Driving Simulator Study of J-Turn Acceleration/Deceleration Lane and U-Turn Spacing

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16. Abstract

The J-turn, also known as RCUT (Restricted Crossing U-Turn) and Superstreet, is an innovative geometric design that can improve intersection safety. Even though this design has been in use in several states for many years, there is very little research-based guidance for several design parameters. A driving simulator study was conducted to analyze the parameters of lane configuration, U-turn spacing, and signage. Two lane configurations were examined: 1) acceleration/deceleration configuration where acceleration and deceleration lanes are provided and 2) deceleration only configuration where only deceleration lanes are provided. Lane configuration was found to be the most important parameter affecting J-turn safety based on speed-differentials. The only significant interaction effect among parameters was between lane configuration and U-turn spacing. The acceleration/deceleration configuration performed better than the deceleration only configuration with 66.3% fewer safety critical events. Vehicle trajectories and average lane change locations showed that U-turn spacing impacted significantly the acceleration/deceleration configuration (e.g. average merge locations changed by 96% to 101%) but not the deceleration only configuration. No strong preference was demonstrated by the study subjects for either the directional or the diagrammatic signage style. This report presented the first human factors study of the J-turn focused on developing design guidance. This human factors approach complements other traditional approaches such as crash analysis and micro-simulation.

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DRIVING SIMULATOR STUDY OF J-TURN ACCELERATION/DECELERATION LANE AND U-TURN SPACING CONFIGURATIONS

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DISCLAIMER

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EXECUTIVE SUMMARY

A J-turn, also known as a Restricted Crossing U-turn (RCUT) or Superstreet, is an innovative geometric design that helps to improve the safety of intersections involving a major highway with a minor road. With this design, the minor through and left turn movements are prohibited from crossing the major highway directly; instead, vehicles are forced to make a U-turn. Thus, crossing conflicts are eliminated and are replaced with merging conflicts. Safety studies have shown that J-turns reduce severe crashes by around 64%. The longer travel through the U-turn does increase travel times, but not significantly. J-turns have been implemented in Maryland and North Carolina for many years.

Despite the increasing adoption of J-turns in many states, there is a lack of research-based guidance for several J-turn design parameters. Existing guidance uses certain values out of convenience. For example, some guides recommend for the spacing between the minor road approach and the U-turn to be 660 feet, 1,320 feet, or 2,640 feet because they correspond to 1/8, 1/4, and 1/2 mile; no empirical studies were conducted to show the safety effects of such spacings. This report discusses the research-based results associated with three design parameters: 1) J-turn lane configuration, 2) U-turn spacing, and 3) minor road signage. Figure ES1 illustrates these design parameters. Lane configuration refers to the inclusion or exclusion of acceleration and deceleration lanes. Figure ES1a shows the J-turn lane configuration with both acceleration and deceleration lanes (AD). Figure ES1b shows the J-turn lane configuration with deceleration lanes only (DF). U-turn spacing, or offset, refers to the distance between the minor road and the U-turn. The two signage styles investigated were diagrammatic and directional.

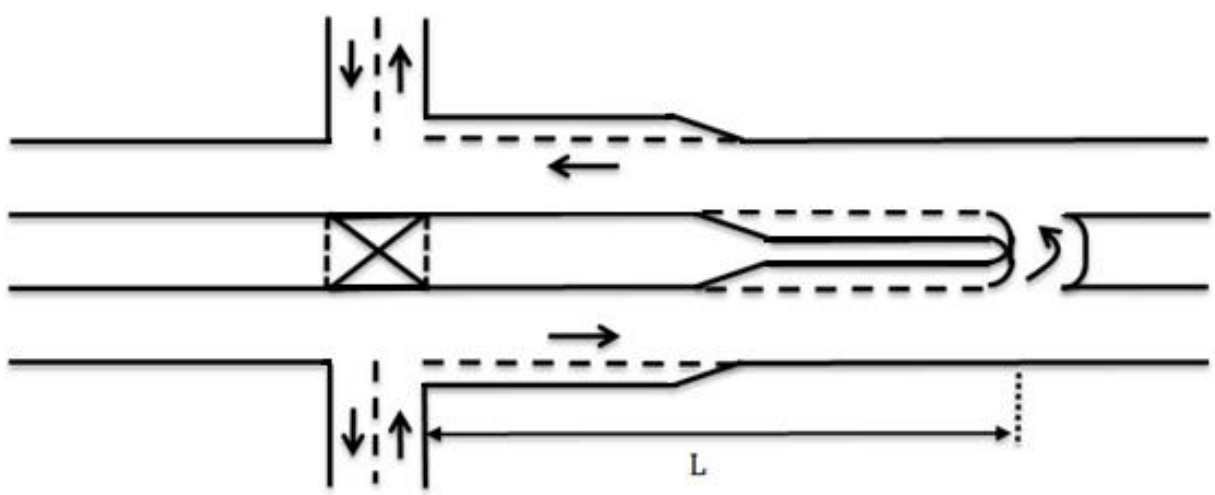


FIGURE ES1a Acceleration and deceleration lanes (AD).

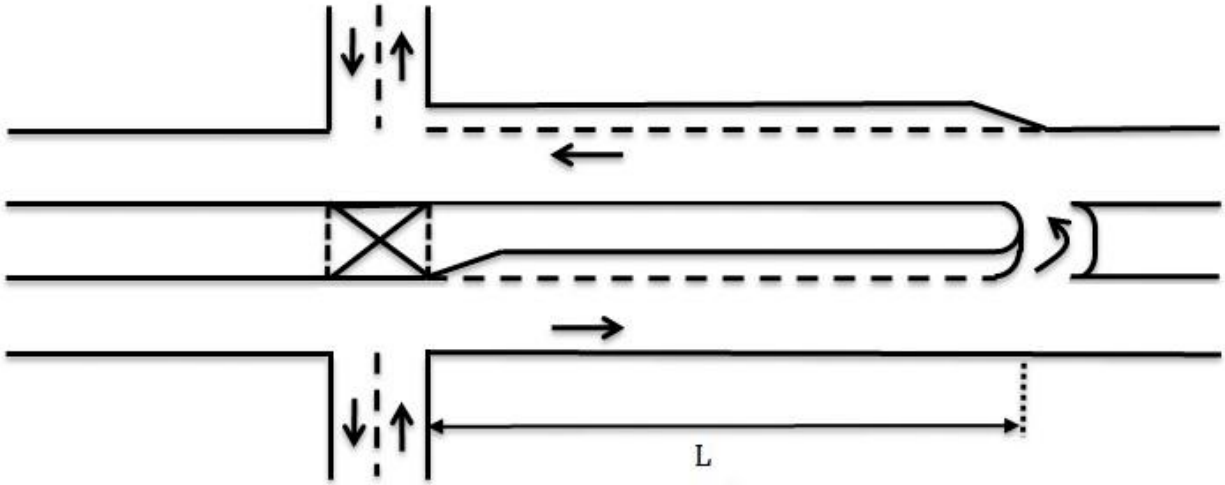


FIGURE ES1b Full deceleration lanes only (DF).
FIGURE ES1 J-turn turn design considerations.

The ZouSim driving simulator was used to examine the three design parameters. Simulator studies are well-suited for such investigations because they can study a large combination of design parameter values while controlling for other factors. Here, nine separate design scenarios were investigated involving differing lane configurations, U-turn spacings, signage styles, and traffic volumes. Thirty human subjects from wide ranging demographics participated in the study. Experimenters followed carefully Institutional Review Board-approved rules and procedures in order to safeguard subject confidentiality and to minimize risks.

Several performance measures were derived from the simulator experiments. These measures include speed differential, Time-To-Collision (TTC), lane change locations, vehicle trajectory plots, and missed U-turns. Performance measure results were analyzed using applicable statistical methods. Speed differential results showed that there was a relationship between lane configuration and U-turn spacing. The results also showed that the lane configuration was the most important design factor. Regression models were developed for TTC versus standardized explanatory variables. The coefficient for lane configuration was 0.714, while the coefficient for U-turn spacing was only 0.0938. TTC results showed that there is a statistical significant difference ($p=0.0243$) of 106 (66.3%) more total safety-critical TTC values with the DF configuration as compared to the AD. Average lane change locations were much shorter for the DF design as compared to the AD design. The difference in lane change locations was also verified visually from vehicle trajectory plots generated from simulator output. Post-simulator surveys produced results that were consistent with the simulator study results showing a preference for the AD design and longer spacing. The results did not show a strong advantage of one signage style over another.

In summary, the AD lane configuration design is recommended over the DF lane configuration. Thus, when possible, acceleration lanes should be provided at J-turn sites. With the AD design, longer spacing improves safety. Locations with high traffic demand should especially consider longer lengths such as 2,000 feet. If the DF design is used, then a 1,000 foot spacing is adequate,

but such a design is not suited for locations with high traffic volumes and small traffic gaps. Diagrammatic-style and directional-style signage performed about equally. A public educational campaign before J-turn deployment can help to improve driver understanding and to reduce the instances of missed U-turns.

CHAPTER 1 INTRODUCTION

J-turn intersections, also known as restricted crossing U-turn (RCUT) intersections, serve as an alternative to a two-way stop controlled intersection on high-speed roadways. This design has been in operation in Maryland and North Carolina for many years (Kramer, 1987). J-turns force the through and left turn movements from the minor street to turn right and make a U-turn at a downstream location. Figure 1a and 1b are schematic diagrams of the J-turn design. These figures contain a large X in the center of the intersection, representing the prohibition of the through and left-turn movements from the minor approach. Figure 1 does not show the alternative J-turn configuration that allows left-turn movements from the major road to the minor road. The J-turn design improves safety due to fewer conflict points and less severe conflict types. The number of crossing conflicts can be completely eliminated if the major road left turns are not allowed at a J-turn. Several empirical safety studies (e.g., Edara et al., 2015; Hummer et al., 2010) document the safety effectiveness of the J-turn design, such as a fatal and injury crash reduction of around 64%. Studies have also examined J-turn's operational performance; these studies (Kim et al., 2006; Inman and Haas, 2012; Haley et al., 2011; and Edara et al., 2015) found that the overall intersection performance is improved even though minor road movements can experience a slight increase in travel time.

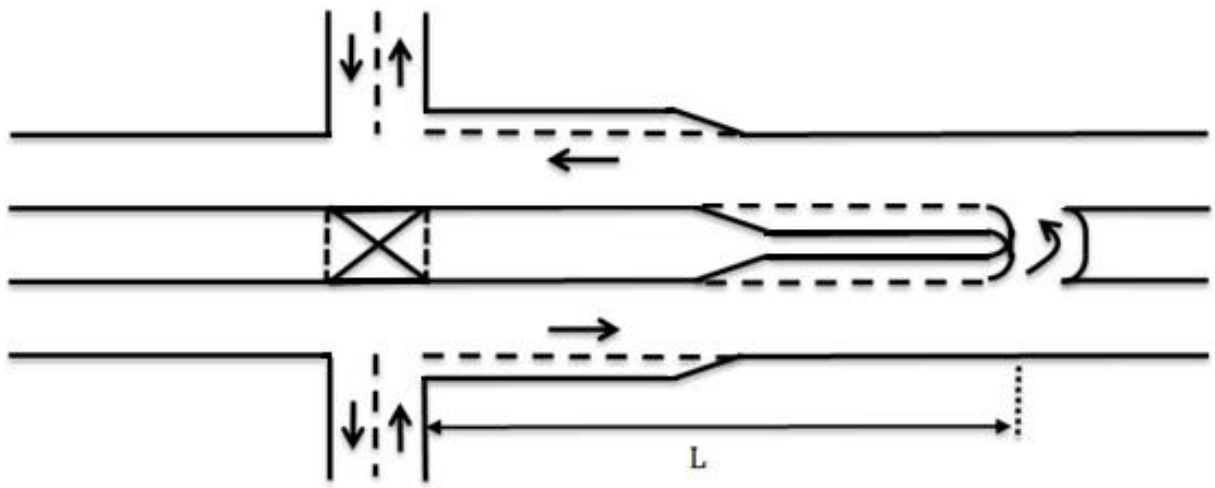


FIGURE 1a Acceleration and deceleration lanes (AD).

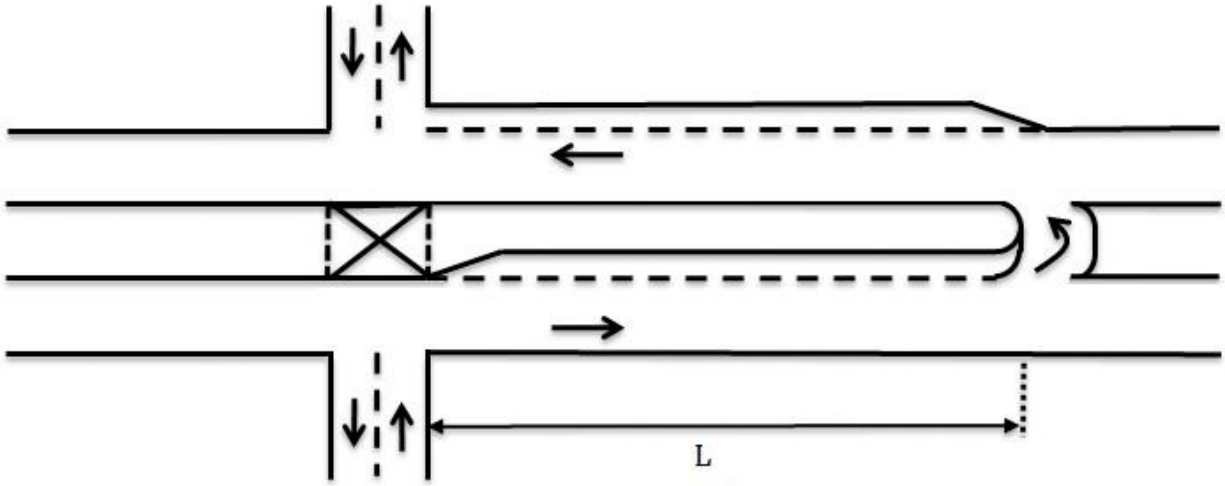


FIGURE 1b Full deceleration lanes only (DF).
FIGURE 1 J-turn turn design considerations.

There are some J-turn design considerations that require guidance derived from empirical research. One consideration involves the implementation of the crossroad acceleration and deceleration lanes. Figure 1 shows the two possible options. Option A includes both deceleration and acceleration lanes at half length, while Option B only includes deceleration lanes, but at full length. Figure 1 also illustrates the issue of appropriate spacing between the crossroad and the U-turn. A longer spacing provides more distance for vehicles to maneuver to the U-turn but at a cost of greater travel distance. Another type of consideration involves signage for both the crossroad and the mainline. One function of signage is to prohibit the crossing of the crossroad traffic at the intersection. For the crossroad, the signage needs to guide drivers who desire to cross the mainline or to make a left turn to do so via the downstream u-turn. For the mainline, the signage needs to guide drivers who want to access the crossroad to do so via the downstream u-turn.

Some options for investigating J-turn design considerations include empirical, driving simulator, and micro-simulation studies. These options are complementary and have different tradeoffs. This paper describes the driving simulator study only; the authors were also previously involved with empirical and micro-simulation studies of J-turn design. One benefit of the simulator study is the ability to examine multiple design considerations via a factorial experiment design that assesses relative contributions and interactions among different variables of interest (NIST, 2012). Also, a driving simulator provides human perspectives and perceptions that are not directly measurable by other existing approaches. A post-simulator survey provides human participants the opportunity to express their opinions on the J-turn design, providing additional data.

CHAPTER 2 LITERATURE ON J-TURN INTERSECTIONS

2.1 Lane Configuration

There are many considerations involved in the design of a J-turn intersection. These considerations can include intersection elements, median U-turn crossover elements, loons, medians, auxiliary lanes, and shoulders. Despite the increasing interest in the J-turn design, there are certain design considerations that require additional empirical research. One consideration involves the implementation of the acceleration and deceleration lanes. An acceleration lane onto a major highway allows for easier entry for the minor road vehicles, but adds cost and additional right-of-way. Figure 1 shows two possible options that have been implemented in Missouri. Figure 1a includes both deceleration and acceleration lanes at half the length (AD), while Figure 1b only includes deceleration lanes, but at full length (DF). Other states, such as Mississippi, also make mainline deceleration lanes mandatory before the U-turn, but make acceleration lanes optional after the U-turn (ABMB, 2010). The Green Book (AASHTO, 2011) recommends that deceleration lane lengths be based on the design volume at median U-turns, but note the difference between a J-turn U-turn and a median U-turn. A simulator study that tracks the lane changing locations of the with and without right-turn acceleration lane configurations will help to test the conclusions presented in Inman and Haas (2012) and Zhang and Kronprasert (2014) that the U-turn spacing affects the two lane configurations differently.

Even though crash analysis was outside the scope of this project, the authors performed a brief crash analysis of J-turn configurations. The results of this analysis can be compared to the results from Zhang and Kronprasert (2014) and the results from the simulator study. The University of Missouri (MU) had J-turn crash data processed and readily available from previous MoDOT projects. Crash rates were computed by considering segment length and AADT. For some existing Missouri J-turn sites, DF configuration contained partial deceleration lanes. In order to utilize a larger sample, all DF configurations were used, regardless of whether deceleration lanes were full length or not. Table 2.1.1 shows the twelve J-turn sites along with the relevant characteristics. The area, Column 3, refers to either urban or rural. The years of operation is from the opening date until January 1, 2015. The unit of crash rate is in crashes per million vehicle miles traveled. Each J-turn site can have up to four separate segments with two in each direction of travel, from the U-turn to the minor road and from the minor road to the U-turn. As shown in Figure 2.1.1, the comparison of crash rates shows that the AD crash rate is approximately half of the DF crash rate.

TABLE 2.1.1 Missouri J-turn Crash History

Location	City	Area	Op. Yrs.	Lane Config.	U-turn Dist. (ft)	AADT by Road		Crashes	Crashes/MVMT
						Major	Minor		
RT-M and Old Lemay Ferry Co.	Imperial	U	7.3	DF	800	9,320	358	1	0.5091
			7.3	DF	1,900	9,320	358	1	0.2144
MO-13 and Old MO-13 (364 E)	Osceola	R	5.5	AD	1,100	11,109	467	3	1.2378
			5.5	DF	1,100	11,109	467	2	0.8252
			5.5	AD	980	11,109	467	8	3.7049
			5.5	DF	980	11,109	467	1	0.4631
US-65 and MO-215	Sheridan	R	5.2	DF	630	7,573	982	2	2.0766
			5.2	DF	630	7,573	982	3	3.1150
			5.2	DF	630	7,573	982	0	0.0000
			5.2	DF	630	7,573	982	0	0.0000
US-65 and MO-38	Jackson	R	5.2	DF	630	6,975	822	3	3.4178
			5.2	DF	630	6,975	822	1	1.1393
			5.2	DF	630	6,975	822	0	0.0000
			5.2	DF	630	6,975	822	1	1.1393
US-65 and Ash St.	Jackson	R	5.2	DF	630	6,631	524	0	0.0000
			5.2	DF	630	6,631	524	0	0.0000
			5.2	DF	630	6,631	524	0	0.0000
			5.2	DF	630	6,631	524	0	0.0000
US-65 and RT-AA	Sheridan	R	5.2	DF	650	9,407	932	0	0.0000
			5.2	DF	650	9,407	932	0	0.0000
			5.2	DF	1,300	9,407	932	4	1.6654
			5.2	DF	1,300	9,407	932	1	0.4164
US-54 and Route E	Jefferson City	R	3.3	AD	1,700	15,097	1,017	1	0.3245
US-54 and Honey Creek Rd.	Jefferson City	R	3.2	AD	1,900	18,213	435	0	0.0000
			3.2	AD	1,900	18,213	435	0	0.0000
			3.2	AD	1,900	18,213	435	0	0.0000
			3.2	AD	1,900	18,213	435	0	0.0000

TABLE 2.1.1 Continued

Location	City	Area	Op. Yrs.	Lane	U-turn Dist. (ft)	AADT by Road		Crashes	Crashes/MVMT
						Major	Minor		
US-63 and Route AB	Columbia	R	2.2	AD	2,300	26,956	1,020	1	0.2075
			2.2	AD	2,300	26,956	1,020	0	0.0000
			2.2	AD	3,000	26,956	1,020	1	0.1591
			2.2	AD	3,000	26,956	1,020	1	0.1591
US-63 and B. Femme Church Rd.	Columbia	U	2.2	DF	900	26,388	1,504	6	3.1909
			2.2	AD	900	26,388	1,504	2	1.0636
			2.2	DF	1,400	26,388	1,504	1	0.3419
			2.2	AD	1,400	26,388	1,504	0	0.0000
MO-30 and Upper Byrnes Mills Rd.	Byrnes Mill	U	2.1	AD	1,500	23,091	2,226	0	0.0000
			2.1	AD	1,500	23,091	2,226	0	0.0000
			2.1	AD	1,700	23,091	2,226	0	0.0000
			2.1	AD	1,700	23,091	2,226	0	0.0000
US-65 and Rochester Rd.	Ridgedale	R	2.1	DF	730	11,584	486	0	0.0000
			2.1	DF	730	11,584	486	0	0.0000
			2.1	DF	990	11,584	486	0	0.0000
			2.1	DF	990	11,584	486	0	0.0000

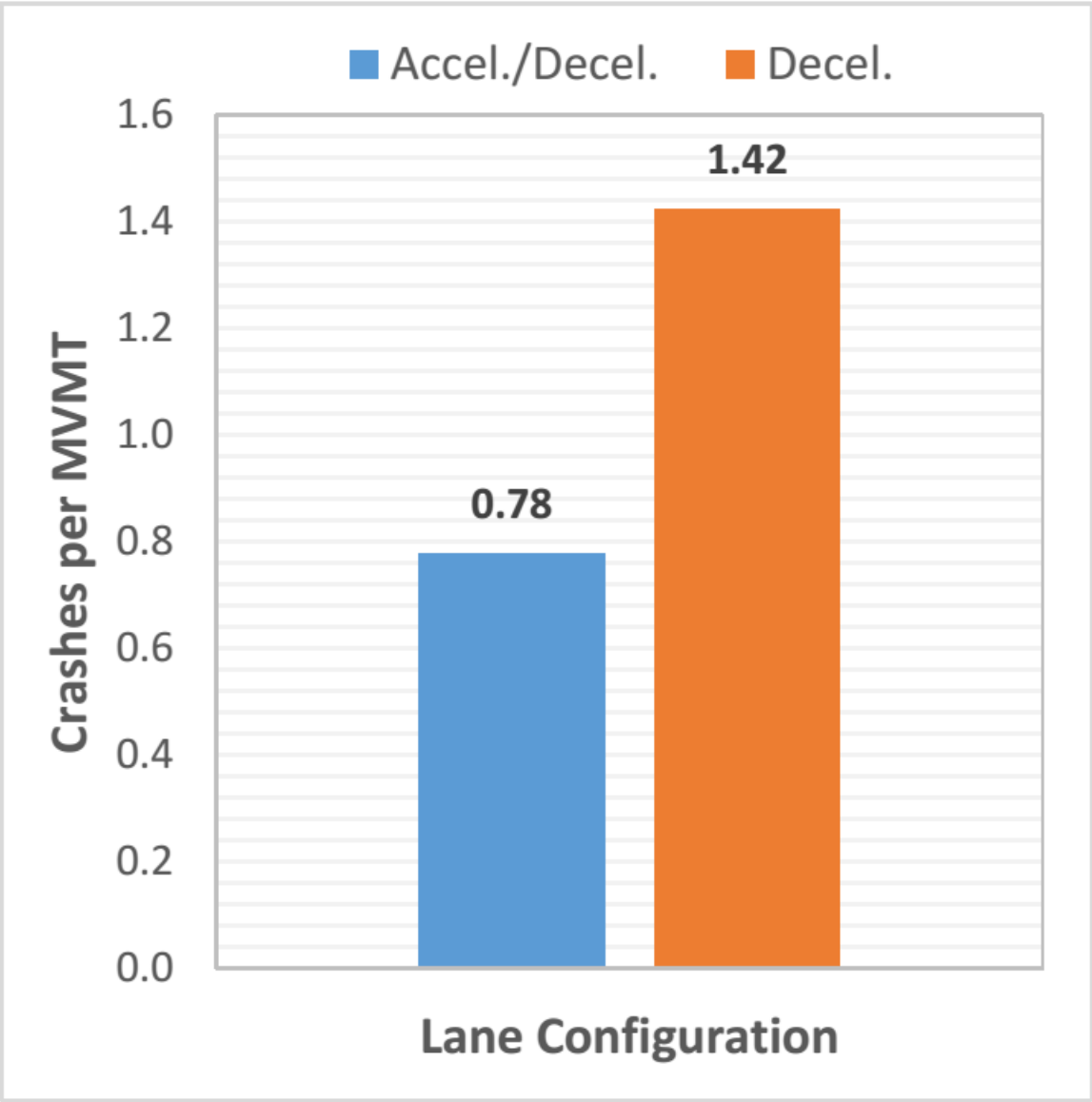


FIGURE 2.1.1 J-turn crash rates by lane configuration.

2.2 U-turn Spacing

The dimension shown as L in Figure 1 illustrates the issue of appropriate spacing between the crossroad and the U-turn. The dimension L is also called U-turn offset by some authors (e.g. Zhang and Kronprasert, 2014). A longer spacing offers a greater distance over which a vehicle can maneuver from the minor road to the U-turn and reduces the possibility of spillback; however, the longer spacing increases travel time. In the example of a two-lane major highway, a vehicle from the minor road will need at least two lane changes to reach the deceleration lane leading to a U-turn. Some sources of guidance related to the design of J-turn spacing include state DOT guidelines, the AASHTO Green Book, and the TRB Access Management Manual.

J-turns spacing recommendations from several DOTs (e.g., North Carolina, Michigan, Oregon, Mississippi, and Missouri) range from 400 feet to 1,320 feet (ABMB, 2010; Bared, 2009; MDOT, 2013). In Missouri, actual spacings range from 630 feet to 3,000 feet. The Green Book (AASHTO, 2011), citing a FHWA guide on signalized intersections (Rodergerdts, 2004), recommends an optimum spacing of 660 feet. However, this recommendation is oriented towards signalized intersections and not unsignalized high-speed facilities. TRB's Access Management Manual (TRB, 2014) recommends a distance of 400 to 1,000 feet. The FHWA RCUT Informational Guide (Hummer et al., 2014) states that the spacing can vary from 400 feet for a stop or signal-controlled intersection to 2640 feet (1/2 mile) for a merge-controlled intersection. The literature presents several recommendations for the U-turn spacing, but none of them appear to be based on research, many are based on convenient distances such as 1/8 mile (660 feet), 1/4 mile (1320 feet) or 1/2 mile (2640 feet).

One article that did include empirical research using crash data was Zhang and Kronprasert (2014). The authors developed crash prediction models from 35 J-turn sites from Maryland, Minnesota, Missouri, and North Carolina. They found that the U-turn offset is highly dependent upon the type of lane configuration. For the configuration with acceleration lanes, increasing the U-turn spacing beyond 1,500 feet reduced crash likelihood due to increased distance and gaps for lane changing maneuvers. However, for the non-acceleration lane configuration, crash likelihood did not vary much beyond 1,500 feet since drivers typically completed lane changes within the first 1,000 feet. But if there were to be a significant traffic volume that decreases gap availability, then the non-acceleration configuration becomes unsuitable for both capacity and safety reasons.

2.3 J-turn Signage

A third consideration involves J-turn signage. Currently, the Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2009) does not contain specific guidance for the signing of J-turns. A driver on the minor road desiring to make a left or through movement requires signage to guide the driver to the U-turn. Two options for minor road signage used by the Missouri DOT (MoDOT), diagrammatic versus directional, are shown in Figure 2.3.1, circled in red. The diagrammatic signage shows the bird's eye view, including the U-turn movement, while the directional signage only directs the minor road traffic to the major road where other signage continues to guide the traffic. Some DOTs, such as Mississippi DOT, recommends the use of the diagrammatic signage in their J-turn design guide (ABMD, 2010). WisDOT (2011), on the other hand, uses neither diagrammatic nor directional signage at the minor road approach, but does use extensive signage on the major road to guide drivers. There is no existing guidance on the effectiveness of the three approaches, i.e., diagrammatic, directional, or none. The guidelines developed in this paper for the acceleration/deceleration configuration, length of spacing, and signage help to address knowledge gap in the existing literature.

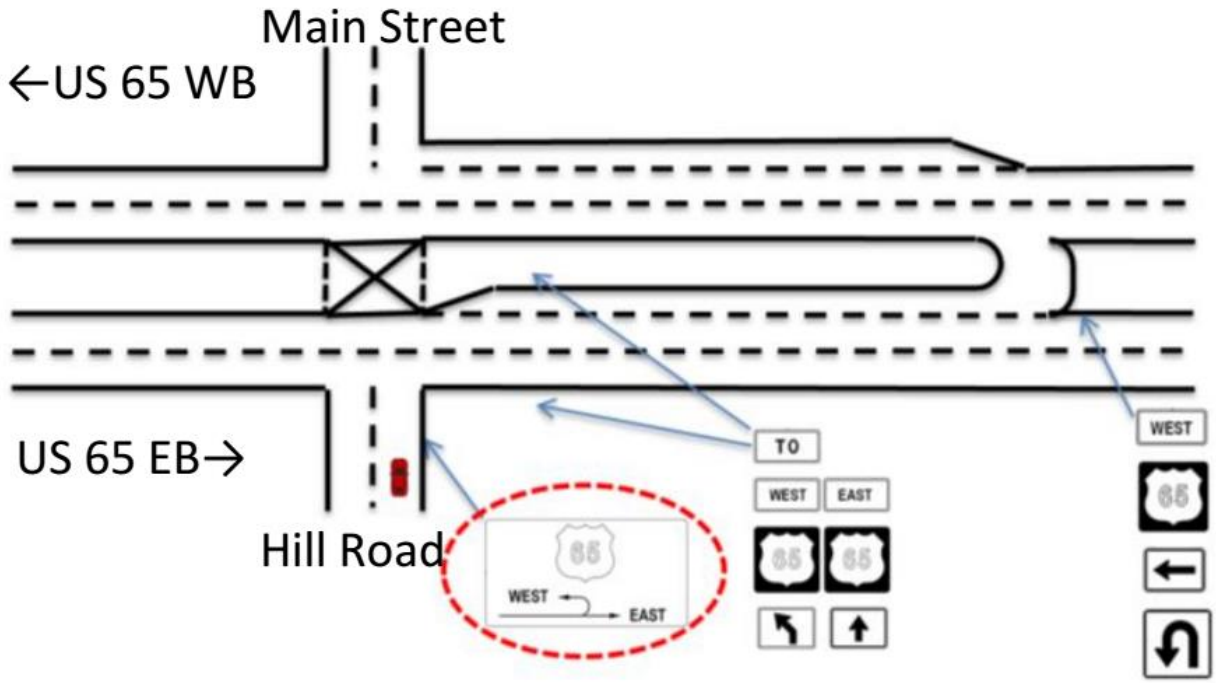


FIGURE 2.3.1a Diagrammatic-style signage on minor road.

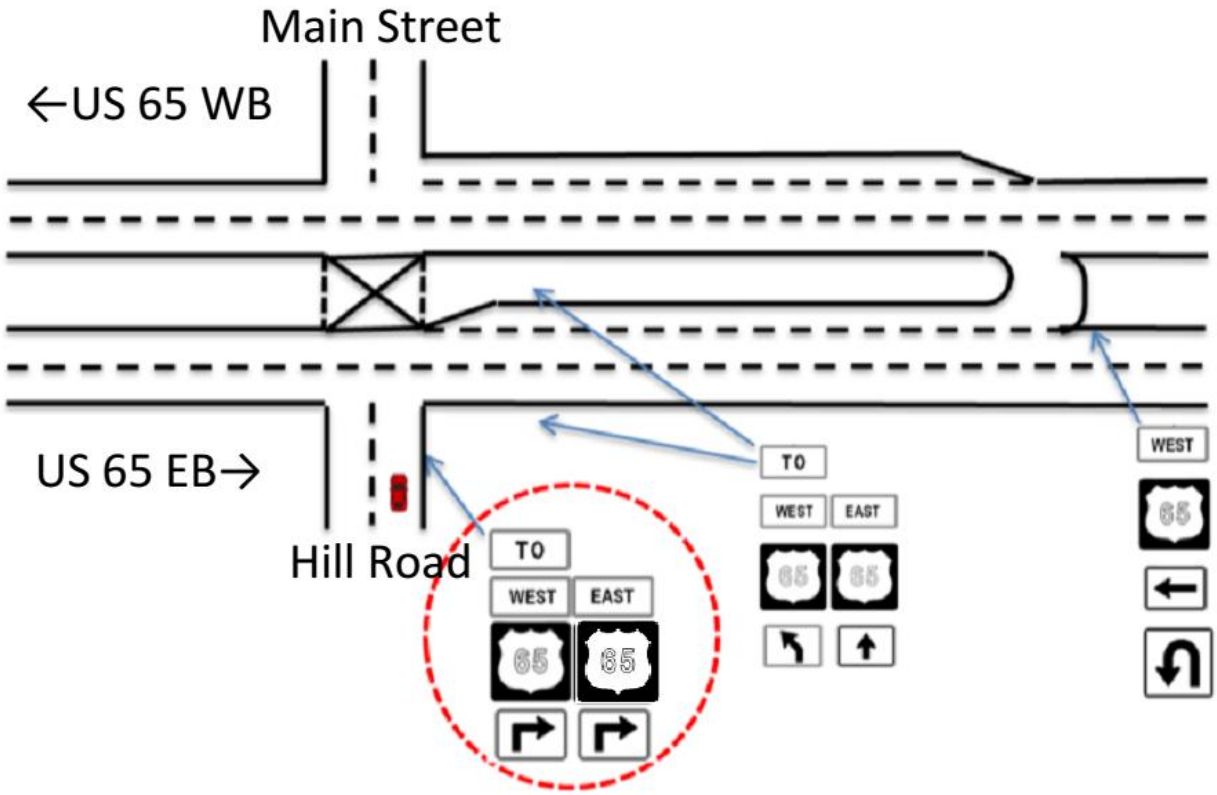


FIGURE 2.3.1.b Directional-style signage on minor road.
FIGURE 2.3.1 J-turn signage alternatives.

After consulting with the MoDOT technical advisory panel (Mike Curtit, John Miller, Bill Stone, and Jen Harper) at the project kick off meeting on December 8, 2014, the research team settled on the following design considerations to be investigated in this simulator study:

- lane configurations: ½ length acceleration/deceleration (AD), full length deceleration only (DF)
- U-turn spacing: 1,000 foot (1K), 2,000 foot (2K)
- minor road signage: directional (DR), diagrammatic (DA)
- flow rates: medium (ME), high (HI)

A limited number of design considerations was necessary in order to make the experiments manageable since there are theoretically 2^x runs that need to be made based on x design considerations. Also, there were only certain design values that were of interest. For example, low flow rates were not insightful since few vehicles means very few vehicle to vehicle conflicts. For this project, x=4 so there were a possible 2^4 or 16 runs. However, since the signage design consideration only differed on the minor road, signage runs were separated from the rest of the other runs. In other words, there were 2^3=8 runs for investigating lane configuration, U-turn spacing, and flow rates, plus one additional run for investigating a different signage. Thus, there were a total of 9 runs per participant. Even with the moderate number of runs of nine total, the simulator experiment resulted in a long actual runtime of greater than 30 minutes per participant. As will be discussed in detail in the section on simulator results, this long runtime is at the upper limit of human participant trials due to subject fatigue and simulator sickness issues. With the addition of human subject orientation and post-simulator surveys, the entire experiment lasted about an hour per subject.

CHAPTER 3 LITERATURE ON DRIVING SIMULATORS

3.1 Introduction

Driving simulator research has expanded greatly in the past decade and beyond. Underwood et al. (2011) reported that the average number of driving simulator papers rose from 124 between 1965 and 1999 to 573 in the 2000s. Van Leeuwen (2015) found 2,752 papers that included the words "driving simulator" in the title, abstract, or keywords between 2000 and 2013. Undoubtedly, the increase in popularity of driving simulator research is due to the usefulness of the driving simulator for a variety of fields, the affordability of such systems, and improvements in graphical, software, and computing technologies. Examples of fields that employ driver simulator research include civil engineering and specifically transportation engineering, mechanical engineering, psychology, medicine/epidemiology, electrical engineering, occupational therapy, and computer science. With such a large number of publications on the subject, it is impossible for any literature review to comprehensively discuss all the literature. Thus, only select literature that is directly relevant to the investigation of evaluating geometric design using driving simulators will be included in this review.

3.2 Applications of Driving Simulators

As discussed previously, there is a diverse range of disciplines that utilize driving simulators and a large number of resultant studies. It is evident that driving simulators have become an accepted and oft-used experimental tool. Instead of presenting specific examples of simulator studies, the classification of simulator applications by Weir and Clark (1995) is repeated here. One type of application summarized by Weir and Clark (1995) relates to roadway and other environmental variables. These applications include road geometry, intersections, delineation, surface properties, roadway textures, roadside features, visual texture and color, signs, signals, illumination, presence of other vehicles and pedestrians, obstacles, and even off-road driving. Another type of application relates to drivers and includes impairment, age, fatigue, mental workload, emotional state, alertness, personality, disabilities, medical conditions, aggressiveness, training, regulations, and instructions. A third type of application relates to vehicles such as vehicle type, dynamic properties, workspace layout, display format and content, communication devices, external field-of-view, restraint systems, and presence of passengers.

3.3. Early History of Driving Simulation

The pre-cursor to modern driving simulators was the use of displayed road scenes in front of a car body (Wachtel, 1995). These early systems were used, for example, at Berkeley/California Department of Motor Vehicles, Ford, General Motors, American Automobile Association, and Rockwell (Decina et al., 1996). The modern driving simulator, characterized by the use of computer generated imagery, began in the 1970s as computing equipment became more affordable and increased in graphical capabilities (Blana, 1996).

3.4 Advantages of Driving Simulator

One main advantage in the use of a driving simulator is the ability to conduct studies that would otherwise be risky or even unethical if they were conducted in the field (Decina et al.,1996). For example, Freeman et al. (2014) conducted run-off road studies as simulator experiments because they were too dangerous as field experiments. Another advantage of a driving simulator is the ability to control the experiment and to eliminate extraneous events that would negatively impact experimental consistency. Weather and traffic intensity are two examples of factors that are difficult to control in the field (Kaptein et al., 1996). In safety research, a major difficulty in the use of crash statistics is accounting for confounding factors. For example, the reduction of certain types of crashes could be the result of a change in land-use (e.g., reduction of alcohol establishments) instead of the purported safety countermeasure. Thus, a simulator allows a level of optimal control that is nearly impossible to achieve using real world experiments and data. Driving simulators can investigate nonexistent designs such as road elements that are not currently employed (Kaptein et al., 1996). Thus, the use of a simulator is an efficient way for new designs to be investigated such as the development of the Diverging Diamond Interchange in the United States (FHWA, 2007). A further advantage is the relative affordability of such experiments when compared to costly field experiments that are sometimes infeasible due to safety risks. Often the simulator is used as a pre-cursor to field trials, thus it can serve as a first step before riskier experiments are undertaken.

3.5 Simulator Validity

One of the most important considerations in conducting simulator research is simulator validity. Validity refers to the congruence between the simulator design and the research questions that are to be answered (Kaptein el al., 1996). Thus, validity is only defined with respect to specific research questions and not to a simulator in general. Results cannot stem from simulator characteristics that are not part of the real world. But at the same time, it is generally unnecessary for a simulator to reproduce all aspects of reality, since a particular task might only depend on the reproduction of certain aspects of reality. The critical issue in simulator experiments is whether or not the necessary cues related to the performance of a driving task are provided via a simulator. Thus, simulator results are valid when similar patterns of behavior are observed in both a simulator and in the field and with similar differences among individuals (Underwood, et al., 2011). Simulator validity is sometimes also known as behavioral validity and differs from physical validity or fidelity (Blaauw, 1982).

Kaptein et al. (1996) differentiates between absolute and relative validity and also between internal and external validity. For the current J-turn simulation study, relative validity is important in order to discern differences between the proposed design alternatives based on u-turn spacing, acceleration/deceleration lane configuration, signage, and traffic volume. Absolute validity refers to the production of identical numerical values between the simulator and real world (Godley et al., 2002). While relative validity refers to the ability of a simulator to reproduce results in the same direction and with a similar magnitude as real world. Thus, relative

validity is achieved when the relationship between the treatment and control conditions are the same for the simulator and real world, even though there are differences between the simulator and real world for the treatment and control conditions, individually. Relative validity is important, for example, to differentiate among different alternatives such as in comparing one alternative against the baseline or another alternative. Internal validity refers to the ability to explain the relationship between a treatment and a resulting effect (Kaptein, 1996). An example of this is the direct relationship between police presence and greater speed compliance. In contrast, external validity refers to the transferability of specific simulator experiment results to real life.

In addition, other aspects of validity have also been discussed in the literature. Two other types of validity include face validity and statistical validity (Kaptein et al., 1996). Face validity refers to the realistic appearance of the simulator. Face validity could affect the other aforementioned aspects of validity. Statistical validity refers to the statistical significance of the results, which is a function of the sampling distribution or the distribution of simulator trial results. Some have employed a four category validation classification scheme of concurrent, predictive, content, and construct, while others employed a three category scheme of construct-related, content-related, and criterion-related (Blana, 1996). Regardless of the scheme employed, the goal is to gather as much quality evidence as possible from all categories, including evidence from literature on similar simulators, in order to validate the use of a simulator for a specific experiment.

One early validation study involved the comparison of instrumented cars versus a fixed-base driving simulator (Blaauw, 1982). Subjects were measured in terms of their performance in lateral and longitudinal vehicle control. Results showed that the simulator exhibited both absolute and relative validity with respect to longitudinal vehicle control. The simulator only exhibited relative validity for lateral control, possibly due to the lack of motion feedback.

Kaptein et al. (1996) surveyed driving simulator validity studies for behavioral research and reported that medium-level simulators show absolute validity of route choice behavior and relative validity of speed and lateral control behavior. They suggested that a moving base and higher image resolution could increase validity.

Reed and Green (1995) observed twelve subjects driving an instrumented vehicle and compared their performance against a simulator. The authors found that speed control was comparable between the car and the simulator. The larger speed variance for the car could be due to differences in the display (i.e., analog in the vehicle and digital in the simulator) and the lack of environmental disturbances (e.g., wind gusts, road irregularities) in the simulator. Subjects drove less precisely in terms of lane-keeping performance in the simulator, although the negative effects of a phone task was seen similarly in both actual driving and simulator driving.

A validation study of driving simulator speeds was performed by Godley et al. (2002) using a simulator composed of a vehicle cab, a quad screen projector, a sound system, and a vertical motion platform (pitch and roll). The averaged relative validity was assessed by comparing the

mean speeds across an entire measurement area of a straight road partly treated with transverse rumble bars. The interactive relative validity was assessed by comparing the speed profile across the measurement area. Absolute validation was not established nor deemed important, since the goal was only to analyze differences between treatment and non-treatment. The study found that simulator results were relatively valid as participants reacted to rumble strips in very similar ways in both the simulator and the instrumented car.

Lee at al. (2003) observed 129 older adult drivers in simulator and on-road tests. They used ten performance criteria divided into the general categories of road skills and cognition/perception. Some of these measures include rule and sign compliance, speed compliance, use of indicator, working memory, multi-tasking, and speed consistency. They found that there was a significant positive association between the measures resulting from on-road driving and from simulator driving. And they concluded that the driving simulator is valid for assessing the driving performance of older drivers.

Even though Behr et al. (2010) did not perform a simulator validity study, their comparison of real driving behavior versus simulator driving behavior did implicitly support the validity of simulator results. Their study focused on defining the posture and muscular behavior during emergency braking. The real car tests consisted of a rubber ball thrown at a vehicle traveling at 70 km/h to induce emergency braking. In the simulator, driver joint angles were recorded via a six-camera motion-capture system. The authors derived a mean initial condition configuration for driver frontal impact composed of joint angles from both real car tests and simulator experiments. Thus, they implied that simulator results were valid for examining some aspects of human posture. However, the authors also noted that there were some differences between simulator and real-car behavior, including differences in brake pedal loading strategy.

Underwood et al. (2011) found simulator studies are relatively valid for assessing cognitive skills in addition to perceptual-motor skills. They focused on the task of hazard perception and compared a driver's ability to detect hazards while actually driving, watching film recorded from vehicles and driving a fixed-base simulator. In all three cases, they found increased scanning by more experienced drivers. Furthermore, professional drivers were found to fixate on hazards earlier.

Freeman et al. (2014) validated run-off-road (ROR) simulator scenarios by comparing simulator results against existing knowledge, either accepted theories or published data on ROR crashes, and driver surveys. They found a general correspondence between the trends from the simulator studies and existing knowledge for three factors known to affect ROR recovery, namely, vehicle velocity, friction coefficient difference, and curvature. However, the lip height trends were not significant, possibly due to simulator limitations. Since field data from actual ROR events is lacking, it is understandable that the authors pursued a validation scheme by making comparisons against general existing knowledge.

There were additional older validation studies that were summarized in detail by Blana (1995). The reader is referred to Blana's (1995) review for references and for detailed information on validation studies performed at the TNO Human Factors Research Institute, Swedish Road and Transport Research Institute (VTI), Institut National de Recherche sur les Transports et leur Securite, Renault, Transport Research Laboratory, Japan Automobile Research Institute, FHWA Highway Driving Simulator (HYSIM), University of Michigan Transportation Research Institute, and Daimler-Benz simulator.

It is understandable why there are so few comparisons between in-simulator and in-car driving and why the existing validation studies are limited (Underwood et al., 2011). One main reason is that driving simulators are used for investigating nonexistent technologies or are used for experiments that are too dangerous for field experimentation. Ground-truthing data for validation studies is difficult to acquire under those circumstances. For example it is arguable whether or not the experiments conducted by Behr et al. (2010) in France, which involved a large rubber ball being thrown at vehicles traveling at 43 mph to induce emergency braking, would be allowed by institution review boards in the United States. However, there are some exciting new data sources that could provide field data for validating driving simulators. The naturalistic driving studies are one such data source that involves the long term collection of driver behavior and driving events via instrumented vehicles. Such instrumented vehicles could contain a myriad of sensors mounted unobtrusively, including accelerometers to measure longitudinal and lateral kinematics, vehicle computer interface, lane trackers, and camera views of driver's face, forward, rear, and both sides of the vehicle (Neale et al., 2005). The 100-Car Naturalistic Driving Study (Neale et al., 2005), for example, collected data from 241 primary and secondary drivers over a 12 to 13 month time period and over two million vehicle-miles of driving. Extreme cases of driving were captured, including severe fatigue, impairment, risky and aggressive driving, multi-tasking, and traffic violations.

In summary, the accumulated driving simulator research shows that they can be valid for different types of experiments depending on the sophistication of the simulator (Godley et al., 2002). Validation experiments have used a variety of performance measures including speed, lane-keeping, rule/sign compliance, working memory, multi-tasking, attention, decision and judgment, congruence with published data/accepted theories, and driver posture/musculature. Some of these studies are dated and the tremendous advances in technology could mean that simulator validity have improved since. Many aspects of simulator technology, such as display resolution, refresh rate, display size, and feedback mechanisms have experienced at least a ten-fold improvement over the past decade. Even though previous validation studies have not directly focused on some of the measures of interest related to J-turn design (i.e., gap acceptance, time-to-collision, missed movements), the accumulation of validation literature suggests that a medium-level simulator like ZouSim could produce valid acceleration/braking profiles and resulting trajectories which give rise to the aforementioned performance measures. Note that some studies addressed simulator fidelity for time-to-collision and accidents (e.g., Parks (2005)).

3.6 Simulator Fidelity

Physical fidelity refers to the degree of realism exhibited by a driving simulator (van Leeuwen et al., 2015). In other words, it is the closeness with which a simulator imitates the real world. Fidelity is sometimes divided into the different aspects of visual (e.g., field-of-view, luminance, resolution, refresh rate), vehicle interior (e.g., dashboard appearance, realistic cab), simulation engine (e.g., vehicle dynamics, car-following), and other non-visual sense feedback (e.g., motion, force, auditory). Van Leeuwen et al. (2015) and others argue that visual fidelity is the most important factor for driving. For example, Chatziastros et al. (1999) discussed the fundamental importance of lateral position in driving and how textural cues can improve lateral lane control accuracy. Warren et al. (1988) showed that heading accuracy was a function of dot density. And Pritchard and Hammett (2012) indicated that driving behavior was affected by luminance and a decrease in luminance resulted in a reduction in driving speeds in simulator experiments.

Even though fidelity and validity are different concepts, fidelity could affect validity. For example, increasing the visual fidelity or face validity does not necessarily result in enhanced behavioral validity (Blana, 1995). However, high visual fidelity could affect a subject's motivation which in turn could improve validity. Some have cautioned against possible drawbacks of high fidelity. First, high fidelity can possibly undermine experimental control and data collection due to the complexities of high fidelity design (van Leeuwen et al., 2015). Second, the high level of customization in a high fidelity simulator could make the results too unique, non-replicable, and dissociated from the wealth of driving simulator literature. Third, the relationship between fidelity and simulator discomfort is complex. Even though, theoretically, higher fidelity should lead to less conflict between visual and vestibular systems, some evidence suggests that high fidelity simulators suffer similar or even higher potential for discomfort (Dziuda et al. 2014). They reported that oculomotor and disorientation symptoms persisted at the highest level for a high fidelity simulator using a motion base with six degrees of freedom. A possible trade-off exists between the advantages of high fidelity and the potential for discomfort, as the removal of visual details could reduce the amount of perceived self-movement. Last, details may not be needed for achieving validity, or worse, could distract from the main driving task (van Leeuwen et al., 2015). Thus, the goal is to produce generalizable outcomes versus phenomenologically realistic driving.

Despite possible drawbacks, some studies demonstrated advantages of higher fidelity. Park et al. (2005) found that control fidelity affected handling behavior such as braking and steering, and graphical fidelity affected lane position, vehicle speed, time-to-collision, and simulator sickness. Van Leeuwen et al. (2015) examined the effects of visual fidelity on curve negotiation, gaze behavior, and simulator discomfort. They utilized three different visual fidelity levels of high, medium, and low. High fidelity included detailed texturing of surfaces and the simulation of landscape such as trees and grass. Medium fidelity did not contain textures or roadside objects or scenery. Low fidelity was monochromatic and showed only lane markings. The results show there were statistically significant differences between the high and the other fidelities in terms

of steering activity, lane keeping, and speed choice. They observed higher steering activity with high fidelity which explained the higher accuracy and precision in lane keeping, and they found that simulator sickness was not increased with higher fidelity.

3.7 Modern Driving Simulator Classification

Weir and Clark (1995) used a simulator classification scheme that was based upon physical and functional characteristics. They defined a medium-level simulator as one containing a large roadway display, animated computer graphics, dedicated vehicle cab, steering feel system, interactive controls and displays, and parametrically configurable vehicle dynamics. Park et al. (2005) explains that a medium-level simulator lacks the environmental fidelity of six degrees-of-freedom motion that is available in a high-level simulator, such as the National Advanced Driving Simulator (NADS) sponsored by NHTSA or the Daimler-Benz simulator (Kaptein et al., 1996). On the other side of the spectrum, the low-level simulator is characterized by a lack of a vehicle cab, a limited display with limited field-of-view, and limited auditory cueing. Decina et al. (1996) describes the low-level driving simulators as less dynamic and realistic than higher level simulators and with limited simulation and interactivity. The low-level simulator can be a simple desktop computer with steering wheel controls and has been promoted for driver training applications.

Kaptein et al.'s (1996) classification was slightly different. They defined a low-level simulator as a desktop computer, a monitor, and a simple cab with controls. The medium-level simulator was defined to include advanced imaging, a large projection screen, a realistic base, and sometimes a simple motion base. The high-level simulator was differentiated by a 360-degree field-of-view and an extensive moving base.

Some simulators are using cost as a surrogate for simulator capability and design. For example, Blana (1996) classified simulators into low, medium, and high-cost. Regardless of the classification scheme, whether it is cost-based or functionality-based, the classifications seem to be mostly consistent. Thus, despite some minor differences in simulator classification schemes, the ZouSim driving simulator fits within the definition of a medium-level simulator. It has a realistic cab that was modified from a Toyota Corolla sedan, force feedback for the steering wheel, large forward and side displays, and software configurable vehicle dynamics.

Parks et al. (2005) found that significant differences existed between the low and medium-level simulator in terms of certain performance measures. The low-level simulator participants exhibited increased vehicle speed and a higher number of instances of hard braking and excessive steering. On the other hand, the medium-level simulator participants exhibited a greater number of improper turn signal uses, lane deviations from the center, road edge excursions, off road collisions, and higher simulator sickness ratings. For the evaluation of the J-turn design, the medium-level simulator seems to be a better fit, as it is more accurate in reproducing the most relevant measures related to speeds and braking.

3.8 Simulator Equipment

Simulator makeup differed among individual simulators. In fact, many simulators were custom designed. However, simulators had similar equipment for display, controls, and other driver feedback. The following are some examples of driving simulators and the equipment components. Park et al. (2005) used a medium-level simulator composed of a 123x32 inch curved screen located 72 inches from the driver's eyes. It had a total field-of-view of 135 degrees using three projectors (45 degrees each). The controls had realistic force feedback. They also used a low-level simulator involving three 19-inch CRT monitors. This simulator also had a total field-of-view of 135 degrees using three projectors (45 degrees each). The control did not have force feedback. Gable and Walker (2013) used a medium-level simulator, the MiniSim, developed by the National Advanced Driving Simulator (NADS). It uses three 42-inch plasma monitors, LCD for the instrument panel, sound, steering wheel, gas and brake pedals, and gear shift. Mourant et al. (2007) used an actual vehicle buck, a large curved screen located 12 feet in front of driver's eyes, and a projector with a 1024x768 resolution and 45 degrees horizontal field-of-view at 60 frames/second. The simulator had a force feedback steering wheel and accelerator and brake pedals. Van Leeuwen et al. (2015) used a fixed-base driving simulator with fields-of-view of 180 degrees horizontal and 45 degrees vertical. The front project produced 1024x768 pixels and 2100 lumens while lateral projectors had 800x600 pixels and 2000 lumens.

3.9 Simulator Sample Size

In contrast to traffic parameter studies, where sample sizes could be upwards of over 100,000 using 30 second detector data as a single sample, driving simulator studies typically involve small sample sizes of around 30 subjects. One main reason for the disparity in sample size between these two types of experiments is that simulator studies are able to collect and utilize much more information. For example, a simulator experiment on emergency braking recorded acceleration, speed, clutch depression, accelerator depression, brake pedal load, and electromyography readings (Behr et al., 2010). Another example is a simulator study on adult driving behavior that tracked 10 separate performance measures (Lee et al., 2003). In comparison, a traffic parameter study might only use one or two parameters, such as speed and flow. Another reason for a smaller sample size is the labor-intensive nature of simulator studies since they require hosting, briefing, observing, de-briefing, and analyzing each human subject. The small sample sizes of simulator studies have been the norm in research studies as exemplified in the following published literature.

Godley et al. (2002) utilized 24 instrumented car participants and 20 driving simulator participants in a simulator validation study for speed measurements. The study participants were graduate students and staff members at Monash University. The participants in the instrumented car ranged in age from 22 to 52 years and the gender was divided equally. Brooks et al. (2007) examined observer estimates of steering and vision under low luminance and used a sample of 54 participants; the average age of participants was 53 years with 61% being males. Mourant et al. (2007) used 16 participants (8 males and 8 females) to study the effect of driving

environments on simulator sickness; these participants ranged in age between 50 and 65 and were all faculty and staff members of Northeastern University. Martin et al. (2007) compared younger and older drivers in terms of preferred driving speeds under various luminance conditions. The older drivers averaged 72 years, while the younger drivers averaged 20 years; there were 36 participants with 56% of them being males. Klein and Brooks (2008) used 24 participants in studying the impact of luminance and blur on older driver preferences in regards to speed and acuity. The older drivers averaged 72.2 years and the younger drivers averaged 20.5 years; the sample contained 42% males. Behr et al. (2010) used a sample of 34 simulator subjects to investigate posture and muscular behavior in emergency braking. The sample consisted of 24 men and 10 women with various ages (mean = 36), weight (mean = 75 kg), and height (mean = 174 cm). They compared the 34 simulator subjects with real car data collected from 13 subjects. Dziuda et al. (2014) utilized 12 professional drivers in a truck simulator for studying simulator sickness; the drivers were all males with ages between 24 and 33 years, and none had prior simulator driving experience. Despina et al. (2014) conducted simulator trials using a group of 20 participants (10 male, 10 female). They examined the issue of immersion and realism on driving simulator reliability using three dimensional displays. Van Leeuwen (2015) conducted simulator fidelity experiments using 24 participants, 19 males and 5 females; the participants were members of the Delft University student and employee community. The average age was 24 years and the average number of licensed years was six; five of these participants wore corrective lenses or contacts.

3.10 Duration of Simulator Trials

A natural trade-off exists in the design of human subject simulator trials. While a longer trial results in more data being collected, it could lead to subject fatigue and discomfort. Brooks et al. (2010) discussed that the fact that incidence of simulator sickness is related to exposure length. The length of simulator trials varied significantly in previous studies.

Godley et al. (2002) conducted four minute simulator trial runs with a one minute break in between, although the entire participation lasted around one hour for each subject. Mourant et al. (2007) conducted 48 minute long simulator experiments composed of five to seven minute trials separated by 10 to 20 second breaks. Brooks et al. (2010) conducted five minute simulator trials preceded by two minute training sessions and followed by two minute mandatory breaks. Dziuna et al. (2014) asked subjects to perform three 30-minute tasks along the same route in three different simulator configurations. Presumably, the break in between each 30-minute trial means that the duration could be considered to be 30 minutes instead of a cumulative 90 minutes. Van Leeuwen et al. (2015) conducted three sessions of 9.5 minute trials with a five minute break outside the simulator.

3.11 Simulator Sickness

Simulator sickness refers to the range of symptoms experienced by participants of simulator studies, including driving simulators (Gable and Walker, 2013). Such symptoms can include

disorientation, dizziness, eye strain headache, dry mouth, drowsiness, nausea, and vomiting (Aykent et al., 2014). Negative consequences of simulator sickness include participant dropout, degradation of simulator reliability, and simply the negative physical impact on human subjects (Dziuda et al., 2014).

Three popular theories for explaining simulator sickness include sensory conflict, postural instability, and eye movement (Brooks et al., 2010). Sensory conflict theory, or a conflict between visual and vestibular stimuli, is arguably the most popular theory (Hettinger et al., 1990). Sickness results when the optical illusion of self-motion, a.k.a. vection, is not corroborated by the vestibular stimuli. The vestibular system is the sensory system in the body that coordinates human motion and balance. The postural instability theory suggests that the natural inclination of humans to maintaining postural stability is at the root of the sickness (Brooks et al., 2010). An example of postural instability is the sway a person feels when returning to land after being on a ship. The eye movement theory suggests that errors in eye movements, caused by certain stimuli, create such tension in the eye that sickness results.

Aykent et al. (2014) compared sickness between static and dynamic simulations. A dynamic simulator differs from a static one in having a motion platform that provide movements such as roll, pitch, and yaw. They found that the main factor for inducing static simulator sickness was longitudinal head (vestibular-level) dynamics. In contrast, the main factor for dynamic simulator sickness was vertical head dynamics. Contrary to intuition, Dziuda et al. (2014) found that the enrichment of proprioceptive cues by using a motion base with six degrees of freedom led to the intensification of sickness symptoms; the authors suggest that the introduction of the motion base actually provided more sources of information mismatch.

The Simulator Sickness Questionnaire (SSQ) is a widely used subjective assessment tool for simulator sickness (Kennedy et al., 1993). This survey measures different dimensions of simulator sickness including nausea, visuomotor (i.e., coordination of movement and visual perception) disturbance, and disorientation. SSQ uses the following scale to assess the magnitude of symptoms: none, slight, moderate, and severe. Sixteen different symptoms are included in the SSQ, including questions about general discomfort, fatigue, eye strain, sweating, and nausea. Another questionnaire, the Motion Sickness Assessment Questionnaire (MSAQ) (Gianaros et al., 2001), was based on four dimensions of motion sickness: gastrointestinal, central, peripheral, and sopite-related (fatigue). The MSAQ uses a nine point severity scale to measure sixteen different questions about sickness experiences, including questions on stomach sickness, sweating, queasiness, lightheadedness, drowsiness, nausea, and spinning. A total score and separate scores for the four dimensions are used to summarize MSAQ results. Brooks et al. (2010) raised some issues with the MSAQ scale, such as participants' preference for 0 being no symptoms instead of 1, and 10 being severe instead of 9.

Some key factors related to the likelihood of experiencing sickness can include participant age, experience, gender, illness, mental rotation ability, postural instability, and length of exposure (Brooks et al., 2010). A reason given for the correlation of age and sickness is the increased

number of balance and dizziness problems with aging. There is disagreement over the association of sickness and gender (e.g., Mourant et al., 2007). Some driving scenarios that impact sickness include curves, steady braking, intersections, and speed (Gable and Walker, 2013). Ambient conditions, such as room temperature, could also impact sickness.

Several strategies exist for preventing simulator sickness. They include screening participants based on motion sickness, migraines, or pregnancy, keeping the room temperature cool, providing a way for participants to gradually adjust to the simulator, providing breaks between simulator trials, and encouraging participants to speak up when experiencing symptoms (Brooks et al., 2010). However, a potential drawback to encouraging feedback on simulator sickness is the possibility of cueing participants towards symptoms. Other strategies for mitigating sickness relate to experiment design. Mourant et al. (2007) discussed strategies such as the reduction in the number of turns, especially left-turns, using large turning radii, having few roadside objects in the periphery, and reducing optical flow, i.e., the movement of elements in the visual world. Turning and driving on curves produced optical flow distortions and rapid optical flow changes. However, textured road surfaces did not lead to greater sickness, even though there is fast optical flow of the texture directly in front of the vehicle, an area that is not often looked at by drivers. Related to the number of turns, participants reported less sickness in country versus city driving.

In addition to providing safeguards against simulator sickness, Brooks et al. (2010) recommend preparing the laboratory in the event that participants become sick. They recommend stocking sick bags, plastic gloves, mouthwash, water, light snacks, and cleanup equipment.

3.12 Stereoscopic 3D (S-3D)

De Winter et al. (2007) listed the advantages of stereoscopic driving simulators as providing a relevant near-distance cue, inducing positive participant reaction, improving data validity and credibility, improving performance and learning, and creating new possibilities for instructions. In the field of sports broadcasts, Weigelt and Wiemeyer (2012) found that stereoscopic 3D provided a strong influence on both depth perception and spatial presence in addition to selective influences on camera distance. Li et al. (2012) explored the use of consumer-grade 3D displays and found that stereoscopic 3D improves user perception of depth over the standard head coupled perspective.

Despina et al. (2014) tested a 3D driving simulator that consisted of the Unity simulation engine, Head Mounted Display (HMD), and a joystick controller. The authors assessed the relative validity of the 3D HMD versus a 2D monitor. Relative validity was assessed by recording the number of successful challenges, such as slow moving vehicles or red traffic lights, navigated by a driver. They found that although the HMD provided greater immersion, it was less valid than the 2D monitor. The authors explained that a possible reason was due to the increase in simulator sickness with the HMD.

One of the major benefits of using S-3D is the availability of additional depth perception via physiological and psychological factors (De Silva et al., 2010). However, cost is an obvious drawback of S-3D. Other potential drawbacks include increased discomfort, greater distraction, and induced performance reduction due to display artifacts (de Winter et al., 2007). By using a questionnaire designed to measure disorientation and oculomotor cybersickness, Benzeroual and Allison (2013) did not find participants to be particularly susceptible to cybersickness in S3D motion controller games.

CHAPTER 4 ZOUSIM DRIVING SIMULATOR EXPERIMENT DESIGN

4.1 ZouSim Driving Simulator Description

ZouSim, the University of Missouri Driving Simulator, is a medium fidelity simulator that is built around the half cab of an actual sedan. There are several graphical interface options as part of ZouSim, including large projection screens (e.g., 10 feet by 7.5 feet) with projectors, the Oculus Rift virtual reality (VR) goggle, four large screen 65 inch LED monitors, and stereoscopic 3D monitors. Figures 4.1.1 and 4.1.2 show examples of ZouSim using the projection screen and VR options. The choice of the type of graphical display and the number of displays was decided based on the purpose of this study and tradeoffs associated with various factors such as experiment validity, visual fidelity, field-of-view, immersion, and simulator sickness. The field-of-view is defined as the "portion of space in which objects are visible at the same moment during steady fixation of gaze in one direction" (Walker et al, 1990).

FIGURE 4.1.1 Example of ZouSim with projection screen display.

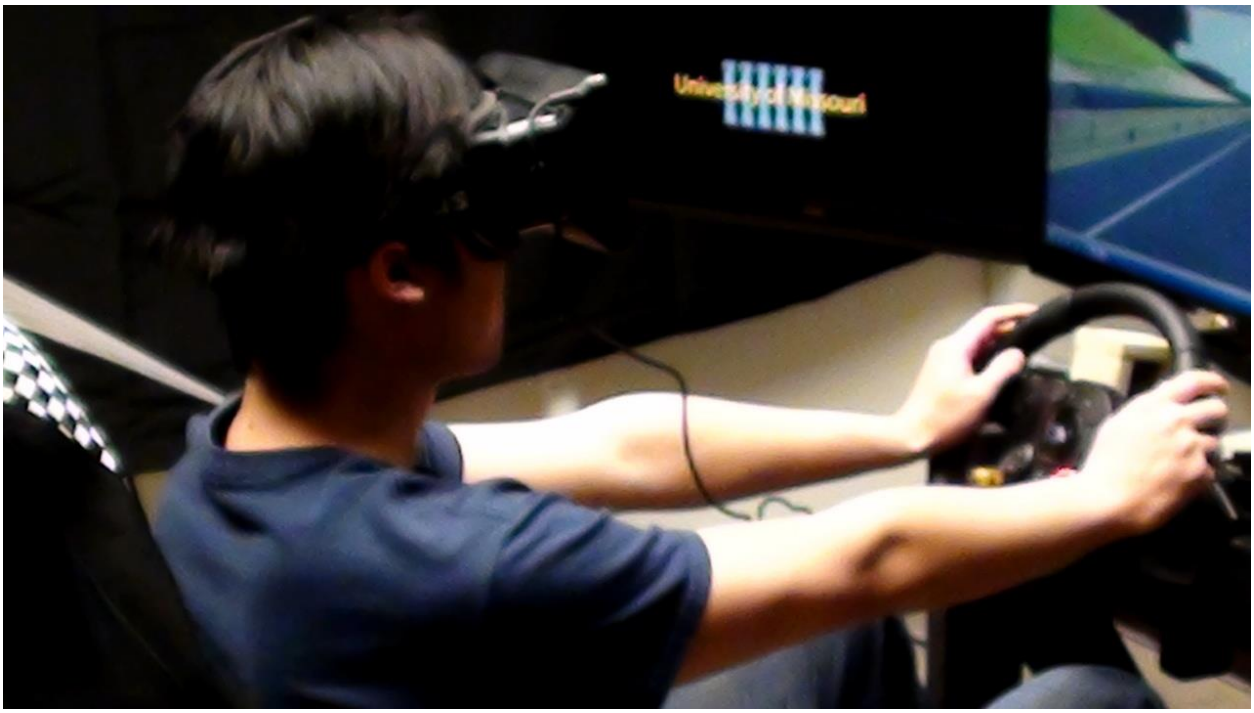


FIGURE 4.1.2 Example of ZouSim using VR display.

The minimum horizontal field-of-view for driving is 120 degrees (Chrisholm, 2008). For this J-turn project, additional situational awareness is needed from the side since a driver stopped at the minor road needs to turn to look for gaps in the mainline traffic, and the side view provides important clues to a driver as to the vehicle speed. Figure 4.1.3 shows an example of the side view in the triple screen implementation of the J-turn experiment. In spanning multiple monitors/screens, there are issues associated with where and how each monitor is placed with respect to the participant. One rule of thumb for the monitor distance is to maximize visual fidelity, i.e., maintain a realistic visual representation of objects such as size and appearance. Here, the mid-peripheral field-of-view is required which led to the use of a triple monitor configuration covering 135 degrees with each monitor covering 45 degrees (e.g., Park et al (2005)). Using multiple monitors also requires for objects to transition smoothly from monitor to monitor. For example, when a vehicle nears an intersection, the crossing traffic has to appear consistent through multiple monitors for the vehicle to react properly. Monitor bezels was accounted for via both graphics card settings and via simulator software.

FIGURE 4.1.3 Side view of ZouSim J-turn driving scenario.

For the J-turn experiment, a triple large screen 65 inch LED monitor setup was used because it provides side views and greater clarity and brightness than the other options, leading to a lower probability of sickness. Minimizing sickness was a major concern since the experiment involved extreme turns (i.e., U-turns), and frequent weaving and acceleration/deceleration. Figure 4.1.3 shows a picture of ZouSim from the inside of the sedan. The active instrumentation in the vehicle includes a force-feedback steering wheel, brake and acceleration pedals, turn signals, and engine vibration generator.

The VR headset has the ability to cover 360 degrees of horizontal vision, but one of its greatest drawbacks so far is the prevalence of simulator sickness. The possibility of sickness is a major concern in this study since the J-turn involves U-turn movements. A lesser issue with VR is the inability for the rider to see the real world such as seeing the steering wheel, pedals, and turn signals. For the aforementioned reasons, a VR headset was not used in this project. Sharing the VR headset sickness concerns, the use of S-3D was also not a good fit for this particular J-turn study.

ZouSim has capabilities for eye tracking and psycho-physiological monitoring of human subjects. The eight-channel ProComp Infiniti psychophysiological system allows the capturing of ECG (electrocardiogram), facial EMG (electromyography), and skin conductance data. SMI mobile eye tracking glasses are capable of capturing gaze data. Figure 4.1.4 shows an example of a screenshot from a ZouSim experiment involving driver dwell times on work zone signage.

These capabilities were not utilized in the current project as they were outside the scope of the project. However, they are tools that can be used in the future to provide greater understanding of driver behavior in regards to different design configurations.

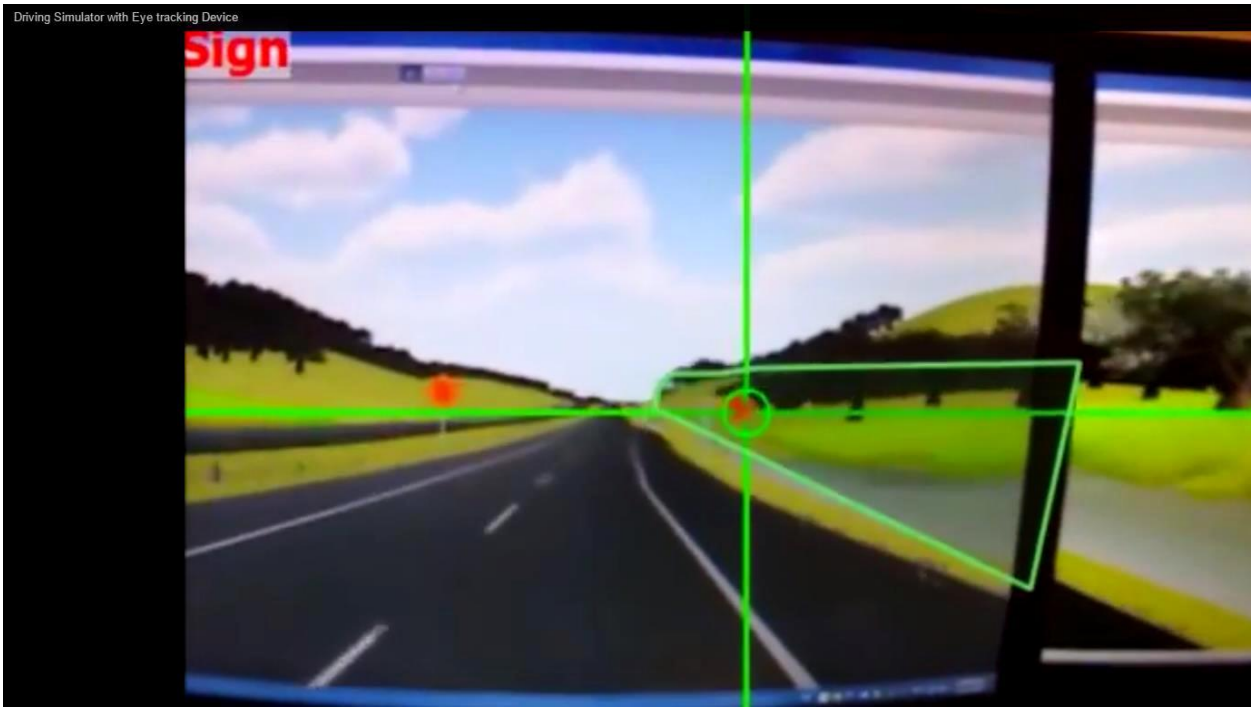


FIGURE 4.1.4 Example of eye tracking during while driving ZouSim

4.2 ZouSim Software Development

Simulator Engine

Some factors influencing the choice of the simulator software engine and design environment include ease of use, flexibility, cost, and capabilities. The two major options are a general software development environment or a simulator-oriented development environment. There are many software languages with the associated development environment that can be an adequate choice for building a simulator. Examples of languages include Java, C-family languages, Python, and MATLAB (Jia et al., 2011). Many development environments are available for any of these languages with the ability for testing, debugging code, and linking to various libraries for simplifying programming for graphics, physics, and devices. The alternative to the aforementioned languages is the use of a simulator engine that is geared towards the graphics-intensive tasks that are required of simulator experiments. Examples of 3D simulator engines include Unity, OpenSimulator, Unreal, and CryENGINE. ZouSim used this alternative approach with the Unity engine to simplify software development. Such simulation-specific engines include many benefits such as a realistic physics engine, 3D capabilities, animation tools, and compatibility with popular 3D software such as 3ds Max and Sketchup. An additional advantage of building an environment using a simulator engine is the existence of large user communities that provide sample code, modeled objects, and troubleshooting assistance. For example, ZouSim was able to import a network model of a section of Paris from the community database

with minimal development. Another example is the use of pre-developed automobile models of various makes for quickly populating a downtown network. A last example is the assistance from the user community for interfacing with new technology such as a VR headset.

Scene Creation

A scene is the Unity name for any simulator experiment designed. A scene is composed of the background, surfaces, and various static and moving objects. The first step in scene creation is to generate the plan view in AutoCAD of the J-turn site. Figures 4.2.1 shows the basic plan view of four different J-turn configurations:

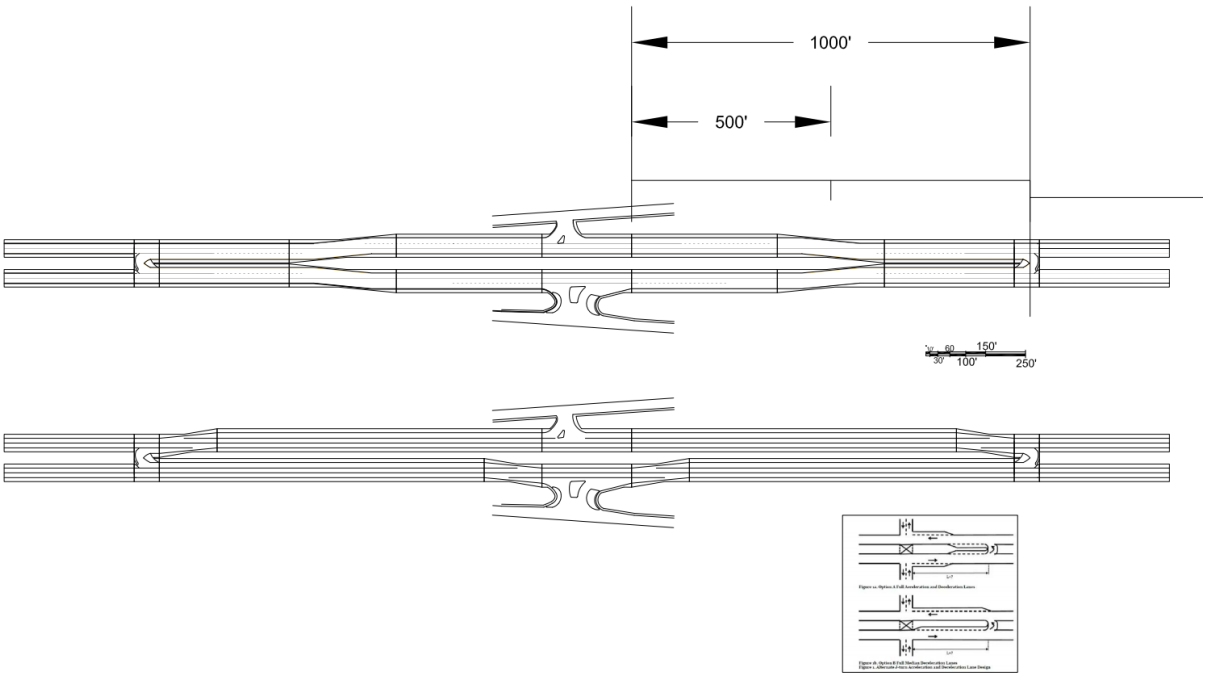


FIGURE 4.2.1a 1000 foot spacing, acceleration/deceleration and acceleration only configurations.

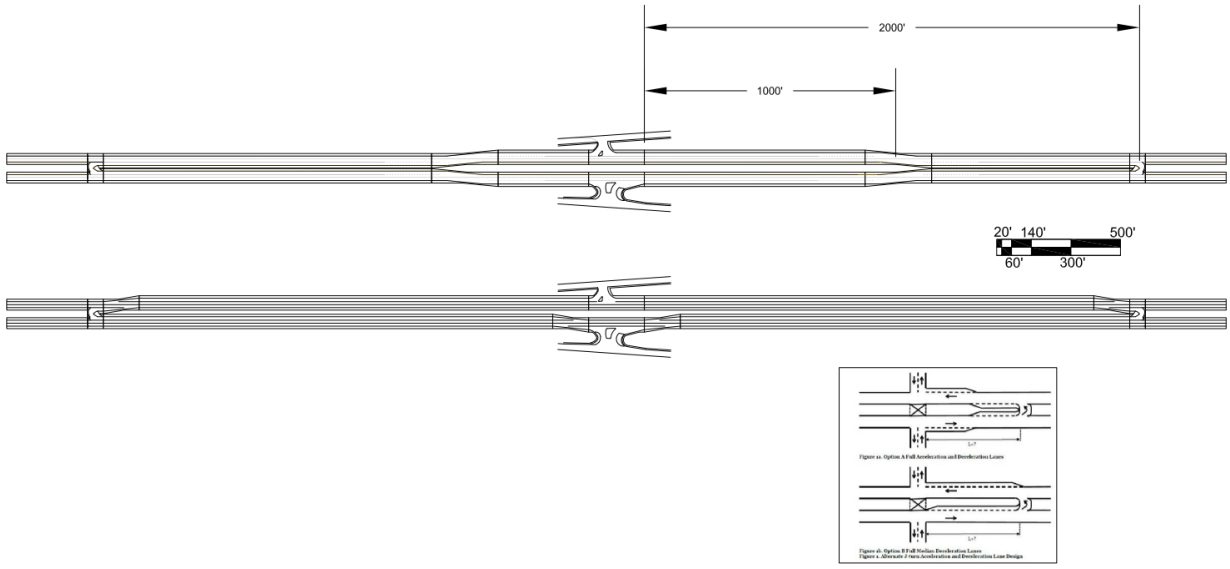


FIGURE 4.2.1b 2000 foot spacing, acceleration/deceleration and acceleration only configurations.
FIGURE 4.2.1 Plan views of generic J-turns.

These plan views were based on existing J-turns implemented on US-63 near Columbia, Missouri. However, the scenes were designed to appear only as generic J-turns so that human participants do not introduce their own memories of experiencing the drive through specific J-turns. The plan views were then used for creating the 3D scenes. In this experiment, the terrain was kept flat in order to control for vertical elevation changes. Thus, a topographic map was not used for terrain creation.

Figure 4.2.2 shows an example of the scene development for the J-turn network. The left side shows the graphical elements, while the right side shows the inspector of object properties, hierarchies of objects and components, such as scripts and audio resource. The sky box is the sky along with other background in a scene and is made up of images that seamlessly connect at the edges. For example, a sky box can be composed of the night sky and stars or a blue sky with clouds.

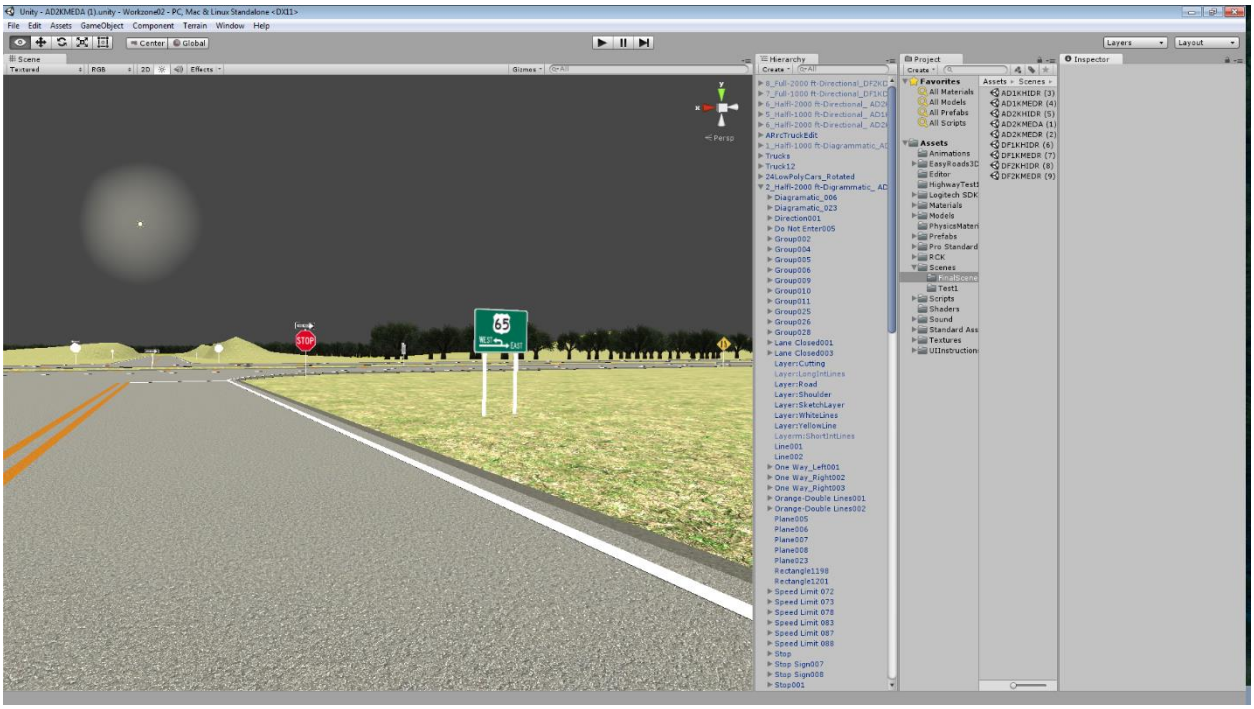


FIGURE 4.2.2 Example of J-turn simulator scene development.

Any number of light sources can be placed in a scene, and real-time shadows will result depending on the type of light. A directional light, such as the sun, is placed infinitely far away and affects everything in a scene. A point light, such as a street light, shines equally in all directions from a set location. A spot light, such as a vehicle headlight, shines from a point in one direction and only illuminates objects within a cone.

The model surfaces in a scene can involve travelway, shoulders, clear zones, and other road facilities. Since the focus of this experiment was on driver performance at J-turns, a flat surface was used; other ZouSim experiments involved the import of an actual terrain via topographic data. Terrain that includes vertical and horizontal curvature was undesirable because it would introduce other factors not pertinent to the J-turn study. The engine's terrain tools allow the terrain to be "painted" for texture, color, and foliage. Surfaces can be textured to replicate different types of pavements, such as asphalt and concrete. Different types of Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2009) striping and markings were painted on surfaces. Figure 4.2.3 shows an example of the J-turn involving MUTCD signage, striping, and markings.

FIGURE 4.2.3 Example of the first person perspective from a human subject.

Scene Objects

Common static objects modeled in scenes include road signs, trees, grass, and buildings. Three dimensional models of objects are made of meshes, which are a combination of thousands of rectangles (polygons). The simulator engine calculates the location of these polygon faces during rendering. Too many faces loaded into a scene at once will overtax the system and be unusable. Typically, detailed models that are close to the screen all of the time should be fewer than 100,000 faces. Details for objects such as signs should be 1,000 faces or fewer.

Objects in a transportation network, such as vehicles, road signs, trees, and buildings, are placed into a scene on top of the surface. An object can be a static or a dynamic object. An object's properties determine how the object interacts with the rest of the scene. The way a dynamic object moves can be set in scripts as part of the object properties. For example, the properties can determine if an object casts shadows, can collide with other objects, or is affected by gravity. If the object has a special function, a custom made script (program) can be applied to it. Moving vehicles were introduced on the major highway at a constant headway; the flow rate was kept constant so that each participant experienced the same scenario. These vehicles were intentionally designed without colliders so that any contact with the subject vehicle would not result in a crash, though incidences of contacts were logged. Figure 4.2.3 shows an example of a scene that includes several static objects such as signage and trees.

In modeling the study subject, one camera is used to replicate the driver's perspective in terms of height, angle, and field-of-view, the so-called first person perspective. The primary virtual camera was the forward windshield view. Five additional virtual cameras represented the left, right, left mirror, right mirror, and rearview mirror perspectives. Figure 4.2.3 shows an example of all five virtual cameras.

The simulator engine uses a hierarchical (a parent-child) system. An object located underneath another object as a child object will follow the higher-level (parent) object. For example, wheels are located under the sedan object. When the sedan moves, the wheels move as well. The driver-perspective camera is also located under the sedan folder. This hierarchy system works just like the folders do on a computer. When a high level folder is moved, all of the lower level folders move also.

An audio script can be used to generate both auditory feedback and vibrations. For example, tire and engine noise were generated based on the road surface and the type of tire. Depending on the purpose, audio can be activated by proximity to the noise source or via a script.

Calibration and Validity

Validity refers to the degree in which a simulator evokes the same behavior as the real world (Kaptein et al., 1996). In other words, the behavior in question cannot be the result of simulator characteristics that are not present in the real world environment. For example, if the region covered by the peripheral vision is not shown, then the investigation of driver comfort with adjoining vehicular traffic cannot be valid. For some experiments, only relative validity is

required as opposed to absolute validity. Relative validity is the ability of a simulator to rank different experiment treatments in the proper order, while absolute validity is the ability of a simulator to produce a size of effect that is comparable to reality.

To improve ZouSim's validity, calibration that is based on the objectives of a particular study was performed. Accurate braking and acceleration are critical to generate realistic behavior. Thus, the acceleration/deceleration profile of an actual Toyota vehicle was replicated in ZouSim. Since this is a study where markings and signage are important, field videos recorded from a driver's field-of-view were used. The simulator scene was calibrated so that the appearance of the road, signs, and markings matched the field video. Figures 4.2.4-4.2.6 shows screenshots of the simulator views juxtaposed next to the calibration video snapshots. Recall that the goal of calibration was not to replicate the video exactly; such a replication is undesirable since the model does not represent a specific location. For example, Figure 4.2.4b shows a horizontal curve on the minor road approach and Figure 4.2.5b shows a vertical curve; neither curve was modeled. Figure 4.2.6b shows additional signage and a large slope in the landscape area, neither of which was important for the experiment. Figures 4.2.4-4.2.6 illustrate the fact that visual calibration involves capturing the essence of the scene in order to generate realistic behavior.

FIGURE 4.2.4a Simulator view of minor road approach.

FIGURE 4.2.4b Calibration video of minor road approach.
FIGURE 4.2.4 Calibration using minor approach video footage.

FIGURE 4.2.5a Simulator view of approach to deceleration lane.

FIGURE 4.2.5b Calibration video of approach to deceleration lane.
FIGURE 4.2.5 Calibration using footage of approach to deceleration lane.

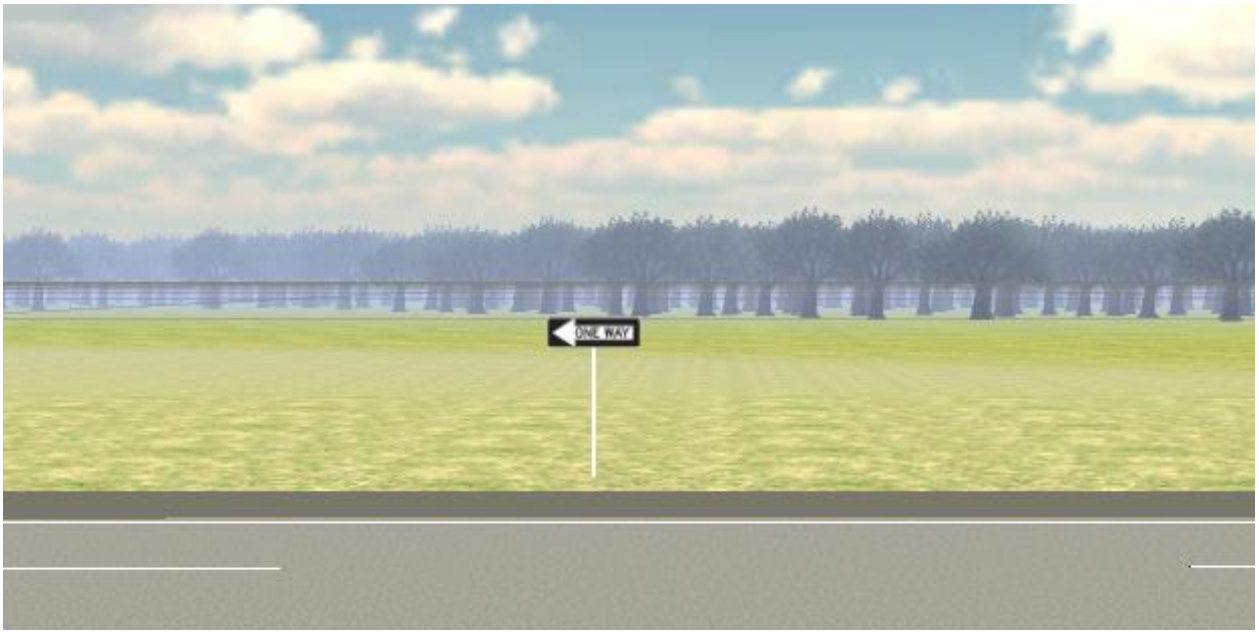


FIGURE 4.2.6a Simulator view at U-turn.

FIGURE 4.2.6b Calibration video view at U-turn.
FIGURE 4.2.6 Calibration using U-turn footage.

Other Miscellaneous Abilities and Issues

A useful ability of the simulator engine is the capability to automatically collect driver performance measures and other information related to simulator trials. Vehicle speed, braking, acceleration, location, and relative location to signage can all be downloaded into a separate log

file for each participant for post-processing; the post-processing can be accomplished with automated scripts to derive various safety and other performance measures depending on the goals of a specific study. As will be discussed in more details in other sections, the performance measures of speed, travel time, wait time, speed differential, headway, time-to-collision, merge location, and vehicle trajectory were automatically captured for each participant. Figure 4.2.7 shows an example snippet from the automated log. This example shows the XYZ coordinates and time values that can be used for recreating vehicle trajectories. Lane changes are clearly detected from the data logged information (e.g., from acceleration lane to the right lane).

```
Time:35.75417 ;
Status: None ;
Facing: East  95.88723Degrees ;
Turn: None(Straight) @ 0.00Steer ;
XYZ Coordinates:(-69.6, 0.2, 11.2) ;
Position: East Bound, Acceleration Lane ;
Speed:58 MPH ;

Time:36 ;
Status: None ;
Facing: East  95.88815Degrees ;
Turn: None(Straight) @ 0.00Steer ;
XYZ Coordinates:(-73.9, 0.2, 10.7) ;
Position: East Bound, Acceleration Lane ;
Speed:58 MPH ;

Acceleration Line Crossed at: 315.38 Feet From Origin ;

Time:36.25426 ;
Status: None ;
Facing: East  95.88882Degrees ;
Turn: None(Straight) @ 0.00Steer ;
XYZ Coordinates:(-77.9, 0.2, 10.3) ;
Position: East Bound, Right lane ;
Speed:57 MPH ;
```

FIGURE 4.2.7 Sample snippet from automated data logged from simulator runs.

Finally, there are some miscellaneous issues related to the implementation of experiments. It was important to ventilate and cool the room in order to minimize the likelihood of simulator sickness. High-powered fans and air conditioning worked together to increase comfort for human subjects. For this study, as in most studies, it is best not to replicate real-world locations exactly. Otherwise, human subjects will introduce memory-related expectations and be disappointed when the field site is not replicated completely. For example, a subject familiar with a particular street will expect the building facades, landscaping, and other unique features of that street to look the same.

4.3 ZouSim Simulator Calibration

The ZouSim J-turn experiment was calibrated in four main ways: acceleration/deceleration data, field videos, flow rates, and speed distributions. The first two were for the subject vehicle and the last two were for the background traffic. Since the physical cab used was a sedan, the vehicle performance was modeled after the manufacturer's data on maximum acceleration and braking rates (e.g. 190 feet stopping distance from 70 mph). Drive videos were recorded for the J-turn on US-63/AB. Multiple iterations of evaluation and refinement with test drivers improved the correspondence with real-world driving conditions. These refinements included improvements in the representation of the physical environment as well as the human-machine-simulation interactions between the test subject and the hardware configuration, involving steering wheel, pedals, and turn indicators. In other words, steering, acceleration, braking, and signalization were fine-tuned to match realistic driving.

Flow rates were collected from both major and minor approaches at the US-63/AB J-turn for both morning and evening peak hours. Vehicle speeds of the major road traffic were collected using radar guns. The mainline traffic in ZouSim was then modeled after the field traffic characteristics from US-63/AB. The details of the field data collection were documented in Edara et al. (2013).

4.4 Experiment Configurations and Sequence

The three design considerations investigated, acceleration/deceleration lane configuration, U-turn spacing, and signage, were restricted to certain values in order to make the experiments feasible in terms of duration. As shown previously, the half-length acceleration/deceleration lane configuration (AD) and the full length deceleration lane configuration (DF) were the only two designs tested. For the U-turn spacing only two values were used: 1,000 and 2,000 feet. As discussed previously, the diagrammatic and the directional minor road signage were the only two signage options tested. In addition, the effect of the major road traffic was investigated. For the major road, the following two flow rates were used in each of the two lanes per direction: 545 vphpl (medium) and 720 vphpl (high). The values for spacing and flow rate were selected by the project technical advisory panel as the most relevant for J-turn design in rural Missouri.

Each experiment run was designed with a unique set of lane configuration, U-turn spacing, signage, and traffic flow rate. Table 4.4.1 shows the different combinations of runs from the possible design values. For example, Run 2 in Table 1 represents a J-turn design with the half-length acceleration/deceleration lane configuration (AD), a U-turn spacing of 2,000 feet (2K), medium major road traffic (ME), and directional minor road signage (DR). In order to further reduce the number of experiment combinations, the signage consideration was separated from the other design considerations. The reason for this separation was twofold. First, if the U-turn movement was missed due to signage confusion, then important data related to the U-turn would be absent from that particular run. Second, signage is assumed to be somewhat independent from the other considerations of lane configuration, spacing, and traffic flow. Therefore, in terms of

the order of experimentation, the signage runs were always conducted first, i.e., Runs 1 and 2. For these first two runs, participants were only told to start from the minor road and to continue on the minor road, and they were not told that a J-turn was involved. Thus, there was the potential for participants to miss the U-turn, and some did. After Runs 1 and 2 were completed, then the participants were told about the J-turn so as to not miss the U-turns in the later runs.

TABLE 4.4.1 ZouSim J-turn Experiment Runs

Run	Pattern Code	Lane Configuration	Spacing (feet)	Major Road Traffic	Signage
1	AD2KMEDA	Accel./Decel.	2,000	Medium	Diagrammatic
2	AD2KMEDR	Accel./Decel.	2,000	Medium	Directional
3	AD1KHIDR	Accel./Decel.	1,000	High	Directional
4	AD1KMEDR	Accel./Decel.	1,000	Medium	Directional
5	AD2KHIDR	Accel./Decel.	2,000	High	Directional
6	DF1KHIDR	Full Decel.	1,000	High	Directional
7	DF1KMEDR	Full Decel.	1,000	Medium	Directional
8	DF2KHIDR	Full Decel.	2,000	High	Directional
9	DF2KMEDR	Full Decel.	2,000	Medium	Directional

Sequence bias, or order effect, is the influence of the order in which the runs are conducted in a human participant study. This is because early runs can act as an "anchor" affecting subsequent runs (Perreault, 1976). One way of controlling for this bias is to randomize the runs. The signage runs and the non-signage runs were randomized separately.

In administering the experiments, each experimenter followed a script closely in order to provide the same, uniform instructions to each participant. Appendix A contains the exact script followed by each experimenter. The participants were not told to make a U-turn in order to study driver signage comprehension. Instead, the participants were simply asked to view a map, as shown in Figure 4.4.1, and to continue on the minor road and to cross the major highway.

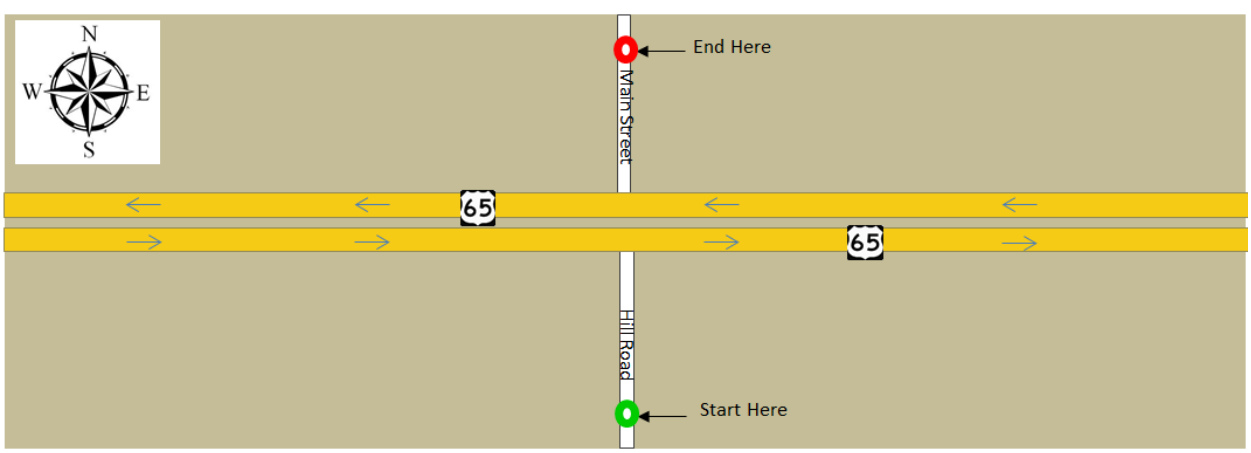


FIGURE 4.4.1 Map of the J-turn location.

Two post-simulator surveys were administered after a participant completed the nine simulator runs. The first survey is a 17-question survey on a participant's view on J-turn lane configuration, U-turn spacing, minor road signage, J-turn knowledge, safety, simulator realism, and demographics. For questions involving the preference between two alternatives, such as between the acceleration/deceleration configuration versus the full deceleration configuration, a five point Likert scale was used as a response. The second survey is the well-known Simulator Sickness Questionnaire (SSQ) (Kennedy, 1993). The SSQ asks 16 questions, each one related to a symptom, such as eye strain, nausea, or dizziness.

CHAPTER 5 SIMULATOR AND SURVEY RESULTS

5.1 Simulator Results

The study protocols and measurement tools were evaluated and approved by the campus institutional review board (IRB). The experiments were judged to be exempt from IRB review since the experiment involves very minimal risk, if any. The human participant recruitment flyer is included in Appendix B. All experiments were conducted in the ZouSim laboratory (Heinkel Room 15) on the University of Missouri campus. Informed consent of the human participant was obtained in writing at the beginning of each study. Appendix C shows the consent form used in this study. The consent form describes the study, discusses risk and benefits, emphasizes confidentiality, and reminds participants that withdrawal is allowed at any time for any reason.

Of the 34 participants, 30 completed all the runs. Three participants were unable to continue after experiencing symptoms during the warm up scenario. The participants who completed the runs reflected a wide range of demographics and they were all licensed Missouri drivers. The participants were divided equally in gender between male and female. Even though the age distribution was skewed slightly towards younger drivers, the majority were older than 26 years old, with 10% older than 56 years old. The participants were all from the metropolitan Columbia, Missouri area and reflected a wide range of professions.

Several measures of performance (MOEs) were recorded automatically from the simulator experiments. Some of the safety MOEs, such as speed differential and Time-To-Collision (TTC), were used because actual collisions are rare in real life and in simulator experiments. Previous research (e.g., Zhang and Kronprasert, 2014) indicated that the location where vehicles change lanes to reach the U-turn vary between the AD and DF configurations. Thus, the average locations of lane changes were measured along with full trajectories of subject vehicles. Travel times and wait times were measured to compare the efficiency among different designs. The record of a driver missing the U-turn on a run was used to assess driver comprehension of signage. In other words, a participant who did not understand the J-turn signage would continue past the U-turn.

MOEs derived from vehicle speeds can be helpful for assessing both safety and operations. Speed differential is defined here as the difference in speeds between the subject vehicle and the speed of a vehicle approaching the subject vehicle at the instance the subject vehicle crosses a lane for a lane change maneuver. Even though the relationship between speed measures and safety is complicated (TRB, 1998), the speed differential measure adds to the safety information provided by other measures. Speed measures also help to assess J-turn operations. A large speed differential that causes merging turbulence can lead to the deterioration of mainline traffic flow.

Analysis of variance (ANOVA) (NIST, 2012) was used for modeling and residual assessment of the dependent variable, speed differential (SD). The requirements of normality, independence,

and homoscedasticity were verified before modeling. The speed differential was recorded for six separate lane change movements:

1) from the minor road or acceleration lane, depending on the lane configuration, to the outside lane
2) from the outside lane to the inside lane
3) from the inside lane to the deceleration lane
4) from the U-turn to the inside lane in the opposite direction
5) from the inside lane to the outside lane in the opposite direction,
6) from the outside lane to the minor road or deceleration lane, depending on the lane configuration in the opposite direction

Figure 5.1.1 shows these movements for the two lane configurations.

Similar analysis was performed for movements 1, 2, 4, and 5, and the results were similar. No speed differentials were computed for lane changes 3 and 6, since there were no vehicles from the mainline that used the U-turn. The independent variables were lane configuration (AD or DF), U-turn spacing (1,000 or 2,000 feet), and traffic volume (545 vphpl or 720 vphpl). The variable names were M for lane configuration/movement, L for U-turn spacing/length, and V for traffic volume. L and V were standardized since the variables have different units of measurement. By considering interaction effects, the following seven possible variables resulted: M, V, L, MV, VL, ML, and VML. Thus there were 7! or 5,040 possible variable combinations for modeling.

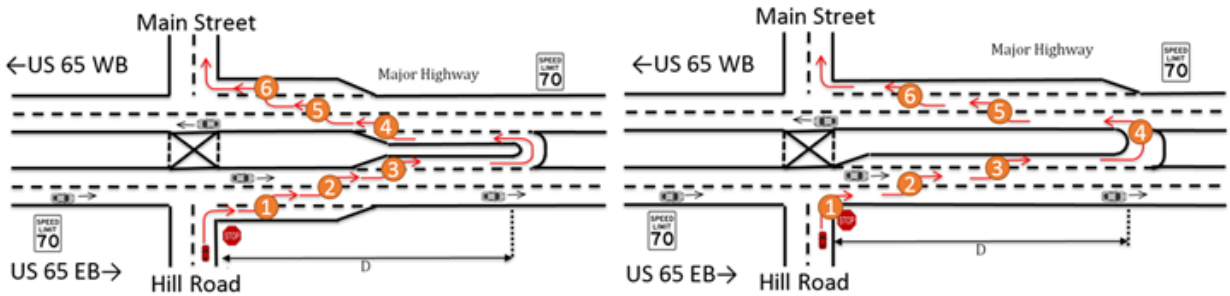


FIGURE 5.1.1a. Acceleration deceleration. FIGURE 5.1.1b. Full deceleration lane only.
FIGURE 5.1.1 J-turn lane change movements.

Table 5.1.1 shows the results of ANOVA modeling of the lane change 4 post-turn speed differentials that included all possible variables. The source column shows the relevant variable of the overall model. The sum of squares is a measure of deviation from the mean. The degrees of freedom, df, is the number of values that are free to vary in the model. The mean square is the variance estimate among a given set of variables. The F value is a measure of the size of the effects. And the p value is the significance level. Table 5.1.1 is in a format that is typical of ANOVA results. Ultimately, the most important column is the the p value column which shows if a variable is significant or not. Typically, a value of less than 0.05 is considered significant. The variables M, L, and M*L were significant.

Note that it is common in human behavioral cross-sectional studies for the magnitude of ANOVA R^2 values to be lower than other studies; the estimate of the relationship between the independent and dependent variables are still valid (Wooldridge, 2015). R^2 values were 47% for lane change 1 and 53% for lane change 4. Table 5.1.1 shows the variables M, L, and M*L were the only significant ones. Thus, a final model was developed using M, L, and M*L variables; equation 1 represents this model. Equation 1 implies that the lane configuration is the most important design factor with the largest coefficient of 0.7141. The U-turn spacing was also significant, although with the much smaller coefficient of 0.0938. The only interaction effect was between lane configuration and spacing. This means that lane configuration and spacing are related. This interaction will be examined further with other performance measures such as lane change distances and vehicle trajectories.

TABLE 5.1.1 ANOVA Modeling for Post U-turn "Lane Change 4" Speed Differentials

Source	Sum of Squares	df	Mean Square	F value	p value
Model	127.797	7	18.257	35.04	0.000
M	122.464	1	122.464	235.03	0.000
L	2.101	1	2.101	4.03	0.046
V	0.228	1	0.228	0.44	0.509
M*L	2.607	1	2.607	5.00	0.026
M*V	0.007	1	0.007	0.01	0.908
L*V	0.024	1	0.024	0.05	0.829
M*L*V	0.007	1	0.007	0.01	0.905
Error	112.549	216	0.521		
Total	240.346	223			

$$SD = -0.0509 + 0.7141M + 0.0938L + 0.1043M * L \quad (1)$$

TTC is defined as the expected time until a collision will occur if two vehicles were to continue on the same course without changing speeds (Vogel, 2003). In other words, it is the time that is needed to travel the space separating the lead and the following vehicle at the relative speed between the lead and following vehicles. The equation for TTC is

$$TTC = \frac{x_{i-1} - x_i - l_{i-1}}{v_i - v_{i-1}}, v_i > v_{i-1}$$

where,

x_{i-1} = the position of the lead or merging vehicle;

x_i = the position of the trailing or mainline vehicle;

l_{i-1} = length of the leading vehicle (20 ft. was used as the average vehicle length);

v_{i-1} = velocity of the lead or merging vehicle;

v_i = velocity of the trailing or mainline vehicle.

In analyzing TTC values, large TTC values were not included since they are not safety critical. A value of 6 seconds was the threshold applied following Vogel's research (2002) that vehicles with a headway of more than 6 seconds chose their speed independent of the leading vehicle. Furthermore, there does not exist any research that point to a TTC larger than 6 seconds as impacting safety (Vogel, 2003); instead, some studies have suggested an even smaller TTC threshold of 4 seconds (Hirst and Granham, 1997).

The TTC results show that there is a statistically significant difference (p=0.0243) of 106 (66.3%) more total safety-critical TTC values with the DF configuration as compared to the AD. This is consistent with the speed differential results that indicate M as a significant variable. When examining each lane configuration individually, the U-turn spacing affected the number of TTC conflicts in the AD design (p=0.326), but not the DF design. While the 1,000 foot spacing in AD had 22 (31.9%) more total safety-critical TTC events than the 2,000 foot spacing, there was no observable difference between the two spacing values for DF design.

Where a vehicle makes lane changes while traveling through a J-turn has both safety and practical implications. A safety issue arises if a vehicle is forced to either make a lane change into a small gap or miss the U-turn or minor road. Unnecessary extra travel time results if the U-turn spacing is never fully utilized and a shorter spacing could have been just as effective. Lane change behavior is analyzed in two complementary ways. A vehicle trajectory plot overlays each individual vehicle maneuvers on top of each other. When trajectories overlap, it appears darker and thicker. Thus, the vehicle trajectory plot shows the locations and patterns of lane changes qualitatively. Figure 5.1.2 shows the vehicle trajectory plots for the aggregated DF1K, AD1K, DF2K, and AD2K runs. These subfigures show a visual difference between the DF and AD trajectories in that the AD lane changes are distributed across a longer spacing. The DF trajectories, for both 1K and 2K, show more concentrated maneuvers near the beginning, either at the minor road or at the U-turn. The implication is that a shorter spacing is adequate for the DF design as compared to the AD.

FIGURE 5.1.2a DF1K (top) AD1K (bottom).

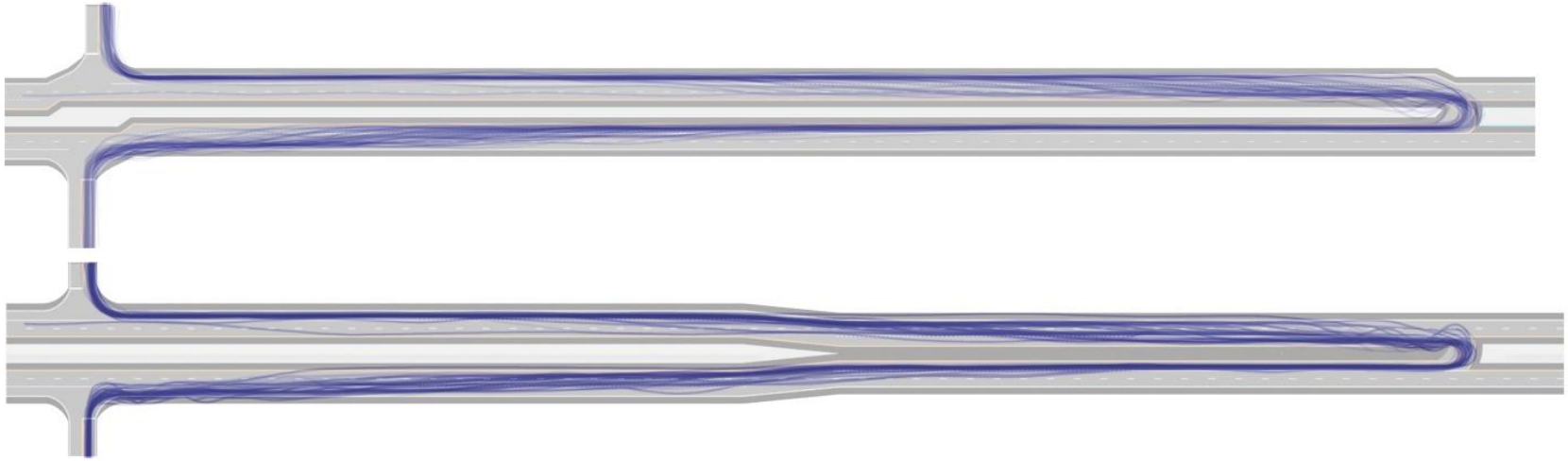


FIGURE 5.1.2b DF2K (top) AD2K (bottom).

FIGURE 5.1.2 Vehicle trajectory plots.

The average lane change distance represents a single quantitative measure where a lane change occurs for a particular lane change maneuver. The following four lane changes are of particular importance:

- LC1: from the minor road (DF) or acceleration lane (AD) to the outside lane
- LC2: from the inside lane to the deceleration lane towards the U-turn
- LC3: from the U-turn (DF) or acceleration lane (AD) to the inside lane in the opposite direction
- LC4: from the outside lane to the deceleration lane towards the minor road in the opposite direction

Table 3 shows the average lane change distance for LC1-LC4. For LC1 and LC2, the distance is measured from the intersection of the minor road with the major highway. For LC3 and LC3, the distance is measured from the U-turn. The average lane change distances are consistent with the vehicle trajectory plots. For AD, Table 5.1.2 shows that LC1 and LC3 do not differ much in magnitude as this is the first lane change in each direction. However, LC2 and LC4 show a large magnitude difference between AD1K and AD2K, both statistically significant ($p<0.000$). In contrast to AD, the DF LC2 and LC4 magnitudes to not differ by much. Furthermore, the DF LC2 and LC4 values are both less than 1,000 feet. For DF, LC1 and LC4 values are always 0.000 since there is no acceleration lane at the minor road or U-turn.

TABLE 5.1.2 Lane Change Locations

	AD1K	AD2K	difference	T-test
LC1	312.67	420.32	34.4%	<0.000
LC2	628.04	1106.90	76.3%	<0.000
LC3	136.26	274.27	101.3%	<0.000
LC4	494.99	971.77	96.3%	<0.000
	DF1K	DF2K	difference	T-test
LC1	0.00	0.00	NA	NA
LC2	517.11	575.83	11.4%	<0.138
LC3	0.00	0.00	NA	NA
LC4	348.67	418.81	20.1%	<0.000

The results of the lane change analysis show that the lane changing patterns differed significantly between the AD and DF designs. For the AD design, lane changes are distributed across a longer spacing, whereas the 2K spacing is underutilized in the DF design. These results validate the hypothesis raised in existing literature about the differing AD and DF lane change behavior (e.g., Zhang and Kronprasert, 2014).

Average wait times were measured at the minor road and at the U-turn. There was not a significant difference in wait times at the minor road (p=0.381), but there was a significant difference of 4 seconds at the U-turn (p=0.001) between AD (11.69 sec) and DF (15.69 sec). And, as expected, wait times increased by 4.53 seconds with the higher mainline flows scenario (p=0002). In terms of operations, AD was more efficient than DF.

The performance of signage was measured by recording any vehicles that missed the U-turn. Recall that for the signage runs, participants were not informed that they needed to make a U-turn. In other words, if the J-turn signage was unclear, then a driver would not comprehend the need to make a U-turn. The number of missed U-turns were exactly the same for DR and DA with 10 each.

5.2 Survey Results

Both the post-simulator survey and the simulator sickness survey (SSQ) are included as Appendix D and E. Responses from the post-simulator survey complemented the data obtained through the simulator experiments. The majority of the respondents have driven through actual J-turns (77%), believe they are easy to navigate (73%), know about the safety benefits (70%), and feel safer driving through J-turns (76%). In regards to the auxiliary lane configuration, 73% of the respondents preferred the acceleration/deceleration configuration over the full deceleration configuration. The top reasons given for the preference are safety and ease of maneuvering. For the U-turn spacing, 83% of the respondents preferred the 2,000 foot over the 1,000 foot spacing. In terms of signage, there was not a majority preference with 37% preferring diagrammatic, 47% preferring direction, and 16% neutral.

There were several questions related to simulator realism. A large majority of respondents agreed that the simulator was realistic, which was consistent with researcher observations of the participant driving behavior; drivers appear to exhibit natural care while turning and lane changing. A majority of respondents answered that the experience was natural (80%), they felt they were actually there (67%), and they could drive around freely (73%). However, there is potential for refining the movement of the simulator (e.g., steering, accelerator and brake pedals) as a minority expressed that the movement was not natural (23%).

The responses to the SSQ revealed that a significant number of participants experienced one or more symptoms of simulator sickness. The most frequent symptoms experienced were general discomfort (57%), eye strain (40%), nausea (53%), and stomach awareness (50%). These results were unsurprising due to the length and nature of the study. Even though each design consideration was limited to two values, the combination of several considerations required nine runs. On average, each participant spent approximately 30 minutes with the simulator, including the breaks between runs. This duration did not include the pre-simulator orientation or the post-simulator survey. The long duration of the simulator study was one contributing factor for the symptoms. Another contributing factor was the sudden maneuvering involved in traveling the

through movement from the minor road. Sudden acceleration, braking, and turning were all involved in weaving multiple lanes and making the U-turn; these are the very scenarios that researchers recommend to minimize in order to avoid simulator sickness (Balk et al., 2013). Despite the frequency of symptoms, the dropout rate of 10% was comparable to the rate of other studies (e.g., 14% for Balk et al., 2013). In hindsight, it would have been more preferable to shorten the study and to use multiple groups to cover the required sample size.

CHAPTER 6 CONCLUSION

The simulator experiment results were consistent with post-simulator survey results. Both the simulator and survey results favored the acceleration/deceleration lane (AD) design due to smaller speed differentials, safer TTCs, and higher survey ratings. Vehicle trajectory plots generated from the trials also showed that drivers traveled differently on the AD versus the deceleration lane (DF) configurations. The 1K versus 2K U-turn spacing results were similar for DF, while results improved with the longer spacing for AD. The practical design guidance is to use the AD configuration over the DF. With the AD design, increasing the U-turn spacing will increase safety. Locations with high traffic demand should especially consider longer spacing lengths such as 2,000 feet. With the DF design, U-turn spacing greater than 1,000 feet was not found to provide any noticeable improvement in safety.

Even though survey results showed a slight preference for the directional (DR) style over the diagrammatic (DA), the simulator results did not vary between the two signage styles. Therefore, both signage styles performed similarly. There were a significant number of drivers that missed the U-turn. Perhaps, a strong media and public information campaign could be employed when J-turns are implemented in communities unfamiliar with their operation. An agency can consider using additional signage to guide left-turn and through traffic on the minor road to reinforce the single signage on the minor road.

The results from this study add to the knowledge of this innovative geometric design and presents guidance for the design of the lane configuration, U-turn spacing, and signage. These findings can be incorporated into a design guide to assist designers in the deployment of this low-cost safety countermeasure for intersections.

REFERENCES

AASHTO. *A policy on Geometric Design of Highways and Streets*, 6th Edition. American Association of State Highway and Transportation Officials, 2011.

ABMB. *Synthesis of J-turn Designs Standards and Criteria*. Final Report. Mississippi Department of Transportation. 2010.

Aykent, B., Merienne, F., Guillet, C., Paillot, D., and Kemeny, A. Motion Sickness Evaluation and Comparison for a Static Driving Simulator and a Dynamic Driving Simulator. In *Journal of Automobile Engineering*, V. 228(7), 2014, pp. 818-829.

Balk, S., Bertola, A., and Inman, V. Simulator Sickness Questionnaire: Twenty Years Later. In *Driving Assessment 2013: Proceedings of the 7th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*, 2013.

Bared, J. *Restricted Crossing U-Turn Intersection*. Technical Brief. Federal Highway Administration. FHWA-HRT-09-059, 2009.

Behr, M., Poumarat, G., Serre, T., Arnoux, P., Thollon, L., and Brunet, C. Posture and Muscular Behaviour in Emergency Braking: An Experimental Approach. In *Accident Analysis and Prevention*, V. 42, 2010, pg. 797-801.

Chisholm, C. (2008). "Visual Requirements for Driving." Clinical Overview 25(01), pp. 40-44.

De Silva, D., Fernando, W., Worrall, S., Ysakethu, S., and Kondoz, A. (2010). "Sensitivity Analysis of the Human Visual System for Depth Cues in Stereoscopic 3-D Displays." 2010 IEEE International Conference on Multimedia and Expo (ICME), DOI: 10.1109/ICME.2010.5582582.

De Winter, J., Wieringa, P., Dankelman, J., Mulder, M., Van Paassen, M., and De Groot, S. (2007). "Driving Simulator Fidelity and Training Effectiveness." Proceedings of the 26th European Annual Conference on Human Decision Making and Manual Control, Lyngby, Denmark.

Decina, L., Gish, K., Staplin, L., and Kirchner, A. *Feasibility of New Simulation Technology to Train Novice Drivers*. Final Report. National Highway Traffic Safety Administration, Washington, D.C., 1996.

Despina, M., Kleanthous, M., Savva, M., Christodoulou, S., Pampaka, M., and Gregoriades, A. Impact of Immersion and Realism in Driving Simulator Studies. In *International Journal of Interdisciplinary Telecommunications and Networking*, V. 6(1), 2014, pg. 10-25.

Dziuda, L., Biernacki, M., Baran, P., and Trszczynski, O. The Effects of Simulator Fog and Motion on Simulator Sickness in a Driving Simulator and the Duration of After-Effects. In *Applied Ergonomics*, v. 45, 2014, pp. 406-412.

Edara, P., S. Breslow, C. Sun, and B. Claros. Empirical Evaluation of J-Turn Intersection Performance: Analysis of Conflict Measures and Crashes. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2486*, Transportation Research Board of the National Academies, Washington, D.C., 2015, pp. 11-18.

Edara, P., Sun, C. and Breslow, S. *Evaluation of J-turn Intersection Design Performance in Missouri*. Final Report 25-1121-0003-179. Mid-American Transportation Center, 2013.

FHWA. *Manual on Uniform Traffic Control Devices*. Federal Highway Administration. Washington, D.C., 2009.

Freeman, P., Rodriquez, J., Wagner, J., Switzer, F., Alexander, K., and Pidgeon, P. Validation of a Fixed-Base Automotive Simulator for Run-Off-Road Safety and Recovery Training. In *Journal of Automobile Engineering*, Vol. 229 (5), 2014, pp. 574-589.

Gable, T. and Walker, B. Driving Simulator Sickness Screening: Efficient and Effective New Protocol. In *Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, October 28-30, Eindhoven, The Netherlands, 2013.

Godley, S., Triggs, T., and Fildes, B. Driving Simulator Validation for Speed Research. In *Accident Analysis and Prevention*, V. 34, 2002, pp. 589-600.

Haley, R., S. Ott, J. Hummer, R. Foyle, C. Cunningham, and B. Schroeder. Operational Effects of Signalized Superstreets in North Carolina. In *Transportation Research Record: Journal of the Transportation Research Board, No.2223*, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 72-79.

Hirst, S. and Granham, R. The Format and Presentation of Collision Warnings. In *Ergonomics and Safety of Intelligent Driver Interfaces*, Erlbaum, New Jersey, 1997.

Hummer, J., R. Haley, S. Ott, R. Foyle, and C. Cunningham. *Superstreet Benefits and Capacities*. FHWA/NC/2009-06. North Carolina Department of Transportation, Raleigh, 2010.

Hummer, J., Ray, B., Daleiden, A., Jenior, P., and Knudsen, J. *Restricted Crossing U-turn Informational Guide*. Federal Highway Administration, Washington, D.C., 2014.

Inman, V.W., and R.P. Haas. *Field Evaluation of a Restricted Crossing U-turn Intersection*. FHWA-HRT-11-067. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 2012.

Kaptein, N., Theeuwes, J., and van der Horst, R. (1996). Driving Simulator Validity: Some Considerations. In *Transportation Research Record, No. 1550*, 1996, pp. 30-36.

Kennedy, R., Lane, N., Berbaum, K., and Lilienthal, M. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. In *The International Journal of Aviation Psychology*, Vol. 3, Iss. 3, 1993.

Kim, T., P. Edara, and J. Bared. Traffic Efficiency of Two Non-Traditional Intersections; Super Street and Through-About. In *7th Conference on Access Management*. Transportation Research Board, Park City, Utah, 2006.

Kramer, R.P. New Combinations of Old Techniques to Rejuvenate Jammed Suburban Arterials, In *Strategies to Alleviate Traffic Congestion: Proceedings of Institute of Transportation Engineers National Conference*, Washington, D.C., 1987, pp. 139-148.

Li, I., Peek, E., Wunsche, B., and Lutteroth, C. (2012). "Enhancing 3D Applications Using Stereoscopic 3D and Motion Parallax." Proceedings of the 13th Australasian User Interface Conference (AUIC2012), Melbourne, Australia.

MDOT. *Michigan Design Manual, Road Design*. Michigan Department of Transportation, Lansing, Michigan, 2013.

NIST. *Engineering Statistics Handbook*. National Institute of Standards/Sematech. 2012.

Park, G., Allen, W., and Fiorentino, D. (2005). "Training Effectiveness: How Does Driving Simulator Fidelity Influence Driver Performance?" Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting, pg. 2201-2205.

Perreault, W. Controlling Order-Effect Bias. In *The Public Opinion Quarterly*, Vol. 39, No. 4, 1976.

Rodegerdts, L. A., B. Nevers, B. Robinson, B., Ringert, J., Koonce, P., Bansen, J., Nguyen, T., McGill, J., Stewart, D., Suggett, J., Neuman, T., Antonucci, N., Hardy, K. and and Courage, K.. *Signalized Intersections: Informational Guide.* No. FHWA-HRT-04-091. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 2004.

TRB. *Access Management Manual*, 2nd Edition. Transportation Research Board of the National Academies, Washington, D.C., 2014.

TRB. *Managing Speed: Review of Current Practices for Setting and Enforcing Speed Limits*. Transportation Research Board Special Report 254, December, 1998.

van Leeuwen, P., Gomez S., Jimenez, A., Happee, R., and Winger, J. Effects of Visual Fidelity on Curve Negotiation, Gaze Behavior, and Simulator Discomfort. In *Ergonomics*, 58(8) DOI:10.1080/00140139.2015.1005172, 2015.

Vogel, K. A Comparison of Headway and Time to Collision as Safety Indicators. In *Accident Analysis & Prevention*, 35(3), 2003, pp. 427–433

Vogel, K. What Characterizes a Free Vehicle in an Urban Area? In *Transportation Research Part F: Traffic Psychology and Behavior*, 5(1), 2002, pp. 15-29.

Walker H., Hall, W., Hurst, J., editors. (1990). "Clinical Methods: The History, Physical, and Laboratory Examinations." 3rd Edition. Boston, Butterworths.

Weigelt, K. and Wiemeyer, J. (2012). "Depth Perception and Spatial Presence Experience in Stereoscopic 3D Sports Broadcasts." Proceedings of the 2012 International Conference on 3D Imaging (IC3D), IEEE Computer Society, DOI: 10.1109/IC3D.2012.6615135.

Weir, D. and Clark, A. A Survey of Mid-Level Driving Simulators. In *SAE Transactions: Journal of Materials and Manufacturing*, V. 104-5, DOI: 10.4271/950172, 1995.

WisDOT. *Traffic Guidelines Manual*. Wisconsin Department of Transportation. December, 2011.

Wooldridge, J. *Introductory Econometrics: A Modern Approach*. Cengage Learning, September, 2015.

Zhang, W., and Kronprasert, N. The ABCs of Designing RCUTs. Public Roads. FHWA-HRT-14-006, Vol. 78, No. 2, September/October 2014.

APPENDIX A. EXPERIMENT SCRIPT

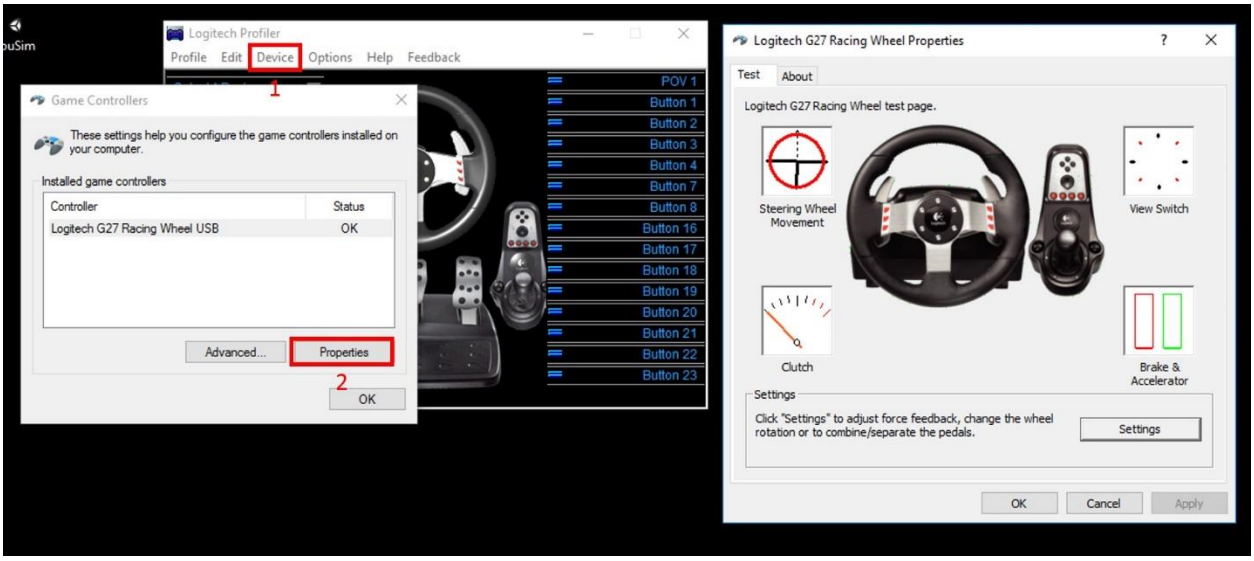
ZouSim Driving Simulator - J-turn Running Process Manual

A. Preparation stage

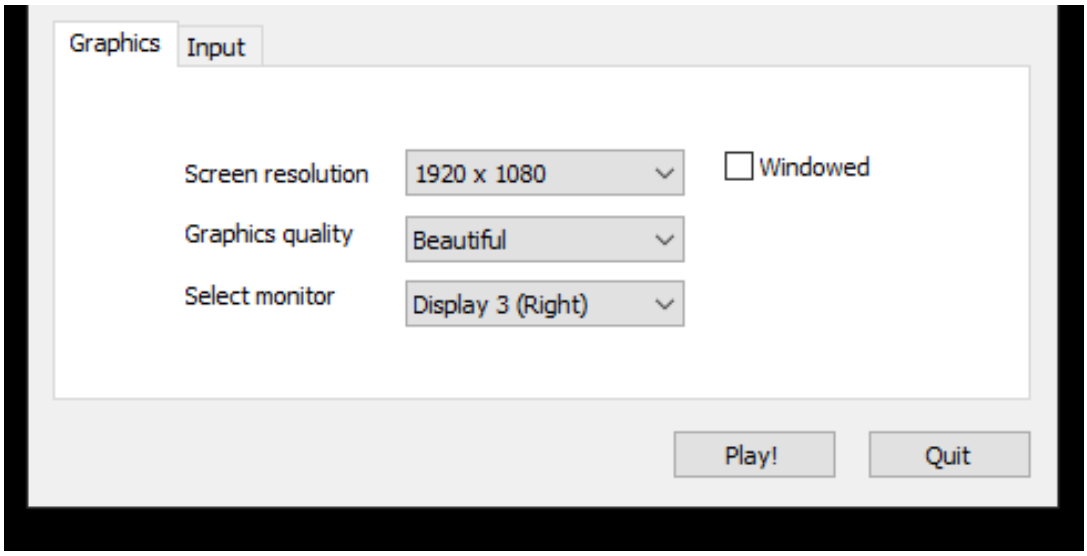
1. Check on availability of bottled water, mint candy, and trash bags, in case of participant discomfort.
2. Multi-TV screens setting - Three TV screens, reset all the TV screens to match up the white gaffing tape on the floor.
3. Air conditioner setting - Keep the temperature as low as possible (move the variable adjust bar to the lowest point). The controller is behind the black curtain.
4. Keyboard settings
   Keyboard. 0 – Start warm-up run
   Keyboard. B – Exit current run to the driving control screen.
   Keyboard. 1-9 – Run 1-9, explained in the below table.
   Win + M – Minimize all the windows (Hot key to back to desktop)

Run	Pattern #	Lane Configuration	Spacing (feet)	Traffic Volume	Signage
1	AD2KMEDA	AD (Full acceleration and deceleration lane)	2k (2,000)	ME (Medium)	DA (Diagram-style)
2	AD2KMEDR	AD	2k (2,000)	ME	DR (Direction-style)
3	AD1KHIDR	AD	1k (1,000)	HI (High)	DR
4	AD1KMEDR	AD	1k (1,000)	ME	DR
5	AD2KHIDR	AD	2k (2,000)	HI	DR
6	DF1KHIDR	DF (Full median deceleration lanes)	1k (1,000)	HI	DR
7	DF1KMEDR	DF	1k (1,000)	ME	DR
8	DF2KHIDR	DF	2k (2,000)	HI	DR
9	DF2KMEDR	DF	2k (2,000)	ME	DR

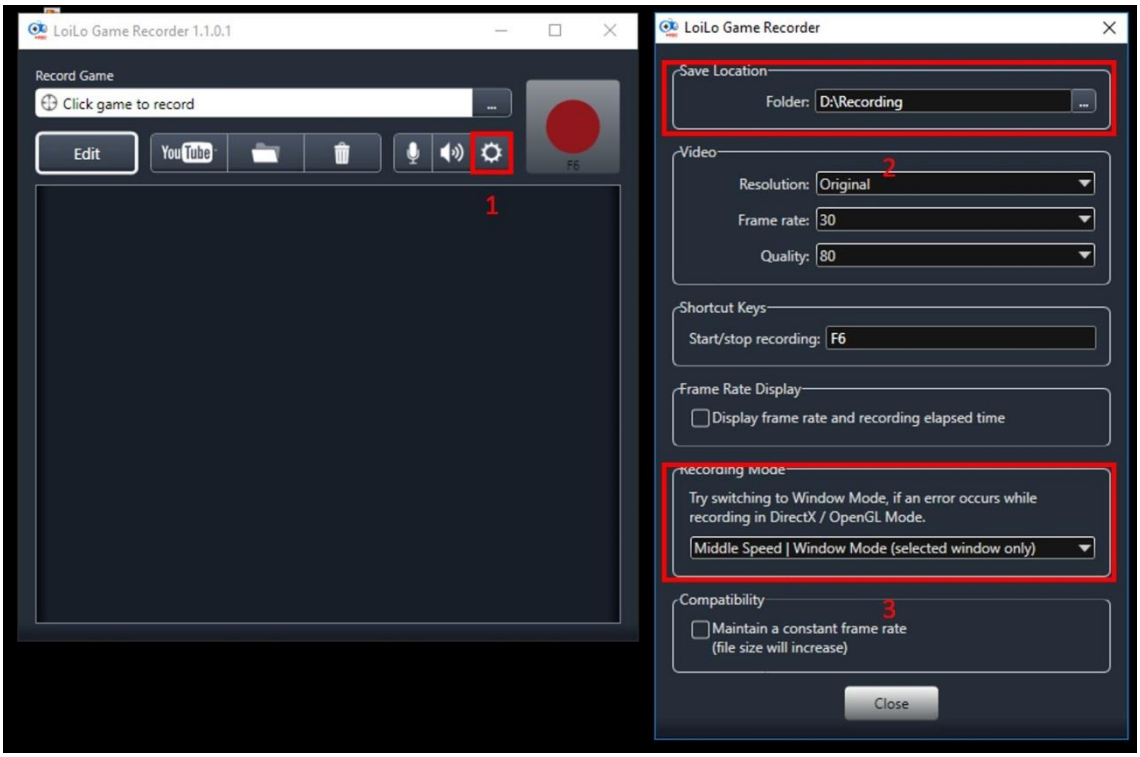
5. Brake, accelerator and steering checking. Open steering wheel profiler execution file (in taskbar button) and test to press any button on steering wheel to test connection. Go to Device --> Controller -->Properties, test the break and accelerator, and turn the steering wheel to see if the turning motion is captured.



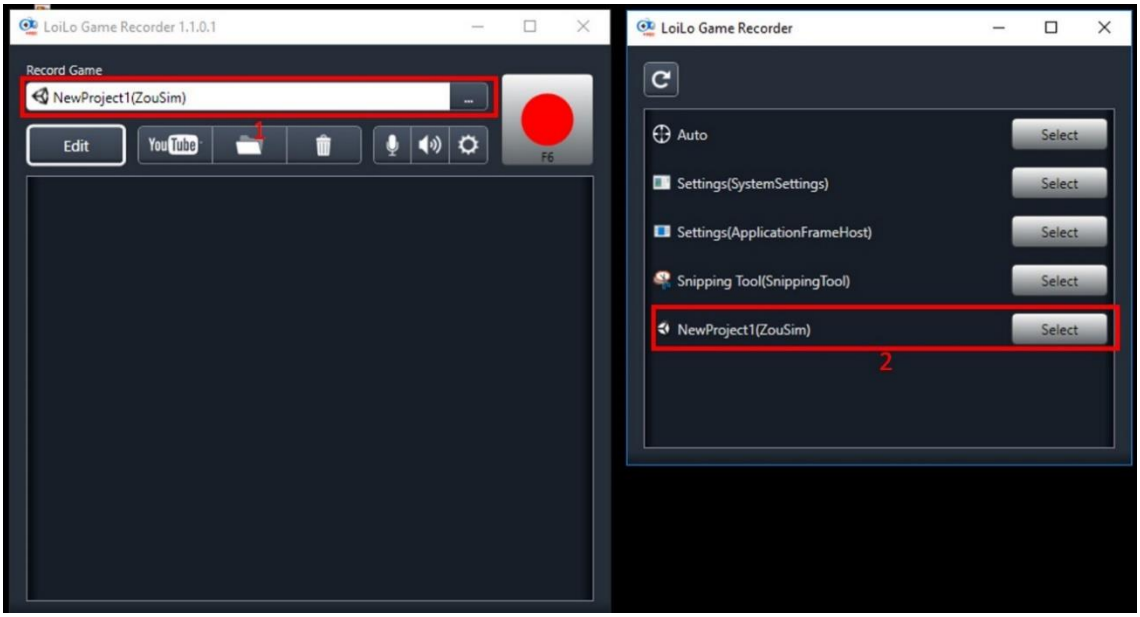
6. Before the participant arrives, start execution of file named Zousim.exe on the desktop. Settings will pop up, choose full screen mode (Do NOT check “window” option), graphic quality set to “BEAUTIFUL”, select monitor to “display 3 (Right)”.



7. Start Loilo Recorder, go to settings (Mark 1). The save location is in D:\recording folder (Mark 2), where you can access all the video file and copy them to the external hard drive later. Then, change the recording mode to Middle Speed | Window Mode (selected window only) (Mark 3), then close the window.



8. Choose correct subject in Record Game (Mark 1). Then select "NewProject1 (ZouSim)" (Mark 2). To switch between Loilo and Unity ZouSim file, press Alt + Tab. Begin recording after the warm-up run and end recording after completing all the runs. Do not pause at any breaks between runs. Do not use the shortcut keys.



B. Welcome participant to the study

1. Introduce yourself
   "Welcome to the ZouSim lab, thank you for participating in our experiment. My name is xxx."
2. Restrooms – exit room to your left.
3. Offer bottled water to participants.
4. Ask the participant to sign two copies of the same consent forms. One copy is for the participant, and the other one is for us to keep.
5. **Attention!**
   a. If a participant were to ask, "What is a J-turn?" Answer, "This is a new road design that you are going to experience soon, drive and find out."
   b. Try to use the standard answer for driving-related questions, "Relax and drive normally."
6. Pre-instruction: Show a non-detailed map (Participant Instructions). Let them read the map and explanation by themselves.
7. After a participant enters the car and closes the door, ask him/her to fasten the seatbelt. Reset the left TV screen to match up with the white gaffing line on the floor.

C. Simulator execution

1. Return to Unity.
   Move mouse to the bottom of the rightmost TV to make it non-intruisve.
2. Warm-up run, before starting, ask participant to press the brake. "Please hit the brake and do not release it until the driving control screen disappears." Press **key 0**, to start warm up run. Ask the participant to drive the vehicle on the highway.

   a. "Please feel free to drive around in this test network until you are comfortable accelerating, decelerating, and turning. My suggestion for warm up is stay in a lane, make a U-turn, then pass a vehicle after a U-turn."
   b. "Remember that we are not testing your performance, so relax and try to drive in a normal manner."
   c. "Please let me know when you are ready to begin the experiment."
3. When the participant has completed the warm up scenario and is ready for the actual test, **press B** to return to the main menu.

4. Before starting run, ask the participant if he/she would like to look at the map again. Check if he/she needs water, mint, or a bathroom break.

5. Instructions for starting, then press **Alt + Tab.** Switch to Liolo and press record button to start recording, then press **Alt + Tab** again to jump back to Unity file – ZouSim.exe.
    a. Ask the participant to hit the brake, "Please press the brake until the driving control screen disappears."
    b. Within the box of the main menu, **input the corresponding character of the participant (Mark 1)**. If this is the first participant of today, then the corresponding character is A, if this is the 5th participant today, then the character is E. Follow Appendix B to enter the number of run, and start. For example, press 6 for Run Six.

6. Break between runs – check for participant discomfort and offer mint and bottled water.
    a. If participant exits the car for a break, reset the left monitor after he/she returns in the car.
7. After completing all runs, press **Alt + Tab** to switch to Liolo and stop recording.

E. In case of a missed turn

1. If either first or second turn is missed, then do NOT repeat.
2. If both first and second turns (signage-related runs) were missed, then explain, "i.e., please make a U-turn to cross the highway". Do NOT repeat first two turns!
3. If any turn within 3-9 is missed, repeat the run at the end.

F. Wrap-up – After 9 runs (and additional make-up runs) are completed, check for simulator discomfort.
G. Administer paper surveys J-turn and SSQ
H. Give participant gift card.
I. Backup data

1. Copy videos from computer to external hard drive. Name FOLDER participant number and date – P#MM_DD_YY
2. Copy Unity data log file (.txt) to external hard drive. Name FOLDER participant number and data – P#MM_DD_YY.

APPENDIX B. EXPERIMENT RECRUITMENT FLYER

AN INVITATION TO DRIVE THE ZOUSIM DRIVING SIMULATOR

What: You are warmly invited to participate in a driving simulator study at the University of Missouri to help improve road design in Missouri. Participants will drive through a few roads and intersections and give their opinions on different aspects of road design. The study will take approximately 30 minutes.

Where: The study will take place in the ZouSim Lab in Heinkel Building Room 15.
- Heinkel is in the SW corner of Locust and 7th streets
- Enter the south door
- Room 15 will be on your left
- Street metered parking available

When: May, 2016

Benefits: Your feedback will help to improve the safety and efficiency of road design in Missouri.

Risks: A small percentage of participants may experience some simulator discomfort such as eye strain or dizziness.

Compensation: A participant may withdraw from participation at any time for any reason without losing the $10 gift certificate.

Confidentiality: Personal identifying information will be kept confidential.

Thank you for your help in improving roads in Missouri.

If you are interested in participating in this study, please contact Dr. Carlos Sun in the Department of Civil and Environmental Engineering at csun@missouri.edu or at 573-884-6330.

APPENDIX C. PARTICIPANT CONSENT FORM

INVESTIGATION OF RURAL J-TURN DESIGN FACTORS USING THE ZOUSIM DRIVING SIMULATOR CONSENT FORM

You are being asked to take part in a research study of the J-turn road design. We are asking you to take part in this study to obtain driver feedback about this road design. Please read this form carefully and ask any questions you may have before agreeing to take part in the study.

What the study is about: The purpose of this study is to learn about driver preferences to variations in the J-turn road design. The data that we collect from this study will help us to determine the best way of designing J-turns in Missouri.

What we will ask you to do: If you agree to be in this study, we will ask you to drive a vehicle simulator multiple times through a sample road network consisting of approximately 9 J-turn intersections. We will collect data from the simulator trips to help us evaluate how best to design road spacing, signs, and lane configurations. Upon completion of the simulator trips, we will ask you to take a brief survey of approximately 17 questions. The survey will ask you about your preferences regarding J-turn design that you encountered during the simulator trips. The entire study will take less than one hour.

Risks and benefits: Even though the probability of experiencing simulator sickness is low, there is a potential for some participants to experience general discomfort, eye strain, dizziness, and/or nausea. The results of the study will benefit the state of Missouri by using driver preference information to design intersections.

Compensation: A small incentive, a $10 gift card to a local restaurant, will be offered. A participant may withdraw from participation at any time for any reason without losing such compensation.

Your answers will be confidential. In any type of report we make public, we will not include any information that will make it possible to identify you individually. Research records will be kept in a locked file; only the researchers will have access to the records.

Taking part is voluntary: Taking part in this study is completely voluntary. You may skip any survey questions that you do not want to answer. If you decide to take part in this study, you are free to withdraw at any time.

If you have questions: The researchers conducting this study are Drs. Carlos Sun, Praveen Edara, and Bimal Balakrishnan. Please ask any questions you have now. If you have questions later, you may contact Dr. Sun at csun@missouri.edu or 573-884-6330. If you have any questions or concerns regarding your rights as a participant in this study, you may contact the Institutional Review Board (IRB) at 573-882-9585 or access their website at https://research.missouri.edu/cirb/.

You will be given a copy of this form to keep for your records.

Statement of Consent: I have read the above information, and have received answers to any questions I asked. I voluntarily consent to take part in the study.

Your Signature _____ Date _____

Your Name (printed) _____

APPENDIX D. POST-SIMULATOR J-TURN SURVEY

No _____ Date _____

J-turn Post-Test Survey

The J-turn intersection design is used as an alternative to two-way stop intersections on high-speed rural highways. Please provide us with your perspective on how best to implement this design.

Figure 1A and 1B show two different J-turn designs. For this survey, assume you are starting at the location of the vehicle shown in the figures below on Hill Road. Your goal is to reach Main Street by following the arrows in the below figures.

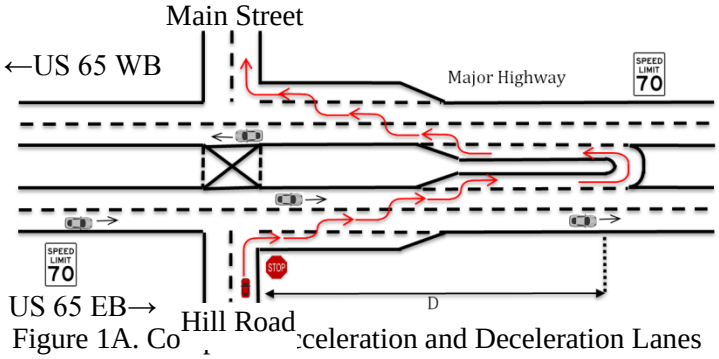
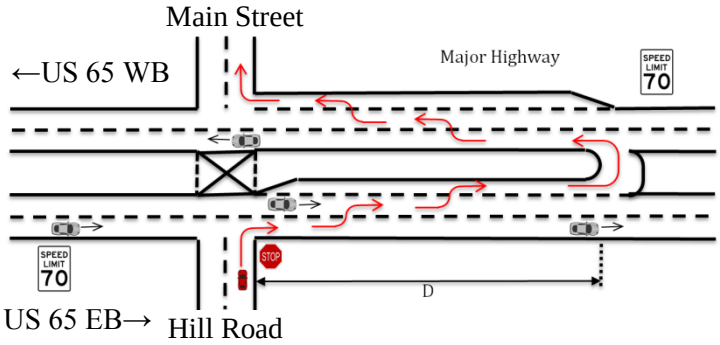


Figure 1A. Co celeration and Deceleration Lanes



1. **Please indicate your level of preference between these two designs. I prefer:**

[] 1A much more [] 1A more [] neutral [] 1B more [] 1B much more

2. **Please explain the reason for your choice on the previous question. Mark all reasons that apply.**

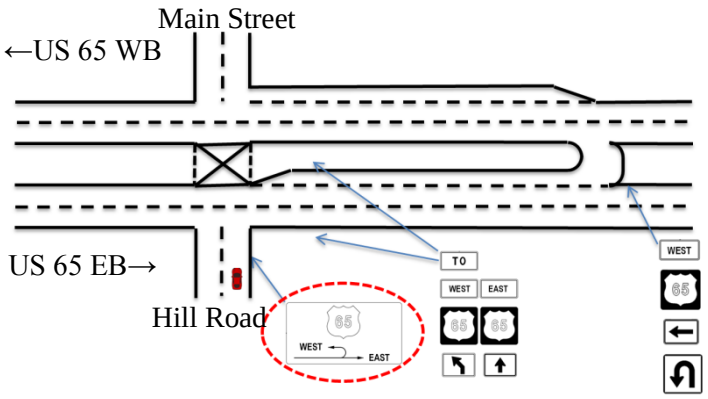
[] Safer [] Easier to maneuver [] Saves time [] Less wait time at the stop sign
[] Other _____

The measurement, D, in Figures 1A and 1B represents the distance between Hill Road and the U-turn. Generally speaking, this distance will be either 1000 ft or 2000 ft. If a vehicle is traveling at 70 mph, it takes around 10 seconds for that vehicle to travel 1000 ft while it would take around double that (20 s) to travel 2000 ft. While the 2000 ft option allows a driver more time to safely maneuver from Hill Road to the U-turn, it does have the tradeoff of taking 10 more seconds to reach the U-turn.

3. **Please indicate your preference between the 1000 ft and the 2000 ft distance. I prefer:**

[] 1000 ft much more [] 1000 ft more [] neutral [] 2000 ft more [] 2000 ft much more

Figures 2A and 2B show two different sign styles. Assume you are coming from Hill Road and want to travel westbound on US-65.



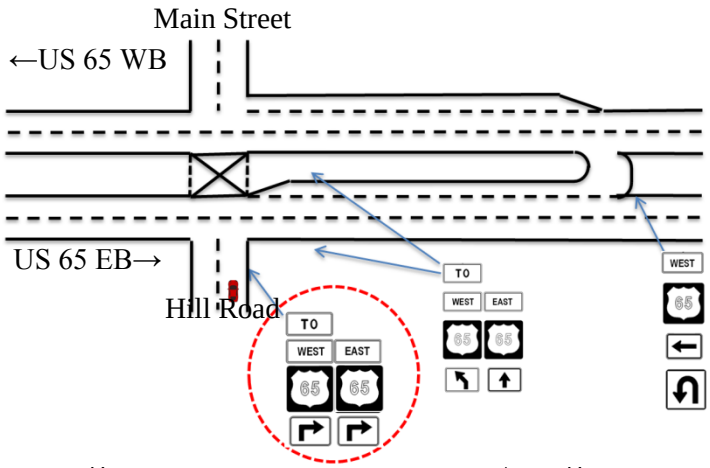


Figure 2A. Minor Road **Diagram**-Style Sign

4. **Please indicate your preference between the Diagram-Style Sign (2A) and the Direction-Style Sign (2B) at the Hill Road. I prefer:**

[] diagram-style much more [] diagram-style more [] neutral [] direction-style more [] direction-style much more

5. **I have driven through J-turn intersections before.**

[ ] Yes [ ] No

6. **The J-turn is easy to navigate.**

[ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree

7. **I am familiar with the safety benefits of a J-turn as compared to a two-way stop intersection on a high-speed highway.**

[ ] Yes [ ] No

8. **I feel safer** using a J-turn to cross a highway compared to using a normal two-way stop intersection.

[ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree

9. **I felt like I was actually there on the highway.**

[ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree

10. **I felt like I could drive around freely.**

[ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree

11. **To what extent did the driving experience seem real to you?**

[ ] Highly realistic [ ] Realistic [ ] Neutral [ ] Unrealistic [ ] Highly unrealistic

12. **My sense of movement on the highway seemed very natural.**

[ ] Strongly agree [ ] Agree [ ] Neutral [ ] Disagree [ ] Strongly disagree

13. **Did any issues arise during the use of the J-turn simulator?**

[ ] Yes [ ] No

If yes, please explain the issue(s) that you experienced:

_____

_____

Please answer the demographic questions below.

14. Age range

[ ] 16-25 [ ] 26-40 [ ] 41-55 [ ] 56-70 [ ] 71-95

15. Gender

[ ] Male[ ] Female

16. My Residency

[ ] Urban [ ] Rural

17. My Regular Vehicle Type

[ ] Passenger Car [ ] Vehicle towing trailer [ ] Delivery/Moving Truck
[ ] Tractor trailer truck [ ] Bus

Please contact Dr. Carlos Sun (csun@missouri.edu) for additional comments, concerns or information on this survey. Thank you for completing this survey! We greatly appreciate your time!

APPENDIX D. SSQ SURVEY

No _____ Date _____

Simulator Discomfort Questionnaire

Instructions: Circle how much each symptom below is affecting you right now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficult focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. Fullness of the Head	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eye closed	None	Slight	Moderate	Severe
14. *Vertigo	None	Slight	Moderate	Severe
15. **Stomach awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Questionnaire from Kennedy, Lane, Berbaum, and Lilienthal (1993)