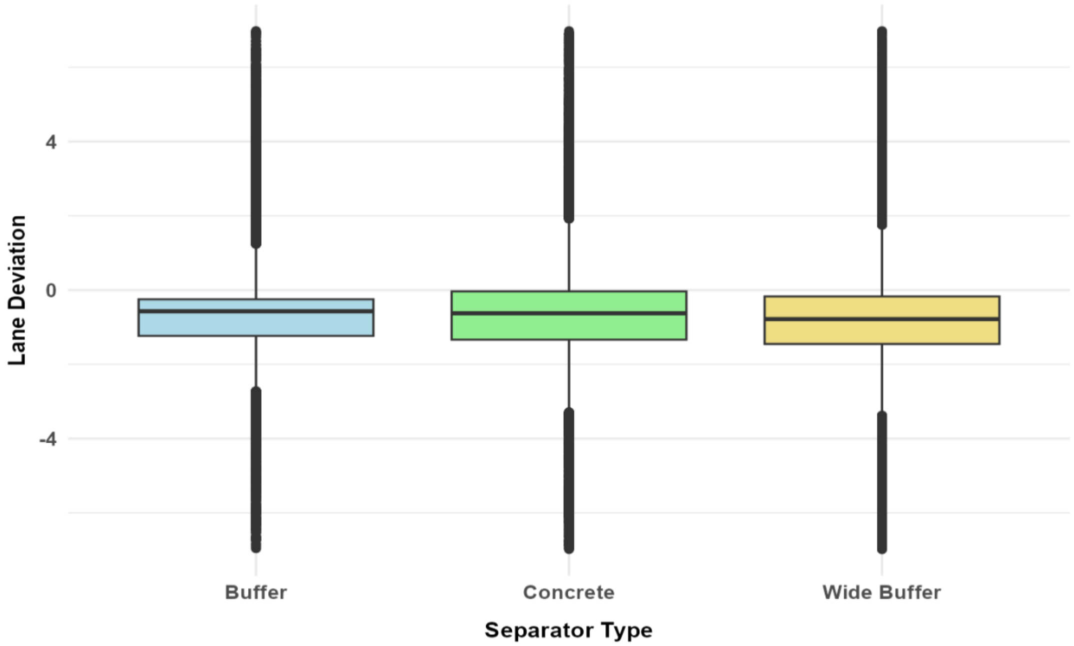


Figure 4.40: Boxplot Diagram for GPLs

4.4.1.2 Descriptive Statistics of Additional Variables

This section discusses the descriptive statistics of additional variables considered in the analysis of the inside lane of the MLs and GPLs, including vehicle, roadway, and driver characteristics. Vehicle characteristics consisted of vehicle type, such as passenger car and SUV, while driver characteristics included gender, age group, ethnicity, vision acuity, and miles driven within the last year. Roadway characteristics included not only the separation type, but also the number of MLs and GPLs in the study corridors.

Inside Lane of the MLs

Table 4.13 presents the descriptive statistics of vehicle, roadway, and driver characteristics variables analyzed for the inside lane of the MLs. As shown in Table 4.13, the response variable, lane deviation, was categorized into three groups: between -0.5 and 0.5 ft (35.9%), greater than 0.5 ft (20.0%), and less than -0.5 ft (44.1%). Additionally, over 38% of the data corresponded to ML facilities with concrete barriers, while facilities with wide buffer and buffer separation types accounted for 15.8% and 46.1%, respectively.

Most of trips were conducted by passenger cars (61.5%), compared to SUVs, which accounted for 38.4% of all data points. Single-lane ML facilities were observed in 54.9% of the data points, while facilities with 2+ MLs accounted for the remaining 45.1%. For GPLs, about 40.0% of facilities had three lanes, while 60.1% had four or more lanes.

Regarding driver-related characteristics, 65.9% of trips were made by males, while females accounted for 34.4% of the trips. Most drivers were aged between 20–39 years (41.4%) and between 40–65 years (42.3%), with a smaller percentage of the trips taken by teenage drivers

(5.7%) and drivers over 65 years (10.6%). Drivers identified as Hispanic/Latino represented 12.8%, while 87.2% were non-Hispanic/Latino.

Table 4.13: Descriptive Statistics of Additional Variables for All MLs

Variables	Levels	Count	Percentage
Response Variable			
Lane Deviation	(-0.5 ft to 0.5 ft)	93758	35.9%
	Greater than 0.5 ft	52177	20.0%
	Less than -0.5 ft	115424	44.1%
Vehicle Characteristics			
Vehicle Class/Type	Passenger Car	160679	61.5%
	SUV	100420	38.4%
Roadway Characteristics			
Separation Type	Buffer	120542	46.1%
	Concrete Barrier	99482	38.1%
	Wide Buffer	41335	15.8%
Number of Lanes - ML	1	143480	54.9%
	2+	117879	45.1%
Number of Lanes - GPL	3	104439	39.9%
	4+	156920	60.1%
Driver Characteristics			
Gender	Male	172365	65.9%
	Female	88994	34.1%
Age Group	<20 years	14866	5.7%
	20-39 years	108255	41.4%
	40-65 years	110507	42.3%
	65+ years	27731	10.6%
Ethnicity	Hispanic/Latino	33377	12.8%
	Not Hispanic/Latino	227982	87.2%
Vision Acuity - Far	Exactly 20/40	10105	3.9%
	Greater than 20/40	1025	0.4%
	Less than 20/40	250229	95.7%
Vision Acuity - Near	Exactly 20/40	9315	3.6%
	Greater than 20/40	8811	3.4%
	Less than 20/40	243233	93.0%
Miles Driven Last Year	Between 6000 – 10000	83696	32.0%
	Less than 6000	24880	9.5%
	Greater than 10000	152783	58.5%

Note: ML = Managed Lane; GPL = General Purpose Lane.

Vision acuity data revealed that 95.7% of drivers had far vision acuity of better than 20/40, while 0.4% had worse than 20/40. Similarly, for near vision acuity, 93.0% of drivers had better than 20/40, and 3.6% had worse than 20/40. Based on the total miles driven last year, about 59% of trips were made by drivers who drove more than 10,000 miles, while about 10% of trips were made by drivers who drove less than 6,000 miles in total.

Inside Lane of the GPLs

Table 4.14 presents the descriptive statistics of vehicle, roadway, and driver characteristics variables analyzed for the inside lane of the GPLs. As shown in Table 4.14, lane deviation was categorized into three groups: between -0.5 and 0.5 ft (35.7%), greater than 0.5 ft (10.5%), and less than -0.5 ft (53.8%). Additionally, over 29% of the data corresponded to facilities with a concrete barrier as a separation type, while facilities with wide buffer and buffer separation types accounted for 11.2% and 59.7%, respectively.

Most trips were conducted by passenger cars (70.0%), compared to SUVs, which accounted for 29.9% of all data points. Single-lane ML facilities were observed in 60.6% of the data points, while facilities with 2+ MLs accounted for 39.4%. For general-purpose lanes (GPLs), over 20.7% of facilities had three lanes, while 79.3% had four or more lanes.

Regarding driver-related characteristics, 53.9% of trips were made by males, while females accounted for 46.1% of the trips. Most drivers were aged between 20–39 years (53.0%) and between 40–65 years (23.8%), with a lesser percentage of the trips taken by teenage drivers (10.7%) and drivers over 65 years (12.5%). Drivers identified as Hispanic/Latino represented 13.0%, while 87.0% were non-Hispanic/Latino.

Vision acuity data revealed that 95.9% of drivers had far vision acuity of better than 20/40, while only 0.1% had visual acuity worse than 20/40. Similarly, for near vision acuity, 97.3% of drivers had less than 20/40, and 2.1% had greater than 20/40. Based on the total miles driven last year, over 50% of trips were made by drivers who drove more than 10,000 miles, while about 11.8% of trips were made by drivers who drove less than 6,000 miles in total.

Table 4.14: Descriptive Statistics of Additional Variables for the GPLs

Variable	Levels	Count	Percentage
Response Variable			
Lane Deviation	(-0.5 ft to 0.5 ft)	53197	35.7%
	Greater than 0.5 ft	15639	10.5%
	Less than -0.5 ft	80337	53.8%
Vehicle Characteristics			
Vehicle Class/Type	Passenger Car	104313	70.0%
	SUV	44723	29.9%
Roadway Characteristics			
Separation Type	Buffer	89008	59.7%
	Concrete Barrier	43443	29.1%
	Wide Buffer	16722	11.2%
Number of Lanes - ML	1	90309	60.6%
	2+	58864	39.4%
Number of Lanes - GPL	3	30880	20.7%
	4+	118293	79.3%
Driver Characteristics			
Gender	Male	80275	53.9%
	Female	68898	46.1%
Age Group	<20 years	15939	10.7%
	20-39 years	78940	53.0%
	40-65 years	35475	23.8%
	65+ years	18819	12.5%
Ethnicity	Hispanic/Latino	19341	13.0%
	Not Hispanic/Latino	129832	87.0%
Vision Acuity - Far	Exactly 20/40	5883	4.0%
	Greater than 20/40	96	0.1%
	Less than 20/40	143194	95.9%
Vision Acuity - Near	Exactly 20/40	902	0.6%
	Greater than 20/40	3018	2.1%
	Less than 20/40	145253	97.3%
Miles Driven Last Year	Between 6000 – 10000	45879	30.8%
	Less than 6000	17660	11.8%
	Greater than 10000	85634	57.4%

Note: ML = Managed Lane; GPL = General Purpose Lane.

4.4.2 Methodology

4.4.2.1 ANOVA Analysis

In this analysis, a comparative cross-sectional study design was employed to examine the differences in mean lane deviation values between ML sites with different separation types. ANOVA was used to assess whether the separation type significantly influenced the vehicle's lateral position. Refer to Section 4.3.2.1 for a detailed explanation on the principles and equations of the ANOVA analysis.

4.4.2.2 Hypothesis Testing

The null hypothesis (H_0) states that there are no differences in the population means of lane deviation values across different separation types (see Equation 4.17). The alternative hypothesis states that at least two of the population means of lane deviation values are different.

$$\mu 1 = \mu 2 = \mu 3 \tag{4.17}$$

where,

$\mu 1$ = Mean lane deviation for separation type 1 (MLs with buffer separation),
$\mu 2$ = Mean lane deviation for separation type 2 (MLs with wide buffer separation), and
$\mu 3$ = Mean lane deviation for separation type 3 (MLs with concrete barrier separation).

The ANOVA test was conducted at a 95% confidence level to determine whether to reject or fail to reject the null hypothesis. If the null hypothesis was rejected, a post hoc analysis would follow, as the results would indicate that the type of separator influences the vehicle's lateral position. However, if the null hypothesis was not rejected, the analysis would conclude, suggesting that there are no significant differences in the mean lane deviation values for the different separator types.

4.4.2.3 Post-Hoc Analysis

Post-hoc analysis refers to statistical analyses that are conducted after an initial analysis has been completed, aiming to find patterns, trends, or differences within the data that were not specified in the earlier study. In this study, in case the null hypothesis was rejected, a Tukey range test was adopted as the post hoc analysis test. This test compared all the possible pairs of means. It applied simultaneously to the set of all pairwise comparisons and identified any difference between two means that was greater than the expected standard error, which in this case was 5%. Refer to Section 4.3.2.3 for a detailed explanation on the principles and equations of the Tukey test.

4.4.2.4 Statistical Modeling

A mixed-effect multinomial model with a Bayesian inference approach was applied to assess the influence of managed lane separation type on lane deviation. The “brm” function under the “brms” package of R programming was used to perform the mixed effect multinomial logistic regression (Bürkner, 2017).

Let y_{ij} be the value of the categorical response variable associated with level-2 unit i and level-1 unit j. In this study, three categories of the response variable "lane deviation" were coded as 0 (no deviation), 1 (positive deviation), and 2 (negative deviation). Adding random effects to the multinomial logistic regression model (Hedeker, 2003), the probability that $y_{ij} = d$ (in this study, the response occurs in category $d = 3$) for a given level- 2 unit i, conditional on γ, is given by Equation 4.18 (He et al., 2021).

$$P_{ijd} = P\left(y_{ij} = d \mid \gamma\right) = \frac{\exp\left(z_{ijd}\right)}{1 + \sum_{h=1}^{K} \exp\left(z_{ijh}\right)} \text{ for } d = 0,1,2$$
$$P_{ij1} = P\left(y_{ij} = 1 \mid \gamma\right) = \frac{1}{1 + \sum_{h=1}^{d} \exp\left(z_{ijh}\right)} \quad (4.18)$$

where $Y_{ijd} = X'_{ij}\alpha_d + V'_{ij}\gamma_{id}$. Here, X_{ij} is the $p \times 1$ explanatory variable vector, and V_{ij} is the design vector for the u random effects. In this study, Participant ID was used as a random parameter.

It is convenient to standardize the random effects by letting $\gamma_{id} = J_d\delta_i$, where $J_dJ'_d = \Sigma_d$ is the Cholesky decomposition of Σ_d. Equation 4.19 presents the model formula (Hartzel et al., 2001).

$$Y_{ijd} = X'_{ij}\alpha_d + V'_{ij}J_d\delta_i \quad (4.19)$$

This formulation clearly generalizes Bock's model for educational test data by incorporating explanatory variables X_{ij} (Darrell Bock, 1972). Then, the probability of any y_i, conditional on the random effects δ and given α_d, μ_d, and J_d, is equal to the product of the probabilities of the level-1 responses as presented by Equation 4.20 (Gerber & Craig, 2021).

$$\ell(y_i \mid \delta; \alpha_d, \mu_d, J_d) = \prod_{j=1}^{n_i} \prod_{d=0}^{3} \left[P\left(y_{ij} = d \mid \delta; \alpha_d, \mu_d, J_d\right)\right]^{a_{ijd}} \quad (4.20)$$

where $a_{ijd} = 1$ if $y_{ij} = d$, and 0 otherwise. The marginal density of the response vector y_i in the population is expressed by Equation 4.21.

$$h(y_i) = \int_{\theta} \ell(y_i \mid \delta; \alpha_d, \mu_d, J_d) g(\delta) d\delta \quad (4.21)$$

where $g(\delta)$ represents the population distribution of the random effects. For parameter estimation, the marginal log-likelihood from the N level-2 units can be written as $\log\ L = \sum_{i}^{N} \log\ h(y_i)$. Then, using η_d to represent an arbitrary parameter vector (see Equation 4.22) (Hedeker & Mermelstein, 1998).

$$\frac{\partial \log\ L}{\partial \eta_d} = \sum_{i=1}^{N} h^{-1}(y_i) \int_{\delta} \left[\sum_{j=1}^{n_i} \left(a_{ijd} - H_{ijd}\right) \frac{\partial z_{ijd}}{\partial \eta_d} \right] \ell(y_i \mid \delta; \alpha_d, \mu_d, J_d) g(\delta) d\delta \tag{4.22}$$

4.4.3 Results

This section presents the results of the ANOVA analysis, Tukey test of significance, and the statistical modeling for the lane deviation study.

4.4.3.1 Significance Test Results

ANOVA was conducted to check whether there is a significant difference in the mean lane deviation values by separation type in different managed lane facilities. Tukey test of significance was conducted as a post hoc analysis to determine which separation types differ, if any.

Significance Test Results for All MLs

Table 4.15 presents the ANOVA results for the MLs. Table 4.16 presents the results of the Tukey test of significance at 95% confidence level for all ML facilities. The conclusion from the ANOVA analysis was that there was a significant difference in the mean lane deviation values between at least two separation types at a 95% CI. Since the null hypothesis was rejected, a post hoc analysis was required to analyze each pair separately to identify whether there was a significant difference between the pairs. Results from the Tukey test of significance revealed that there was a statistically significant difference in mean lane deviation values between ML facilities with different separation types.

Table 4.15: ANOVA Results for Lane Deviation in All MLs

Factor	Df	Sum Sq	Mean Sq	F-value	p-value
Separation Type	2	3480	1740.00	950.60	<0.001
Residuals	261356	478411	1.80		

Note: Df = degree of freedom; Sum Sq = sum of the squares; Mean Sq = mean square value.

Table 4.16: Tukey Test of Significance Results for All MLs

Separation Type	Difference	p-value
Concrete barrier - Buffer	0.208	<0.001*
Wide buffer - Buffer	-0.087	<0.001*
Wide buffer – Concrete barrier	-0.294	<0.001*

Note: * = Values are significant at a 95% CI.

Significance Test Results for GPLs

Table 4.17 presents the ANOVA results for the GPLs. Table 4.18 presents the results of the Tukey test of significance at a 95% confidence level for GPLs. The conclusion from the ANOVA analysis was that there was a significant difference in the mean lane deviation between at least two separation types at a 95% CI. Since the null hypothesis was rejected, a post hoc analysis was required to analyze each pair separately to identify whether there was a significant difference between the pairs. Results from the Tukey test of significance revealed that there was a statistically significant difference in mean lane deviation values between facilities with wide buffer and concrete barrier separation types, as well as between facilities with wide buffer and buffer separation types.

Table 4.17: ANOVA Results for Lane Deviation in GPLs

Factor	Df	Sum Sq	Mean Sq	F-value	p-value
Separation Type	2	70	34.96	19.48	<0.001
Residuals	149170	267692	1.79		

Note: Df = degree of freedom; Sum Sq = sum of the squares; Mean Sq = mean square value.

Table 4.18: Tukey Test of Significance Results for GPLs

Separation Type	Difference	p-value
Concrete barrier - Buffer	-0.014	0.190
Wide buffer - Buffer	-0.070	<0.001*
Wide buffer – Concrete barrier	-0.057	<0.001*

Note: * = Values are significant at a 95% CI.

4.4.3.2 Mixed Multinomial Logit (MMNL) Results

The mixed multinomial logit (MMNL) model was used to explore the influence of separation type on the lane deviation values. Table 4.19 presents the results of the mixed multinomial logit model for all MLs. Table 4.20 presents the results of the mixed multinomial model for all GPLs.

Based on the results from Table 4.19, the following factors were associated with an increase in the likelihood of a vehicle driving away from the separator when traveling in the ML.

Both concrete barrier and wide buffer separation types were associated with an increase in the mean lane deviation away from the separator when compared buffer separation type. Older drivers (>65 years) were associated with an increase in the mean lane deviation away from the separator when compared to drivers aged between 20 and 40 years. A similar observation was reported for male drivers, who were associated with an increased likelihood to drive farther away from the separator compared to female drivers.

Results from Table 4.19 also show that drivers with visual acuity worse than 20/40 were associated with increased likelihood of driving farther away from the separator when compared to drivers with visual acuity of 20/40. Lastly, drivers who drove less than 6,000 miles in the previous year were associated with an increased likelihood of driving farther away from the separator when compared to drivers who drove between 6,000 and 10,000 miles. These factors increase the risks for sideswipe crashes as the vehicles would be encroaching the adjacent managed lanes for multi-lane ML facilities.

On the contrary, several factors were associated with an increase in the likelihood of a vehicle driving towards the separator when traveling in the ML. First, teenage drivers (<20 years) were found to be likely to drive closer to the separator compared to drivers aged between 20 and 40 years. Drivers who drove more than 10,000 miles in the previous year were associated with an increased likelihood of driving towards the separator when compared to drivers who drove between 6,000 and 10,000 miles. Interestingly, vehicles classified as SUVs were found to be likely driven closer to the separator compared to passenger cars.

According to Table 4.20 the following factors were associated with an increase in the likelihood of a vehicle driving away from the separator when traveling in the GPL.

The wide buffer separation type was associated with an increase in the mean lane deviation away from the separator when compared to the buffer separation type. Both teenage drivers (<20 years) and older drivers (>65 years) were associated with an increase in the mean lane deviation away from the separator when compared to drivers aged between 20 and 40 years. drivers who drove less than 6,000 miles in the previous year were associated with an increased likelihood of driving farther away from the separator when compared to drivers who drove between 6,000 and 10,000 miles. Lastly, drivers with visual acuity worse than 20/40 were associated with an increased likelihood of driving farther away from the separator when compared to drivers with visual acuity of 20/40. These factors increase the risks of sideswipe crashes as the vehicles would be encroaching the adjacent GP lanes.

On the contrary, the following factors were associated with an increase in the likelihood of a vehicle driving towards the separator when traveling in the GPL. Concrete barrier separation type was associated with a decrease in the mean lane deviation away from the separator when compared to the buffer separation type. Vehicles classified as SUVs were found to decrease the lane deviation away from the separator. Drivers who drove more than 10,000 miles in the previous year were associated with an increased likelihood of driving towards the separator when compared to drivers who drove between 6,000 and 10,000 miles. Finally, male drivers were associated with an increased likelihood to drive towards the separator compared to female drivers.

Table 4.19: Mixed Multinomial Logit (MMNL) Model Results for All MLs

Variables	Factor 1	Estimate	Std. Error	t-value	p-value	Factor 2	Estimate	Std. Error	t-value	p-value
(Intercept)		-0.260	0.027	-9.446	**<0.001**	(Intercept)	-0.482	0.025	-18.915	**<0.001**
Separation Type	Buffer*					Buffer*				
	Concrete Barrier	-0.186	0.037	-5.102	**<0.001**	Concrete Barrier	0.326	0.028	11.486	**<0.001**
	Wide Buffer	-0.027	0.026	-1.029	0.304	Wide Buffer	0.388	0.019	20.064	**<0.001**
Gender	Female*					Female*				
	Male	-0.103	0.015	-6.724	**<0.001**	Male	0.141	0.012	11.560	**<0.001**
Vehicle Type	Passenger Car*					Passenger Car*				
	SUV	-0.063	0.016	-3.856	**<0.001**	SUV	-0.055	0.013	-4.303	**<0.001**
Ethnicity	Non-Hispanic or Latino*					Non-Hispanic or Latino*				
	Hispanic or Latino	0.285	0.020	13.912	**<0.001**	Hispanic or Latino	0.353	0.016	21.514	**<0.001**
Age Group	20-40*					20-40*				
	<20	-0.926	0.036	-25.821	**<0.001**	<20	-0.509	0.024	-21.145	**<0.001**
	40-65	0.242	0.017	14.250	**<0.001**	40-65	0.250	0.014	18.054	**<0.001**
	65+	0.002	0.023	0.096	0.924	65+	0.042	0.018	2.276	**0.023**
License Age	16 +*					16 +*				
	16 or less	0.123	0.016	7.492	**<0.001**	16 or less	-0.069	0.013	-5.392	**<0.001**
Miles Last Year	(6000, 10000]*				**<0.001**	(6000, 10000]*				
	Less than 6000	0.103	0.026	3.982	**<0.001**	Less than 6000	0.465	0.020	23.526	**<0.001**
	Greater than 10000	-0.286	0.016	-18.076	**<0.001**	Greater than 10000	-0.212	0.013	-16.534	**<0.001**
Risk Taking Behavior - Secondary Tasks	Moderately Risk*				**<0.001**	Moderately Risk*				
	Less Risk	0.263	0.027	9.671	**<0.001**	Less Risk	0.157	0.021	7.380	**<0.001**
	More Risk	0.177	0.020	8.918	**<0.001**	More Risk	0.112	0.015	7.240	**<0.001**
Far Acuity in Both Eyes	20/40 Only*					20/40 Only*				
	Less Than 20/40	0.865	0.129	6.701	**<0.001**	Less Than 20/40	1.902	0.099	19.202	**<0.001**
	Greater than 20/40	0.014	0.037	0.377	0.706	Greater than 20/40	-0.049	0.030	-1.649	0.099
Near Acuity in Both Eyes	20/40 Only*					20/40 Only*				
	Less Than 20/40	0.375	0.051	7.310	**<0.001**	Less Than 20/40	1.463	0.050	29.454	**<0.001**
	Greater than 20/40	-0.077	0.035	-2.187	**0.029**	Greater than 20/40	1.152	0.038	30.275	**<0.001**
Number of Lanes - ML	1*					1*				
	2+	0.235	0.033	7.031	**<0.001**	2+	-0.470	0.026	-18.173	**<0.001**
Number of Lanes - GPL	3*					3*				
	4+	-0.229	0.013	-17.022	**<0.001**	4+	0.133	0.011	12.032	**<0.001**
Shoulder Width		-0.003	0.002	-1.793	0.073		-0.029	0.001	-21.237	**<0.001**

Note: * = Base condition; Values in bold are significant at a 95% CI; Factor 1 corresponds to driving away from the separator; Factor 2 corresponds to driving towards the separator.

Table 4.20: Mixed Multinomial Logit (MMNL) Model Results for GPLs

Variables	Factor 1	Estimate	Std. Error	t-value	p-value	Factor 2	Estimate	Std. Error	t-value	p-value
(Intercept)		-0.792	0.083	-9.593	**<0.001**	(Intercept)	-0.391	0.059	-6.567	**<0.001**
Separation Type	Buffer*					Buffer*				
	Concrete	-0.332	0.127	-2.624	**0.009**	Concrete	-0.153	0.070	-2.172	**0.030**
	Wide Buffer	0.033	0.129	0.252	0.801	Wide Buffer	0.110	0.073	1.513	0.130
Gender	Female*					Female*				
	Male	-0.276	0.023	-11.746	**<0.001**	Male	-0.030	0.015	-1.999	**0.046**
Vehicle Type	Passenger Car*					Passenger Car*				
	SUV	-0.020	0.029	-0.687	0.492	SUV	-0.233	0.018	-12.699	**<0.001**
Ethnicity	Non-Hispanic or Latino*					Non-Hispanic or Latino*				
	Hispanic or Latino	0.057	0.034	1.669	0.095	Hispanic or Latino	0.233	0.023	10.258	**<0.001**
Age Group	20-40*					20-40*				
	<20	0.138	0.045	3.096	**0.002**	<20	0.429	0.028	15.427	**<0.001**
	40-65	0.569	0.031	18.542	**<0.001**	40-65	0.578	0.020	29.472	**<0.001**
	65+	0.313	0.037	8.358	**<0.001**	65+	-0.060	0.024	-2.462	**0.014**
License Age	16 +*					16 +*				
	16 or less	0.122	0.025	4.964	**<0.001**	16 or less	-0.058	0.015	-3.892	**<0.001**
Miles Last Year	(6000, 10000]*					(6000, 10000]*				
	Less than 6000	0.365	0.039	9.311	**<0.001**	Less than 6000	0.352	0.026	13.660	**<0.001**
	Greater than 10000	-0.173	0.026	-6.584	**<0.001**	Greater than 10000	-0.133	0.016	-8.181	**<0.001**
Risk Taking Behavior - Secondary Tasks	Moderately Risk*					Moderately Risk*				
	Less Risk	0.800	0.043	18.410	**<0.001**	Less Risk	0.459	0.028	16.174	**<0.001**
	More Risk	0.234	0.032	7.285	**<0.001**	More Risk	0.301	0.020	15.336	**<0.001**
Far Acuity in Both Eyes	20/40 Only*					20/40 Only*				
	Less Than 20/40	-0.051	0.548	-0.093	0.926	Less Than 20/40	0.745	0.255	2.919	**0.004**
	Greater than 20/40	1.242	0.075	16.672	**<0.001**	Greater than 20/40	2.041	0.047	43.128	**<0.001**
Near Acuity in Both Eyes	20/40 Only*					20/40 Only*				
	Less Than 20/40	-0.516	0.152	-3.396	**0.001**	Less Than 20/40	-0.292	0.112	-2.611	**0.009**
	Greater than 20/40	-0.857	0.137	-6.268	**<0.001**	Greater than 20/40	-0.806	0.102	-7.868	**<0.001**
Number of Lanes - ML	1*					1*				
	2+	0.693	0.125	5.534	**<0.001**	2+	-0.165	0.069	-2.375	**0.018**
Number of Lanes - GPL	3*					3*				
	4+	-0.525	0.026	-20.241	**<0.001**	4+	-0.001	0.018	-0.074	0.941
Shoulder Width		-0.012	0.003	-3.524	**<0.001**		-0.027	0.002	-12.297	**<0.001**

Note: * = Base condition; Values in bold are significant at a 95% CI; Factor 1 corresponds to driving towards the separator; Factor 2 corresponds to driving away from the separator.

4.4.4 Summary

Lane deviation is defined as an offset between the position of the vehicle centroid and the centerline of the lane. This section presents the summary findings of the study on the impacts of the ML separation type on the lane deviation for vehicles traveling in the lanes adjacent to the separation type.

The lane deviation analysis revealed the following key findings:

- Data utilized in the analysis were collected from the SHRP2 program in Washington State.
- Three separation types were considered in this analysis: buffer, concrete barriers, and wide buffer.
- On average, the drivers in the ML lane adjacent to the separator tend to drive away from the separator for all separation types. However, the magnitude varies across the separation types, with drivers on buffer-separated ML facilities tending to drive farther away from the separator compared to those on ML facilities with concrete barrier or wide buffer separation types.
- When considering only single-lane ML facilities, drivers on wide buffer separated ML facilities tend to drive further away from the separator compared to those on ML facilities with buffer or concrete barrier separation types.
- On average, the drivers traveling in the left-most lane of the GPL tend to drive towards the separator and away from adjacent GP lanes, as observed by the negative values of the mean lane deviation.
- Vehicles on facilities with buffer separation showed the lowest variability in the mean lane deviation values compared to vehicles traveling on the other separation types.
- Results from the ANOVA analysis concluded that there is a statistically significant difference in the mean lane deviation values on at least two separation types.
- A Tukey test of significance confirmed that for vehicles traveling in the managed lane adjacent to the separator, the mean lane deviation values were different for all separation types at a 95% CI. However, for vehicles traveling in the inside lane of the GPLs, there were no significant differences in the mean lane deviation values when compared to the wide buffer and concrete barrier separation types.
- The following factors were associated with an increase in the likelihood of a vehicle driving away from the separator when traveling in the ML.
    - Separation type
    - Visual acuity
    - Gender

  - Age of driver
  - Total miles driven the previous year

- The following factors were associated with an increase in the likelihood of a vehicle driving away from the separator when traveling in the GPL.

  - Separation type
  - Visual acuity
  - Age of driver
  - Total miles driven the previous year

CHAPTER 5
CONCLUSIONS

The objective of this research was to understand driver behavior on managed lane facilities, specifically pertaining to the type of separation between the MLs and the GPLs, using a human factors study approach. Questions related to driving behavior cannot be answered using traditional crash data analyses and, therefore, require a human factors approach. This research employed two types of human factors analyses, one using the naturalistic driving data and the other using the driving simulator with eye-tracking equipment. The general focus of the two studies was to understand how different separation types affect driver behavior on managed lane facilities. While the naturalistic driving study considered drivers of all ages combined, the driving simulation study considered drivers across different age groups, namely young (18–34), middle-aged (35–64), and older (65+) drivers.

A comprehensive literature review was conducted on managed lane separation types, including existing guidelines specific to separation treatments. The focus was on three separation types: pylons, buffer, and concrete barrier. Available literature on human factors and driver behavior related to the three separation types was also reviewed. While previous studies have established that human factors and driver behavior represent an integral component and potential profound influence on various aspects of transportation and road safety, gaps in research, with respect to driver behavior and managed lane separation types, remain. Studies and information on driving simulation were also reviewed.

Driving Simulator Study

The purpose of the driving simulator study was to understand how different age groups of drivers; younger (18-34), middle-aged (35-64), and older (65+) behave in managed lane facilities with various combinations of delineator (pylon) heights and separation pavement markings in a controlled setting using a driving simulator and eye tracking device. The experiment was conducted at the Intelligent Transport Systems lab at the University of Central Florida (UCF) using a compact version (miniSim^{TM}) of the National Advanced Driving Simulator (NADS) developed by the Driving Safety Research Institute (DSRI) at the University of Iowa.

The simulation model consisted of a 6-mile roadway with a 1.5-mile section with 4 GPLs + ML and 1.5-mile section with 3 GPLs + 2 MLs. Both sections contained straight and curved segments. Separation width (pavement marking type) was examined in both straight and curved sections, while separation height (pylon height) was evaluated only in curved sections. Delineator heights consisted of 36” pylons in straight segments and 24-inch or 28-inch pylons in curved segments. Data from 60 participants were included in the analysis.

Key findings from the driver simulator study include:

- Separations with double solid lines resulted in higher deceleration rates at ML entry segments.
- Separation height had no significant fixed effect on the deceleration rate.

- 67.5% of participants reported that 28-inch pylons were more noticeable in the curved segments.
- Double solid lines were linked to higher mean speeds, especially when combined with 28-inch pylons in the curved segments.
- Lane deviation away (i.e., shifting left) from the separators was greater with double solid lines with 24-inch pylons.
- 51% of participants reported that double solid lines were more noticeable.
- Double solid lines with 28-inch pylons resulted in shorter fixation durations.
- Among the age groups, middle aged drivers (35-64) were the most who noticed the changes in the separation width and height.
- Younger drivers had lower TTFN and longer fixation durations overall.
- Younger drivers (ages 18–34) showed lower deceleration when entering MLs and maintained higher mean speeds across straight and curved segments.
- Among younger drivers, females exhibited greater lane deviation.
- Regardless of age, female drivers had longer fixation on the separation treatment compared to males.
- Mean speed on MLs were higher at night than during the day; however, lane deviation away from the separators was greater in daytime conditions.

Naturalistic Driving Study

The purpose of the naturalistic driving study was to examine how drivers behave in the real world on ML facilities with different separation treatments. This study utilized naturalistic driving data from ML facilities in Florida and Washington State using data collected from the Regional Integrated Transportation Information System (RITIS) and the Second Strategic Highway Research Program (SHRP2), respectively. Performance measures analyzed included lane utilization, travel speed, and lane deviation.

Lane Utilization

In this performance measure, two research questions were addressed: do drivers tend to avoid the inside lane of the general-purpose lanes, and do drivers avoid the managed lane adjacent to the separator? The analysis aimed to determine whether the differences in lane utilization ratios across various separation types were statistically significant. The results suggested that the ML separation types have an impact on lane utilization.

The analysis of the lane utilization in the leftmost GPL revealed that buffer-separated facilities had the highest left-lane utilization ratio, ranging from 0.35 to 0.40 during daytime hours, indicating that drivers prefer this lane for faster travel due to the absence of a physical barrier. Conversely, concrete barrier-separated facilities showed the lowest utilization, particularly during non-peak hours, with ratios as low as 0.12 to 0.20. Buffer-separated lanes also had the lowest MSE value when compared to the balanced utilization ratio of 0.33 (for a 3-lane facility). The GLM analysis further indicated that both concrete barriers and pylon separation types were associated with the reduction of the lane utilization ratio compared to buffer separation by 12.8% and 8.6% respectively, with traffic volume and time of day also playing significant roles.

In examining the lane utilization for the ML adjacent to the separator, both buffer-separated and concrete barrier-separated MLs showed similar high lane utilization patterns, with ratios between 0.60 and 0.70 during daytime hours. However, pylon-separated MLs had a lower utilization peak of 0.50, suggesting a more even distribution of traffic across lanes. The Welch's t-test confirmed significant differences in the lane utilization ratios, though the difference was less pronounced between buffer and concrete barrier separation types. The results showed that pylon-separated MLs had the lowest MSE value when compared to the balanced ratio of 0.50 for a 2-lane ML facilities. The GLM analysis revealed that concrete barriers increased lane utilization by 1.4% compared to buffer-separated facilities, while pylon separations decreased lane utilization by over 20%.

Travel Speed

In this performance measure, the research question addressed was whether travel speed is affected by the lane separation type. The analysis aimed to determine whether the differences in the average speed across the various separation types were statistically significant. The results suggested that the ML separation types have an impact on a driver's speed choice.

The analysis indicated that buffer-separated ML facilities were characterized by higher average speeds compared to those with pylons or concrete barriers. Concrete barrier-separated ML facilities also exhibited higher average speeds than pylon-separated MLs, especially during the day, though this trend reversed at night. ANOVA and subsequent Tukey tests confirmed significant differences in the average speed, particularly highlighting that buffer-separated MLs were associated with significantly higher average speeds than others. The GLM analysis further concluded that both concrete barriers and pylons were associated with a decrease in the average travel speeds compared to buffer separations. In addition to that, the time of day and traffic volume variations significantly influence travel speed, with PM peak periods associated with lower average speeds.

Lane Deviation

In this performance measure, the research question addressed was whether the driver's lateral position was affected by the ML separation type. The analysis considered both positions, the leftmost lane of the GPLs and the ML adjacent to the separator. The results suggested that ML separation types have an impact on the lane deviation regardless of the vehicle's position.

Utilizing data from the SHRP2 program in Washington State, the analysis revealed that drivers in the ML adjacent to the separator tend to drive away from the separator, with the extent differing by separation type. Notably, drivers on buffer-separated ML facilities deviate the furthest away from the separator compared to those on concrete barrier or wide buffer facilities. In contrast, drivers in the leftmost GPL tend to drive towards the separator and away from the adjacent GPLs, as indicated by the negative mean lane deviation values. ANOVA and Tukey tests confirmed significant differences in lane deviation values across the separation types. Results from the MMNL showed that the factors influencing drivers to move away from the separator include the type of separation, visual acuity, gender, driver's age, and total miles driven the previous year, with similar influences observed for vehicles traveling in both the ML adjacent to the separator and the leftmost GPL.

This research provides FDOT and other transportation agencies with a better understanding of the effects of different ML separation treatments on driver behavior across all age groups. The findings will also enable FDOT and local agencies to make informed decisions on appropriate separation treatments between the MLs and GPLs aimed at improving safety and mobility on ML facilities for drivers of all ages.

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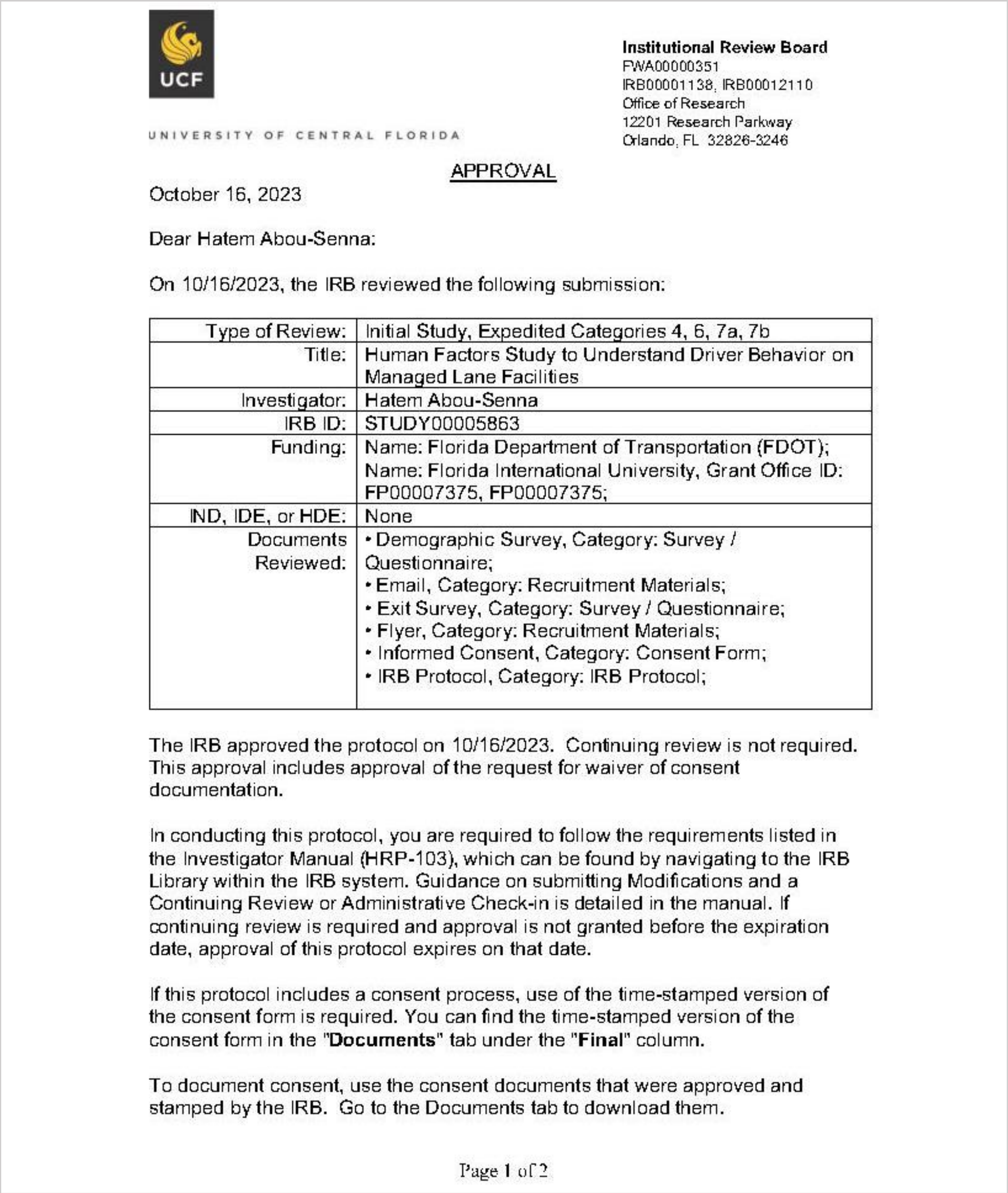
APPENDIX A: UCF’S IRB APPROVAL LETTER



UCF
UNIVERSITY OF CENTRAL FLORIDA

Institutional Review Board
FWA00000351
IRB00001138, IRB00012110
Office of Research
12201 Research Parkway
Orlando, FL 32826-3246

APPROVAL

October 16, 2023

Dear Hatem Abou-Senna:

On 10/16/2023, the IRB reviewed the following submission:

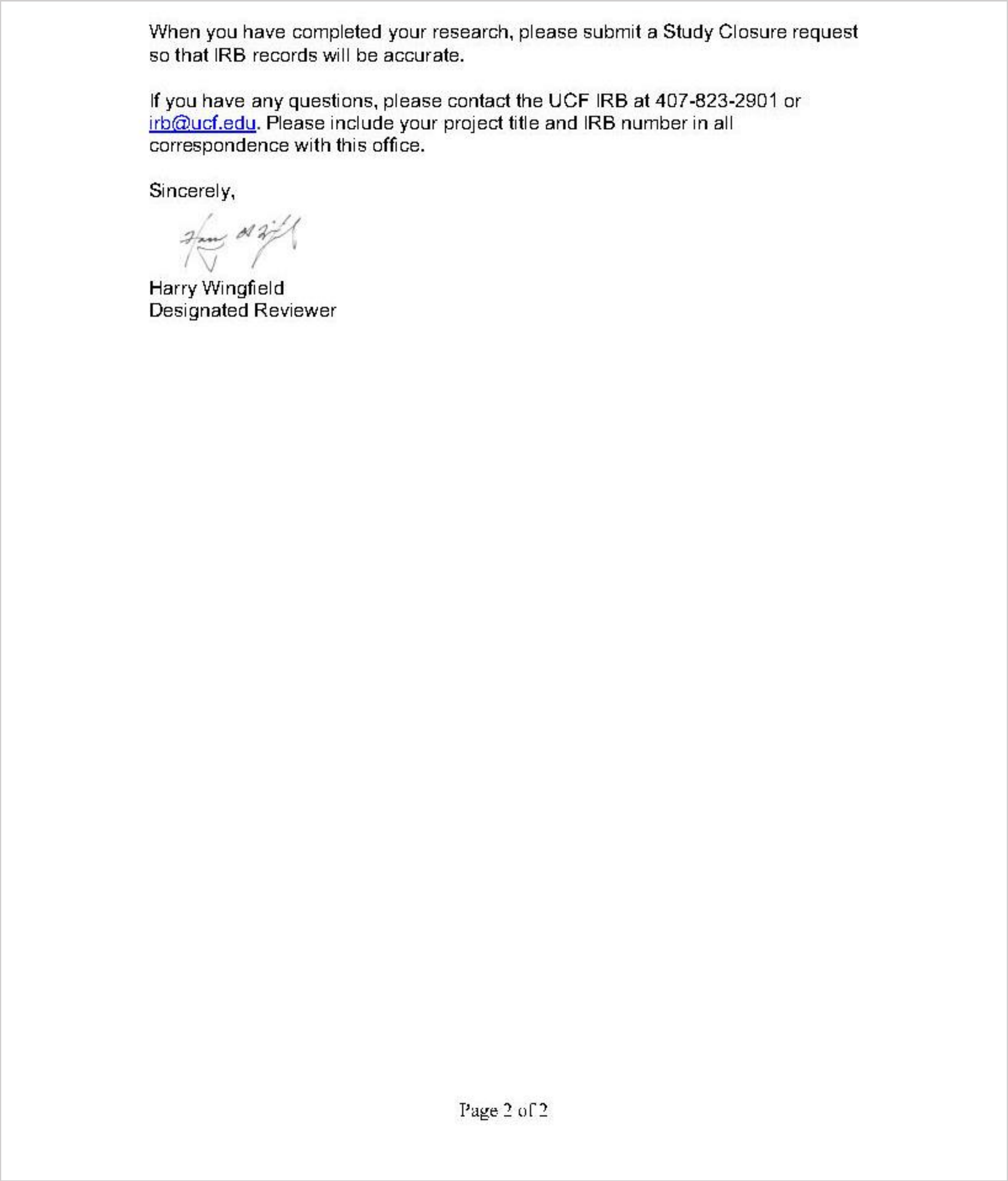
Type of Review:	Initial Study, Expedited Categories 4, 6, 7a, 7b
Title:	Human Factors Study to Understand Driver Behavior on Managed Lane Facilities
Investigator:	Hatem Abou-Senna
IRB ID:	STUDY00005863
Funding:	Name: Florida Department of Transportation (FDOT); Name: Florida International University, Grant Office ID: FP00007375, FP00007375;
IND, IDE, or HDE:	None
Documents Reviewed:	• Demographic Survey, Category: Survey / Questionnaire; • Email, Category: Recruitment Materials; • Exit Survey, Category: Survey / Questionnaire; • Flyer, Category: Recruitment Materials; • Informed Consent, Category: Consent Form; • IRB Protocol, Category: IRB Protocol;

The IRB approved the protocol on 10/16/2023. Continuing review is not required. This approval includes approval of the request for waiver of consent documentation.

In conducting this protocol, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB system. Guidance on submitting Modifications and a Continuing Review or Administrative Check-in is detailed in the manual. If continuing review is required and approval is not granted before the expiration date, approval of this protocol expires on that date.

If this protocol includes a consent process, use of the time-stamped version of the consent form is required. You can find the time-stamped version of the consent form in the "**Documents**" tab under the "**Final**" column.

To document consent, use the consent documents that were approved and stamped by the IRB. Go to the Documents tab to download them.



When you have completed your research, please submit a Study Closure request so that IRB records will be accurate.

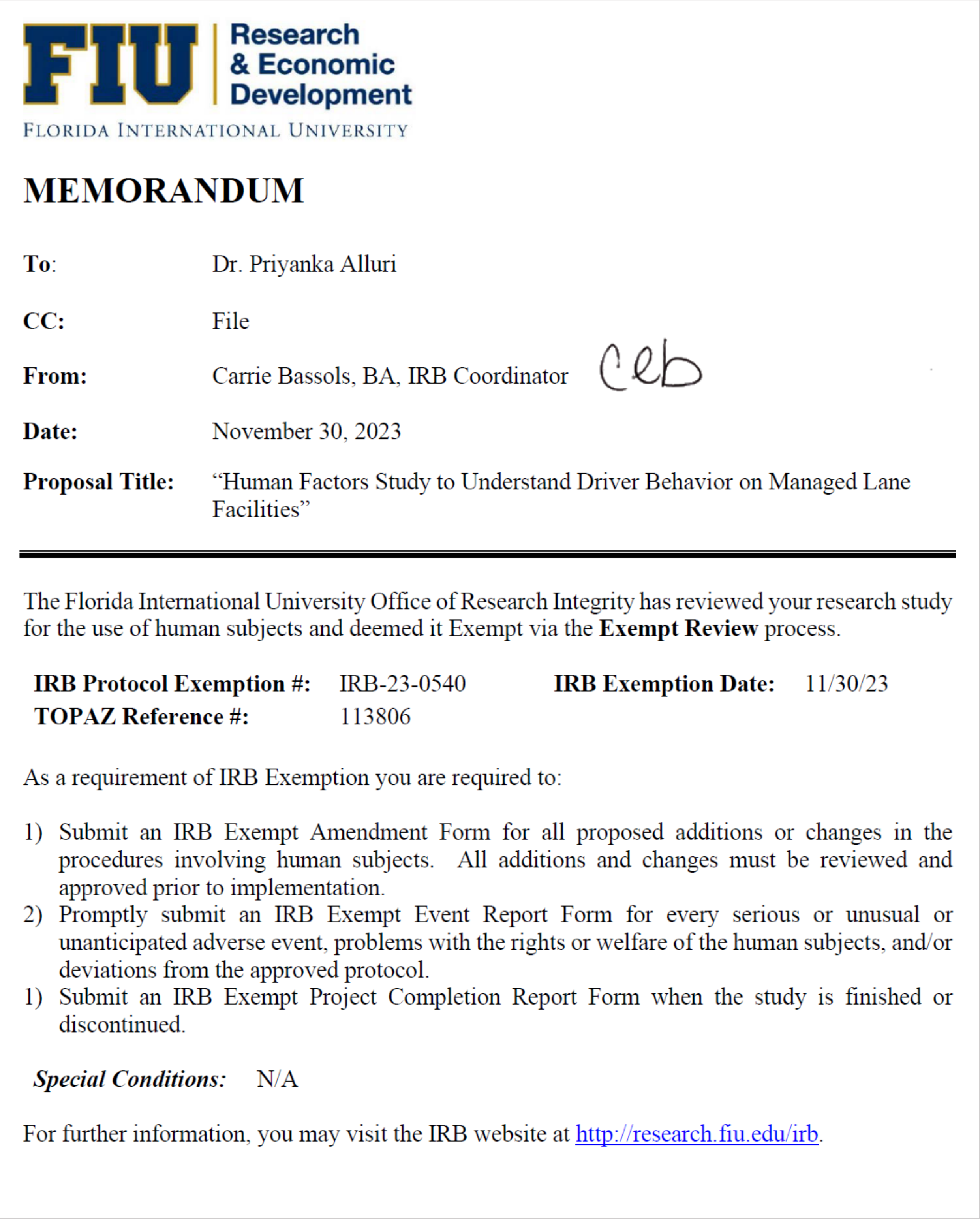
If you have any questions, please contact the UCF IRB at 407-823-2901 or irb@ucf.edu. Please include your project title and IRB number in all correspondence with this office.

Sincerely,

Harry Wingfield
Designated Reviewer

Page 2 of 2

APPENDIX B: FIU'S IRB APPROVAL LETTER



FIU | Research & Economic Development
FLORIDA INTERNATIONAL UNIVERSITY

MEMORANDUM

To: Dr. Priyanka Alluri

CC: File

From: Carrie Bassols, BA, IRB Coordinator ceb

Date: November 30, 2023

Proposal Title: "Human Factors Study to Understand Driver Behavior on Managed Lane Facilities"

The Florida International University Office of Research Integrity has reviewed your research study for the use of human subjects and deemed it Exempt via the **Exempt Review** process.

IRB Protocol Exemption #: IRB-23-0540 **IRB Exemption Date:** 11/30/23
TOPAZ Reference #: 113806

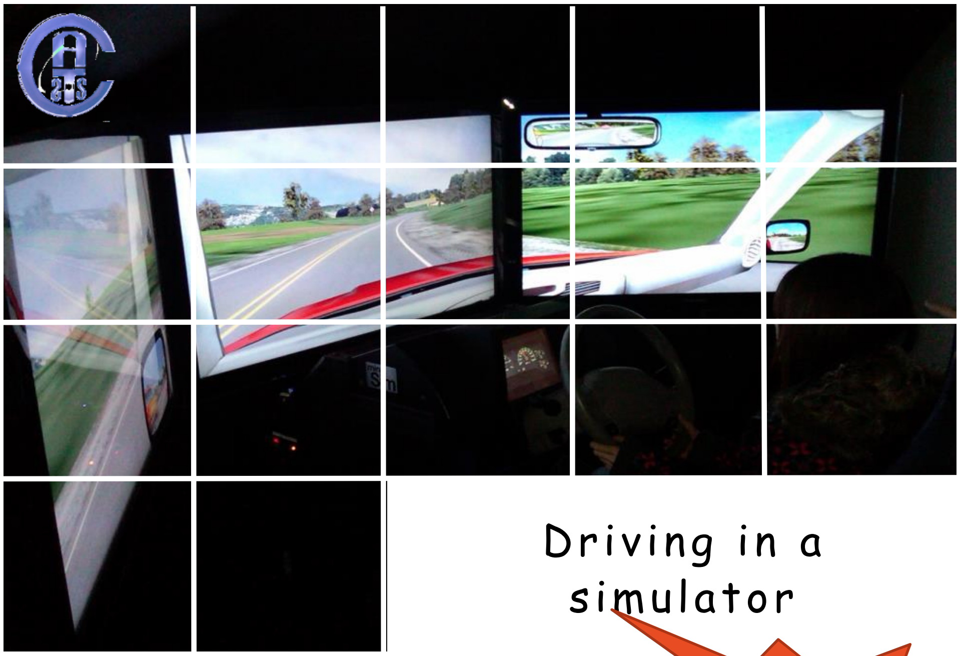
As a requirement of IRB Exemption you are required to:

1) Submit an IRB Exempt Amendment Form for all proposed additions or changes in the procedures involving human subjects. All additions and changes must be reviewed and approved prior to implementation.
2) Promptly submit an IRB Exempt Event Report Form for every serious or unusual or unanticipated adverse event, problems with the rights or welfare of the human subjects, and/or deviations from the approved protocol.
1) Submit an IRB Exempt Project Completion Report Form when the study is finished or discontinued.

Special Conditions: N/A

For further information, you may visit the IRB website at http://research.fiu.edu/irb.

APPENDIX C: ADVERTISEMENT FLYER



Driving in a simulator

Now Accepting !!!

Bored by driving in the real world?

Try to drive in a virtual environment & Earn <u>$50</u>!

You may be qualified to help in our transportation research study

<u>Only takes 2 hours of your time!</u>

Reserved parking and light refreshments provided !!!

Requirements: You must have a valid driver's license. You cannot be prone to extreme motion sickness. **Age must be over 18**.

Please contact the research assistants to schedule an appointment
Sharfuddin.Ahmed@ucf.edu or MdRezwan.Hossain@ucf.edu

Location: Transportation Lab room 325
Engineering Building II
University of Central Florida
12800 Pegasus Drive, Orlando, FL 32816

Principal Investigator: Dr. Hatem Abou-Senna, P.E. **The research study has been approved by UCF IRB.**

APPENDIX D: DEMOGRAPHIC QUESTIONNAIRE

1. How long have you had a Florida driver's license?
    a. Less than 5 years
    b. 5-10 years
    c. 11-15 years
    d. 16-20 years
    e. 21+
2. How old are you?
    a. 18-24
    b. 25-40
    c. 40-64
    d. 65+
3. How far do you typically drive in one year?
    a. 0-5000 miles
    b. 5,000-10,000 miles
    c. 10,000-15,000 miles
    d. 15,000-20,000 miles
    e. 20,000 miles+
4. What is your highest level of education?
    a. High school
    b. College
    c. Bachelor's Degree
    d. Graduate School
5. What is your range of income?
    a. 0-10,000
    b. 10,000-25000
    c. 25,000-40,000
    d. 40,000-55,000
    e. 55,000-70,000
    f. 70,000+
6. Have you been in any accidents that involved pedestrian(s) in the last 3 years?
    a. Yes
    b. No

If so, how many pedestrians were involved? Where did the crash occur (e.g. intersection, highway, freeway, mid-block, etc.)?

7. What vehicle do you normally drive?
    a. Sedan
    b. Pickup Truck or Van
    c. Motorcycle or Moped
    d. Professional Vehicle (Large Truck or Taxi)
    e. Other
8. Are you a professional driver, like taxi driver, truck driver?

   a. Yes
   b. No

9. Do you have a history of severe motion sickness or seizures?
   a. Yes
   b. No

10. Do you have an experience about virtual reality games (such as simulator)?
    a. Yes
    b. No

APPENDIX E: EXIT SURVEY

1) While driving, did you notice the change in Express Lanes separation lines?

a) Yes
b) No

If yes, which separation line caught your attention the most in the daytime scenario?

a) Single solid lines
b) Double solid lines

2) Which separation line was more noticeable at night?
a) Single solid lines
b) Double solid lines
c) Have not noticed

3) Which separation line was more noticeable in rainy conditions?
a) Single solid lines
b) Double solid lines
c) Have not noticed

4) Which separation line was more noticeable in high traffic conditions?
a) Single solid lines
b) Double solid lines
c) Have not noticed

5) Did you notice the change in Express Lanes separation height (height of the white posts)?
a) Yes
b) No

Short white posts (24 inches)

Tall white posts (28 inches)

if yes, which white posts appeared more prominent at the curves in the daytime scenario?

a) Short white posts
b) Tall white posts
c) Have not noticed

6) Which white posts at the curves were more noticeable at night?

a) Short white posts
b) Tall white posts
c) Have not noticed

7) Which white posts at the curves were more noticeable in rainy conditions?

   a) Short white posts
   b) Tall white posts
   c) Have not noticed

8) Which white posts at the curves were more noticeable during high traffic conditions?

   a) Short white posts
   b) Tall white posts
   c) Have not noticed

9) Did the driving scenarios seem realistic?
   a) Yes
   b) No

10) Do you have any suggestions or feedback on what you liked or disliked about the simulation, its alignment with real-life situations, and how to improve the scenarios, if any?

APPENDIX F: ONE-PAGE SUMMARIES

DRIVING SIMULATOR EXPERIMENT

Methodology

Participant Recruitment:

Age Group	Gender	
	Male	Female
18 - 34	10	10
35 - 64	10	10
65+	10	10
Total	30	30

Experiment Setting:

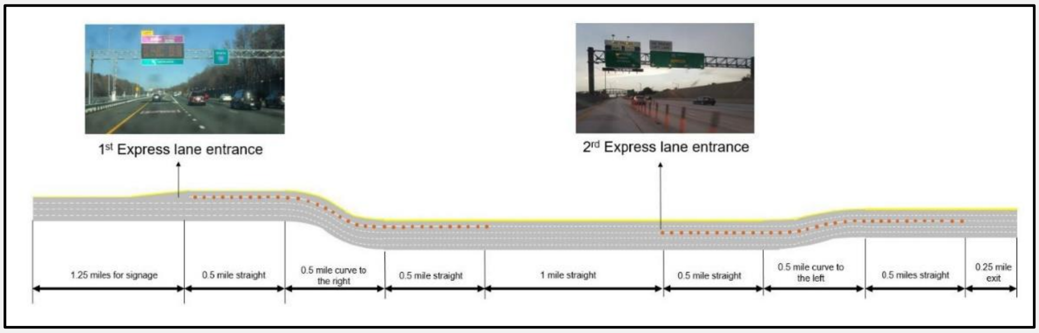
- Equipment:
  - MiniSim Driving Simulator
  - FOVIO Eye Tracker
- Roadbed Design: A 5.5-mile road with 1 & 2 managed lanes (ML) entrances consisting of two 0.5-mile straight sections, and a 0.5-mile curved section at each entrance.
- Statistical Analysis: Mixed effect models.

Background:

- Understand how different age groups of drivers behave in managed lane facilities with various combinations of delineator's heights and separation pavement markers in a controlled setting using a driving simulator and eye tracking device.
- Total number of scenarios = 16 scenarios.
- D-Optimality Criterion was applied to minimize the scenario count while still effectively capturing the full factorial effects which would require $2^5 = 32$ scenarios.

Surveys: 1) Demographic survey to capture drivers' characteristics.
2) Exit survey to capture participants feedback on separation treatments.

Total Duration of Experiment Per Participant: 120 minutes.



Factors

Separation Width:

- Single Solid White Lines
- Double Solid White Lines

Separation Height (*At Curves*):

- 24-inch Delineators
- 28-inch Delineators

Time of Day:
- Day
- Night

Visibility:
- Low
- High

Traffic Density:
- Low
- High

Response Measures

- Deceleration (ft/s^2)
- Velocity (mph)
- Lane Deviation (ft) – Deviation from Lane Centerline
- Steering Angle Rate (degree/s)
- Time to First Notice (s)
- Fixation (s)

Results & Conclusions

Exit Survey Results

- 75% of participants detected changes in separation width, while only 62% noticed changes in separation height.
- Double solid lines and 28-inch delineators were more noticeable across various conditions.

Drivers' Responses in Straight Sections of ML

- Double solid lines were associated with higher deceleration rates at the entrances, but with higher mean velocities.
- With double solid lines, drivers shifted to the left side of the lane (away from separation treatment).

Drivers' Responses in Curved Sections of ML

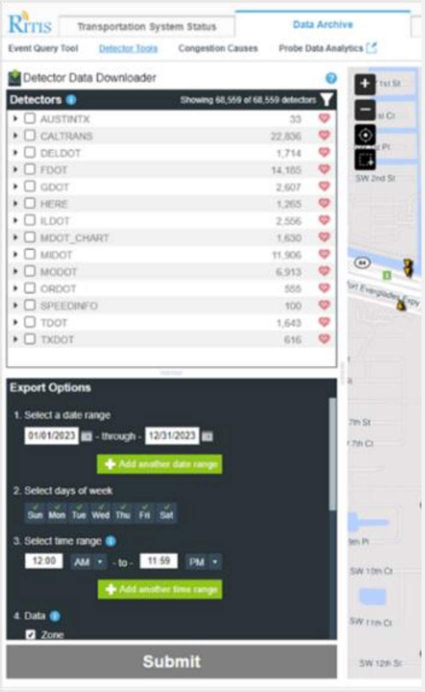
- 24-inch delineators with double solid lines significantly increased deceleration rates and lowered mean speeds.
- Double solid lines positively influenced speed differentials between curved & straight sections especially during daytime, but separation height had no significant impact on speed behavior.
- Both double solid lines and 24-inch delineators influenced vehicle position as drivers tend to align more to the left side of the lane.
- Double solid lines showed shorter fixation durations compared to the single solid lines, and 24-inch delineators had longer fixation duration compared to 28-inch delineators.

For more information, refer to FDOT Report: BED29 977-08.

REGIONAL INTEGRATED TRANSPORTATION INFORMATION SYSTEM (RITIS)

Introduction

- Regional Integrated Transportation Information System (RITIS) is a comprehensive transportation data platform that integrates real-time information from multiple transportation agencies and sources.
- RITIS offers a wealth of traffic data, including **speed** and **volume** information collected from various sensors and detectors positioned along the roadway network.
- The data used in this research effort was collected at 15-minute intervals over twelve months, from **January 1st, 2023**, to **December 31st, 2023**.
- The RITIS dataset was used for lane utilization and travel speed analyses. The study area was the State of Florida.
- Separation Types considered were, pylons, buffer, and concrete barrier



☐ AUSTINTX	33
☐ CALTRANS	22,836
☐ DELDOT	1,714
☐ FDOT	14,185
☐ GDOT	2,607
☐ HERE	1,265
☐ ILDOT	2,556
☐ MDOT_CHART	1,630
☐ MIDOT	11,906
☐ MODOT	6,913
☐ ORDOT	555
☐ SPEEDINFO	100
☐ TDOT	1,643
☐ TXDOT	616

1. Select a date range
01/01/2023 - through - 12/31/2023
Add another date range
2. Select days of week
✓ Sun ✓ Mon ✓ Tue ✓ Wed ✓ Thu ✓ Fri ✓ Sat
3. Select time range
12:00 AM - to - 11:59 PM
Add another time range
4. Data
☑ Zone

Selected Facilities

FL-528: Buffer Separation

Veterans Exp: Pylons Separation

I-595: Concrete Barrier Separation

I-95: Pylons Separation

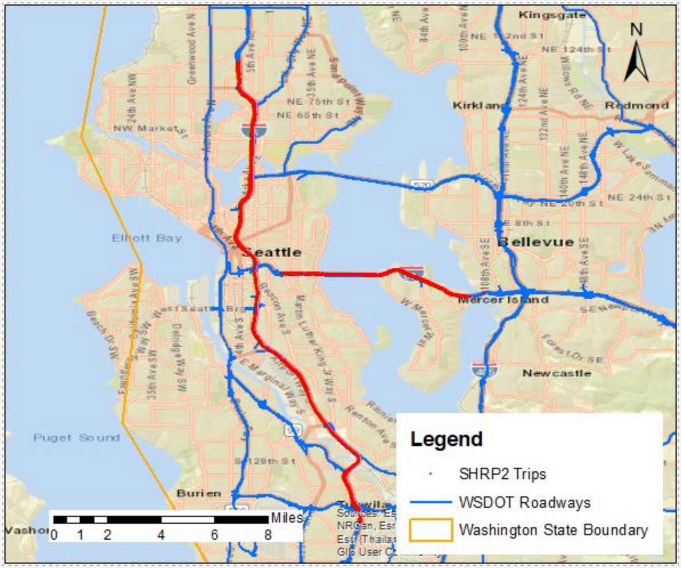
I-4: Concrete Barrier Separation

For more information, refer to FDOT Report: BED29 977-08.

STRATEGIC HIGHWAY RESEARCH PROGRAM 2 (SHRP2)

Introduction

- The Naturalistic Driving Study (NDS) data used in this research effort was collected and maintained by Virginia Tech Transportation Institute (VTTI).
- The data used in this research was collected from 310 participants of the Strategic Highway Research Program 2 (SHRP2) naturalistic study program. All trips analyzed involved vehicles in the inside lane of the managed lane (ML) or general-purpose lane (GPL), closest to the separator.
- Initial data review revealed that 96% of the trips originated from Washington State, specifically from I-5 and I-90 freeways.
- Note: SHRP2 Data was used for the lane deviation analysis.
- Other datasets used to complement SHRP2 include the WSDOT Geospatial shapefiles and Google Earth Pro, mainly for geometric characteristics.



Descriptive Statistics

Facility Type	Separation Type	Trips	Observations	Lane Deviation	
				Mean (ft)	SD (ft)
All MLs	Buffer	3,362	120,542	-0.445	1.33
	Concrete barrier	502	99,482	-0.237	1.34
	Wide buffer	2,112	41,335	-0.532	1.46
	Total	**5,976**	**261,359**		
Single-lane MLs	Buffer	3,362	120,542	-0.445	1.33
	Concrete barrier	124	750	-0.627	1.32
	Wide buffer	1,343	22,188	-0.626	1.52
		4,829	**143,480**		
Multi-lane MLs	Buffer	-	-	-	-
	Concrete barrier	396	98,732	-0.231	1.34
	Wide buffer	1,091	19,147	-0.417	1.38
		1,487	**117,879**		
All GPLs	Buffer	2,222	89,008	-0.631	1.11
	Concrete barrier	269	43,443	-0.644	1.55
	Wide buffer	261	16,722	-0.701	1.79
		2,752	**149,173**		

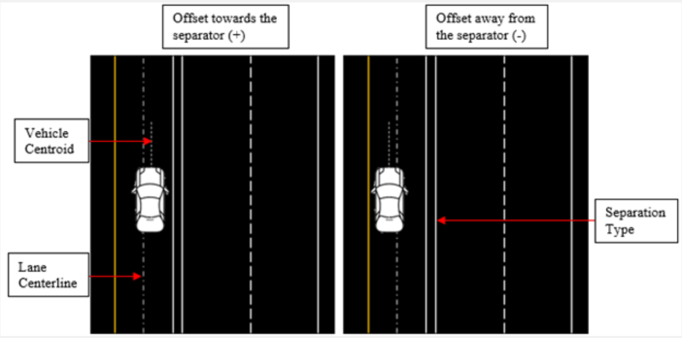
Note: ML = Managed Lane; GPL= General-purpose Lane; SD = Standard Deviation.

For more information, refer to FDOT Report: BED29 977-08.

LANE DEVIATION

Definition

- Lane deviation is defined as an offset between the position of the vehicle centroid and the centerline of the lane.
- Lane deviation is positive when the vehicle centroid is to the right of the lane centerline and negative when the vehicle centroid is to the left of the lane centerline.



$\text{Offset} = \text{Vehicle Centroid} - \text{Centerline}$

Data

Separation Types:

- Buffer separation
- Concrete barriers
- Wide buffer separation

Data Source: SHRP2 NDS from Washington State

Vehicle Position:

- Inside lane of the Managed Lanes (MLs)
- Inside lane of the General-purpose Lanes (GPLs)

Methodology

Significance Tests

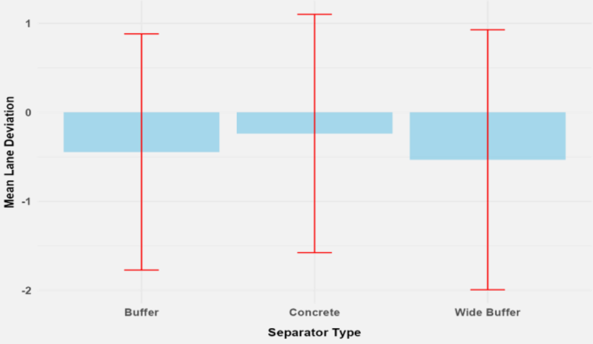
- ANOVA Test
- Tukey Honest Test

Statistical Model

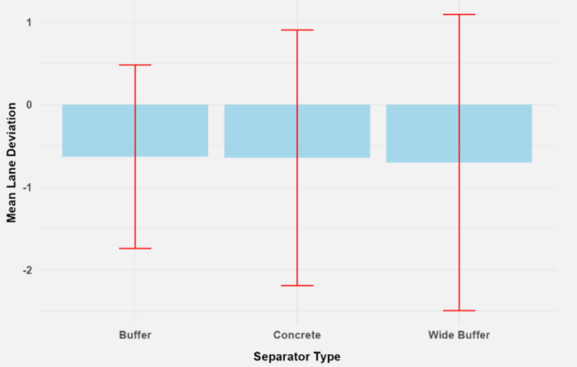
- Mixed Multinomial Logit (MMNL) Model
- Response Variable: Lane deviation
- Explanatory Variables: Driver, Geometric, & Vehicle characteristics

Results and Discussion

- **ANOVA analysis** showed a significant difference in mean lane deviation values between at least two separation types at a **95% CI**.
- Post-hoc analysis for ML revealed significant differences in mean lane deviation values between each pair of separation types.
- For GPL, post-hoc analysis found significant differences only when comparing wide buffer vs. buffer and wide buffer vs. concrete barrier.
- MMNL results for ML showed that concrete barrier and wide buffer were associated with increased lane deviation away from the separator compared to buffer.
- Factors such as older age, male drivers, and poor vision (< 20/40) were linked to driving away from the separator, raising the risk of sideswiping vehicles in adjacent MLs.
- **MMNL results** for **GPL** indicated that **wide buffer** increased lane deviation away from the separator compared to **buffer**.
- Older drivers, poor vision (<20/40), and those who drove < 6,000 miles in the past year were more likely to drive away from the separator on the leftmost GPL.



Mean Deviation (ML)



Mean Deviation (GPL)

For more information, refer to FDOT Report: BED29 977-08.

AVERAGE TRAVEL SPEED

Introduction

- Managed lanes (MLs) are designed to provide mobility, and speed is one of the most important mobility-focused performance measures.
- The analysis aims to answer the following question. Does the managed lane adjacent to the separator exhibit different mean speeds across sections with varying separation types?

Performance Measure

Average Speed

Data

- Source: RITIS
- Period: January 01, 2023 - December 31, 2023

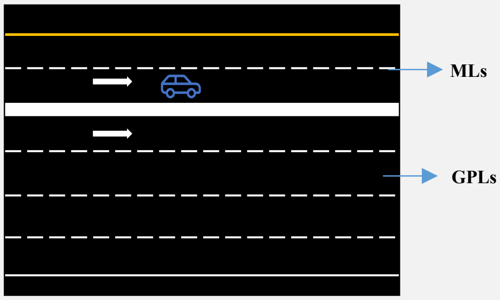
Separation Types

- Buffer separation
- Concrete barriers
- Pylon separation

Methodology

Vehicle Position

- Inside lane of the MLs



Pairwise Comparison

- ML facilities with similar characteristics were compared using the performance measures.

Significance Tests

- ANOVA Test
- Tukey Test

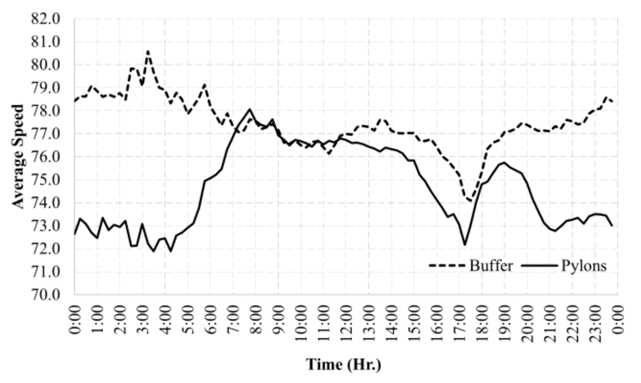
Statistical Model

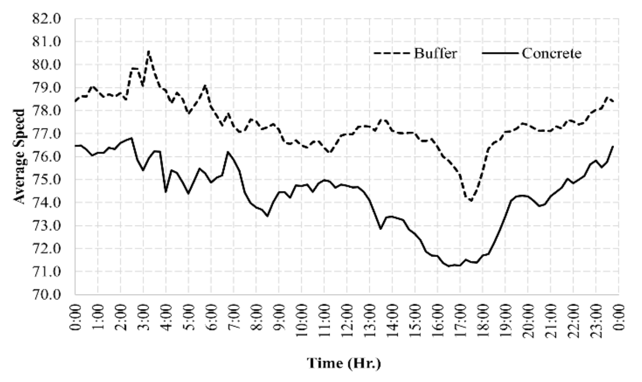
- Generalized Linear Model
- Response Variable: Average Speed

Results & Discussion

Inside Lane of the ML

- **ANOVA analysis** showed a significant difference in average travel speed values between at least two separation types at a **95% CI.**
- Post-hoc analysis found significant differences when comparing concrete barrier vs. buffer and pylons vs. buffer.
- GLM results show that vehicles traveling on ML facilities with concrete barriers and pylon separations were found to travel at a lower average speed compared to ML facilities with buffer separation.
- An increase in traffic volume on the inside lane of the managed lanes was associated with a slight decrease in average speed.
- PM peak periods were associated with a decrease in the average speed compared to daytime off peak periods. The same observation was observed for nighttime off-peak periods indicating a decrease in the average speed in low light conditions.





For more information, refer to FDOT Report: BED29 977-08.

LANE UTILIZATION

Definition

Lane utilization refers to the distribution of traffic across available lanes on a freeway section. This distribution is influenced by factors such as geometric characteristics, traffic conditions, and driver behavior.

Performance Measure

Lane Utilization Ratio

$$R_{LU,i} = \frac{V_i}{\sum_{i=1}^{i=n} V_i}$$

Balanced Lane Utilization Factor

$$f_{bal,j} = \frac{1}{\text{number of lanes}}$$

Separation Types

- Buffer separation
- Concrete barriers
- Pylon separation

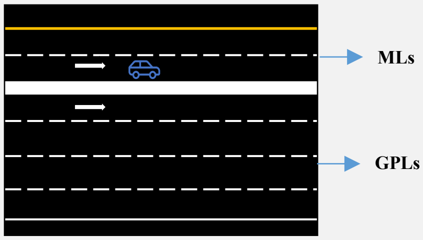
Data

- Source: RITIS
- Period: Jan 01, 2023 - Dec 31, 2023

Methodology

Vehicle Position

- Inside lane of the Managed Lanes (MLs)
- Inside lane of the General-purpose Lanes (GPLs)



Pairwise Comparison

- ML facilities with similar traffic and geometric characteristics were compared using the performance measures.

Significance Tests

- Welch's t-Test was used for comparison

Statistical Model

- Generalized Linear Model (GLM)

Results & Discussion – Inside Lane of the GPLs

- The lane utilization ratio is highest in buffer-separated facilities compared to those with concrete barriers or pylons.
- Buffer-separated facilities maintain a consistent left-lane utilization of ˜0.35–0.40 during daytime hours.
- Pylon-separated facilities exhibit a higher utilization than concrete barriers.
- Concrete barrier-separated facilities have the lowest utilization, ranging from 0.15–0.18 (during AM peak period) to 0.14–0.20 during PM peak period).
- Welch t-test results show a statistically significant difference in mean utilization across separation types.
- Buffer-separated facilities deviate least from the balanced utilization ratio.
- GLM results show concrete barriers and pylons reduce lane utilization by 12.8% and 8.6%, respectively, compared to buffer separation.

Results & Discussion – Inside Lane of the MLs

- ML facilities with buffer and concrete barriers have similar lane utilization, both higher than pylon-separated MLs.
- Buffer and concrete barrier-separated MLs maintain ˜0.60–0.70 utilization during daytime hours (6 AM – 7 PM).
- Pylon-separated MLs have the lowest utilization, ˜0.50 during daytime hours.
- Welch's t-test confirms a significant difference in mean lane utilization ratio across separation types.
- Pylon-separated facilities deviate least from the balanced ratio, based on lower MSE in peak and off-peak periods.
- GLM results show concrete barriers increase utilization by 2%, while pylons reduce it by 20% compared to buffer separation.

For more information, refer to FDOT Report: BED29 977-08.