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Safety and Operational Characteristics of Lane Widths on Urban and Rural Roadways A Simulator Study

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SAFETY AND OPERATIONAL CHARACTERISTICS OF LANE WIDTHS ON URBAN AND RURAL ROADWAYS

A DRIVING SIMULATOR STUDY

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Civil Engineering

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by
Meredith LaDue
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Accepted by:
Dr. Jennifer H. Ogle, Committee Chair
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ABSTRACT

The primary goal for this study was to further evaluate and assess the effect of lane width on the safety and operation of roadways in South Carolina. Due to various site conditions that affect the safety and operations of roadways, highway design engineers often face many challenges when developing appropriate road design standards. To investigate specific site conditions for the South Carolina Department of Transportation (SCDOT) a research study took place. In 2011, Part 1 of this research included field studies conducted by Kevin Baumann and Trey Jordan. Due to the various limitations of the field studies it was evident that additional research needed to take place.

This study (Part 2) uses a driving simulator study to examine three different lane and shoulder width combinations on a rural curvy two-lane highway to determine the effects on lateral position. These roadways were composed of various curves and straight sections with a speed limit of 50 miles per hour. The study also examined how three different two-way left turn lane (TWLTL) widths affected gap acceptance and maneuverability within the lane for a three lane highway with a center lane (3T) and a five lane highway with a center lane (5T). Below is a list of all the conditions that were tested.

Combinations

- 12 ft. lane width, no paved shoulder
- 12 ft. lane width, 2 ft. paved shoulder
- 10 ft. lane width, 2 ft. paved shoulder

TWLTL Widths

- 12 ft.
- 14 ft.
- 16 ft.

The simulated scenarios were designed to provide comparable data among the three roadway combinations and comparisons between three TWLTL widths. Together the results from this study and from Part 1 will coalesce to form design recommendations regarding the selection of standard lane and shoulder widths for new projects in South Carolina.

ACKNOWLEDGEMENTS

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I would also like to acknowledge my team of hard working students that helped throughout the duration of this project. Completing this study would not have possible without your hard work and diligence. Thank you Kweku Brown and Vijay Bendigeri for all of your help and hard work spent designing the scenarios and testing the participants. I also want to thank Brian Maleck for helping during the testing phase. Additional thanks go out to Xi Zhao and Adika Mammadrahimli for their help with data analysis. Lastly, I want to give thanks to Matt Chrisler for all his help and expertise during the design process. Once again I want to thank you all for your dedication and hard work for this project was truly a team effort.

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CHAPTER 1 : INTRODUCTION

The main goal of this study is to determine the influence that flexible lane width standards have on the safety and operation of roadways in South Carolina. In 2011, Part 1 of this research was conducted in which field studies were performed. Due to various limitations from the field studies it was apparent that to fully investigate the effects of variable lane widths, Part 2, a driving simulator study needed to take place. Throughout Part 1, several limitations were discovered as the project progressed. As an observational study, data was limited based on the availability of site specific parameters and what could be observed in the field. It is no surprise that the majority of sites fell within a small range of allowable limits set forth in the Highway Design Manual. Thus, the study of flexible lane widths was limited by the lack of variable lane width combinations found in the field. Due to such limitations, it was difficult to obtain and analyze an adequate sample of roadways regarding the desired lane and shoulder width attribute combinations. By using a driving simulator controlled tests can be performed and designed for the lane and shoulder width combinations that could not be analyzed in Part 1. The addition of this study will help further identify how South Carolina will benefit from implementing more flexible lane width standards.

Based on the following objectives, the aim of this study is to ultimately provide and build upon the design recommendations made from Part 1 pertaining to the selection of standard lane and shoulder widths for new projects. The objectives for this experiment are provided below:

1.) Analyze the effect lane and shoulder width combinations have on driver performance.
2.) Analyze the effect of curves on lane position for various lane and shoulder width combinations.
3.) Analyze the operational performance (gap acceptance and maneuverability) of TWLTLs for minimum and maximum widths.

To incorporate all of these objectives into one study, three scenarios were designed. Three different lane and shoulder width combinations were tested on a rural curvy two-lane undivided highway. These combinations included a 12 ft. roadway with no paved shoulder, a 12ft. roadway with a 2 ft. paved shoulder and a 10 ft. roadway with a 2 ft. paved shoulder. These combinations were implemented to test their effect on lateral position. Analyses for the TWLTLs were conducted on both a 3T and 5T. The TWLTL widths were 12, 14 and 16 ft. Participants were instructed to make left turns out of a development/ driveway into the TWLTL. Analyses were conducted to determine if the width had any effect upon gap acceptance. Operational analysis of the TWLTL was also examined based on how participants maneuvered in the center lane as a function of the lane width.

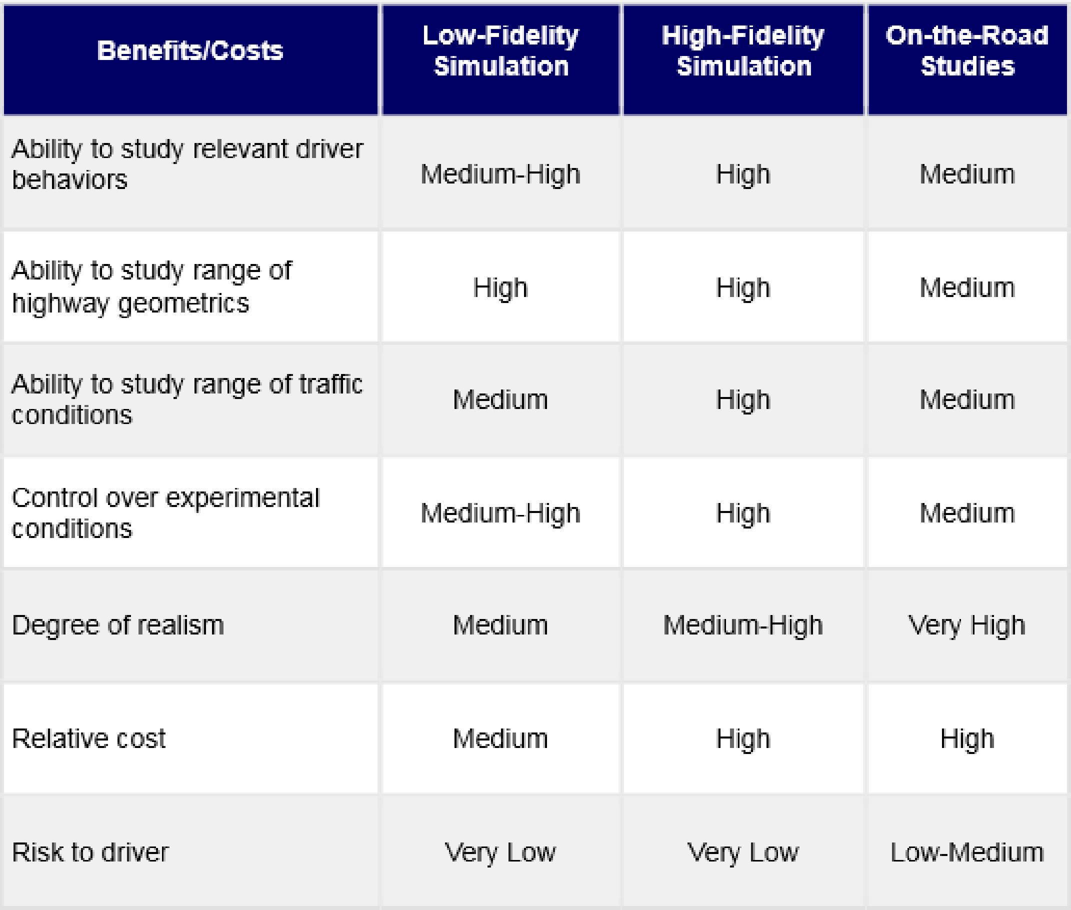
The remainder of this document is composed of numerous chapters that expand upon the various aspects of this study. Chapter 2 consists of a comprehensive literature review of previous driving simulator studies that evaluated the effect of lane width on driving behavior. Following the literature review is Chapter 3 which provides a detailed description of the methods used to perform the study. Results from the study are presented in Chapter 4 followed by a discussion in Chapter 5. Both of these chapters provide findings regarding the effects of lane and shoulder width combinations on lane position and out of lane encroachments and the effects of the TWLTL width on gap acceptance and maneuverability. Lastly, Chapter 5 consists of final conclusions regarding the objectives that were tested and recommendations for the SCDOT. Appendices are also attached to expand upon findings and processes that took during the study.

CHAPTER 2 : LITERATURE REVIEW

While field studies are critical in learning about various roadway treatments, the diversity of environments and driver characteristics often cause difficulty in conducting comparative research. To be specific, adverse weather and unaccounted traffic congestion can easily interfere with a study. Due to the various conditions, driving simulators have proven to be an influential tool providing additional avenues for research. The unique ability to design specific scenarios has increased our ability to explore and learn more about driving behavior, driver responses, user performances and training. Simulators allow researchers to emulate real life roadway conditions in a safe and practical manner. As stated by van der Horst et al. " Systematic control over the experimental conditions with respect to road design elements, traffic management, other traffic, and environmental conditions makes human factors research in a driving simulator attractive, efficient and effective." After performing their driving simulator study Godley et al., (2001) also stated that simulators enable "Experimental control, efficiency, expense, safety and ease of data collection." Given the ability to manipulate various environmental factors and test multiple treatments, driving simulators have become an effective tool for comparative research.

Despite the beneficial use of reducing risk and increasing safety, simulators also have drawbacks- including potential simulator sickness. This syndrome is commonly perceived as motion sickness as both conditions express similar side effects such as nausea, headaches, sweating, disorientation and vomiting (Brooks et al., 2010) .While driving a simulator, it is common for the body's vestibular senses to perceive the discontinuity between the visual and physical effects, thus causing these symptoms to occur (Brown, 2012). Simulator sickness can be detrimental to an experiment by undermining the effectiveness of training and causing various participants to drop out of the study (Brooks et al., 2010) (de Winter et al.,). Additional limitations and challenges of driving simulators focus on fidelity and validity. The quality of simulator use is often determined by these two aspects (Riener, 2011). Fidelity refers to the level of realism expressed by the simulation, while validity is “the degree to which behavior in a simulator corresponds to behavior in real-world environments under the same conditions (Riener, 2011).” Studies by (Engström et al., 2005) expressed a relationship between these two variables in which high fidelity simulators provide a more realistic environment, thus producing results of higher validity in comparison to a low fidelity simulator. Costs and benefits between the two types of simulators and field studies can be seen in the table below. As shown, the high fidelity simulation exceeds on the road studies in all categories except degree of realism. Low fidelity simulators also exceed on the road studies in most of the categories excluding degree of realism and ability to study range of traffic conditions.

Table 2.1: Driving simulation and on the road studies comparison (Hein, 2007)



Benefits/Costs	Low-Fidelity Simulation	High-Fidelity Simulation	On-the-Road Studies
Ability to study relevant driver behaviors	Medium-High	High	Medium
Ability to study range of highway geometrics	High	High	Medium
Ability to study range of traffic conditions	Medium	High	Medium
Control over experimental conditions	Medium-High	High	Medium
Degree of realism	Medium	Medium-High	Very High
Relative cost	Medium	High	High
Risk to driver	Very Low	Very Low	Low-Medium

Based on the parameters of the study, funds, and availability of resources the desired fidelity may be hard to obtain. The second quality-defining parameter and constant challenge of simulator use is validity. Validity is the premise in which findings from the simulated environment can be applied to the real world. It can be broken down into two categories, physical validity and behavioral validity. Physical validity is represented as the degree in which the simulator's visual components, dynamics and layout replicate the real world hence, fidelity (Brown, 2012; Blaauw, 1982). Behavioral validity measures the similarity between driving behavior in the simulator compared to behavior in the real world. The validity of a study can further be defined as absolute or relative. Research suggests that validation is best tested by comparing driving in the simulator to a real car while performing tasks that are extremely similar for both conditions (Blaauw, 1982). When comparing variables between the simulated and real world environment it is possible to achieve absolute or relative validity. Absolute validity is established if the numerical values between the two systems are the same. Relative validity is expressed when "the differences found between experimental conditions are in the same direction, and have a similar or identical magnitude on both systems (Godley et al., 2002)." Results from driving simulators are considered useful if relative validity is achieved (Törnros, 1998).

In 1998 Wade and Hammond conducted a study testing the relative validity of lateral lane position measurements. In the study 26 participants drove on simulated and real-world rural roadways. By using several vehicle performance measures, kinematic variables and a questionnaire comparing the two environments the team was able to conclude relative validity based on lateral position.

Lane/Shoulder Width and Road Geometry

One of the main objectives of this study is evaluating the effect lane width, shoulder width and roadway geometry has on driver perception and behavior. While roadway design is typically associated with accident rate, there are very few studies that investigate the effect roadway design features have on driver behavior. A specific attribute affected by the driver's perception of the road's safety is speed. Several studies suggest that narrow roads and lanes will reduce driver speed and produce safer driving behavior (Shinar, 2007). It is predicted that drivers assess narrower roads as being more dangerous thus causing the driver to slow down to avoid accidents and risky situations. De Waard also proposed that narrower roadways require more mental effort for the driver to maintain lane position. Contrary to these findings, other studies indicate a negative effect between narrow shoulders and safe driving behavior. A study by Dewar and Olson found that narrow shoulders on two-lane roads caused drivers to steer closer to the center of the road increasing the risk of a head-on collision.

Another characteristic that can affect driver behavior is the roadway geometry. To be specific, it requires more effort from the driver to stay in the lane while driving through curves. The limited visibility when encountering a curve limits the driver's ability to perceive the route ahead which increases uncertainty (Martens et al., 1997). It is often difficult to evaluate the effects of roadway geometry alone due to the extreme influence that lane and shoulder width play on the driver's perception. To help understand and distinguish such effects many researchers have started to perform driving simulator studies.

Lane Keeping Studies

Green et al. (1994) used the UMTRI driving simulator to test the relationship between roadway geometry and driver performance. In this study eight participants drove a series of six winding road segments with varying sight distance and widths ranging 15 to 24 ft. Results from the study revealed significant effects on the standard deviation of lane positioning due to road width. It was also evident that the standard deviation of lateral position increased as the road became wider and decreased as the sight distance increased.

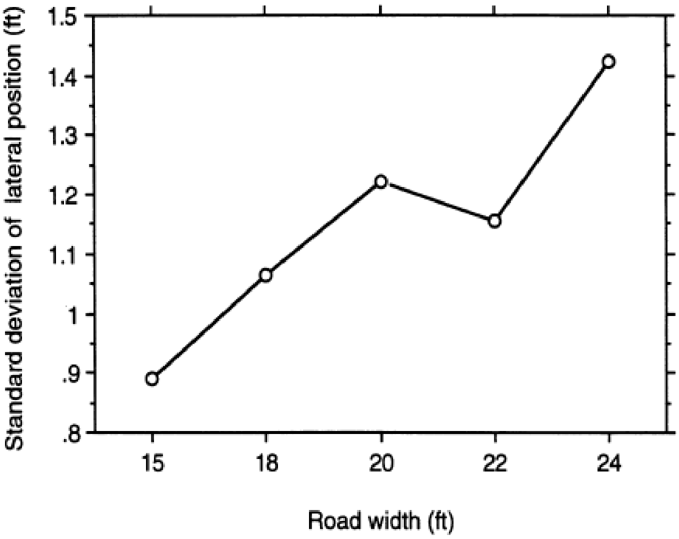


Figure 2.1: Effect of lane width on standard deviation of lane position
(Green et al., 1994)

In 2011, Dijksterhuis et al., used a driving simulator to observe lane position between four levels of lane width: 3.00, 2.75, 2.50, 2.25 m. Subjects were also exposed to high and low densities of oncoming traffic while driving each lane width section within the scenario. Each section was designed identically on rural roads that consisted of 85% curves with 382 m radii. The remaining 15% of the roadway was composed of straight sections and intermittent towns that separated the four sections of altering roadway widths. Results showed no significance between the different levels of lane width and oncoming traffic density. Marginal significance was found between the 3.00 m and the 2.50 m lane width conditions and the 2.75 m and 2.50 m conditions. Though, no statistical evidence or trend was found for lane position of the vehicle due to lane width variations, Figure 2.3 indicates that further studies on the matter are required. Graph B within this figure shows that participants drove over the lines the most while driving in the 2.25 m lane width. As the lane width increased participants' lane keeping performance increased.

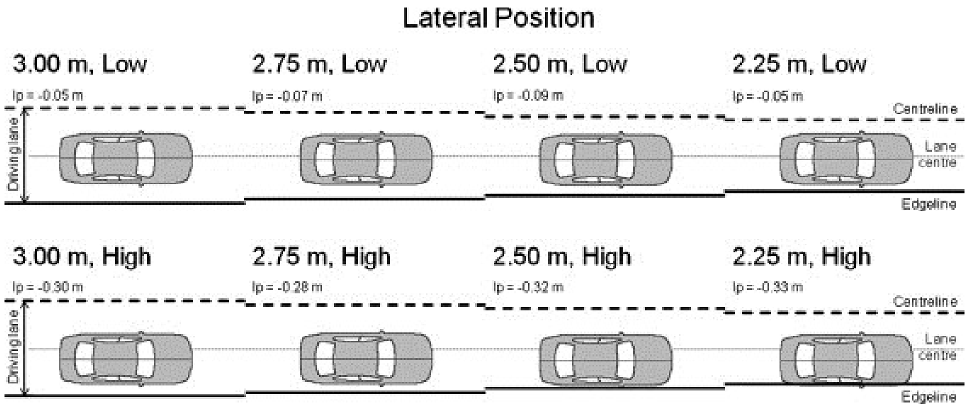


Figure 2.2: Mean lateral position of the vehicle in the lane (Dijksterhuis et al., 2010)

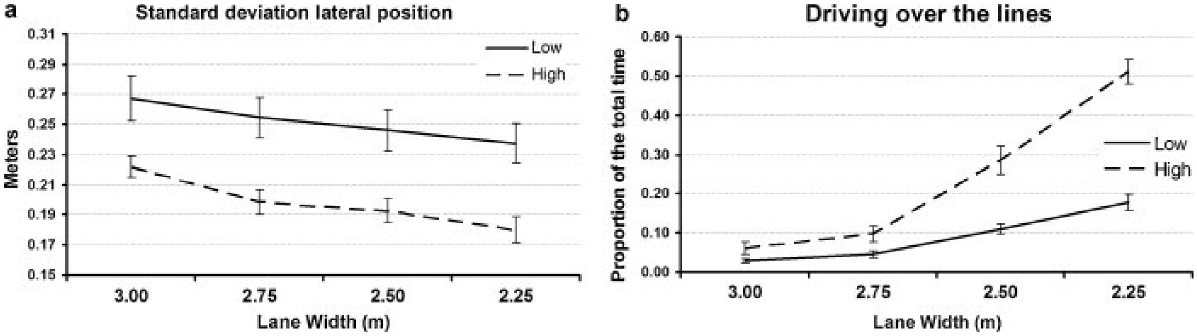


Figure 2.3: (Dijksterhuis et al., 2010)

A study conducted by Ben-Basset (2011) evaluated lane wandering as a function of shoulder width and presence of guardrail. The paved shoulder widths evaluated were 0.5, 1.2 and 3.0 m. The roadway geometry in each scenario included right and left sharp and shallow curves. Curve radii were set at 80 m and 380 m respectively. Roads in the scenario were two- lane divided highways with two 4.5 m lanes in each direction. Results from the study found an extreme deviation in variance for all three shoulder widths when driving sharp left turns. Analysis also revealed significant effects of shoulder width on the average lane position. Values for lane position were determined as the distance of the center jersey to the center of the vehicle. This is shown in Figure 2.4.

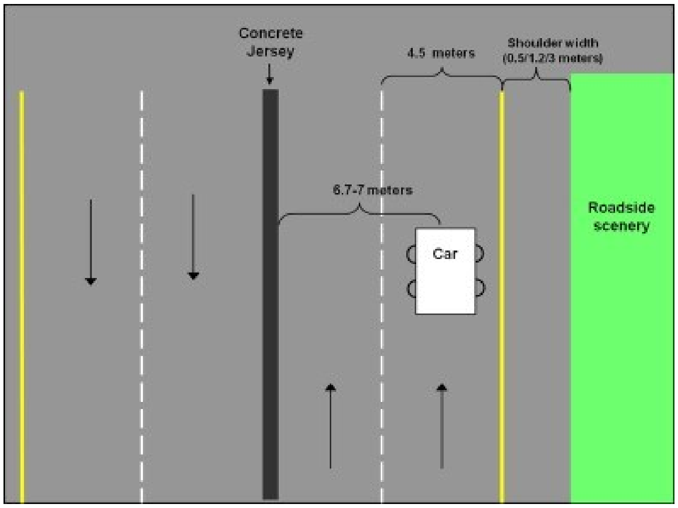


Figure 2.4: Lane position (Ben-Bassat and Shinar, 2011)

Subjects drove significantly closer to the left lane with a 0.5 m shoulder than the 1.2 and 3.0 m shoulders. Average lane position values for these widths were 6.9, 7.1 and 7.3 m respectively. From these results it is evident that as the road shoulder became wider the participants gravitated more towards the middle and right edge of the lane. The trend can be seen in Figure 2.5. Additional analysis compared the standard deviation of lane position against road geometry. From Figure 2.6 it is evident that the roadway geometry had a significant impact on the driver's ability to keep in the center of the right lane. The large standard deviation of lane position for the sharp left turn indicates that the participants were wandering along the lane and may have veered off the road.

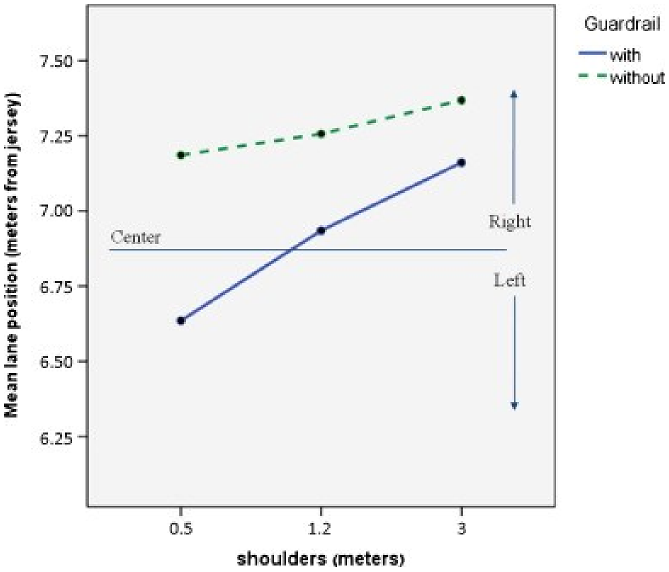


Figure 2.5: Effect of shoulder width on mean lateral position
(Ben-Bassat and Shinar, 2011)

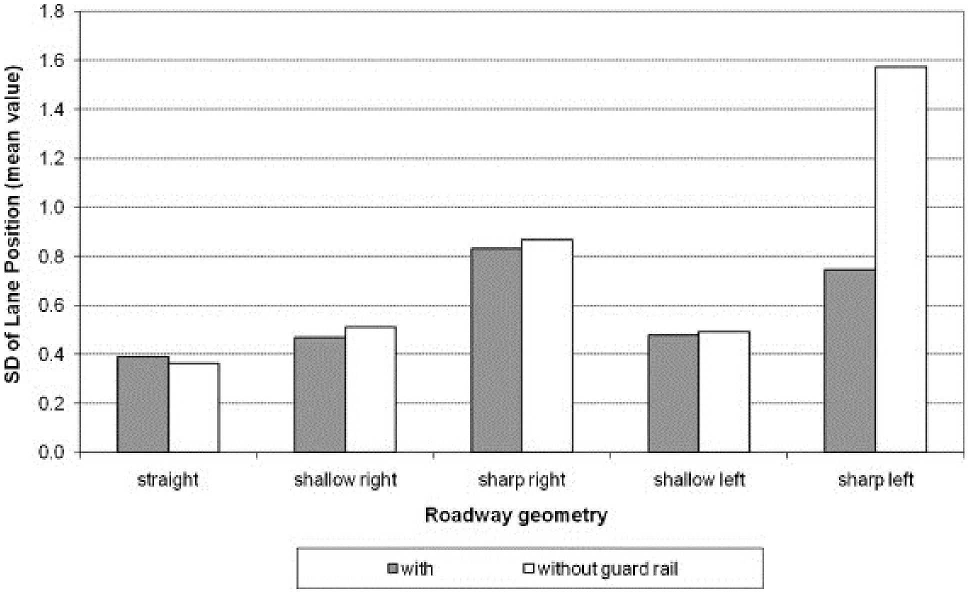


Figure 2.6: Effect of roadway geometry on lane position standard deviations (Ben-Bassat and Shinar, 2011)

Gap Acceptance

Other essential aspects of this paper focus on the operational performance of two-way left turn lanes (TWLTL) and gap acceptance. Gap acceptance as defined by the Highway Capacity Manual (HCM) 2010 is “The process by which a driver accepts an available gap in traffic to perform a maneuver.” This behavior is often seen at a two-way stop- controlled intersection (TWSC). A TWSC intersection is one of the most commonly used unsignalized intersections in the United States (Kittelson and Vandehey, 1991). They are composed of a “major” street that is uncontrolled and a “minor” street that is controlled by stop signs (Nabaee, 2011), (HCM, 2010). In this setting, gap acceptance behavior is expressed when a vehicle on the minor street needs to cross the major street and when a vehicle must make a left turn that crosses the path of the opposing movement. This concept is also seen on midblock arterials when a driver must make a left turn out of a development into a two-way left turn lane. All of these cases test the driver’s ability to perceive a stream of dynamic oncoming traffic and evaluate the availability and usefulness of the gaps to safely maneuver across through travel lanes(Zohdy et al., 2010),(Nabaee, 2011). Gap also referred to as headway is further defined by the HCM (2010) as the elapsed time between two successive vehicles as they pass a specific point on the roadway measured from the same feature of both vehicles. The minimum gap that a driver will accept is commonly known as the critical gap. It is assumed that drivers would accept gaps equal to or larger than the critical gap and reject gaps that are less than the critical gap (HCM, 2010). This parameter is typically used to determine the safety and operational performance of TWSC intersections (Nabaee, 2011).

While gap acceptance is a common behavior many factors affect the drivers' decision making process in deeming a gap acceptable. External factors include time of day effects, type of intersection control, intersection geometry, driver's sight distance, and speed of opposing vehicles (Zohdy et al., 2010). Studies have also led to results indicating that driver characteristics age and gender influence a driver's gap acceptance behavior (Moussa et al., 2012).

In 2007 a driving simulator study was conducted by Yan et al. to determine the effects of age and gender on drivers' left turn gap acceptance behavior at a two-way stop controlled intersection. The equipment used throughout the experiment was a high fidelity driving simulator composed of five channels providing 180 degree field of view, a motion base and Saturn Sedan cab. The study tested a total of 63 participants with defining age categories of young (20-30), middle (31-55) and old (56-83). Vehicle gaps in the two scenarios were arranged in a uniformly ascending order from 1 to 16 seconds.

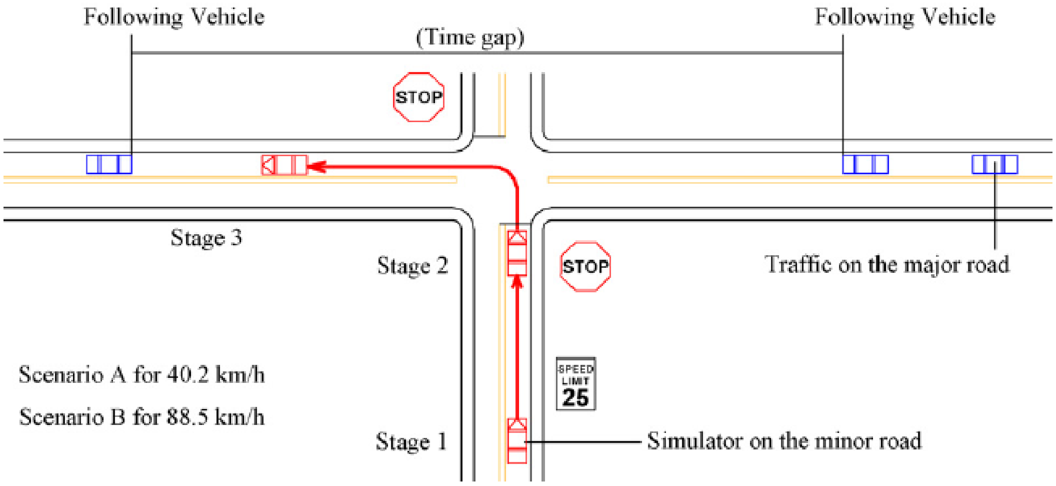


Figure 2.7: Traffic scenario design for left-turn gap acceptance (Yan et al., 2007)

Results indicated that older drivers accepted larger gaps than middle age and young drivers. Average gap values were 7.94 s, 6.20 s, and 6.29 s respectively. No significant difference between young and middle age drivers was found. Gender results showed that male drivers accept smaller gaps at an average of 6.38 s than females with an average gap of 6.93 s. Such findings lead Yan et al. to suggest that female drivers and older drivers are more conservative.

Another study that evaluated left-turn maneuvers at a two-way stop controlled intersection was conducted by Moussa et al. (2011). This study integrated simulation with a field study through the use of an augmented reality vehicle system, “ARV.” The system is a tool installed in a vehicle that allows the driver to see an augmented video where virtual objects can be added to the real-world view in real time. A total of 44 participants drove one scenario where they made a left-turn maneuver at a two-way stop controlled intersection. Results revealed that all participants accepted gaps in a range of 4 to 9 s. Older drivers in the study accepted larger gaps averaging 7.36 s compared to younger drivers who averaged 6.20 s gaps. Agreeing with Yan, Moussa’s findings suggest that older drivers are the most conservative (Yan et al., 2007). The results also found no significance between gender and gap acceptance. The frequencies of gaps taken throughout the study are expressed in Figure 2.8.

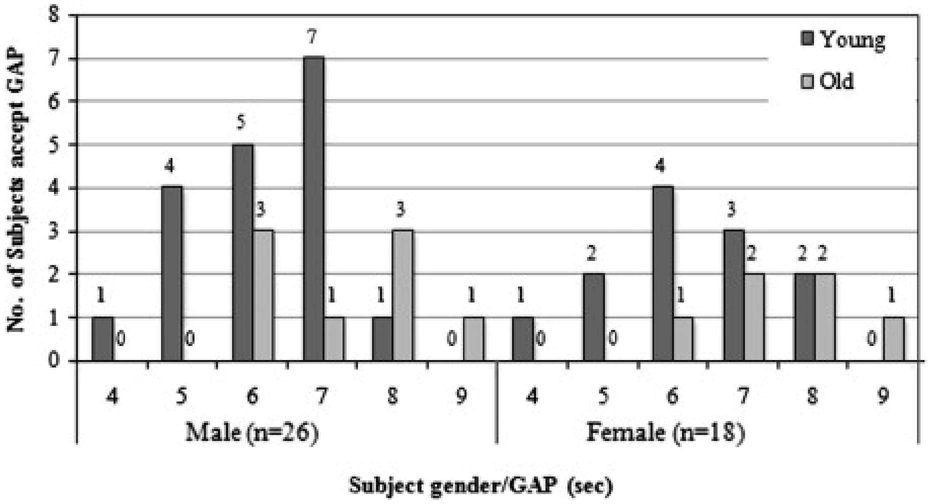


Figure 2.8: Gap acceptance as a function of subject's gender and age (Moussa et al., 2012)

Due to various factors, the critical gap for a specific maneuver can vary greatly. It has also been found that waiting time can affect a driver's gap acceptance behavior. As the waiting time increases the driver will become more inclined to take the risk of accepting a smaller gap. Results from Xiaoming et al's study found that after a long wait time many drivers would accept shorter gaps that they had previously rejected.

Two-way Left Turn Lane

As previously stated, intersection geometry can have a major impact on gap acceptance behavior. A specific instance is when the major street has a storage area, otherwise known as a TWLTL. The TWLTL is a separate lane used for left turning vehicles and property access. They are typically the center lane of a five and three lane roadway, as seen in the figure below.

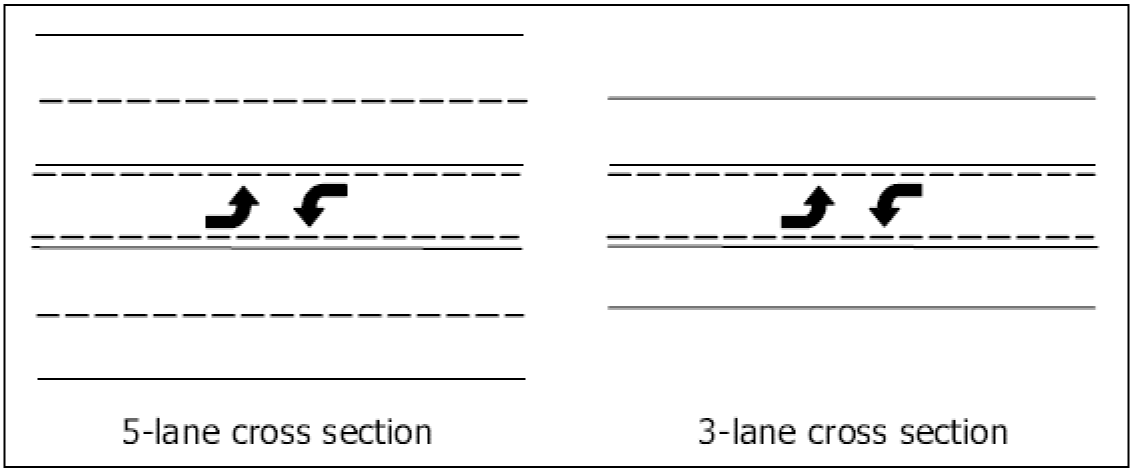


Figure 2.9: Roadway configuration (Manual, 2004)

In these settings, drivers that want to make a left turn experience two-stage gap acceptance. During the process, drivers will first assess and use gaps in the near side major street traffic and wait in the TWLTL until they find another acceptable gap in the far-side major street traffic stream (HCM, 2010). Due to the presence of a central storage place, drivers on the minor street do not need coinciding gaps in both major directions thus increasing the capacity for minor movements (Brilon and Wu, 2003) Often TWLTLs are implemented on urban and suburban roadways where mid-block entrances are too close for turn lanes or when the percentage of turning volumes is high causing congestion for through lanes. Studies suggest that adding a TWLTL on roadways under these conditions with can result in improved safety and capacity (Manual, 2004). A study conducted in Minnesota between 1991 and 1993 revealed that three lane roadways with a TWLTL are about 27% safer than a four lane undivided roadway and a five lane roadway with a TWLTL is approximately 41% safer than a four lane undivided roadway(Manual, 2004). Lane width guidelines for these facilities typically vary by state. Ranges depicted by *A policy of Geometric Design of Highways and Streets,* "AASHTO Greenbook," include 10 to 12 ft. for urban/suburban arterials and 10 to 16 ft. for urban/suburban collectors. While there are many studies that evaluate the change in the operational performance of the roadway through the addition of a TWLTL very few have focused on the effects produced by the TWLTL width. The lack of research in this area further encourages the necessity for further studies. To gain more knowledge the simulator study performed in this paper analyzed the effect varying TWLTL widths had on driver maneuverability and gap acceptance.

CHAPTER 3 : METHODOLOGY

The purpose of this study was to evaluate three main objectives:

1. Test and analyze the effect lane and shoulder width combinations have on driver performance
2. Test the effect of curves on lane position for various lane/shoulder width combinations
3. Test operational performance of TWLTL for minimum and maximum widths

This study evaluated how various roadway design elements affect driver behavior. Treatment effects were compared through the use of a driving simulator. The study was conducted through a series of five different phases: 1.) Determine study procedures and obtain IRB approval 2.) Scenario Development 3.) Scenario Review 4.) Full study 5.) Data Analysis. The first step of the study included outlining the experimental procedure for testing subjects. Prior to using the simulator it was imperative to ensure that all requirements for the experiment were met and to gain approval from Clemson's Institutional Review Board for the testing of human subjects. The second phase consisted of scenario development. In this part of the study, all experimental parameters were implemented into the design of three scenarios. These encompassed three lane width and shoulder width combinations and six two-way –left turn lane (TWLTL) treatments. Once all of the scenarios were designed, sample tests were conducted to test the various capabilities and limitations of the simulator and examine the measured variables of lane position, speed, gap acceptance and vehicle heading. For these sample experiments various South Carolina Department of Transportation Officials and graduate students were tested and produced feedback on the scenario layout. After making several alterations to improve the experiment, the full scale study took place. In this phase, subjects drove five adaptation scenarios to acclimate them to the simulator followed by the three treatment scenarios. During the full scale study, data was collected for all participants, thus leading to the final phase of data analysis.

The next four sections will provide extensive detail on the materials used, project details, the scenario layout, participants and data analysis procedure.

Materials

This experiment was conducted through the use of Clemson University's driving simulator located in Brackett Hall. The simulator is a high performance and high fidelity product produced by Drive Safety. It has five projection screens and three configurable rear view mirrors. The simulator has a partial Ford Focus cab with standard driver controls and a full width front interior. The car functions with an automatic transmission and has a 3-D audio system to incorporate the sounds of the engine and traffic noise to the driving experience. The simulator also sits on a platform enabling longitudinal movement.

The software for the simulator is composed of three different components: Vection, Dashboard and HyperDrive Authoring Suite. Vection is the component that runs the simulation. The HyperDrive Authoring Suite is a windows-based software package that enables the ability to design scenario layouts and manipulate various variables relating to traffic, road side entities, and community types amongst others. The software can also collect data on 25 user defined variables pertaining to lane position, acceleration, deceleration, heading and more. Lastly, Dashboard is the interface that bridges the design aspect of HyperDrive to a virtual reality. It transfers the newly developed scenarios in HyperDrive to the driving simulator, thus allowing one to drive their design.

Figure 3.1: Drive Safety DS600 driving simulator

Project Details & Layout

The main objectives for this study were to test and analyze the effect lane and shoulder width combinations have on driver performance, to test the effect of curves on lane position for various lane/shoulder width combinations and to test the operational performance of TWLTLs for minimum and maximum widths. The first two objectives were accounted for in the beginning of the three scenarios. Each scenario started with a

1.5 mile rural curvy two lane highway. The roadway consisted of numerous curves and straight sections. Specific curve radii and roadway layout for the scenarios can be seen in Figure 3.3 and Table 3.1. Along this section, each scenario had different lane/shoulder width combinations. These combinations included 12 ft. lanes and no shoulder for Scenario 1, 12 ft. lanes and a 2 ft. paved shoulder for Scenario 2 and 10 ft. lanes with a 2 ft. paved shoulder for Scenario 3. The speed limit for each roadway was set at 50 miles per hour. Lane position and speed data was collected for this section to analyze the number of right and left edge touches and percent time out of lane per curve. To reduce the effect of speed on the measured variables a 10 miles per hour threshold was allowed. An audio recording was set to say "Increase your speed" if the driver drove below 45 miles per hour and "Slow Down" if the driver exceeded 55 miles per hour.

Figure 3.2: Rural two-lane undivided roadway

Table 3.1: Curve radii per scenario for rural section

Scenario 1 and 2		
Curve	**Radius (m)**	**Radius (ft)**
1	418.0	1371.4
2	378.0	1240.2
3	416.8	1367.5
4	352.7	1157.2
5	375.9	1233.3
6	604.3	1982.6
7	362.3	1188.6

Scenario 3		
Curve	**Radius (m)**	**Radius (ft)**
8	1665.0	5462.6
9	451.6	1481.6
10	344.0	1128.6
11	296.0	971.1
12	370.0	1213.9
13	654.0	2145.7

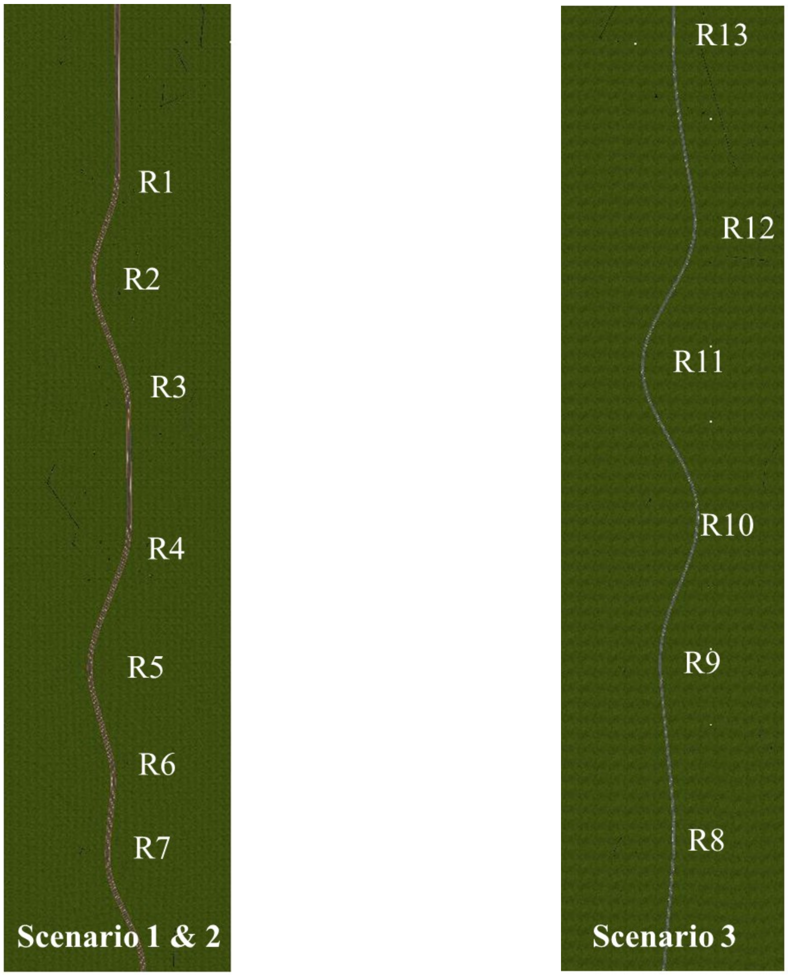


Figure 3.3: Rural roadway geometry

Following the curvy section was a continuous town segment where subjects made a total of four left turns into two-way-left turn lanes. Gap acceptance and vehicle position were measured on both a three lane roadway with a center two-way left turn lane (3T) and a five lane roadway with a center two-way left turn lane (5T). Two of the left turns were made on a 3T roadway, and the remaining two were made on a 5T roadway. Images of these roadways are expressed in Figure 3.4 and 3.5. Both roadway geometries were tested with TWLTL widths of 12, 14 and 16 ft., creating a total of six combinations. Scenario 1 tested TWLTL widths of 12 ft. for the 3T turns and 16 ft. for the 5T turns. Scenario 2 tested 16 ft. for the 3T turns and 14 ft. for the 5Ts while Scenario 3 tested 14 ft. for the 3Ts and 12 ft. for the 5Ts. Overall, each scenario had the same layout containing a rural curvy section, two 3T and two 5T sections. A comprehensive summary and scenario layout image can be seen below.

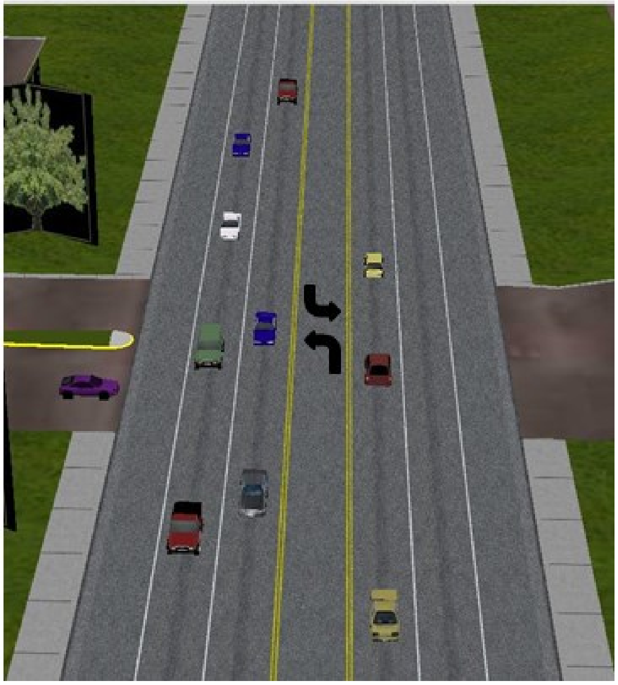


Figure 3.4: 5T section in HyperDrive

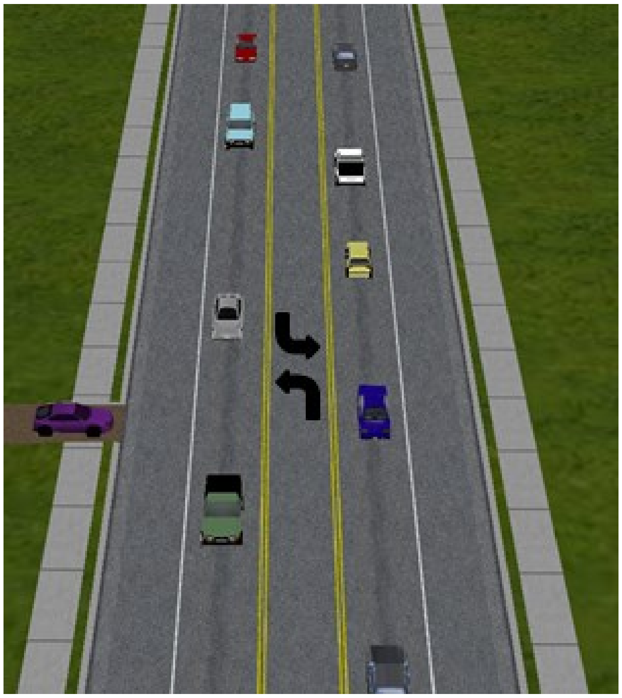


Figure 3.5: 3T section in HyperDrive

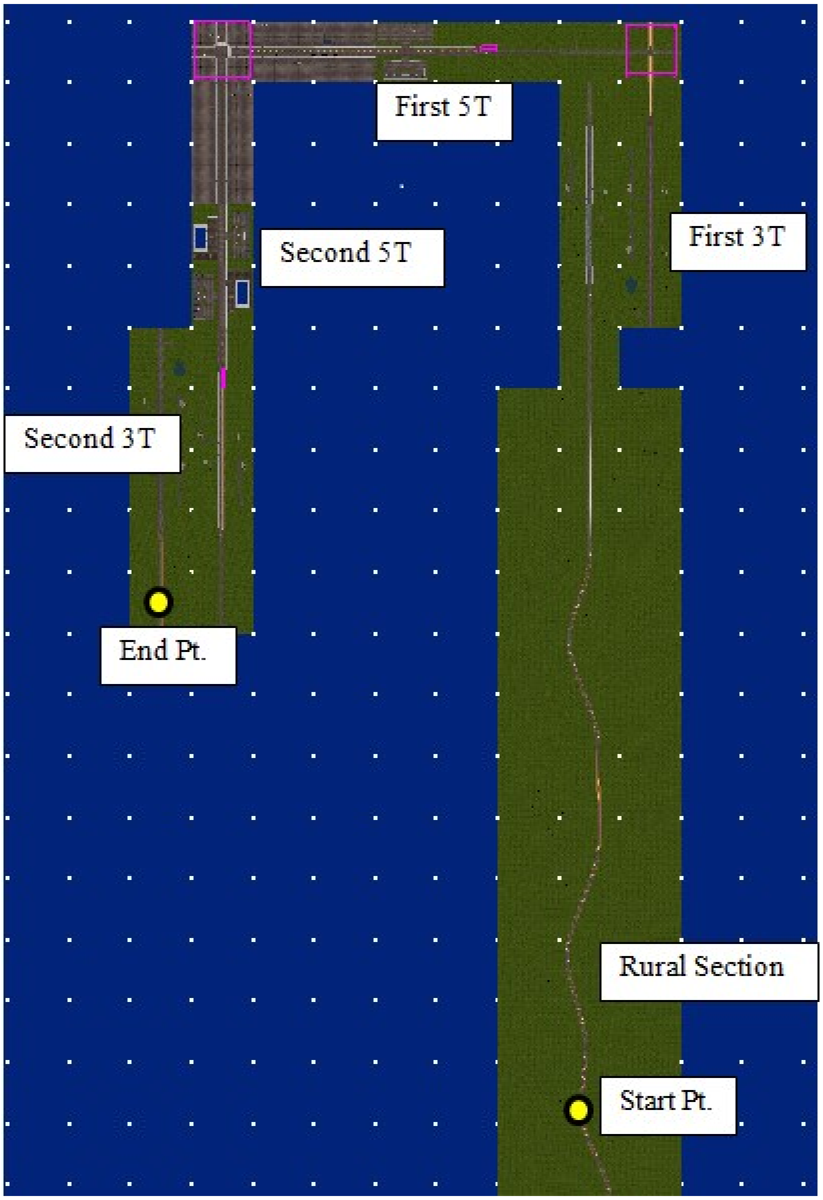


Figure 3.6 : Complete scenario layout in HyperDrive

Scenario Summary

Scenario 1
- Rural 3 mile section (12' lane, no shoulder)
- 3T Section (12' lanes, 12' TWLTL)
- 5T Section (12' lanes, 16' TWLTL)

Scenario 2
- Rural 3 mile section (12' lane, 2' shoulder)
- 3T Section (12' lanes, 16' TWLTL)
- 5T Section (12' lanes, 14' TWLTL)

Scenario 3
- Rural 3 mile section (10' lane 2' shoulder)
- 3T Section (12' lanes, 14' TWLTL)
- 5T Section (12' lanes, 12' TWLTL)

Adaptation Scenarios

To familiarize the participants with the driving simulator's handling, five adaptation scenarios were conducted. The first scenario taught the driver the basics of lane position in the simulator. For this session, the driver drove on a straight road with a speed limit of 45 miles per hour. In the middle of the front screen there were five dots that would light up indicating the vehicle's lane position: far left, left, center, right, and far right. Participants were given the opportunity to drive this scenario twice for thirty seconds to test and understand the different lane boundaries within the simulator. An image of this can be seen in Figure 3.7.

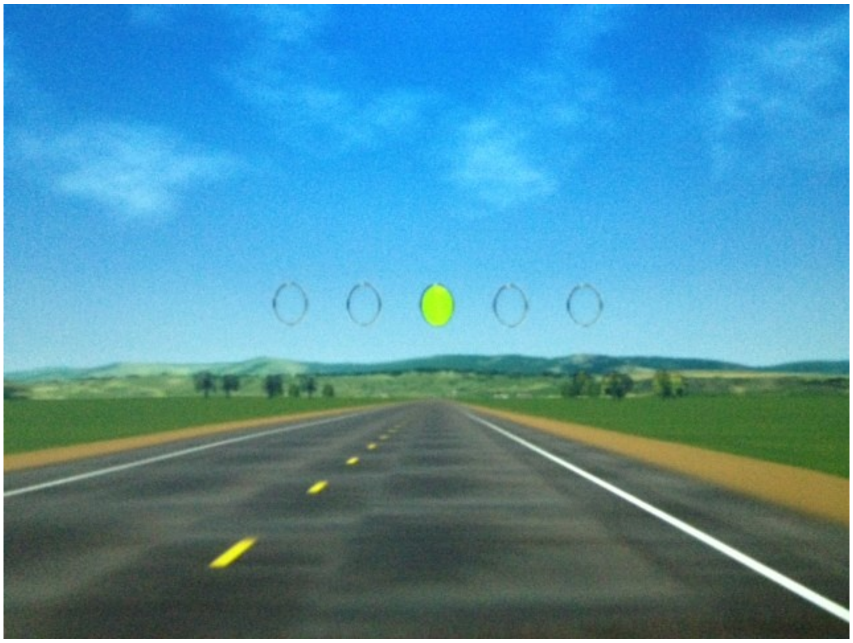


Figure 3.7: First adaptation scenario- lane keeping

The second adaptation scenario practiced lane keeping on a curvy road with a speed limit of 45 miles per hour. For this session, the driver did not have the aid of the five dots on the screen indicating their lane position. The participants drove this scenario for a full sixty seconds, and the number of right and left edge touches during this time period were recorded. The third scenario practiced stopping. Throughout this session, the drivers had to make a series of five stops. Data for this scenario showed how close the car was to the stop bar. A participant performed well if an average of plus or minus two feet was maintained. In the fourth adaptation scenario, the driver had to complete six left turns. The purpose of this scenario was to familiarize the participants with the speed and maneuverability required to perform a left turn. The fifth and final adaptation scenario led the driver to make four right turns. Not only were these scenarios essential in familiarizing participants with the driving simulator, they also helped identify subjects prone to simulator sickness.

Full Scale Study

Participants

The full scale study was conducted for a total of 60 participants. From this total, two age groups were identified. The first age group consisted of 40 young drivers between the ages of 18 to 34. The second group consisted of 20 participants within the age range of 35+ years. All participants were compensated fifteen dollars per hour for the time they spent on the study. The max amount one participant could earn was thirty dollars. Participants were recruited by advertising flyers and word of mouth. The table below is a summary of all the participants that were tested, including those who were unable to complete the study due to simulator sickness.

Table 3.2: Participant data

	Female	**Male**	**Total**
Young	20	20	40
Middle	6	14	20
Dropout- Simulator Sickness	6	6	12
Total # of Participants	-	-	72
# Participants Data used	-	-	60

Design

To design the three experimental scenarios various steps were taken. One of the first steps included determining the different lane and shoulder width combinations and TWLTL widths to be tested. To do this, it was important to become familiar with the driving simulator's program, HyperDrive Authoring Suite where the scenarios were created. This involved learning the functions of the program and identifying useable tiles in its library. The tiles were small roadway segments that would be placed together to form any desired scenario.

It was decided that the first part of each scenario would be the rural curvy two-lane highway section in which the various lane and shoulder width combinations would be tested. Based on the current SCDOT Highway Design Manual guidelines and the availability of lane width tiles within the simulator's library, 12 and 10 ft. lanes were used in this section. The shoulder widths chosen for these lane widths were either a 2 ft. paved shoulder or no shoulder. These values were determined based on the abundance of roadway segments that had either no paved shoulder or a 2 ft. paved shoulder from Part 1 of this study.

Table 3.3: Rural undivided highway variables-Part 1(Baumann and Jordan, 2012)

Independent Variable	Coefficient	Number of Segments
Lane Width (ft)	c_{10}	53
	c_{11}	161
	c_{12}	109
Shoulder Width (ft)	d_0	222
	d_2	101
Speed Limit (mph)	e_{35-}	11
	e_{40-45}	86
	e_{50-55}	226
Driveway Density (Driveways/Mile)	f_{Low}	281
	f_{Med}	42
Moderate Grade	g	68

This produced the roadway combinations of 12ft lanes and no paved shoulder for Scenario 1, 12 ft. lanes with a 2 ft. paved shoulder for Scenario 2 and 10 ft. lanes with a 2 ft. paved shoulder for Scenario 3. To perfect this section of the scenarios a great deal of work was done. One curvy rural tile had 6 ft. shoulders on either side of the roadway. To create no shoulder for Scenario 1 and a 2 ft. shoulder for Scenario 2 various small grass tiles had to be overlapped over the existing large shoulder. Since there was no 10 ft. rural curvy tile, this tile had to be custom made by the designer of Drive Safety. The next step taken to further evaluate this portion of the scenario was to determine the speed of the roadway. It was assumed that the rural tile in each scenario had a superelevation value of 6%. Based on the minimum radius, a design speed of 50 mph was determined from the Policy of Geometric Design of Highways and Streets.

The next part of each scenario was the development of the town segments where participants drove a series of four left turns into TWLTLs. For this step it was important to choose TWLTL widths that would provide acceptable comparative data. Based on the available tiles in the HyperDrive library and the distribution of TWLTL widths that were measured in the field during Part 1 of this study, widths of 12, 14 and 16 ft. were used. The distributions of TWLTL widths for 3T and 5T roadways from Part 1 of the study can be seen in Figure 3.8 and 3.9. Several of these tiles had to be custom designed from DriveSafety.

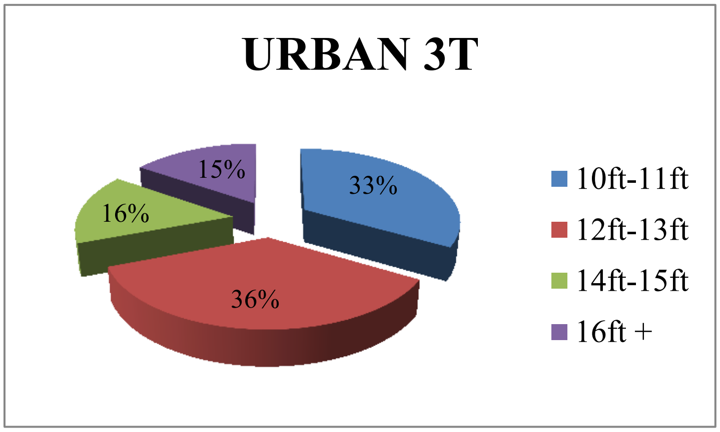


Figure 3.8: Distribution of urban 3T TWLTL widths from Part 1 of study

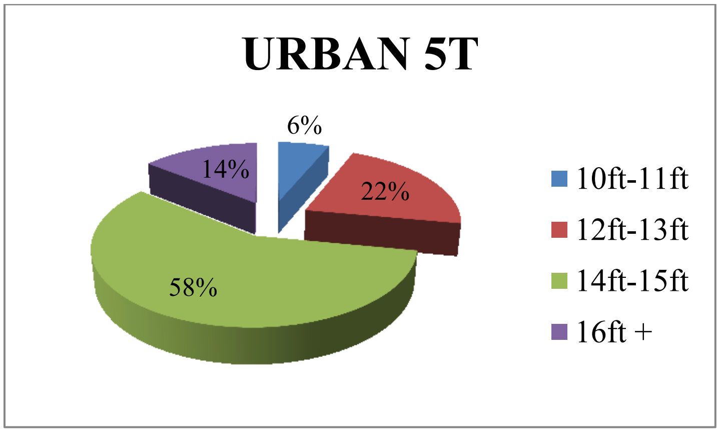


Figure 3.9: Distribution of urban 5T TWLTL widths from Part 1 of the study

Another design aspect of the scenarios that needed to be taken into consideration was the development of the gaps for the 3T and 5T sections. The goal here was to try and emulate the traffic as realistically as possible to get the drivers to perform a left turn maneuver as they would in the real world. To help produce randomization each participant was exposed to two sets of traffic intervals at each left turn. The first interval was composed of several small gaps under 2 s that were unlikely to be accepted by the participants. The second set consisted of 50 gaps that ranged from 3.5-8.0 s. The gaps in this set were arranged in a pseudo-random order. The specific values can be seen in Appendix A. The gaps were implemented into the scenarios through the use of various triggers and TCL coding. Once each scenario was laid out the final step included adding a data collection trigger that would continuously collect lane position, speed, heading, vehicle position, and gap acceptance.

The main problem sought throughout the design process was reducing the effect of simulator sickness. The main cause of simulator sickness in the scenarios was due to the abundance of left turns. To enhance the scenario, before every left turn into a TWLTL the participant was guided by a yellow “follow car.” The follow car would guide the driver to the entrance of the driveway or development and trigger the warp command. This would cause the screens of the simulator to turn black for a few seconds. When the screens returned the subject vehicle would be placed at the exit of the development where they needed to make the left turn. This helped to eliminate many extra left turns in the scenarios. Due to the lengthy time period required for testing, bias measures were also taken into account. To reduce the effects of driver fatigue and driver recognition the order that each participant drove the scenarios was randomized. This allowed for each scenario to be driven first, second and last an equal number of times.

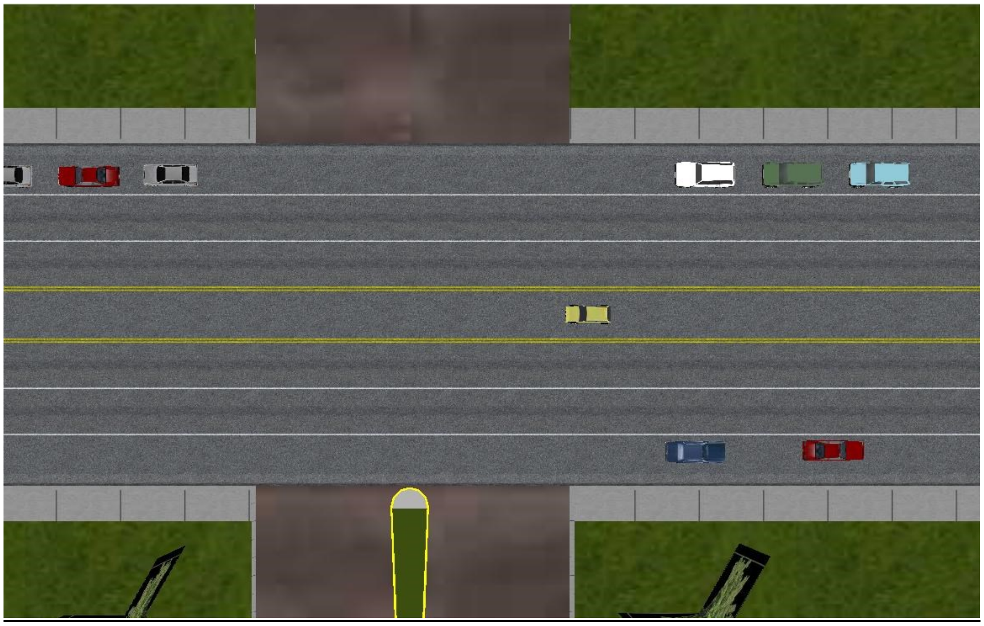


Figure 3.10: Yellow follow car in 5T section

Procedure

All tests for the experiment were conducted by a proctor that read from a set script which can be found in Appendix C. The script was used to maintain uniformity and provide a controlled experiment as there were four people who conducted the experiment for different participants. Before participating in the study, all subjects were required to read and sign a consent form. Then they were asked a series of demographic questions pertaining to their age, gender, and driver's license ownership which was recorded on the participant data sheet which can be found in Appendix D. Next, the participant's blood pressure was measured. Five readings were recorded during a time span of five minutes.

Afterwards, the participants were asked to sit in the car as they were taught about the various operations of the vehicle. Before driving the three test scenarios each participant drove a series of five adaptation scenarios to familiarize them with the driving simulator and test if they get motion sickness. A detailed explanation of the adaptation scenarios can be found in the previous section under Project Details and Layout. Throughout the adaptation scenarios participants were given breaks if they seemed necessary. At the end of each driving session, adaptation and experimental, participants were asked a series of motion sickness questions that were rated from 0-10, with 10 being severe. Examples of these questions include, dizzy, light headed, nauseous, and sweaty. The remaining questions can be found in the data sheet in Appendix D.

After the training sessions participants were instructed to drive as he/she would in their own vehicles as they drove the test scenarios. These consisted of three scenarios that lasted approximately 15 minutes each to complete. All three scenarios tested lane position, gap acceptance and maneuverability into TWLTLs. Scenario differences lied in the roadway geometry. To be specific, Scenario 1 tested lane position on 12 ft. lanes and no paved shoulder for the rural section and gap acceptance and maneuverability on a 12 ft. TWLTL width for the two 3T turns and a 16 ft. TWLTL width for the two 5T turns. Scenario 2 had a 12 ft. lane and 2 ft. paved shoulder for the rural section, 16 ft. TWLTL width for the 3Ts and a 14 ft. TWLTL lane for the 5Ts. Lastly, Scenario 3 had 10 ft. lanes with a 2 ft. shoulder for the rural section and 16 ft. TWLTL width for the 3Ts and 12 ft. TWLTL width for the 5Ts. In between each of the test scenarios, the participants took a break and were asked to complete a safety survey. The survey had various images of different roadways where the participant was asked to rate the scenario in each picture based on their perceived safety. At the very end of the testing session five readings of the participant's blood pressure were taken for a span of five minutes. The blood pressure measurements and safety survey helped to distract participants from the actual variables that were tested in the study.

Procedure for Data Analysis

Rural Section

Continuous data collected from the authoring computer included speed, lane position, vehicle heading, and vehicle position among others. For the rural section the primary variable was the vehicle lane position. Based on the vehicle lane position each participant's percent time out of lane per curve and total number of left or right edge touches was calculated. Lane position values were defined by the driving simulator as the distance between the center of the car to the center of the traveling lane. The value was negative if the center of the car moved to the left of the lane and positive if the car moved to the right. Given continuous lane position data for this roadway segment percent time out of lane and the number of out of lane encroachments were calculated for each participant. The vehicle was considered to be out of lane if any portion of the vehicle touched or crossed the white line on the right side of the lane or the double yellow line to the left of the lane. An example of this can be seen in Figure 3.12.

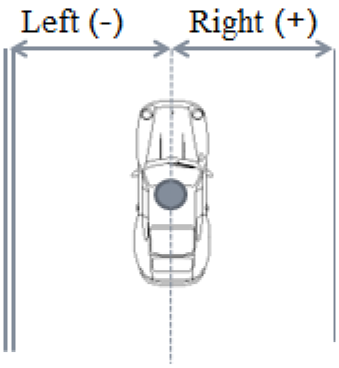


Figure 3.11: Lane position orientation

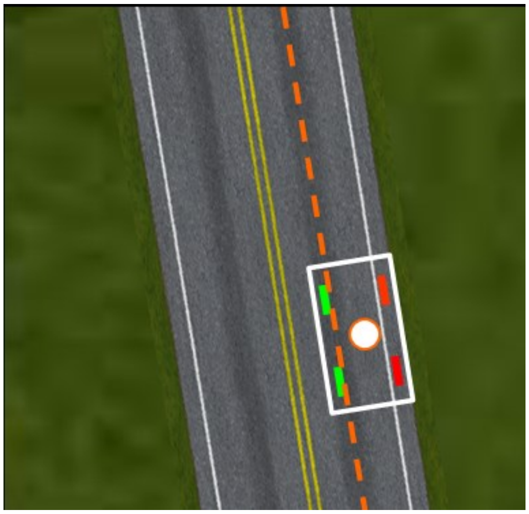


Figure 3.12: Out of lane encroachment

Since the vehicle was a 5.11 ft. wide Ford Focus and the lane was 12 ft. for Scenario 1 and 2, participants had to have lane position values that exceeded 1.0488 or below -1.0488 to be considered out of the lane. Since Scenario 3 had a 10 ft. lane participants were considered out of the lane if the lane position values were greater than .744 or less than -.744. Then each curve and straight section was designated by their starting and ending X, Y coordinates. The specific coordinates chosen for each segment can be found in Appendix B. Based on these boundaries the number of right and left edge touches and percent time out of lane was calculated for each section.

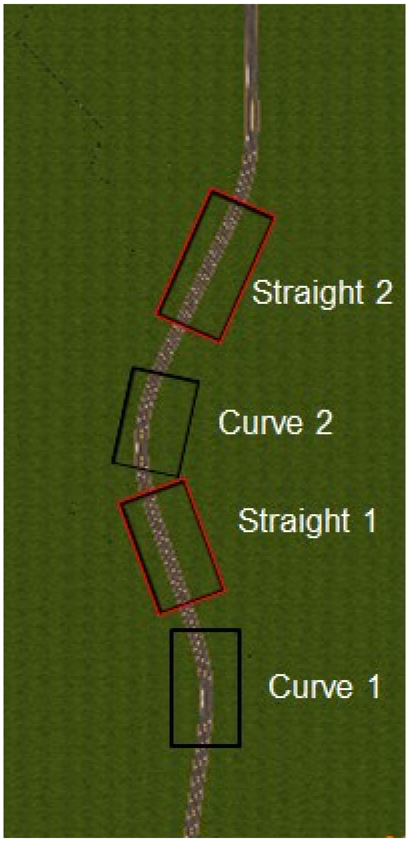


Figure 3.13: Curve and straight section boundaries

Gap Acceptance

Gap data from the study was analyzed descriptively and statistically. For each scenario the mean and standard deviation was computed separately for 3T and 5T turns. To see if there was any statistical significance between the average gaps per scenario for the 3T turns a randomized block design was implemented. In this design, the different lane widths in each scenario were the treatment and the block factor was the participant. Since many participants waited the longest at their first 3T in their first scenario, another evaluation was done after removing the first turn for each participant. The first turn for every participant in each scenario had to be removed to reduce repeated measures so that each participant contributed an equal amount of data points per scenario. A randomized block design was also used for the 5T gap data to see if lane width had an effect on gap acceptance.

TWLTL

Another method used to analyze how the width of the TWLTL affects its operational performance was by creating vehicle trajectories. From these trajectories relationships between the TWLTL width and the participants' maneuverability became more apparent. For this study, trajectories for the second 3T for 30 participants were drawn by applying the vehicle's X and Y coordinates into AutoCAD. Two different layers of a line and car were used to draw the trajectories as seen in image B and C of Figure 3.14. For the scope of this study the number of encroachments for the 30 participants in each scenario was analyzed. Additional analysis in a following paper will be based off of the proportion of time the vehicle was out of the TWLTL for a designated distance. This was calculated by first offsetting the vehicle's path by one foot increments which can be seen in Figure 3.14. Then all of the one foot lines within the boxed area were evaluated. The subject was considered out of the lane if the line crossed the black boundary that is drawn in image A of Figure 3.14.

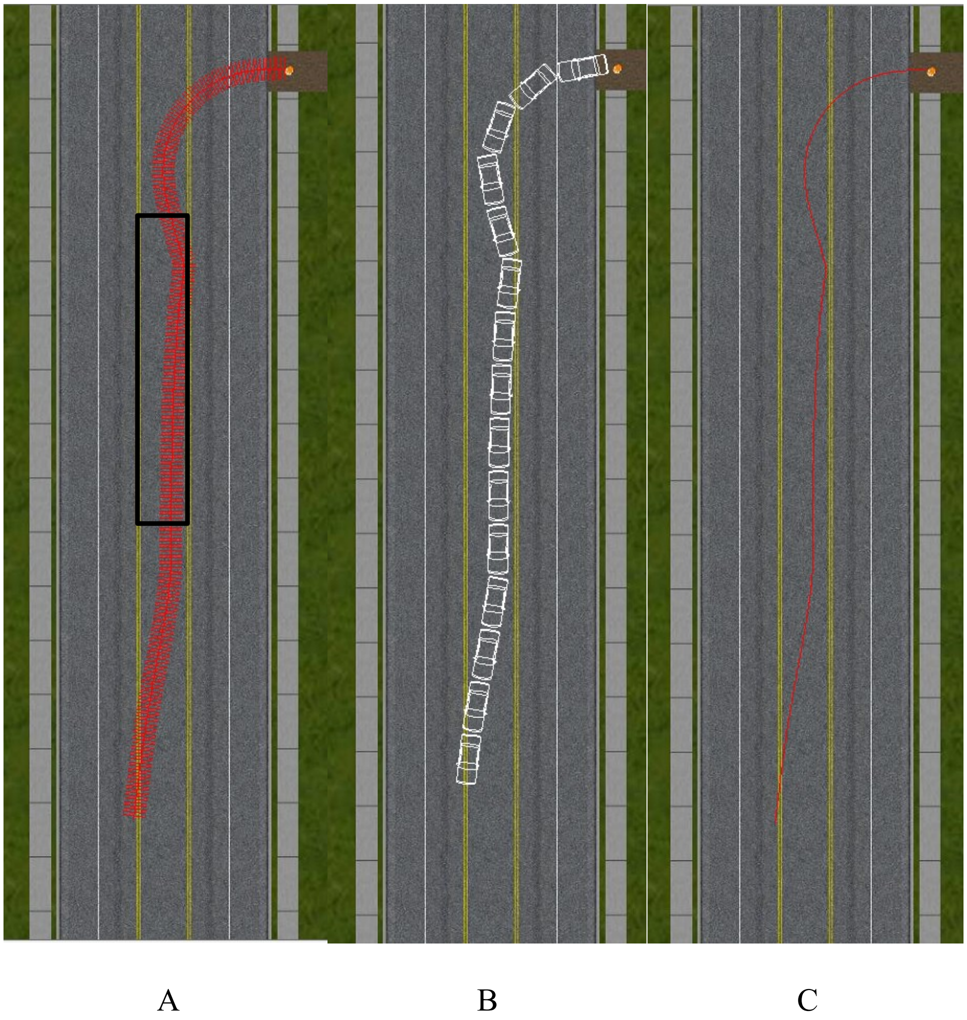


Figure 3.14: Vehicle trajectory for 3T section

CHAPTER 4 : RESULTS

The data is expressed as three separate sections. First, descriptive data representing the percent time out of lane and number of out of lane encroachments per scenario for the rural section is presented. In the second section, comparisons between the six TWLTL widths were statistically examined to determine if there was a significant effect upon gap acceptance. Descriptive statistics were also performed to determine a relationship between age and gender on gap acceptance. Lastly, several 3T trajectories were examined to examine the effect different TWLTL widths have upon diver maneuverability.

All inferential tests were completed as a completely random block design with an alpha of .05. To reduce the variability of repeated measures the participant was the block and the scenarios were the treatment. Based on the design multiple comparison ANOVAs were produced. Additional simple effect tests were used if significant interactions were found.

Rural Section

Percent Time out of Lane

The first step taken to analyze the curvy rural section for each scenario involved calculating the percent out of lane for each participant in each scenario. For Scenario 1, a total of 5 participants went out of lane on the 12 ft. roadway with no paved shoulder. Scenario 2 had a 12 ft. roadway and a 2 ft. shoulder and had a total of 7 participants drive out of the lane. Lastly, Scenario 3 had a 10 ft. roadway and a 2 ft. shoulder and had a high of 14 participants drive out of the lane. Specific percent time out of lane values for each scenario can be seen in the following tables. From the tables a pattern shows that many of the participants that went out of the lane in Scenario 1 also proceeded to go out of the lane in the following scenarios. After looking at age, gender and post test questions regarding crashes and speeding tickets, no correlation between the participants was found. Results from the analysis show very little difference between Scenario 1 and 2. The reduced lane width in Scenario 3 proved to be more challenging as more participants failed to stay within the lane boundaries.

Table 4.1: 12 ft. lane no shoulder- Percent time out of lane data

SCENARIO 1												
C= Curve				**Radius (m)**		418	378	416.8	352.7	375.9	604.3	362.3
S=Straight				**Radius (ft.)**		1371.4	1240.2	1367.5	1157.2	1233.3	1982.6	1188.6
Length (ft.)	1622.0	348.6	658.0	422.2	448.8	415.8	657.6	511.0	466.7	642.7	448.8	628.2
Participant #	**S1**	**S3**	**S4**	**S5**	**S6**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
11	-	-	-	-	-	-	-	-	**11.2%**	-	-	-
22	-	-	-	-	-	-	-	-	-	**3.0%**	-	-
44	-	-	-	-	-	**12.3%**	-	-	-	-	**44.6%**	-
48	-	-	-	-	-	-	-	-	-	-	**23.8%**	-
61	-	-	-	-	-	-	-	-	-	-	**9.5%**	-

Table 4.2: 12 ft. lane 2 ft. shoulder- Percent time out of lane data

SCENARIO 2												
C= Curve				**Radius (m)**		418	378	416.8	352.7	375.9	604.3	362.3
S=Straight				**Radius (ft.)**		1371.4	1240.2	1367.5	1157.2	1233.3	1982.6	1188.6
Length (ft.)	1622.0	348.6	658.0	422.2	448.8	415.8	657.6	511.0	466.7	642.7	448.8	628.2
Participant #	**S1**	**S3**	**S4**	**S5**	**S6**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
11	-	-	-	-	-	-	-	-	-	-	**28.3%**	-
22	**6.4%**	-	-	-	-	-	**39.4%**	-	-	-	-	-
32	-	-	-	-	-	-	**17.1%**	-	-	-	-	-
36	-	-	-	-	-	**36.1%**	-	-	-	-	-	-
44	-	-	-	-	-	**0.3%**	-	-	**22.5%**	-	**73.2%**	-
46	-	-	-	-	-	-	-	**1.5%**	-	-	-	-
48	-	-	-	-	-	-	-	-	-	**16.9%**	**21.7%**	-

Table 4.3: 10 ft. lane 2ft. shoulder- Percent time out of lane data

SCENARIO 3										
C=Curve			**Radius (m)**		654	370	296	344	451.6	1665
S=Straight			**Radius (ft.)**		2145.7	1213.9	971.1	1128.6	1481.6	5462.6
Length (ft.)	485.8	545.7	279.7	811.1	675.6	740.1	1033.2	926.6	588.8	661.7
Participant #	**S13**	**S12**	**S10**	**S8**	**C13**	**C12**	**C11**	**C10**	**C9**	**C8**
5	-	-	-	-	-	-	**12.3%**	-	**13.9%**	-
7	-	-	-	-	-	-	-	-	**38.0%**	-
8	-	-	-	-	-	**15.7%**	-	**12.6%**	-	-
11	-	-	-	-	**9.1%**	-	-	**8.6%**	-	-
20	-	-	-	-	**14.3%**	-	-	-	-	-
22	-	-	-	-	-	-	-	-	**29.0%**	-
31	-	-	-	-	-	-	-	**4.07%**	-	-
36	-	-	-	-	-	**22.7%**	-	**21.8%**	-	**13.9%**
42	-	**15.8%**	**49.5%**	-	-	**6.5%**	-	-	-	-
44	-	-	-	-	-	**53.1%**	**13.2%**	**29.1%**	**26.7%**	-
48	-	-	-	-	-	**1.9%**	**80.0%**	-	-	-
50	-	-	-	-	-	-	-	**6.3%**	-	-
61	-	-	-	-	-	-	**16.1%**	**11.9%**	-	-
64	-	-	-	-	**15.5%**	-	-	-	-	-

The tables also express that those who did go out of the lane typically did so on curvy sections of the roadway. A further evaluation was conducted by calculating each participant’s cumulative time out of lane for all curves and creating a histogram for each scenario. From the graphs the 85th , 90th, and 95th percentile for time out of lane for Scenario 1, 2 and 3 was determined. The 85th percentile values were 0%, 0% and 2.59% respectively. This further indicates no difference between Scenario 1 and 2 as 85% of the participants did not drive out of the lane. However, the 10ft lane with a 2ft. shoulder in Scenario 3 had a significant impact on lane position as 85 percent of people drove 2.59% out of the lane or less.

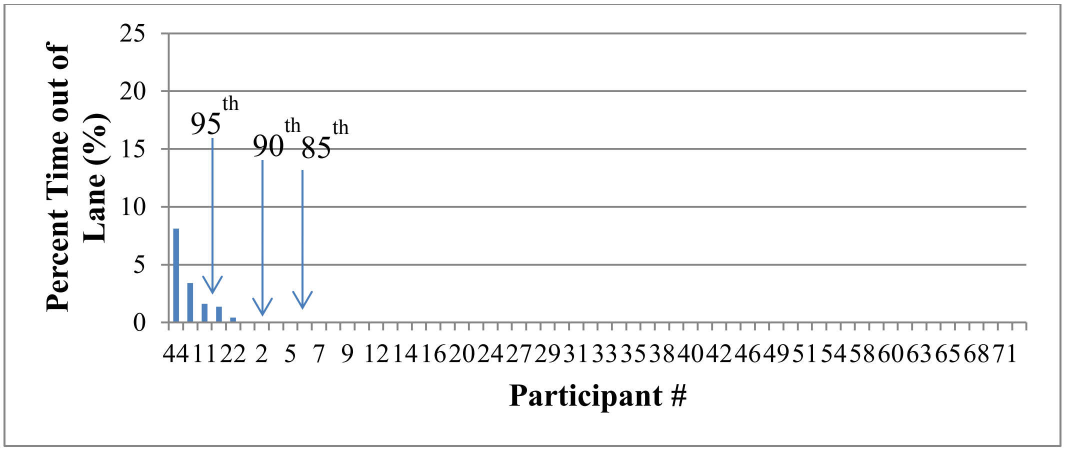


Figure 4.1: Scenario 1- Percent time out of lane in curves

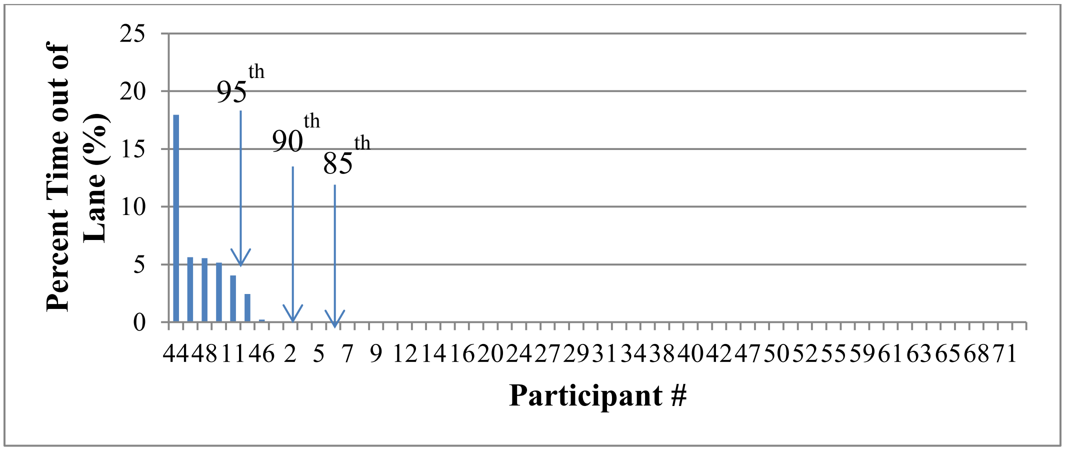


Figure 4.2: Scenario 2- Percent time out of lane in curves

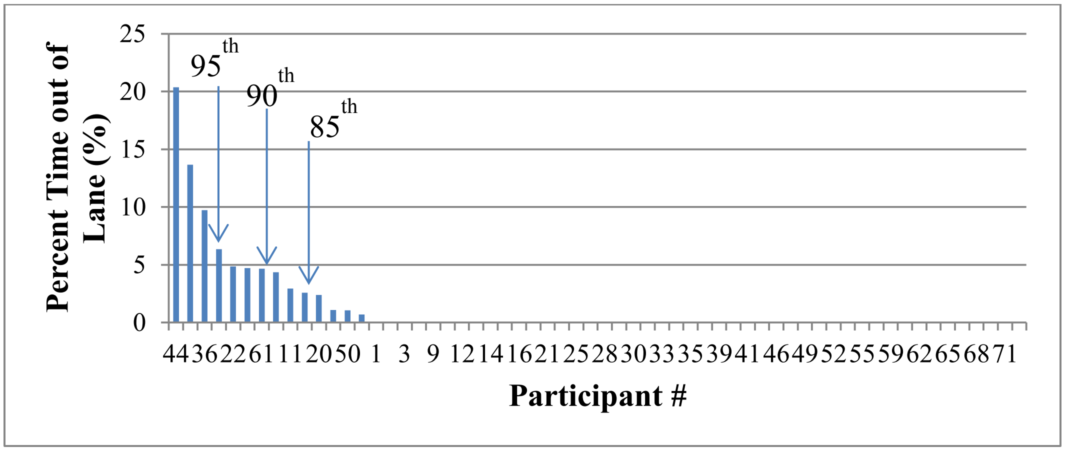


Figure 4.3: Scenario 3- Percent time out of lane in curves

Table 4.4: Total Percent Time out of lane for Curves by percentile

Percentile	Scenario 1	Scenario 2	Scenario 3
85th	0.00 %	0.00 %	2.59 %
90th	0.00 %	0.22 %	4.66 %
95th	1.36 %	5.15 %	6.34 %

Out of Lane Encroachments

Effects from the lane/shoulder width combinations were further analyzed by observing the total number of left and right encroachments for each scenario. Right hand encroachments were defined by the participant crossing the white line on the right side of the lane. Left hand encroachments were cases when the participant moved towards the left of the lane touching or crossing the center line of the roadway.

For the roadway that had a 12 ft. lane width and no shoulder there were 1 right and 5 left encroachments. Due to the absence of a shoulder it is evident that the participants overcompensated their steering by gravitating towards the center of the roadway to avoid going off the road. The 12 ft. lane and 2 ft. shoulder roadway in Scenario 2 had a total of 7 left and 6 right hand encroachments. Here it is believed that the extra space given by the shoulder caused the participants to perceive this road to be safer. From this sense of security it is possible that the participants felt they had more room for errors and corrections thus causing them to utilize more of the roadway width in which these encroachments occurred. The last combination of 10 ft. lanes and a 2ft. shoulder was expressed in Scenario 3 with a high of 14 left and 16 right hand encroachments. The significant increase of encroachments for this combination indicates that the reduced lane width had an effect upon lane position. While there were encroachments for each scenario, none of the crossings in Scenario 2 and 3 exceeded the boundaries of the shoulder. Specific values for each curve can be seen in Table 4.5 and 4.7.

Table 4.5: Left and right encroachments for Scenario 1&2

	Scenario 1 12 ft. lane, no shoulder		**Scenario 2 12 ft. lane, 2 ft. shoulder**	
Section Type	**Left**	**Right**	**Left**	**Right**
Straight 1	-	-	-	1
Straight 3	-	-	-	-
Straight 4	-	-	-	-
Straight 5	-	-	-	-
Straight 6	-	-	-	-
Curve 1 (Left)	1	-	2	-
Curve 2 (Right)	-	-	-	4
Curve 3 (Left)	-	-	1	-
Curve 4 (Left)	1	-	1	-
Curve 5 (Right)	-	1	-	1
Curve 6 (Left)	3	-	3	-
Curve 7 (Right)	-	-	-	-
Total	5	1	7	6

Table 4.6: Curve details for Scenario 1&2

	Radii (m)	**Radii (ft.)**
Curve 1	418	1371.4
Curve 2	378	1240.2
Curve 3	416.8	1367.5
Curve 4	352.7	1157.2
Curve 5	375.9	1233.3
Curve 6	604.3	1982.6
Curve 7	362.3	1188.6

Table 4.7: Left and right encroachments for Scenario 3

Scenario 3 **10ft lane, 2 ft. shoulder**		
Section Type	**Left**	**Right**
Straight 13	-	-
Straight 12	-	1
Straight 10	-	1
Straight 8	-	-
Curve 13 (Right)	-	3
Curve 12 (Left)	5	1
Curve 11 (Right)	-	4
Curve 10 (Left)	8	-
Curve 9 (Right)	0	6
Curve 8 (Left)	1	-
Total	14	16

Table 4.8: Curve details for Scenario 3

	Radii (m)	**Radii (ft.)**
Curve 13	654	2145.7
Curve 12	370	1213.9
Curve 11	296	971.1
Curve 10	344	1128.6
Curve 9	451.6	1481.6
Curve 8	1665	5462.6

Effects from the 10ft. roadway were further identified by creating histograms to determine the 85th, 90th and 95th percentile for each scenario. The 85th percentile fell at 2 encroachments for Scenario 3 and 0 encroachments for Scenario 1 and 2. Based on the relationship found between lane position and the 10 ft. roadway as determined from the results regarding percent time out of lane and number of encroachments it can be suggested that curve widening be applied on 10 ft. roadways.

Table 4.9: Total number of encroachments

Percentile	Scenario 1	Scenario 2	Scenario 3
85th	0	0	2
90th	0	1	2
95th	1	2	2

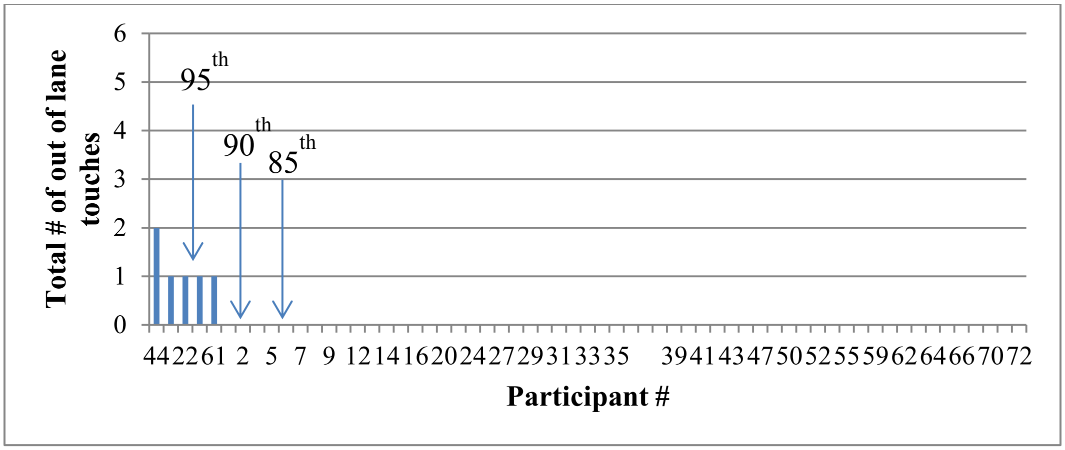


Figure 4.4: Scenario 1 (12 ft.-0 ft.) total encroachments

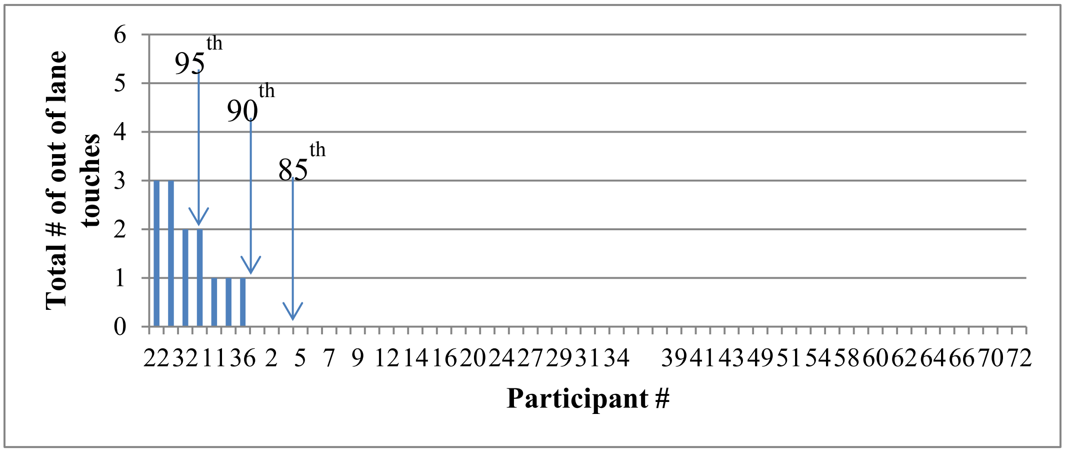


Figure 4.5: Scenario 2 (12 ft.-2 ft.) total encroachments

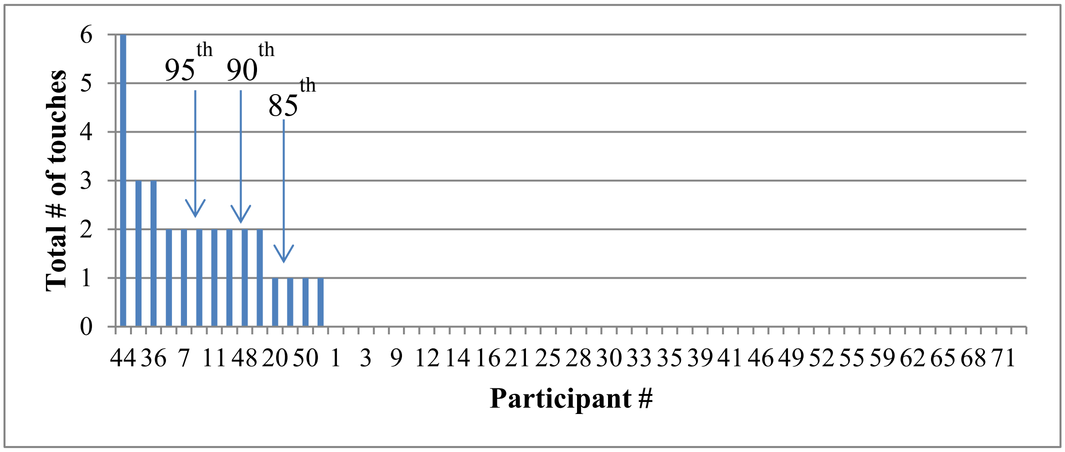


Figure 4.6: Scenario 3 (10 ft.-2 ft.) total encroachments

Lane position was further investigated by comparing the average lane position and standard deviation for each roadway combination. As seen in Table 4.10 the average lane position for Scenario 1 and 2 were towards the left with values of -.212 ft. and -.100 ft. respectively. Scenario 3 had an average lane position towards the right of the lane at .149 ft. From these values it is evident that the roadway without a shoulder caused the participants to drive more towards the left of the lane to avoid driving off the road. The standard deviation values for each scenario also show that more variation was found for the two 12 ft. roadways. The standard deviation reduced for the narrower lane width of 10 ft. as the participants focused more to stay in the lane. These results further express the relationship found in Ben-Bassat and Shinar's (2011) study indicating that the standard deviation of lane position increases as the roadway width increases. Statistical analysis showed that the roadway combination did have an effect upon the mean lane position. Results from the test are expressed in Table 4.11.

Table 4.10: Lane position statistics

	Scenario 1 (12 ft.-0 ft.)	**Scenario 2 (12 ft.-2 ft.)**	**Scenario 3 (10 ft.-2 ft.)**
Avg. Lane Position (ft.)	-0.212	-0.100	0.149
Avg. Std. Deviation (ft.)	0.459	0.461	0.369

Table 4.11: Ordered differences report

Level	**- Level**	**Difference**	**Std Err Dif**	**Lower CL**	**Upper CL**	**p-Value**
S3	S1	0.1098845	0.0115862	0.0823827	0.137386	<.0001*
S3	S2	0.0759006	0.0115862	0.0483988	0.103402	<.0001*
S2	S1	0.0339839	0.0115862	0.0064821	0.061485	0.0112*

Additional observations were made regarding the relationship between the number of encroachments and curve size. All of the curve radii in the three scenarios were split into three categories of small, medium and large. The small curves fell in the range of 900- 1230 ft. Curves within the range of 1231-1500 ft. were recognized as medium and large curves were between 1501-5500 ft. Based on these ranges and the radii of the curves given in the scenarios most encroachments were experienced on the smaller curves.

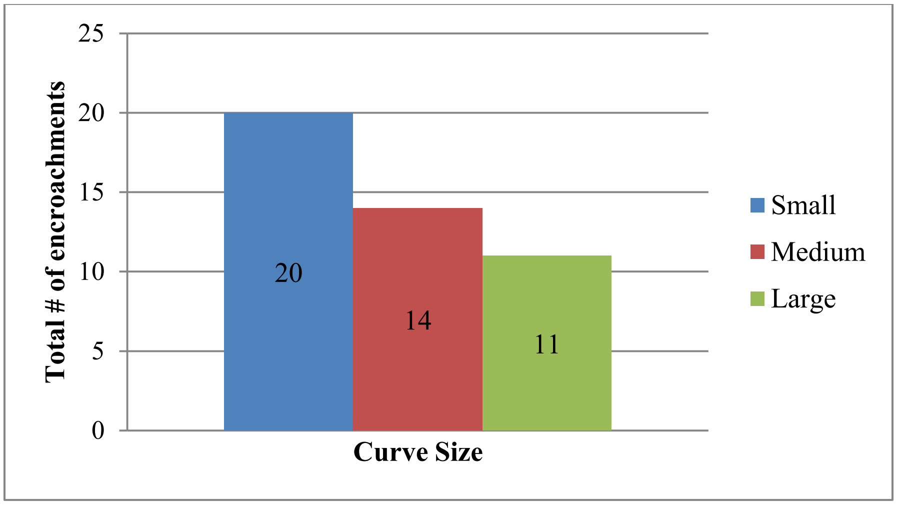


Figure 4.7: Effects of roadway geometry on vehicle encroachments

Gap Acceptance

In each scenario there were two sections that had a three lane roadway with a center lane (3T) and two sections that had a five lane roadway with a center lane (5T). During these sections, participants performed left turns from a development exit or driveway into a two-way left turn lane. From these various left turns analyses were performed to determine if the width of the TWLTL had any effect upon gap acceptance.

3T Sections

As participants entered the continuous town section they completed the left turns in the order of the first 3T followed by both 5T sections and ended the scenario with the last 3T. From this each participant had a total of two 3T gaps recorded for each scenario.

The first analysis performed to determine if the TWLTL width affected gap acceptance for the 3T sections was by comparing the mean gap for each scenario in a completely random block design. The data set used for this test included both turns for each participant for all three scenarios. The mean gap values were 5.4 s for Scenario 1, 5.3 s for Scenario 2 and 5.1 s for Scenario 3. Results from the ANOVA found no significance between the means, thus expressing that the TWLTL width had no effect upon gap acceptance (p= .1137). Analysis between the first and second 3T turn indicated that the order was statistically significant (p= <.0001). Due to this, it was predicted and noted that participants generally took larger gaps on the first turn as they were not yet familiar with making a left turn in this type of setting in the simulator. To remove any effect caused by the first turn data an additional ANOVA was performed on a data set containing only the second turn gaps for each scenario. Despite the removal of the first turn the standard deviation values varied little and the mode remained 5 or 6 s as compared to the data set containing all turns. Results from the ANOVA also expressed that the TWLTL width had no effect upon gap acceptance (p=.1182).

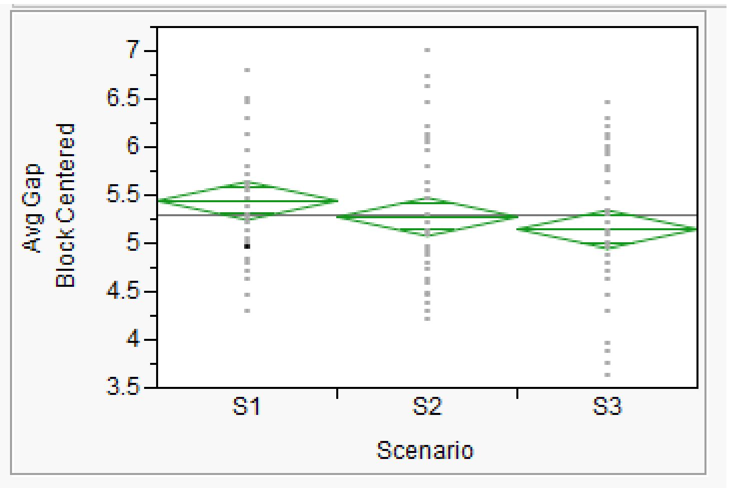


Figure 4.8: All 3T turns

Figure 4.9: Analysis of Variance for all 3T turns

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**	**Prob > F**
Scenario	2	2.64718	1.32359	2.2149	0.1137
Participant	59	181.3	3.07288	5.1421	<.0001*
Error	118	70.51631	0.5976	-	-
C. Total	179	254.4635	-	-	-

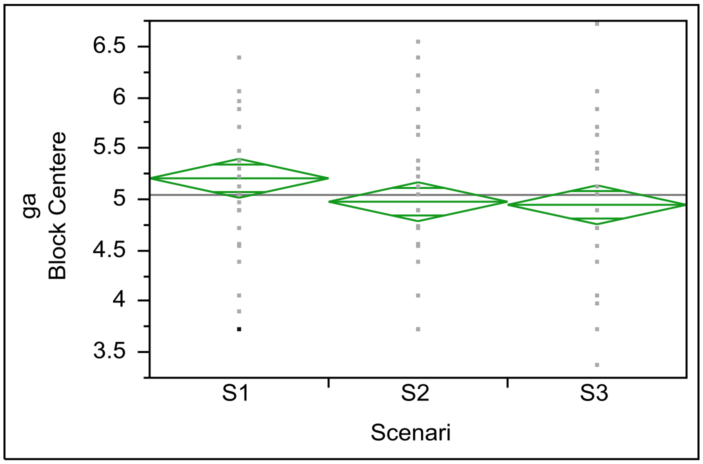


Figure 4.10: Second 3T turn

Table 4.12: Analysis of Variance for second 3T turn

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**	**Prob > F**
Scenario	2	2.4201	1.21007	2.1742	0.1182
Participant	59	227.885	3.86247	6.9399	<.0001*
Error	118	65.6739	0.55656	-	-
C. Total	179	295.979	-	-	-

To further investigate the effect produced based on the order of the turn additional tests were performed to compare the mean values of the first 3T turn to the second 3T turn for each scenario. Mean gap values for the first turn were 5.7 s for Scenario 1, 5.6 s for Scenario 2 and 5.4 s for Scenario 3. The mean gap values for the second turn were 5.2 s, 5.0 s and 4.9 s respectively. From these values it is clear that on average participants took larger gaps on their first turn than the second turn for each scenario. As stated previously, it is assumed that after performing the first left turn the maneuver the driver felt more safe and accustomed to the simulator thus causing them to accept a smaller gap for the second 3T left turn. Several matched pairs comparisons revealed that the mean values between the first and second turn for each scenario were statistically significant.

Table 4.13: Gap Data for All 3T turns

Statistics	Scenario 1 (12 ft.)	Scenario 2 (16 ft.)	Scenario 3 (14 ft.)
Avg. Gap (s)	5.4	5.3	5.1
Std. Deviation	1.3	1.3	1.3
Mode	6.0	6.0	6.0
Median	6.0	5.0	5.0

Table 4.14: Gap Data for First 3T turn

Statistics	Scenario 1 (12 ft.)	Scenario 2 (16 ft.)	Scenario 3 (14 ft.)
Avg. Gap (s)	5.7	5.6	5.4
Std. Deviation	1.2	1.4	1.3
Mode	7.0	6.0	6.0
Median	6.0	6.0	6.0

Table 4.15: Gap Data for Second 3T turn

Statistics	Scenario 1 (12 ft.)	Scenario 2 (16 ft.)	Scenario 3 (14 ft.)
Avg. Gap (s)	5.2	5.0	4.9
Std. Deviation	1.4	1.2	1.3
Mode	6.0	6.0	5.0
Median	5.0	5.0	5.0

Delay

Observations were also made based on the delay participants experienced. For each scenario there was very little difference in mean delay as they were 21.1 s, 21.2 s and 20.5 s. Though when broken down into turn order Table 4.14 shows that on average the participants waited longer on their first 3T turn than their second turn. Figure 4.12 and 4.13 show that the interval range was 0-39 for the first turn and 0-14 for the second turn. The histograms also show that for the second turn more people accepted gaps within the first four intervals.

Table 4.16: Average Delay (s)

	Scenario 1 (12 ft.)	Scenario 2 (16 ft.)	Scenario 3 (14 ft.)
All turns	21.1	21.2	20.5
First turn	23.1	25.2	23.8
Second turn	19.2	17.1	17.1

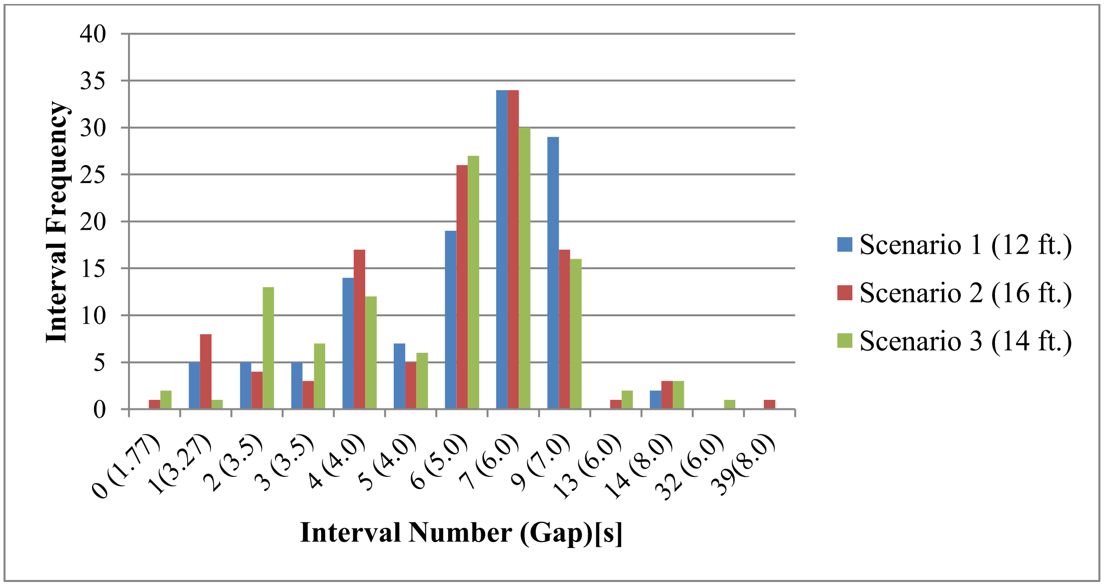


Figure 4.11: Gap interval frequency for All 3T turns

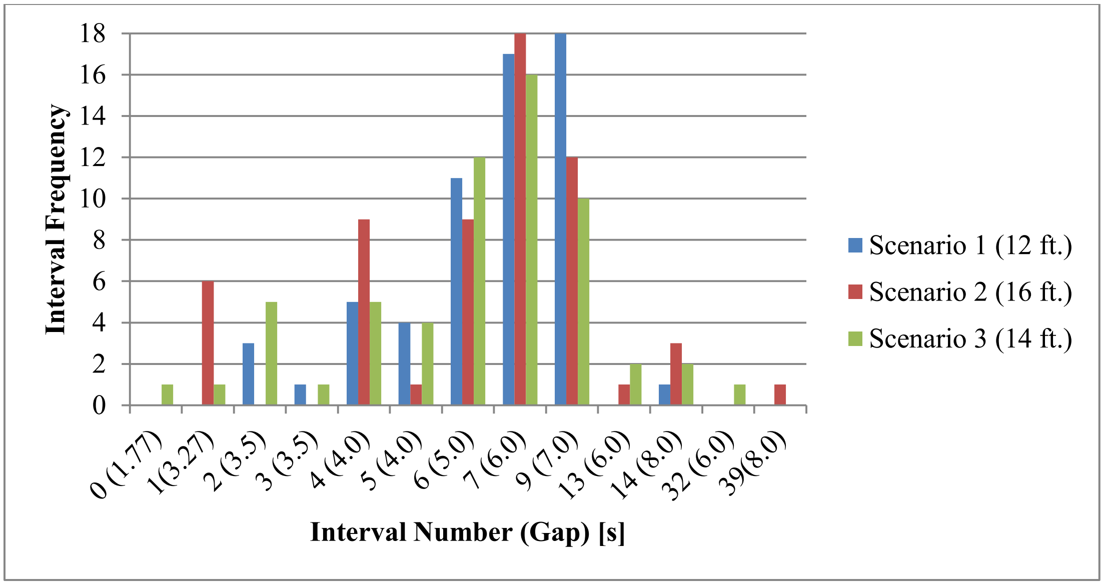


Figure 4.12: Gap interval frequency for First 3T turn

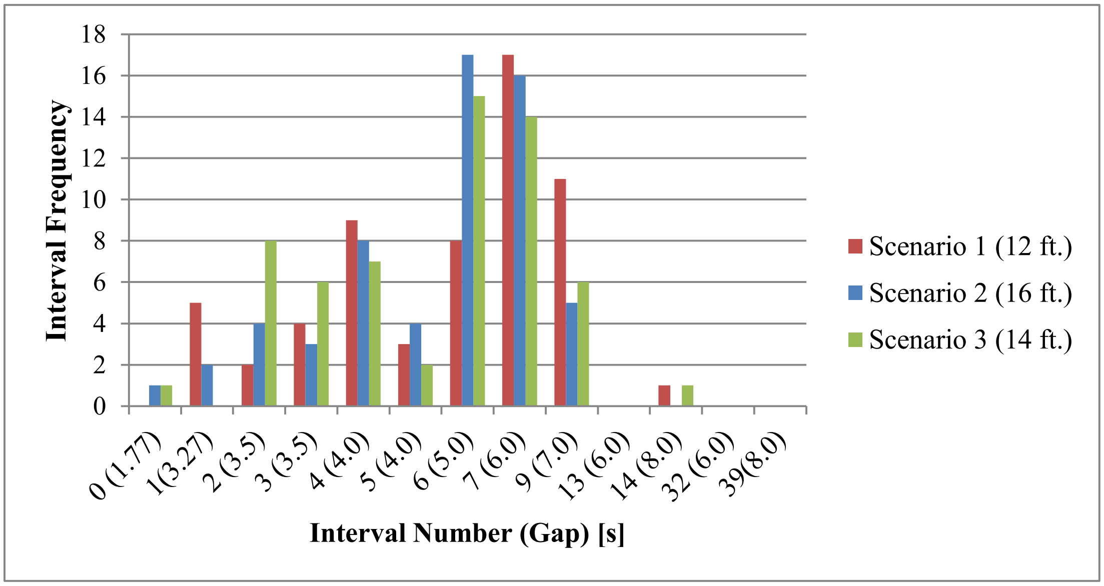


Figure 4.13:Gap interval frequency for second 3T turn

Table 4.17: Cumulative delay per traffic interval for 3T turns

Interval	Delay (s)	Gap (s)
1	1.77	3.27
2	3.27	3.5
3	6.77	3.5
4	10.27	4
5	14.27	4
6	18.27	5
7	23.27	6
9	33.77	7
13	52.77	6
14	58.77	8
32	142.27	6
39	177.77	8

Scenario Order

Since each scenario had identical layouts a final test was conducted to evaluate the effects of driver recognition and fatigue. To try and reduce this effect the scenario order was evenly randomly assigned so that an equal number of participants would begin and end with Scenario 1 and so forth for the other scenarios. To test this, the final analysis for the 3T sections compared the mean gap values based on the first, second and third scenario driven. For this test the scenario numbers were removed as the interest was solely focused on how the participants drove differently based on the order. As shown in Table 4.16 the average gap was 5.88 s for the first scenario, 5.08 s for the second and 4.90 s for the last one. The ANOVA from the completely random block design, as shown in Table 4.17, revealed that there was a significant effect produced by the order (p=<.0001). Effect tests were then conducted proving that the mean gap of the first scenario driven was higher and statistically significant between the second (p=<.0001) and third scenario (p=<.0001). The following results are expressed in Table 4.17 and 4.18.

Table 4.18: Gap Data for Scenario Order

	First	**Second**	**Third**
Avg. Gap (s)	5.88	5.08	4.90
Std. Deviation	0.88	1.14	1.29
Median	6	5.07	4.75
Mode	6	6	4.5

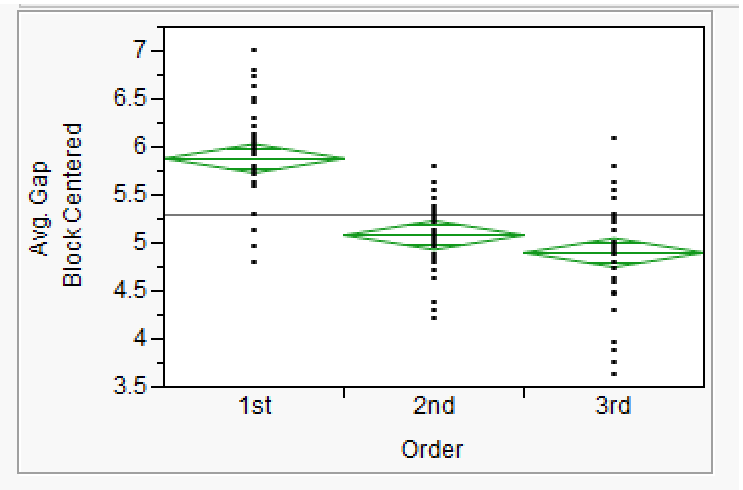


Figure 4.14: Average Gap for Scenario Order

Table 4.19: Analysis of Variance for Scenario Order

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Order	2	32.6932	16.3466	47.6622	<.0001*
Participant	59	181.3	3.0729	8.9597	<.0001*
Error	118	40.4702	0.343	-	-
C. Total	179	254.463	-	-	-

Table 4.20: Pairwise Comparisons for Scenario Order

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
1st	3rd	0.981333	0.106922	0.72754	1.23513	<.0001*
1st	2nd	0.799	0.106922	0.54520	1.05280	<.0001*
2nd	3rd	0.182333	0.106922	-0.07147	0.43613	0.2075

These findings also provide evidence indicating that the participants were more apprehensive and cautious when driving the first scenario as they were unfamiliar with the layout. Once the participants became accustomed to the layout and the left turn maneuver they began to accept smaller gaps in the following scenarios. This trend can also be seen by looking at the delay data. Similar to the average gap data the average delay was highest for the first scenario driven, and decreased for the next two scenarios. The average delay values are 27.77 s, 18.50 s and 16.62 s respectively. From these values it is obvious that there is a large difference of 9.27 s between the first and second scenario and a minimal difference of 1.88 s between the second and third scenario. These differences show that a learning curve took place. For the first scenario many participants waited longer as they anticipated the traffic to stop. Once they realized that the traffic was constantly being generated they eventually accepted a gap and crossed into the TWLTL. By the second and third scenario the participants felt more comfortable with the setting and began to wait less and take shorter gaps. The frequency of intervals taken can be seen in Figure 4.15. From the figure it is clear that the first scenario exceeds the second and third scenario from the 7th interval on. Many participants took the 7th or 9th interval and two even took the 32nd and 39th interval out of a total of 50 intervals. Clearly more people waited less time during the second and third scenario as there are higher values in the lower intervals from 0 to 4.

Table 4.21: Delay data based on scenario order

	First	Second	Third
Avg. Delay (s)	27.77	18.50	16.62
Median	23.27	18.27	18.27
Mode	23.27	18.27	18.27

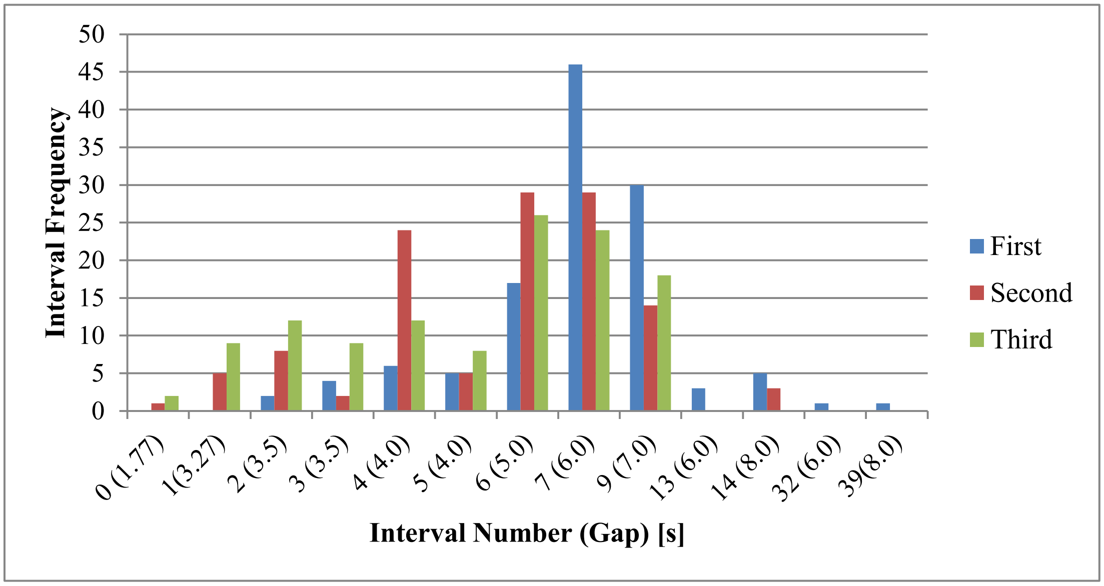


Figure 4.15: Gap interval frequency for scenario order

5T Sections

In between the two 3T sections of the scenarios there were two 5T roadways. For these sections the center lane was 16 ft. for Scenario 1, 14 ft. for Scenario 2 and 12 ft. for Scenario 3. The average gaps were 4.6 s, 4.8 s and 4.5 s respectively. Based on these averages no clear trend between the average gap and center lane width is evident. To further assess if the TWLTL width affected gap acceptance a completely random block design was conducted. Results from the ANOVA table show that the TWLTL width had no effect on gap acceptance (p=.1723). The ANOVA output can be seen in Figure 4.16 and Table 4.21.

Table 4.22: Gap data for all 5T turns

	Scenario 1 (16ft.)	**Scenario 2 (14ft.)**	**Scenario 3 (12ft.)**
Avg. Gap (s)	4.6	4.8	4.5
Std. Dev	1.2	1.3	1.1
Median	4.5	4.5	4.3
Mode	5	4.5	4

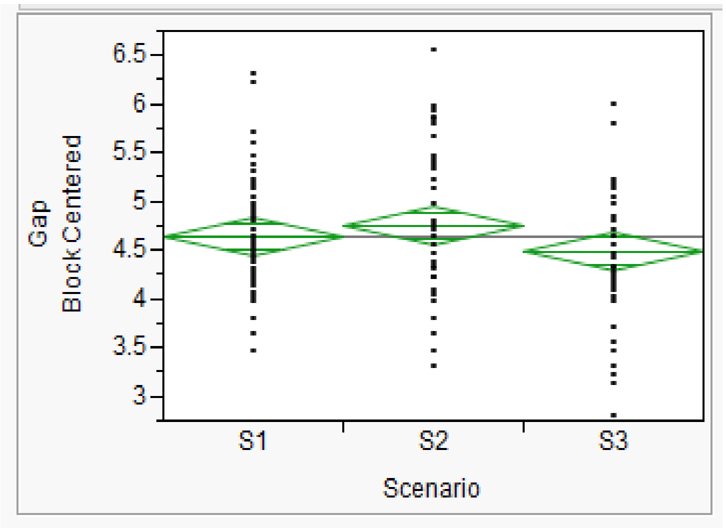


Figure 4.16: Average gap for all 5T turns

Table 4.23: Analysis of Variance for all 5T turns

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**	**Prob > F**
Scenario	2	2.0863	1.04313	1.785	0.1723
Participant	59	189.076	3.20468	5.4839	<.0001*
Error	118	68.956	0.58438	-	-
C. Total	179	260.119	-	-	-

The average delay for each scenario was also calculated as 18.32 s for Scenario 1, 20.29 s for Scenario 2 and 17.14 s for Scenario 3. From these results it appears that participants who waited longer took larger gaps. This correlation can be seen as Scenario 2 had the largest average gap of 4.8 s and the largest average delay of 20.29 s while Scenario 3 had the smallest average gap of 4.5 s and average delay value of 17.14 s. Figure 4.17 shows the distribution of gap intervals that were taken for each scenario. It is evident that Scenario 3 had the smallest average delay as many participants accepted gaps in the 2nd or 4th interval. Scenario 2's average was heavily influenced by the people who took the 11th and 16th interval experiencing delays of 39.54 s and a max of 64.5 s as shown in Table 4.23.

Table 4.24: Delay data for all 5T turns

	Scenario 1 (16 ft.)	**Scenario 2 (14 ft.)**	**Scenario 3 (12 ft.)**
Avg. Delay(s)	18.32	20.29	17.14
Median	20.04	14.04	12.04
Mode	20.04	20.04	5.04

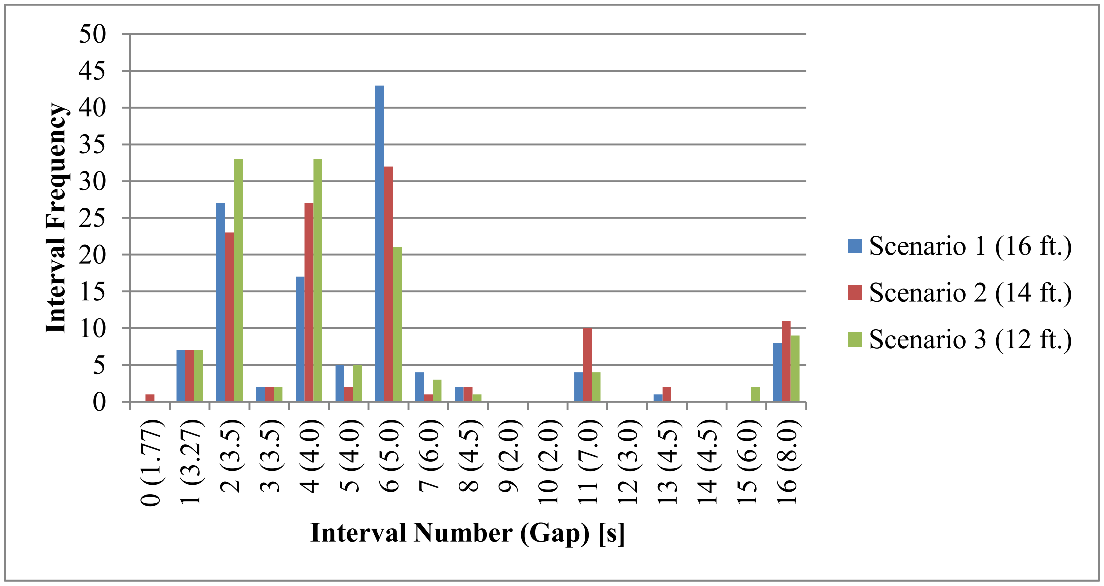


Figure 4.17: Gap interval frequency for 5T turns

Table 4.25: Cumulative delay per traffic interval for 5T turns

Interval	Delay (s)	Gap (s)
0	0	1.77
1	1.77	3.27
2	5.04	3.5
3	8.54	3.5
4	12.04	4
5	16.04	4
6	20.04	5
7	25.04	6
8	31.04	4.5
9	35.54	2
10	37.54	2
11	39.54	7
12	46.54	3
13	49.54	4.5
14	54.04	4.5
15	58.54	6
16	64.54	8

Effects of Age on Gap Acceptance

Throughout the study the participants were defined by two different age groups, young and middle-old. The young participants were between the ages of 18 and 35 years old. The middle-old participants were of ages 35 and older. Out of the 60 successful tests 40 participants were young and 20 were in the middle-old category. To evaluate how the driver age affected gap acceptance various summary statistic were calculated for the two age groups. As seen in Table 4.24 and 4.25 the younger participants accepted smaller gaps than those in the middle-old age group. The average gap values were all below 5 s for the young age group and above 5 s for the middle-old age group. The overall average for all turns for each age group was 4.82 s for young and 5.23 for the middle-old. Results from a comparison test confirmed that these two averages were statistically significant (p=.0002). Similar to the findings of other studies, the older drivers in this simulator driving experiment tended to drive more conservatively.

Table 4.26: Gap data for young participants

Statistics	Scenario 1	Scenario 2	Scenario 3
Avg. Gap (s)	4.87	4.87	4.72
Std. Dev	1.28	1.43	1.30
Mode	4	4	4
Median	5	4.75	4

Table 4.27: Gap data for middle-old participants

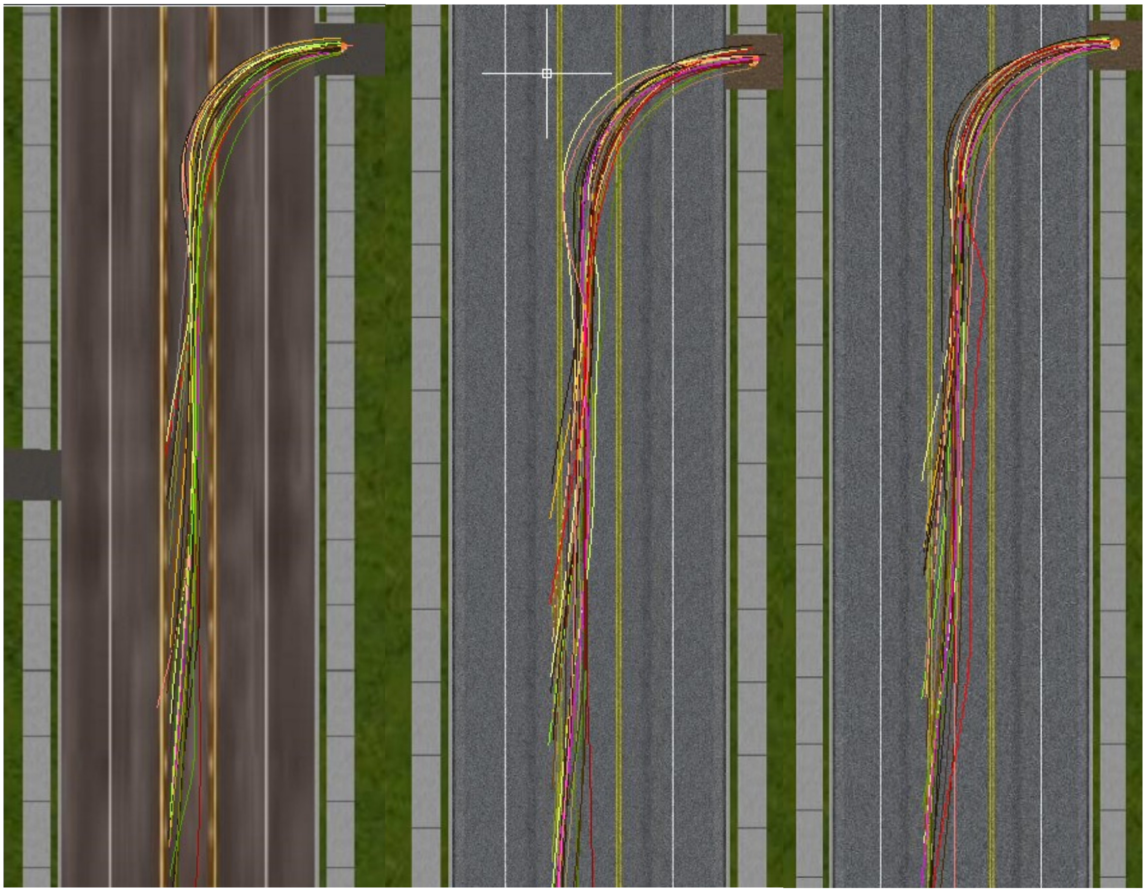
Statistics	Scenario 1	Scenario 2	Scenario 3
Avg. Gap (s)	5.39	5.30	5.00
Std. Dev	1.39	1.34	1.47
Mode	5	5	6
Median	5	5	5

Trajectories

Additional analyses were performed to test how the TWLTL width affected participants' ability to maneuver within the TWLTL when they performed their left turn. For the purpose of this study trajectories were drawn for the second 3T turn for 30 participants. One measurement of maneuverability was based on the number of encroachments for these 30 participants.

From this data sample there was one encroachment for the 12 ft. TWLTL, two encroachments for the 14 ft. and 16 ft. TWLTL. After looking at all of the trajectories for the 12 ft. TWLTL it was apparent that most of the 30 participants stayed within the middle of the center lane. The participants gravitated more towards the left side of the lane for the 14 ft. and 16ft. TWLTLs. Trajectories for these TWLTL widths can be seen in Figure 4.18. From these images it is clear that the variation in lane position and maneuverability increased as the TWLTL lane width increased. The participants were more cautious and controlled when turning into the smaller 12 ft. TWLTL width to prevent any collisions. As the TWLTL width increased the participants tended to utilize more of the lane width as they made their left turn.

Since there were little discrepancies between the TWLTL widths it is evident that further analyses and research need to be completed.



A (12 ft.) B (14 ft.) C (16 ft.)

Figure 4.18: Vehicle trajectories for second 3T turn

CHAPTER 5 : DISCUSSION

The purpose of this driving study was to evaluate the effects of different lane and shoulder width combinations in addition to the effects of different TWLTL widths. Lane and shoulder width combinations were examined based on lateral position and out of lane encroachments while maneuverability and gap acceptance were evaluated for the TWLTLs. The aim of this study is to produce adequate comparisons and recommendations for engineers and roadway designers regarding which lane, shoulder and TWLTL widths that can be applied to roadways to improve safety and operation.

Rural Section

In this section the percent time out of lane and number of out of lane encroachments were evaluated for each lane and shoulder width combination. The following combinations were 12 ft. lane width and no shoulder, a 12 ft. roadway with a 3 ft. paved shoulder and a 10 ft. roadway with a 2 ft. paved shoulder. There was very little difference between the two 12 ft. roadway combinations. A total of 5 participants went out of the lane for the 12 ft. roadway with no shoulder and 7 participants drove out of the lane for the 12 ft. roadway with a 2 ft. shoulder. A larger difference was seen between these two combinations when the total number of encroachments was calculated. The 12 ft. roadway with no shoulder had 6 encroachments while the 12 ft. roadway with a 2 ft. paved shoulder had 13 encroachments. Due to the additional space provided by the shoulder, participants utilized more of the roadway width. In previous studies it has been found that the extra space evokes a sense of security and safety as there is more room for error and corrections. Results from the third combination show larger effects due to lane width. This combination of a 10 ft. roadway with a 2 ft. paved shoulder had a total of 14 participants drive out of the lane boundary with 28 encroachments. These values are exceeding larger than the results sought from the other two combinations. Due to the reduction in lane width it was expected that the drivers would have the most difficulty with this combination. This is also reflected in the average lane position values of -.212 ft. for the 12 ft. roadway with no shoulder, -.100 ft. for the 12 ft. roadway with a 2 ft. shoulder and .149 ft. for the 10 ft. roadway with a 2 ft. shoulder.

Despite the various encroachments, only one of them exceeded the boundaries of the shoulder. The numbers of encroachments were also evaluated based on the curve radii. As expected, the majority of the crossings occurred on the smaller curves that ranged from 900-1230 ft.

Gap Acceptance

Throughout each scenario gap data was collected for two 3T and 5T left turns. TWLTL widths of 12, 14 and 16 ft. were tested for 3T and 5T sections. Based on the average gap many comparisons were made to determine if the TWLTL width had any effect upon gap acceptance. First, the average gaps for all turns in the 3T sections per scenario were compared between each other. Results from the analysis found no significance between any of the scenarios, thus indicating that there was no effect due to the TWLTL width. Another comparison was made by separating the gap data by the order in which the scenarios were driven. To be specific, this grouped gap data as every participants first, second and third scenario driven. These averages were 5.88 s for the first scenario, 5.08 s for the second and 4.90 for the last. Analyses indicated a significant difference between the first and second scenario and the first and last scenario. This indicates that the participants drove more cautiously for the first scenario as they were unaccustomed to the scenario layout and the left turn maneuver into the center lane. As each scenario had two turns additional comparisons were made to determine if there was a difference between the first and second turn. These differences were statistically significant as the majority of the participants accepted smaller gaps for the second turn than the first. This further indicates that the first turn was used as a learning tool.

The 5T turns were also analyzed separately. The average gaps were 4.5s for the 12 ft. TWLTL, 4.8 s for the 14 ft. TWLTL and 4.6s for the 16 ft. TWLTL. Similar to the 3T results the comparison analysis for the 5T sections revealed no significant difference between scenarios. Overall, it is apparent that the TWLTL width had no effect upon gap acceptance. The only effect found was due to the order, first second and third, in which participants drove.

Trajectories

Throughout the study the participants performed various left turn maneuvers on a 3T and 5T roadway. For this study, vehicle trajectories were drawn for 30 participants' second 3T turn in each scenario. The results were inconclusive regarding the effect that the TWLTL width had on the drivers' maneuverability as they turned into the TWLTL. Based on the trajectories there was one encroachment for the 12 ft. TWLTL with and two encroachments for the 14ft. and 16 ft. TWLTL widths. Additional analyses regarding the remaining turns for all participants will need to be evaluated to further determine effects caused by the TWLTL width.

Age Comparison

Driver characteristics pertaining to age was also tested in relationship to gap acceptance. Results found that for each scenario the average gap for older participants was higher than the average gap for younger participants. The overall averages of 4.82 s for young and 5.23 s for the older participants were found to be statistically significant. Similar to Yan et al's, study, these results found that older drivers, driver more conservatively.

CHAPTER 6 : CONCLUSION

The main goal of this study is to determine the influence that flexible lane width standards have on the safety and operation of roadways in South Carolina. After the completion of the field studies in Part 1 of this study it was apparent that to further investigate the effects of lane width a driving simulator study needed to take place. Before commencing the study an extensive literature review was completed to gain knowledge on previous driving simulator studies and to aid in the design of this study. Immense care was taken during the development of the custom design to ensure that sufficient comparative research regarding the SCDOT's inquiries was implemented throughout the study. Based on the findings of this comparative research additional comments and recommendations can be drawn regarding the ultimate goal of using flexible lane width standards in South Carolina.

Recommendations

A major portion of this study involved the evaluation of different lane and shoulder width combinations on a rural two-lane highway with a design speed of 50 miles per hour. Results from this section of the study found very little difference between the 12 ft. roadway with no paved shoulder and the 12 ft. roadway with a 2ft. paved shoulder. A total of 5 out of 60 participants drove out of the lane for the 12 ft. roadway with no paved shoulder and 7 out of 60 participants drove out of the lane for the 12 ft. roadway with a 2 ft. paved shoulder. The total number of encroachments were 6 and 13 respectively. These combinations were also compared to a 10 ft. roadway with a 2 ft.

paved shoulder. This lane width had a larger effect upon drivers as 14 participants drove out of the lane during this roadway section with a total of 30 encroachments. Most of the encroachments took place along the curves of the roadway. The number and magnitude of these encroachments for each combination is show in Table 6.1.

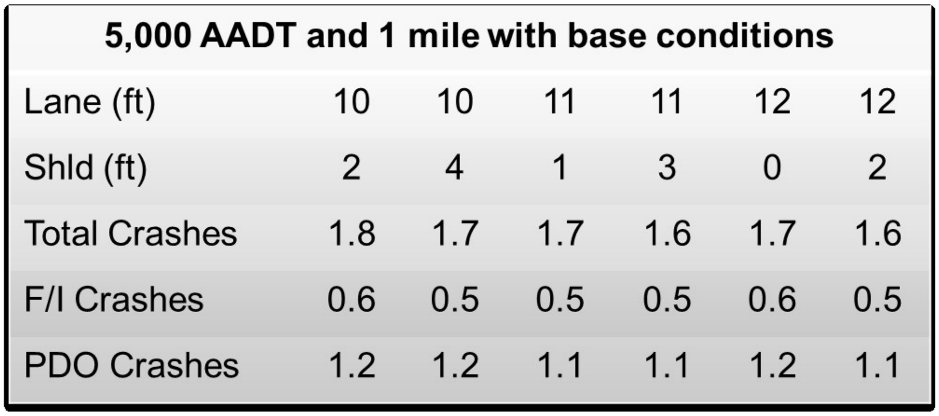
Table 6.1: Magnitude of encroachments

Direction	**Left**			**Right**		
Magnitude (ft.)	**< .5 ft.**	**.51-1 ft.**	**>1 ft.**	**< .5 ft.**	**.51-1 ft.**	**>1 ft.**
Scenario 1 (12 ft. - 0 ft.)	3	2	0	1	0	0
Scenario 2 (12 ft. - 2 ft.)	4	2	1	4 (1)*	1	1
Scenario 3 (10 ft. - 2 ft.)	11	3	0	12 (2)*	4	0

*Number in parenthesis is an encroachment along a straight section

Even though the 10 ft. roadway had more encroachments, none of the right hand crossings exceeded the boundaries of the shoulder. No roadside encroachments occurred for the two scenarios in which a shoulder was present. This can be seen in Table 6.1 as the majority of encroachments for all scenarios were within half of a foot. As there was no shoulder in Scenario 1, there was only one roadside encroachment. From this perspective there was no major difference between the three lane and shoulder width combinations. These results also support the Highway Safety Manual as there is only a 0.2 total crash per mile difference between the three combinations tested in the driving simulator.

Table 6.2: Highway Safety Manual combination comparison



5,000 AADT and 1 mile with base conditions						
Lane (ft)	10	10	11	11	12	12
Shld (ft)	2	4	1	3	0	2
Total Crashes	1.8	1.7	1.7	1.6	1.7	1.6
F/I Crashes	0.6	0.5	0.5	0.5	0.6	0.5
PDO Crashes	1.2	1.2	1.1	1.1	1.2	1.1

These findings further encourage the recommendation made by Part 1 regarding the safety and use of 10-12 ft. lane widths for rural two-lane roadways. Comparisons between the SCDOT's existing HDM guidelines and recommendations made based on Part 1 of this research can be seen in Table 6.3. The full table can be seen in Appendix G.

From the table it is evident that the SCDOT's HDM primarily uses a 12 ft. lane width for rural two- lane arterials and a range of 11-12 ft. for rural two-lane collectors. Results from Part 1 of the research encourage the use of AASHTO standards that include 11 to 12 ft. lane widths for rural two-lane arterials and 10 to 12 ft. lane widths for rural two-lane collectors. Findings from the simulator study also encourage the use of 10 to 12 ft. lane widths on rural two- lane roadways in South Carolina. Recommendations from Part 1, also advised that a 10 ft. lane width only be used on a roadway with a speed limit of 40 miles per hour or less. Results from the simulator study agree with this recommendation as a larger effect due to the narrower lane width was seen at a 50 miles per hour speed limit. As there was a high of 30 encroachments for the 10 ft. roadway, it is also advised that a 2 ft. paved shoulder always be present when a 10 ft. lane is implemented. To compensate for the narrow lane width the 2 ft. shoulder provided additional space for the participants to maneuver. As previously stated, the 2 ft. paved shoulder aided in preventing any roadside encroachments from occurring. While the 12 ft. roadway with no paved shoulder experienced the least amount of encroachments it is important to observe the risk associated without having a shoulder. Any roadside encroachments on this type of roadway cause drivers to encounter a pavement drop off into the grass in which there is a larger risk for loss of control and a crash. As seen in Figure 6.1, roadway departures are the leading cause of fatalities in South Carolina. Due to these potential risks, it is best to use a 10 ft. roadway with a 2 ft. shoulder or a 12 ft. roadway with a 2ft. shoulder for roadways in South Carolina. In a case in which a 12 ft. roadway with no shoulder is the best option it is imperative that the roadside be maintained. While many conclusions and recommendations can be drawn from this study it is important to evaluate various variables regarding the environment, speed limit, and volume for context sensitive areas. By following the AASHTO lane width standards the SCDOT will have more flexibility for design and reconstruction processes.

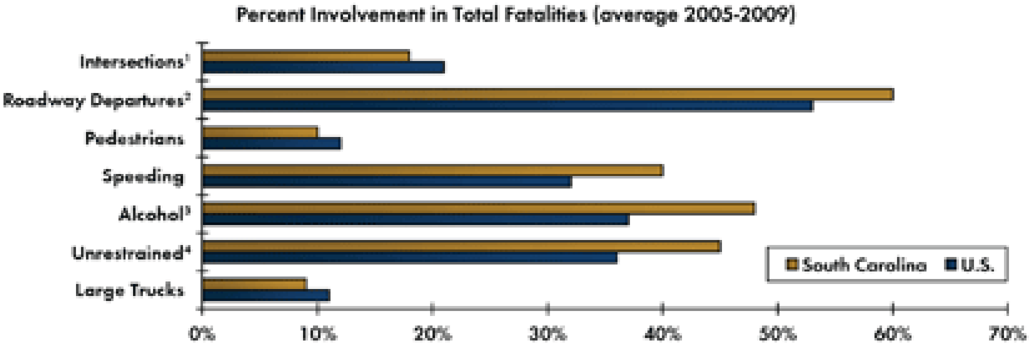


Figure 6.1: South Carolina fatalities comparisons (FHWA)

Table 6.3: Part 1 recommendations

Functional Class	SCDOT HDM Reference	Variable	Existing Values in HDM	Summary of Proposed Changes	Basis for proposed HDM change
Rural Two-Lane Arterials	Fig. 20.1A	Traveled Way Width	24 ft.	22-24 ft.	Research results, AASHTO, other DOT's, Harwood et al, 2000
Rural Two-Lane Collectors	Fig. 20.1B	Traveled Way Width	22-24 ft.	20-24 ft.	Research results, AASHTO, other DOT's, Harwood et al, 2000
Rural Two-Lane Arterials	Fig. 20.1D, Footnote 1 (HDM 13.2.3)	Travel Lane Width	12 ft.	11-12 ft. (see criteria in Table 5.3)	Research results, AASHTO, other DOT's, Harwood et al, 2000
Rural Two-Lane Arterials	Fig. 20.1D (HDM 13.2.5)	Aux. Lane Width	12 ft.	11-12 ft. (see criteria in Table 5.4)	AASHTO, other DOT's
Rural Two-Lane Arterials	Fig. 20.1D (HDM 21.2.7)	TWLTL Lane Width	15 ft.	11-16 ft.	Research results, AASHTO, other DOT's, Fattis et al, 2010
Rural Two-Lane Collectors	Fig. 20.1E, Footnote 1 (HDM 13.2.3)	Travel Lane Width	11-12 ft.	10-12 ft. (see criteria in Table 5.5)	Research results, AASHTO, other DOT's, Harwood et al, 2000
Rural Two-Lane Collectors	Fig. 20.1E (HDM 13.2.5)	Aux. Lane Width	11-12 ft.	10-12 ft. (see criteria Table 5.4)	AASHTO, other DOT's
Rural Two-Lane Collectors	Fig. 20.1E (HDM 21.2.7)	TWLTL Lane Width	15 ft.	11-16 ft.	Research results, AASHTO, other DOT's, Gattis et al, 2010

Additional analyses from the simulator study were performed to determine the effects of TWLTL width on gap acceptance and on turning vehicle encroachments into through lanes. Several ANOVA tests found that the tested TWLTL widths of 12 ft., 14ft. and 16 ft. had no effect upon gap acceptance for the 3T and 5T sections. Trajectories were drawn for 30 participants' second 3T turn to evaluate the effect TWLTL width had on vehicle encroachments into through lanes. Moreover, these results found very little difference between the three widths of 12, 14 and 16 ft. The results defied the prediction that more encroachments would occur in the smaller lane width of 12 ft. For the 30 participants there was one encroachment for the 12 ft. TWLTL and two encroachments for the 14 ft. and 16 ft. TWLTL widths. More lane position variation was found for the larger TWLTL widths as participants took advantage of the larger space for maneuvering. Based on these findings it is recommended that 12, 14 and 16 ft. TWLTL widths can be used in South Carolina. Currently the SCDOT HDM uses 15 ft. TWLTL widths. As there were no major differences in driver behavior for the TWLTL widths tested in the simulator it is recommended that 12 to 16 ft. TWLTL widths can be used in South Carolina. To further investigate any variation between the widths further analyses should be conducted for the remaining turns in the scenarios.

As previously stated, field studies were conducted in 2011 to evaluate the effect different roadway combinations and TWLTL widths had on driver behavior. Due to the limited sample size of roadways with specific attributes from these studies additional research needed to take place. By using the driving simulator our research team was able to directly focus on context sensitive roadways in South Carolina. From the simulator results, additional evidence was provided backing up the recommendations made from the field studies in Part 1. The combined results from both studies indicated that lane widths of 10 to 12 ft. were acceptable for rural two-lane roadways in South Carolina. The simulator study also found that specific combinations of a 12 ft. roadway with no shoulder, 12 ft. roadway with a 2ft. shoulder and a 10 ft. roadway with a 2 ft. shoulder. Additional results from both studies found that 12 to 16 ft. TWLTL widths were acceptable. Together, results from the field and simulator study succeeded in recommending flexible lane width standards for the SCDOT.

APPENDIX A

Traffic Intervals

3T

["1.5" "3.5" "3.5" "4.0" "4.0" "5.0" "6.0" "4.5" "7.0" "3.0" "4.5" "4.5" "6.0" "8.0" "4.5" "5.0" "6.0" "4.0" "7.0" "4.5" "4.0" "5.0" "3.5" "4.0" "5.0" "3.0" "3.5" "3.5" "4.0" "4.0" "5.0" "6.0" "4.5" "7.0" "3.0" "4.5" "4.5" "6.0" "8.0" "4.5" "5.0" "6.0" "4.0" "7.0" "4.5" "4.0" "5.0" "3.5" "4.0" "5.0"]

5T

Left Lane ["1.5" "7.0" "8.0" "11.0" "6.5" "7.0" "7.5" "10.5" "12.5" "11.0" "11.0" "8.5" "8.5" "9.0" "8.5" "8.5" "10.0" "6.5" "9.5" "8.0" "10.5" "9.0" "8.0" "10.5" "10.0" "13.0" "7.0" "3.0" "7.0" "8.0" "11.0" "11.5" "7.5" "10.5" "12.5" "11.0" "11.0" "8.5" "8.5" "9.0" "8.5" "8.5" "10.0" "6.5" "9.5" "8.0" "10.5" "9.0" "8.0" "10.5" "10.0"]

Right Lane [list "5.0" "7.5" "9.0" "10.5" "2.0" "10.0" "9.0" "14.0" "9.5" "10.0" "11.5" "9.0" "7.5" "10.0" "7.0" "11.0" "7.0" "7.5" "9.0" "10.0" "11.0" "6.5" "10.0" "10.0" "11.5" "11.0" "2.5" "6.5" "7.5" "9.0" "10.5" "10.0" "9.0" "14.0" "9.5" "10.0" "11.5" "9.0" "7.5" "10.0" "7.0" "11.0" "7.0" "7.5" "9.0" "10.0" "11.0" "6.5" "10.0" "10.0" "11.5"]

5T Effective Gaps

[list "3.27" "3.5" "3.5" "4.0" "4.0" "5.0" "6.0" "4.5" "2.0" "2.0" "7.0" "3.0" "4.5" "4.5" "6.0" "8.0" "4.5" "5.0" "6.0" "4.0" "7.0" "4.5" "4.0" "5.0" "3.5" "4.0" "5.0" "5.0" "3.5" "3.5" "5.0" "6.0" "4.0" "3.0" "3.5" "4.0" "5.5" "3.5" "4.5" "5.5" "5.0" "6.0" "3.0" "3.5" "4.5" "5.5" "5.0" "5.0" "5.0" "6.5"]

APPENDIX B

Curve Boundaries

Scenario 1 and 2

Straight 1

	Start	End
x	2701.5	2702.1
y	14700.9	15195.4
z	4	0

Curve 1

	Start	End
x	2677.8	2702.2
y	14534.7	14683.5
z	6	4

Curve 2

	Start	End
x	2656.9	2661.3
y	14272	14488.6
z	14.5	6

Straight 3

	Start	End
x	2701.5	2663.1
y	14155	14254.1
z	14	14.9

Curve 3

	Start	End
x	2730	2708.6
y	14010.4	14134.3
z	10	13.4

Straight 4

	Start	End
x	2731.8	2730.1
y	13784.2	13984.8
z	7.4	10.2

Curve 4

	Start	End
x	2713.6	2732.5
y	13615	13758.9
z	0.2	6.6

Straight 5

	Start	End
x	2661.2	2707
y	13476.8	13597.1
z	-2	-0.2

Curve 5

	Start	End
x	2642.5	2652.4
y	13261.1	13453.3
z	1.7	-1.9

Curve 6

	Start	End
x	2688.4	2680.3
y	13005.4	13122.3
z	8.3	4

Straight 6		
	Start	End
x	2671.8	2649.9
y	13154.4	13233.9
z	3	2

Curve 7		
	Start	End
x	2701.8	2677.4
y	12737.7	12899.5
z	12.2	9

Scenario 3

Straight 13		
	Start	End
x	2701.7	2701.7
y	15047.8	15195.9
z	0	0

Curve 12		
	Start	End
x	2715.3	2751.5
y	14377.5	14596.7
z	10.6	8.1

Curve 13		
	Start	End
x	2716.3	2701.7
y	14814.2	15018.8
z	0	0

Curve 11		
	Start	End
x	2667.4	2668.9
y	13996.8	14297.2
z	0.5	7.7

Straight 12		
	Start	End
x	2748.5	2721.7
y	14616	14780.2
z	7.3	0

Straight 10		
	Start	End
x	2715.6	2673.9
y	13910.9	13985.3
z	0	0.3

Curve 10		
	Start	End
x	2736.8	2725
y	13618.4	13892.8
z	8.4	0.1

Straight 8		
	Start	End
x	2693.9	2669.6
y	13044.9	13291
z	15.8	19

Curve 9		
	Start	End
x	2667.4	2687.6
y	13315.9	13493.1
z	19	15.3

Curve 8		
	Start	End
x	2697.2	2697.6
y	12810.1	13011.7
z	13.7	15.4

APPENDIX C

Script to Conduct Experiment

Note: During transitions between sessions it is important NOT to say things such as "good job", "bad job", or anything of this reinforcing nature

Pre-participant

- Consent Form
- Motion Sickness Forms
- Make sure puke can is by car and empty
- Sim Data Forms

Welcome—if you have a cell phone please make sure it is turned off before we begin. Please note that I will be reading from a script throughout the experiment, and I may not be able to answer certain questions that pertain to the experiment until after we have completed the study.

- Place experiment in progress sign on door.
- Thank you for choosing to participate in our study. Before we get started please read and sign this consent form. Should you have any questions, please feel free to ask. After you have read it, please initial the bottom of the pages and sign and date the back page. If you would like a copy of the signed consent form for your records, just let me know.
- The purpose of this study is to investigate driving behavior in various settings.
- Before we get started I am going to ask you some motion sickness questions. I will ask you these same questions after each time you drive today. If you feel uncomfortable at any time during the experiment, please let me know immediately.
- Before we get started we will also be taking a few minutes to take your blood pressure.

- Ask Motion Sickness Questionnaire and Demographics questions
- Take blood pressure as they are doing the questions

You may now get into the car.

- Please sit in the vehicle and move the seat forward or backward so that it suits you.
- Show car controls
- The controls work just like a regular automatic transmission vehicle: the gas is on the right, and the brake is on the left. The car should already be in park, so please do not change gears as the car is already in drive.
- The steering is quite loose and sensitive, meaning the vehicle reacts as if it has too much power steering.
- You will now have several practice sessions to get used to the vehicle and the simulator.
- Once you see the road you may start driving. Your goal for today will be to drive through the scenarios as you would in your own vehicle.
- If you start to feel uncomfortable or uneasy at any time please tell me immediately.
- I will tell you when to begin each scenario.

Load *“*1LaneKeeping_Straight*”*

- ➢ Enter participant number then “#_LWst”

For your first practice session:

- *(Please wait for instructions screen-Press A Scenario shows up*) You will drive on a straight road to familiarize yourself with the vehicle for two 30 second periods.
- (*Press A- Dots show up*) On the screen you can see five dots. These dots will tell you where you are in the lane to help you get a feel for the car.
- (Press A) The green dot appears if you are in the middle of the road.

- (Press A) This yellow dot indicates that you are driving in the left side of the lane.
- (Press A) The red dot shows that you are out of the lane.
- (Press A twice) This yellow dot indicates that you are driving along the right edge of the lane.
- (Press A) This red dot shows you are out of the lane to the right. (Press A) All red dots show that you are completely out of the lane."
- (Press A twice) For the first run you can drive at any speed that you feel comfortable. The scenario will cut off in 30 sec. Please move around inside the lane until you are comfortable with the lane's boundaries.
- (Press A) Now you will get to drive this scenario again for another 30 sec. This time try to maintain the 45 mph speed limit. (Set timer for 30 sec) A voice will also instruct you to slow down if you drive faster than 45 miles per hour. When my timer goes off , lift your foot off the gas, and I will turn off the driving simulator. You may now begin.
- You can repeat practice sessions as many times as necessary to feel comfortable.
- Buzz timer after 30 seconds, wait for them to lift foot off of gas and stop scenario
- Collect Data for this Practice Session

Ask Motion Sickness Questions- Record on Data Sheet

Load "3.Lane Keeping_Curves_DS600"

- ➢ Enter participant number then "#_LWcu"

For your second practice session

- (Please wait for instructions screen-Press A) Now you will practice staying in your lane on a continuously curvy road. It is designed to be difficult for everyone as it is intentionally quite curvy. This time you will not have the dots to show you where you are in the lane.

- A voice will also instruct you to slow down if you drive faster than 50 miles per hour.
- This session will automatically end after you maintained lane position for a minute. When the screen goes black, lift your foot off the gas, and I will turn off the driving simulator.
- You can repeat each practice session as many times as necessary to feel comfortable. (Press A-Car starts) You may begin now.
- At the top of the left screen **record** the number of Departures in the data sheet
- Wait for them to lift foot off of gas and stop scenario
- Collect Data for this Practice Session

Ask Motion Sickness Questions- Record on Data Sheet

- ➢ Take a break. Get participant out of car. Offer restroom break.

Load "5.Stopping_DS600"

- ➢ Enter participant number then "#_LWstop"

For your third practice session

- (Please wait for instructions screen) -You will practice stopping. (Press A- Scenario shows up) For this scenario you will have to do 5 complete stops at a series of stop signs and lights. A voice will tell you to slow down if you drive faster than the posted speed limit. Throughout the scenario you will only drive straight. After each stop proceed through the intersection.
- (Press A-car starts up) You may now begin
- (On the left screen you can see how far the subject gets to the stop bar line, negative means behind the line, positive is they are past the stop bar-**record** these values in data sheet)
- (After they go through last intersection)You have now completed 5 stops so go ahead and stop the car and place it in park. (Stop the scenario)
- Wait for them to lift foot off of gas and stop scenario
- Collect Data for this Practice Session

Ask Motion Sickness Questions- Record on Data Sheet

- ➢ Make participant get out of car. Offer restroom break. (They must get out after this scenario

Load "6.Left turns_DS600"

- ➢ Enter participant number then #_LWleft"

For your fourth practice session

- (Please wait for instructions screen) –Now you will practice making left turns.
- (Press A- Scenario shows up) For this scenario you will make 6 left turns. For the first turn the simulator will control your speed in order to show you how to do a left turn. While this is happening you will need to push on the gas.
- A voice will tell you to slow down if you drive faster than the posted speed limit. At the end when the screen goes black put the car in park.
- (Press A- Start car) You may now begin.
- (On the left screen you can see the number of left turns the subject has made)
  --the scenario will automatically turn black when they have completed all turns
- Wait for them to lift foot off of gas and stop scenario
- Collect Data for this Practice Session

Ask Motion Sickness Questions- Record on Data Sheet

- ➢ Take a break. Get participant out of car. Offer restroom break.

Load "7.Right Turns_DS600"

- ➢ Enter participant number then "#_LWright"

For your fifth and final practice session

- (Please wait for instructions screen-Press A)You will practice making right turns. For this scenario there will be a total of 4 right turns. For the first turn the simulator will control your speed in order to show you the correct way of making a right turn. A voice will also instruct you to slow down if you drive faster the posted speed limit.

- (Press A- Start the car) You may now begin.
- (When they get to second turn) For this second turn you will have a bit more control on your speed but still not full control as the simulator will guide you.
- (Third turn) Tell them they can make a right on red
- (After they complete four right turns)- You have now completed all right turns, stop the car and put it in park.
- Wait for them to lift foot off of gas and stop scenario
- Collect Data for this Practice Session

Ask Motion Sickness Questions- Record on Data Sheet

- ➢ Take a break. Get participant out of car. Offer restroom break.
- ➢ Give part 1 of questionnaire

- *Look at the order in which the three scenarios need to be driven on the **Data Sheet**. Enter subject name as follows*
- *Participant #_LW(Scenario #)_# indicating the order driven*
    - *For Scenario 1: #_LW1_#*
    - *For Scenario 2: #_LW2_#*
    - *For Scenario 3: #_LW3_#*

CONDITION 1

Load "LaneWidth_#"

- Enter participant number then "#_LW#_1"

Now that you have completed the practice sessions, we will begin the actual study. It is important that you drive as you would in your own vehicle. In the beginning of the scenario try to maintain the posted speed limit. A voice will tell you if you are going too fast or too slow. Throughout the scenario you will also be doing a series of left turns. For these turns, turn left into the two way left turn lane and stop until all cars on your right have passed. Please be sure to listen to all of the voice commands in the simulator. This scenario should take about 10 minutes. You may now begin.

Ask Motion Sickness Questions- Record on Data Sheet

- Make participant get out of car
- Offer snack
- Complete part 2 of questionnaire

CONDITION 2

Load "LaneWidth_#"

- Enter participant number then "#_LW#_2"

It is important that you drive as you would in your own vehicle. In the beginning of the scenario try to maintain the posted speed limit. A voice will tell you if you are going too fast or too slow. Throughout the scenario you will also be doing a series of left turns. For these turns, turn left into the two way left turn lane and stop until all cars on your right have passed. Please be sure to listen to all of the voice commands in the simulator. This scenario should take about 10 minutes. You may now begin.

Ask Motion Sickness Questions-Record on Data Sheet

- Make participant get out of car
- Complete part 3 of Questionnaire
- Measure Blood Pressure

CONDITION 3

Load "LaneWidth_#"

- Enter participant number then "#_LW#_3"

It is important that you drive as you would in your own vehicle. In the beginning of the scenario try to maintain the posted speed limit. A voice will tell you if you are going too fast or too slow. Throughout the scenario you will also be doing a series of left turns. For these turns, turn left into the two way left turn lane and stop until all cars on your right have passed. Please be sure to listen to all of the voice commands in the simulator. This scenario should take about 10 minutes. You may now begin.

- Ask Motion Sickness Questions-Record on Data Sheet
- Have person get out of car and sit at table
  - Ask "what do you think was the purpose of this study?"
  - Ask post questions on page 4 of Data Sheet
  - Take Blood Pressure
- Pay participant

Thank you for participating in this research study

- Remember that the purpose of the study was to investigate driving behavior in various settings.
- Complete Master subject list "success" column now.
- Email bmaleck@g.clemson.edu with attendance/success information.
- *Backup data to external hard drive*

APPENDIX D

Participant Data Sheets

Participant Number: _______________

Date: _______________

Experimenter: _______________________

Did you give participant their copy of the consent form? Yes or No
Did you file the signed consent form? Yes or No

Ask prior to running experiment:

- Do you have a valid US driver's license? ______________
- Age _______
- Age Group – Young (18-34) / Middle (35- 65) / Old (65+)
- Gender _______
- Years driving ____
- Are you a resident of SC? Yes / no
- Do you have a past history of motion sickness?__________
- Do you have a past history of migraines?________
- Do you have any vision problems?_________

Participant Number:								
	Perform Blood Pressure Test _______ _______ _______ _______ _______							
Completed	**Scenarios**	**Nausea Questions** Answer each question on a scale from 0 to 10 where 0 is “not at all” and 10 is “severely.”						**Comments**
		Sick to your stomach	**Sweaty**	**Light headed**	**Nauseous**	**Hot/warm**	**Dizzy**	
	1.) Straight							
	2.) Curvy Edge touches _________							
	3.)Stopping Distance to stop bar 1.) _____ 2.) _____ 3.) _____ 4.) _____ 5.) _____							
	4.) Left Turns							
	5.) Right Turns							
	Questionnaire							

Participant Number:								
Completed	**Scenarios**	**Nausea Questions** Answer each question on a scale from 0 to 10 where 0 is "not at all" and 10 is "severely."						**Comments**
		Sick to your stomach	**Sweaty**	**Light headed**	**Nauseous**	**Hot/warm**	**Dizzy**	
	LaneWidth_1 ______							
	Questionnaire							
	LaneWidth_2 ______							
	Questionnaire							
	LaneWidth_3 ______							
	Perform Blood Pressure Test ______ ______ ______ ______ ______							
	Ask Purpose of the study							
	Fill out master subject list							
	Email status to Brian: bmaleck@g.clemson.edu							

Participant Number: _______________

<u>Ask at end of experiment:</u>

- Estimate the number of miles you drive each year _______
- How many days do you drive each week _______
- What kind of vehicle do you drive? Make____ Model____ Year ____
- Have you been in a crash in the last year while driving? Yes / no
- Have you been in a crash in the last 5 years while driving? Yes / no
- Were you considered at fault in any of these crashes? Yes / no
  If Yes, how many? _____
- Have you received a speeding ticket in the last year? Yes / no
- Have you received a speeding ticket in the last 5 years? Yes / no
- Do you typically wear your seatbelt? Yes / no
- Do you ever talk on your cell phone when you drive? yes / no
- Do you ever text message when you drive? Yes / no

APPENDIX E

Participant Data

Participant #	Age Group	Completed
1	Young	Yes
2	Young	Yes
3	Young	Yes
4	Young	No- Sim sick
5	Young	Yes
6	Middle	Yes
7	Young	Yes
8	Young	Yes
9	Young	Yes
10	Young	Yes
11	Young	Yes
12	Young	Yes
13	Middle	Yes
14	Young	Yes
15	Young	Yes
16	Young	Yes
17	Young	Yes
18	Young	No- Sim sick
19	Young	No- Sim sick
20	Young	Yes
21	Young	Yes
22	Young	Yes
24	Young	Yes
25	Young	Yes
26	Young	No- Sim sick
23	Young	No- Sim sick
27	Young	Yes
28	Young	Yes
29	Young	Yes
30	Young	Yes

31	Young	Yes
32	Young	Yes
33	Middle	Yes
34	Middle	Yes
35	Young	Yes
36	Middle	Yes
37	Middle	No- Sim sick
38	Middle	Yes-Little sick
39	Young	Yes
40	Young	Yes
41	Young	Yes
42	Young	Yes
43	Young	Yes
44	Middle	Yes
45	Young	No- Sim sick
46	Young	Yes
47	Young	Yes
48	Middle	Yes
49	Middle	Yes
50	Middle	Yes
51	Young	Yes
52	Young	Yes
53	Middle	No- Sim sick
54	Young	Yes
55	Middle	Yes
56	Middle	No- Sim sick
57	Middle	No- Sim sick
58	Middle	Yes
59	Young	Yes
60	Middle	Yes
61	Middle	Yes
62	Middle	Yes
63	Middle	Yes
64	Middle	Yes
65	Middle	Yes
66	Middle	Yes

67	Middle	No
68	Young	Yes
69	Middle	No- Sim sick
70	Middle	Yes
71	Young	Yes
72	Young	Yes

APPENDIX F

Post Question Results on Driving Behavior

Estimate the number of miles you drive each year

How many days do you drive each week?

Age group	Avg. Age	Avg. Yrs Driving	Avg. Miles/ Yr
Young	21	5.5	11000
Middle/Old	49	31.5	14000

Have you been in a crash in the last year (5 years) while driving?

Age group	Crash -1 yr	Crash-5 yr
Young	2	10
Middle/Old	1	6

Have you received a speeding ticket in the last year (5 years)?

Age group	Ticket -1 yr	Ticket-5 yr
Young	13	26
Middle/Old	1	6

Do you talk on your cell phone while driving?

Cell Phone	Young	Middle/Old
Yes	32	12
No	8	8

Do you text message while driving?

Text Messaging	Young	Middle/Old
Yes	11	4
No	29	16

APPENDIX G

Recommendations

Table 5.1: Summary of Proposed SCDOT HDM Changes for Rural Arterials and Collectors

Functional Class	**SCDOT HDM Reference**	**Variable**	**Existing Values in HDM**	**Summary of Proposed Changes**	**Basis for proposed HDM change**
Rural Two-Lane Arterials	Fig. 20.1A	Traveled Way Width	24 ft.	22-24 ft.	Research results, AASHTO, other DOT's, Harwood et al, 2000
Rural Two-Lane Collectors	Fig. 20.1B	Traveled Way Width	22-24 ft.	20-24 ft.	Research results, AASHTO, other DOT's, Harwood et al, 2000
Rural Two-Lane Arterials	Fig. 20.1D, Footnote 1 (HDM 13.2.3)	Travel Lane Width	12 ft.	11-12 ft. (see criteria in Table 5.3)	Research results, AASHTO, other DOT's, Harwood et al, 2000
Rural Two-Lane Arterials	Fig. 20.1D (HDM 13.2.5)	Aux. Lane Width	12 ft.	11-12 ft. (see criteria in Table 5.4)	AASHTO, other DOT's
Rural Two-Lane Arterials	Fig. 20.1D (HDM 21.2.7)	TWLTL Lane Width	15 ft.	11-16 ft.	Research results, AASHTO, other DOT's, Fattis et al, 2010
Rural Two-Lane Collectors	Fig. 20.1E, Footnote 1 (HDM 13.2.3)	Travel Lane Width	11-12 ft.	10-12 ft. (see criteria in Table 5.5)	Research results, AASHTO, other DOT's, Harwood et al, 2000
Rural Two-Lane Collectors	Fig. 20.1E (HDM 13.2.5)	Aux. Lane Width	11-12 ft.	10-12 ft. (see criteria Table 5.4)	AASHTO, other DOT's

Rural Two-Lane Collectors	Fig. 20.1E (HDM 21.2.7)	TWLTL Lane Width	15 ft.	11-16 ft.	Research results, AASHTO, other DOT’s, Gattis et al, 2010
Rural Four-Lane Divided Arterial	Fig. 20.2A	Traveled Way Width	24 ft.	22-24 ft.	AASHTO, other DOT’s,
Rural Four-Lane Divided Arterial	Fig. 20.2C, Footnote 1 (HDM 13.2.3)	Travel Lane Width	12 ft.	11-12 ft. (see criteria in Table 5.6)	AASHTO, other DOT’s,
Rural Four-Lane Divided Arterial	Fig. 20.2C (HDM 13.2.5)	Aux. Lane Width	12 ft.	11-12 ft. (see criteria in Table 5.4)	AASHTO, other DOT’s,

Table 5.2: Summary of Proposed SCDOT HDM Changes for Urban/Suburban Arterials and Collectors

Functional Class	**SCDOT HDM Reference**	**Variable**	**Existing Values in HDM**	**Summary of Proposed Changes**	**Basis for proposed HDM change**
Four-Lane Suburban/Urban Street	Fig. 21.2A	Traveled Way Width	24 ft.	22-24 ft.	Research results, AASHTO, other DOT's, Potts et al, 2007, Mbatta et al, 2012
Five-Lane Urban Street (with Shoulders)	Fig. 21.2B	Traveled Way Width	24 ft.	22-24 ft.	Research results, AASHTO, other DOT's, Potts et al, 2007, Mbatta et al, 2012
Five-Lane Urban Street (with Shoulders)	Fig. 21.2B (HDM 21.2.7.2)	TWLTL Lane Width	15 ft.	11-16 ft.	Research results, AASHTO, other DOT's, Gattis et al, 2010
Five-Lane Urban Street (Curb and Gutter)	Fig. 21.2C	Traveled Way Width	24 ft.	22-24 ft.	Research results, AASHTO, other DOT's, Potts et al, 2007, Mbatta et al, 2012
Five-Lane Urban Street (Curb and Gutter)	Fig. 21.2C (HDM 21.2.7.2)	TWLTL Lane Width	15 ft.	11-16 ft.	Research results, AASHTO, other DOT's, Gattis et al, 2010

Suburban/Urban Multilane Arterials	Fig. 21.3A (HDM 9.2) (HDM 13.2.3)	Travel Lane Width	12 ft.	11-12 ft. (see criteria in Table 5.7)	Research results, AASHTO, other DOT’s, Potts et al, 2007, Mbatta et al, 2012
Suburban/Urban Multilane Arterials	Fig. 21.3A (HDM 21.2.7.2)	TWLTL Lane Width	15 ft.	11-16 ft.	Research results, AASHTO, other DOT’s, Gattis et al, 2010
Suburban/Urban Collectors	Fig. 20.1E (HDM 9.2) (HDM 13.2.3)	Travel Lane Width	12 ft.	11-12 ft. (see criteria in Table 5.8)	Research results, AASHTO, other DOT’s, Potts et al, 2007, Mbatta et al, 2012
Suburban/Urban Collectors	Fig. 20.1E (HDM 21.2.7.2)	TWLTL Lane Width	15 ft.	11-16 ft.	Research results, AASHTO, other DOT’s, Gattis et al, 2010
Rural Four-Lane Divided Arterial	Fig. 20.2C, Footnote 1 (HDM 13.2.3)	Travel Lane Width	12 ft.	11-12 ft. (see criteria in Table 5.6)	AASHTO, other DOT’s,
Rural Four-Lane Divided Arterial	Fig. 20.2C (HDM 13.2.5)	Aux. Lane Width	12 ft.	11-12 ft. (see criteria in Table 5.4)	AASHTO, other DOT’s,

Table 5.3: Proposed Travel Lane Width Criteria for Rural Two-Lane Arterials

Travel Lane Width (*)	**Criteria and Conditions**
11 ft. min., 12 ft.	Design Speed 55 mph or less, assuming a 2 ft. paved

desirable	shoulder, if shoulder width does not meet minimum requirements, use 12 ft. min
12 ft. min.	Design Speed 60 mph or greater

Footnotes:

1. If lower design speeds are allowed, narrower travel lane widths could be acceptable, 10 ft. min.
2. For industrial areas or locations with higher heavy vehicle use, 12 ft. lanes should be used.
3. Criteria for Travel Lane Width assumes no problematic prior crash histories related to lane width including run off the road, sideswipe (same and opposite direction), head-on crashes.
4. Under no condition should travel lane widths be less than 10 ft. min.

Table 5.4: Proposed Auxiliary Lane Width Criteria for Rural Two-Lane Arterials

Auxiliary Lane Width (*)	**Criteria and Conditions**
10 ft. min., 12 desirable	Design Speed of 35 mph or less
11 ft. min., 12 ft. desirable	Design Speed greater than 35 mph and 55 mph, or less
12 ft. min.	Design Speed 60 mph or greater

Footnotes:

1. For industrial areas or locations with higher heavy vehicle use, 12 ft. lanes should be used.
2. Under no condition should travel lane widths be less than 10 ft. min.

Table 5.5: Proposed Travel Lane Width Criteria for Rural Two-Lane Collectors

Travel Lane Width (1)	**Criteria and Conditions**
10 ft. min.	AADT less than 400 veh./day, design speed 40mph or less, 2ft. paved shoulder required
11 ft. min.	AADT between 401-2000 veh./day, design speed 50mph or less, assuming a 2 ft. paved shoulder, if shoulder width does not meet minimum requirements, use 12 ft. min
12 ft. min.	AADT over 2,000, design speed 60 mph or greater

Footnotes:

1. If lower design speeds are allowed, narrower travel lane widths could be acceptable, 10 ft. min.
2. For industrial areas or locations with higher heavy vehicle use, 12 ft. lanes should be used.
3. Criteria for Travel Lane Width assumes no problematic prior crash histories related to lane width including run off the road, sideswipe (same and opposite direction), head-on crashes.
4. Under no condition should travel lane widths be less than 10 ft. min.

Table 5.6: Proposed Travel Lane Width Criteria for Rural Multilane Arterials

Travel Lane Width (*)	**Criteria and Conditions**
11 ft. min., 12 ft. desirable	AADT less than 4,000 veh./day, Design Speed 55 mph or less, assuming a 2 ft. paved shoulders, if shoulder width does not meet minimum requirements, use 12 ft. min
12 ft. min.	AADT greater than 4,000 veh./day, Design Speed 60 mph or greater, assuming a 2 ft. paved shoulders

Footnotes:

1. If lower design speeds are allowed, narrower travel lane widths could be acceptable, 10 ft. min.
2. For industrial areas or locations with higher heavy vehicle use, 12 ft. lanes should be used.
3. Criteria for Travel Lane Width assumes no problematic prior crash histories related to lane width including run off the road, sideswipe (same and opposite direction), head-on crashes.
4. Under no condition should travel lane widths be less than 10 ft. min.

Table 5.7: Proposed Travel Lane Width Criteria for Suburban/Urban Multilane Arterials and Collectors

Travel Lane Width (*)	**Criteria and Conditions**
10 ft min, 12 ft desirable	Design Speed of 35 mph or less
11 ft. min., 12 ft. desirable	Design Speed greater than 35 mph and 55 mph, or less
12 ft. min.	Design Speed 60 mph or greater

Footnotes:

1. Where space is available, inclusion of curb and gutter and a paved should is preferred.
2. In locations with higher driveway densities, wider travel lane widths may be required.
3. In locations where there is no gutter pan, a wider travel lane with may be required.
4. If lower design speeds are allowed, narrower travel lane widths could be acceptable, 10 ft. min.
5. For industrial areas or locations with higher heavy vehicle use, 12 ft. lanes should be used.
6. Criteria for Travel Lane Width assumes no problematic prior crash histories related to lane width including run off the road, sideswipe (same and opposite direction), head-on crashes.
7. Under no condition should travel lane widths be less than 10 ft. min.

Table 5.8: Proposed Travel Lane Width Criteria for Urban/Suburban Collectors

Auxiliary Lane Width (*)	**Criteria and Conditions**
10 ft. min., 12 desirable	Design Speed of 35 mph or less
11 ft. min., 12 ft. desirable	Design Speed greater than 35 mph and 55 mph, or less
12 ft. min.	Design Speed 60 mph or greater

Footnotes:

1. If lower design speeds are allowed, narrower travel lane widths could be acceptable, 10 ft. min.
2. For industrial areas or locations with higher heavy vehicle use, 12 ft. lanes should be used.
3. Criteria for Travel Lane Width assumes no problematic prior crash histories related to lane width including run off the road, sideswipe (same and opposite direction), head-on crashes.
4. Under no condition should travel lane widths be less than 10 ft. min.

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