RESEARCH & DEVELOPMENT

DESIGN CONSISTENCY ON CORRIDORS

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16. Abstract

Alternative Intersection and Interchange (AII) designs provide an innovative approach to the geometric and control features at intersections. Nevertheless, most of the AII designs have unconventional ways to maneuver through the intersection such as restriction of movements, crossover of traffic to the opposite side of the road, separating left turning movements, etc. As corridor construction or improvement projects continue to utilize AII designs, there is a concern that drivers might be confused on how to safely navigate a corridor when adjacent intersections may handle movements in different ways, especially left turns. This research investigates the challenges for the corridor-level deployment of AII designs through a state-of-the-practice literature review, a focus group interview, and a driving simulator experiment. The objective of this research is to: 1) identify potential combinations of AII designs which NCDOT may build adjacent to one another, 2) collect data on driver's understanding of AII designs, and 3) figure out drivers' performance when navigating various AII corridors in terms of ability to manage navigation and vehicle control.

The project found that at an intersection spacing of ¼ mile, corridors with predominantly traditional, U-turn based or mixed intersection types had similar driver performance. For specific intersection designs, minor left turns at Median U-turn intersections had the most failures to complete the movement compared to Quadrant and Traditional major left turns performed best, while other intersection and movement combinations did not have increased failed movements compared to Traditional intersections. Hard braking events were observed less often in MUT and RCUT movements when they were in corridors without predominantly traditional intersections. Drivers also had decreased approach speeds and increased failed movements on their first simulator trial which can be attributed to unfamiliarity with the driving simulator, as this did not vary by corridor type or test intersection type. Across all intersection and movement types, there was an increase in failed movements when the preceding intersection was an RCUT.

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EXECUTIVE SUMMARY

The North Carolina Department of Transportation (NCDOT) utilizes alternative intersection and interchange (AII) designs at a significant level. These designs innovate on the geometric and control layouts of conventional intersections and interchanges often resulting in significant operational or safety improvements. Nevertheless, most AII designs utilize alternative ways to maneuver through the intersection including restriction of movements, crossover of traffic to the opposite side of the road, separating left turning movements to minimize conflicts, and combining non-conflicting movements into fewer critical signal phases. Due to the range of design and operational differences in these AII designs, there is concern that drivers will be confused how to safely navigate when adjacent intersections may handle movements in different ways.

When NCDOT is considering AII designs at adjacent intersections along a corridor, there is currently no state or federal guidance on human interaction along corridors with combinations of unique AII designs. In this regard, this research aims at investigating the challenges for the corridor-level deployment of AII designs through a state-of-the-practice literature review, focus group interviews, and a controlled driving simulator experiment. The objective of this research is to: 1) identify potential combinations of AII designs which NCDOT may build adjacent to one another without negatively impacting driver expectation, 2) collect data on driver's understanding of AII designs, and 3) figure out drivers' performance when navigating various AII corridors in terms of ability to manage navigation and vehicle control.

Based on the state-of-the-practice literature review, this research determined four AII designs (Reduce Conflict Intersection, RCI; Median U-turn Intersection, MUT; Continuous Flow Intersection, CFI, and Quadrant Roadway Intersection, QRI) in addition to the Conventional 4-leg Intersection (CI) for experiment design. Three corridor treatments were proposed: a standard corridor, a RCI corridor, and a corridor with unique combinations of AII designs. The primary reason for choosing these three corridor types is that MUT and CFI intersections were more likely to be spot treatments vs. full corridor treatments. Next, a total of 12 intersection pairs were designed, where each intersection pair contained a test intersection and a preceding intersection. These intersection pairs were determined to cover the most typical and practical combination of alternative intersections in a corridor setting.

Through questionnaire surveys and open discussions, the focus study found that participants who are familiar with alternative intersection designs were more prepared for non-traditional intersection forms because of their prior experience; however, they may still be confused when approaching an intersection because there are many different alternative intersection types (i.e. they didn't always have the location of each one memorized). In comparison, several of the unfamiliar drivers in our focus groups indicated that they were generally able to guess the right lane to be in, but would still be confused if they had to turn right then loop back to complete a left turn. Even so, participants generally reported that pavement marking and signing options were effective in the real-world videos provided for reference. With regards to potential improvements, both familiar and unfamiliar groups noted more signs and/or markings and to have them earlier – a finding that is consistent with parallel research efforts on grade separated intersections (i.e. additional lane guidance in advance of the decision point). Other notable input was that at key points, overhead signs could be useful during high volume conditions since the visual path was more consistent with expectation versus a side mounted option. Based on the real-world videos used in focus groups, when unconventional intersection designs are considered, more adequate signing (directional guidance) in advance of the decision point was recommended to provide better understanding and advanced warning of the unusual movements to be made in advance of the main intersection. When combinations of movements were considered along the mainline, participants also noted that recommended providing sufficient spacing between adjacent intersections to allow drivers to have more reaction time when recognizing the alternative intersection configuration and making adequate lane-selection maneuvers.

Nine comprehensive driving simulator experiments were developed to investigate drivers' performance when navigating alternative intersection corridors in terms of the number of failed movements (FMs) and driver behavior (i.e., speed, number of hard-braking events, and number of lane-changes). Based on the driver performance data collected from 48 participants, this research found that gender and age do not seem to be contributing factors to the number of FMs. In comparison, trial number (i.e., the sequence that a participant took the 9 experiments during the driving simulator experiment) has a profound impact on driver performance. Specifically, more than half of the FMs (54.7%) occurred during the participants' first trial. Overall, the number of FMs displayed a decreasing trend with increased number of trials they experienced (i.e. as they became more familiar with the traffic operational features at alternative intersections, FM's decreased).

The specific findings from the driving simulator experiment are summarized below:

- The number of FMs for the RCI corridor, the standard corridor, and corridor with unique combination of AIIs are 46, 48, and 43, respectively, indicating that in general, there was no significant difference in the number of failed movements between the three corridor types with AI combinations.
- The preceding intersection of the paired configurations tended to affect participants' performance. There were 59 FMs which occurred at the intersection pair if the preceding intersection was an RCI; in comparison, when the preceding intersection was a conventional intersection, the number of FMs occurred at the tested intersection was 38.
- The test intersection of the paired configurations was also associated with high the occurrence of FMs. Participants were most likely to have FMs at a MUT sidestreet left turn intersection (26 observations), followed by a RCI side through (23 occurrences) and the MUT main left turn intersection (22 occurrences). In contrast, there were only 3 FMs that occurred at the QRI main left turn and 6 FMs for the standard main left turn intersection.
- When the preceding intersection was an RCI, and the tested intersection was a MUT main left turn or side left turn, drivers experienced the highest number of FMs, indicating that the RCI plus MUT design tends to be the most challenging intersection pair.
- Participants had fewer FMs at Standard and QRI main left turn test intersections when the preceding intersection was a Standard or RCI. For example, the intersection pair with a RCI preceding a QRI test intersection only have 1 FM during the entire study, indicating that this intersection pair was the easiest one for participants to navigate.

- In follow-up surveys, drivers stated that the primary reasons for failed movements included unclear instructions, unclear signs, missed sign (i.e. they did not see it), lost focus and confused by the intersection geometric design.

Table of Contents

List of Figures

List of Tables

1. Introduction

Alternative Intersection and Interchange (AII) designs are those which provide an innovative approach to the geometric or control features, such as restriction of movements, crossover of traffic to the opposite side of the road, separating left turning movements to minimize conflicts, and combining non-conflicting movements into fewer critical signal phases, etc., which may improve operations and/or safety for drivers *(1,2)*. In the last two decades, AII designs have been becoming increasingly popular in the United States. This is especially true in the state of North Carolina, where the North Carolina Department of Transportation (NCDOT) has been at the forefront of AII designs. Under the guidance and supervision of NCDOT, transportation professionals have been given freedom to explore alternatives to conventional roadway designs, including but not limited to: Diverging Diamond Interchange (DDI), Reduced Conflict Intersection (RCI, often referred to as a “superstreet” or “Restricted Crossing U-turn, RCUT”), Median U-Turn (MUT, often referred to as a “Michigan left”), Displaced Left-turn Intersection (DLT, also known as “Continaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaauous Flow Intersection, CFI”), Quadrant Roadway Intersection (QRI), etc.

Between the years of 2008 and 2015, a flurry of research was completed on behalf of NCDOT to examine the operational and safety benefits of RCUT’s and DDI’s *(3-6)*. The findings were overwhelmingly positive. Nevertheless, even with all the focus of research and guidance that have been put on AII designs and performance assessment, very little exists in the literature regarding the use of them in succession along a corridor. As corridor construction or improvement projects continue to utilize AII designs, a key concern of driver confusion is identified when different AII designs are adjacent in a corridor. Due to the range of design and operational differences in these AII designs, there are concerns that drivers will be confused on how to safely navigate a corridor when adjacent intersections may handle movements in different ways, especially left turns *(7)*.

According to the Federal Highway Administration (FHWA), the overall driving task consists of three major subtasks: control, guidance, and navigation *(8)*. Specifically, control relates to the physical operation of a vehicle; guidance refers to interacting with other vehicles, such as following, passing, merging, etc.; navigation refers to choosing a route from origin to destination by reading guide signs and using landmarks. In real-world conditions, when driving on an urban corridor that has intersections, drivers need time and space to observe design differences, identify the correct movement to accommodate their route, then change lanes and merge or diverge as needed. Since the geometric configuration of an AII design is usually different from traditional intersections, the presence of AII designs tends to cause additional driving workload for drivers, especially when a driver is unfamiliar with AII designs or the corridor. Studies have found that when a driver is overloaded with information, the driver actively sheds the information load by ignoring the navigational level in order to maintain the physical control of the vehicle and keep from colliding with other vehicles or hazards when navigating an intersection *(8)*. In addition, an expert interview conducted by North Carolina State University (NCSU) researchers revealed that the public's main concerns on AII designs are driver confusion and fear of the unknown *(7)*. With these considerations, this research aims at identifying challenges for the corridor-level deployment of AII designs and research needs with an emphasis on incorporating human factors to the design of AII corridors. The objective of this current study is to 1) identify potential combinations of AII designs which NCDOT may build adjacent to one another, 2) collect data on driver’s understanding of AII designs, and 3) determine drivers' performance when navigating alternative intersection corridors in terms of ability to manage navigation and vehicle control.

2. Literature Review

2.1. Existing AII Design Guidelines

In 2005, the Texas DOT published the "*Urban Intersection Design Guide*: *Volume 1 - Guidelines*" *(9)*. The guide indicates that at each particular location, selecting an intersection type, including an alternative intersection, is mainly influenced by the functional class of intersecting streets, design level of traffic, number of intersecting legs, topography, access requirements, traffic volumes, patterns, and speeds, and availability of right of way.

Soon after, the Community Planning Association of Southwest Idaho (COMPASS) and Wilbur Smith Associates conducted a High-Volume Intersection Study (HVIS); the first stage of this study, "*Innovative Intersections: Overview and Implementation Guidelines,*" outlines information about a variety of innovative intersection concepts and provides implementation guidelines for the most applicable intersection types *(10)*. Generally speaking, this guideline indicated that innovative designs are suitable for intersections with heavy traffic volumes on opposing movements, or high traffic volume on several movements requiring complex signal phasing, and/or intersections that have a high number of conflict points *(10)*. In 2010 the FHWA published the "*Alternative Intersections/Interchanges: Informational Report (AIIR)*" *(2)*. This report provides knowledge of six typical alternative treatments including salient geometric design features, access management issues, traffic signalization, signing and marking treatments, operational and safety issues, costs, and construction sequencing and applicability. This was followed by a series of dedicated alternative intersection/interchange design guides published by the FHWA, which provided general information, planning techniques, evaluation procedures for assessing safety and operational performance, design guidelines, and principles to be considered for selecting and designing DDI *(11)*, DLT *(12)*, MUT *(13)*, RCUT *(14)*, and QRI *(15)*, respectively. Based on the information provided by these documents, a brief summary of the key design considerations for each AII design and/or the criteria for selecting the most suitable AII design configuration is presented as follows.

Median U-Turn (MUT)

Reid et al. *(13)* pointed out that the geometric design of a MUT intersection introduces unique design elements not typically present at a conventional intersection. For instance, a wide median is often needed to facilitate the median U-turn movements, and a large enough vehicle path at the U-turn crossover is required to accommodate trucks and allow for efficient movements through the U-turn by passenger vehicles. In addition, this guidance highlighted that signing, marking, and geometric design elements should promote safe and efficient movements that would otherwise be unexpected or not familiar to motorists.

Superstreet/Restricted Crossing U-Turn (RCUT)

Fitzpatrick et al. *(9)* suggested that a superstreet might be considered for suburban arterials where high arterial through volumes conflict with moderate to low cross-street through volumes, particularly, when a 50/50 arterial through-traffic splits exists for most of the day. Hummer et al. *(14)* further detailed the design considerations for RCUTs, such as the design of an RCUT intersection should begin with some basic information on the number of approaches, through lanes, intersection angle, typical design parameters, turning movement demands in the design hour, and provisions for pedestrians and bicycle facilities. In addition, the report indicated that RCUT width is influenced by the median width and of placing storage lanes heading into the crossovers back-to-back or side-by-side. A shorter cycle length may result in shorter average queues, which may allow for shorter storage bays and a shorter distance from the main intersection to the U-turn crossover. The shorter distance required may reduce travel times for minor street left-turning and through vehicles and improve vehicular levels of service. The short cycle lengths and closer spacing of the U-turn crossover will also generally be beneficial to pedestrians and bicyclists.

Continuous Flow Intersections (CFI)

Fitzpatrick et al. *(9)* pointed out that CFIs should be considered on arterials with high through volumes and little demand for U-turns; additionally, CFI designs need to have some right of way available along the arterial near the intersection and must be able to restrict access to the arterial for parcels near the intersection. Steyn et al. *(12)* listed some unique geometric design features of CFIs, such as the necessity for the main intersection to provide appropriate turning paths for the displaced left-turns and the obligation to consider their interactions with pedestrian crosswalks. For the crossover intersection, a smooth alignment for the through traffic at the crossover intersections is required, and the design should not introduce back–to-back reverse curves along the travel paths.

Quadrant Roadway Intersections (QRI)

Fitzpatrick et al. *(9)* indicated that the spacing of the QRIs from the main intersection is a trade-off between left-turn travel distance and time versus available storage for the left-turn movement. Additional advance signing is required, and additional median U-turns might be considered for missed left-turn opportunities. Recently, Reid and Hummer *(15)* pointed out that the number of lanes on the quadrant roadway and the land use and functionality within the intersection quadrant can impact access management and right-of-way along both crossing roadways. Therefore, it is critical to provide signage and pavement markings to indicate the prohibition of left turns and establish wayfinding for right and left-turn movements through all QRIs.

Bowtie

Fitzpatrick et al. *(9)* recommended transportation agencies consider the bowtie design where there are generally high arterial through volumes and moderate to low cross-street through volumes and moderate to low left-turn volumes. Particularly, arterials with narrow or nonexistent medians and no prospects of obtaining extra right of way for widening are good candidates for the bowtie design.

Jughandle

Fitzpatrick et al. *(9)* suggested that a jughandle design could be considered on arterials with high through volumes, moderate to low left-turn volumes, and narrow rights of way. The distances between signals should be long so that the extra right of way and other costs for the ramps do not overwhelm the savings elsewhere.

Paired Intersection

Fitzpatrick et al. *(9)* recommended considering the paired intersection alternative for arterials with high through-traffic volumes and low cross-street through volumes.

Continuous Green-T Intersection

In comparison with the other alternative intersection designs, the Continuous Green-T intersection was found to have the most restrictive design considerations *(9)*. Usually, it is suitable at signalized three-approach intersections with moderate to low left-turn volumes from the minor-street and high arterial through volumes, where there are no pedestrians crossing and few drivers choose one of the two continuous green lanes.

Diverging Diamond Interchange (DDI)

Schroeder et al. *(11)* pointed out three areas differing between DDIs and conventional diamond forms: left-turn storage between intersections, left-turn curve radii onto the limited access facility, and right-turn curve radii onto the crossroad. Some principles for geometric design of DDI are also proposed, such as accommodating the largest design vehicle at the crossover ramp terminal junctions, promoting reduced and consistent design speeds (25-35mph) through the interchange, channelizing inbound and outbound movements in the crossover design at each intersection to encourage drivers to use the intended lanes, and creating a vehicle path alignment that directs vehicles into appropriate receiving lanes. In addition, this report emphasized that over- or under-pass design can affect the safety and operation of various transportation modes, and the proximity of adjacent signalized intersections to the interchange crossover movements can also affect the operation of a DDI.

Tables 1 to 3 present a brief summary of the key design features and advantages of alternative at-grade intersection, alternative grade-separated intersections, and alternative interchanges, respectively.

Table 1. Summary of the Design Features and Advantages of Alternative At-grade Intersections

A.I.I. Design	Design Features	Advantage(s)
MUT	● Intersection design where left-turn vehicles from one or both roads make U-turns at dedicated median openings to complete the desired movement	● Reduced # of conflict points to16 ● Reduced delay due to fewer # of signal phases and shorter cycle lengths ● Low construction costs
RCI (RCUT, Superstreet)	● Intersection design where all side street movements begin with a right turn ● Side street left-turn and through vehicles turn right and make a U-turn at a dedicated downstream median opening to complete the desired movement	● Reduced # of conflict points to18 ● Improved capacity since each direction of major road operates as one-way street ● Reduced delay due to fewer # of signal phases and shorter cycle lengths ● Low construction costs
CFI (DLT)	● Intersection design where left-turn vehicles cross to the other side of the opposing through-traffic in advance of the main intersection ● Left turns and opposing through movements occur simultaneously at the main intersection	● Reduced # of conflict points ● Allow for simultaneous operation of protected left turns and opposing through-movements ● Better signal coordination hence lower delays
Quadrant Roadway (QR)	● Intersection design with one main intersection and two secondary intersections that are linked by a connector road in any quadrant of the intersection ● Left-turn vehicles from all four legs of the main intersection use the secondary intersections and connector road to complete left-turn movements	● Reduced # of conflict points ● Reroutes left-turn traffic result in fewer signal phases and reduced delay ● Coordination of 3 signalized intersections improves corridor travel time
Bowtie	● An intersection where left-turn movements are completed at an adjacent roundabout ● Traffic entering the roundabout slows and yields to traffic already inside	● Reduced # of conflict points to 20 ● Improved safety for pedestrians and bicyclists ● Reduced delay due to fewer # of signal phases and shorter cycle lengths ● Suitable in limited ROW locations ● Low construction costs
Jughandle	● Remove left turns from the high-speed lanes of an arterial and to reduce left-turn conflicts to improve safety and operations	● Improved safety for pedestrians and bicyclists. ● Reduced delay due to fewer # of signal phases and shorter cycle lengths ● Reduced overall travel time ● Shorter pedestrian crossing distances
Split	● Divides traffic on a major street into two one-way streets that meet the side street at separate signalized intersections	● Spreads out conflict points where vehicles and pedestrians may cross paths ● Separates traffic flow on major street resulting in operations with less delay ● Better signal coordination on major street as well as minor street.
Continuous Green T-Intersection (CGT)	● Intersection design where one major street direction of travel (the top side of the "T") can pass through the intersection without stopping, and the opposite major street direction of travel is typically controlled by a traffic signal	● Improved safety by channelizing left-turn vehicles from the side street reduces the potential for angle crashes ● Increased efficiency as one direction of travel on the major street is free-flow
Offset T-Intersection	● An at-grade road intersection where a conventional four leg intersection is split into two three-leg T-intersections to reduce the number of conflicts and improve traffic flow	● Reduces the number of conflicts points from 32 to 18, indicating that an offset T-intersection has the potential to reduce the risk of collisions and improve the operational efficiency
Hamburger	● Also known as "throughabout", that connects exactly one major road with one or more minor roads using a circled traffic. ● The major road is the one that passes through the circle traffic.	● Allows the main intersection to operate on a two-phase signal
PFI	● Left turns bypass the main intersection by first turning onto a cross street frontage road	● Fewer signal phases and reduced delays ● Eliminates permitted left turns making it safer than conventional intersection ● Has channelizing island for pedestrian refuge

Table 2. Summary of the Design Features and Advantages of Alternative Grade-Separate Intersections

A.I.I. Design	Design Features	Advantage(s)
Center Turn Overpass	• An intersection that elevates all left-turn movements from the main intersection using ramps in the median • Left-turn vehicles use an acceleration lane to merge with through traffic • Both the elevated and at-grade intersections are controlled by a two-phase signal	• Reduces the number of points where vehicles cross paths and decreases the potential for angle crashes • Separates left-turn movements from through traffic - allowing fewer traffic signal phases, which reduces delay and increases capacity • Synchronization of the two signalized intersections improves corridor travel times on both major and side streets
Echelon	• A grade-separated intersection where one approach on both roadways is elevated to create a pair of intersections • Both intersections are signalized and operate like conventional one-way street intersections	• Reduces the number of points where vehicles cross paths and decreases the potential for angle crashes • Each intersection operates with only two traffic signal phases, allowing the intersection to handle more traffic • Fewer traffic signal phases means less time stopped at the intersection
Grade Separated Quadrant	• An intersection where all four left-turn movements and some, or all, right-turn movements are rerouted onto a connector road • Major and side streets are grade separated	• Reduces and spreads out the number of points where vehicles, pedestrians and bicyclists may cross paths • Rerouting left turns allows for fewer traffic signal phases, which means less time waiting for through and right-turn vehicles • Synchronization of the two signalized intersections improves corridor travel times on both the major and side streets
Grade Separated Direct Left		
Downstream Offset	• separated downstream of the signal on the major road • conflicting with opposing left turn and opposing thru	• Reduces and spreads out the number of points • Reduces traffic signal phases so less waiting times and higher capacity
Upstream Displaced	• separated upstream of the signal on the major road • conflicting with opposing thru	• Reduces and spreads out the number of points • Reduces traffic signal phases so less waiting times and higher capacity
Grade Separated Single Point	• separated at the signal on the major road • conflicting with the opposing thru on the major road	• Reduces and spreads out the number of points • Reduces traffic signal phases so less waiting times and higher capacity
Grade Separated RCUT		
U-Turn then Right	• separated downstream of the signal on the major road • conflicting with opposing U-turn and opposing thru at U-turn point on the major road	• Reduces and spreads out the number of points • Reduces traffic signal phases so less waiting times and higher capacity
Right then U-Turn	• separated downstream of the signal on the major road and then detoured to the minor road • conflicting with opposing U-turn on the major road and the opposing thru at U-turn point on the minor road	• Reduces and spreads out the number of points • Reduces traffic signal phases so less waiting times and higher capacity
Contraflow RCUT	• separated upstream of the signal on the major road • conflicting with opposing thru at U-turn point on the major road	• Reduces and spreads out the number of points • Reduces traffic signal phases so less waiting times and higher capacity

Table 3. Summary of the Design Features and Advantages of Alternative Interchanges

A.I.I. Design	Design Features	Advantage(s)
SPUI	● A grade-separated interchange design where all freeway ramps begin or end at a single signalized intersection on the arterial ● Right-turn movements onto and off freeway ramps are made at unsignalized intersections separate from the main intersection	● Requires only one signalized intersection; vehicles cross paths at only one location. ● Operates with 3-phase signals hence reduces overall interchange delay ● Left turns can be made at higher speeds
DDI	● A grade-separated interchange design where arterial traffic crosses to the other side of the roadway between the freeway ramps ● Vehicles can turn left onto and off freeway ramps without stopping or crossing opposing lanes of traffic ● Right turns on and off the freeway ramps occur either before or after the crossover intersections, when traffic is on the "correct" side of the road	● Reduced # of conflict points to 18 ● Can operate with 2-phase signals and can handle higher volume of traffic ● Easy access to freeway; does not require crossing of opposite lanes ● low construction costs
DLT	● left-turn vehicles cross to the other side of the opposing through traffic in advance of the freeway ramps ● Protected left turns and opposing through movements occur simultaneously at the two ramp intersections ● Ramp intersections and crossovers are signalized and timed to work together to minimize stops	● Reduced # of conflict points to 22 ● Simultaneous movement of protected left turns and opposing through movements ● Better signal coordination is possible allowing traffic to spend less time stopped
CFL	● Left-turn traffic on the arterial crosses opposing left-turn traffic via channelized lanes ● Left turns onto the freeway ramps in both directions are made during the same signal phase	● Reduces potential for rear-end crashes ● Operates with 3 signal phases; reduces overall interchange delay. ● Smooth and better traffic flow and hence congestion reduces.
Single Roundabout	● All ramps begin or end at a single roundabout on the arterial ● Traffic entering the roundabout must yield to traffic already inside	● Reduces potential for right-angle and head-on crashes by reducing # of conflict points. ● Eliminates need for traffic signals; traffic can flow in smoothly
Double Roundabout / Raindrop	● A design where all freeway ramps begin or end at one of two roundabouts ● The roundabouts are circular, unsignalized interchanges where traffic moves in a counterclockwise direction around a central island	● Reduces the number of conflict points and eliminates the potential for right-angle and head-on crashes ● Decreases the delay for ramp traffic and eliminates signal coordination between the two ramp terminals
MUT	● left-turning motorists make a U-turn at an adjacent crossover to complete the desired movement ● The crossovers are parallel to the arterial and are accessed from one-way frontage roads adjacent to the freeway ● No left turns are permitted at the main intersection	● Reduces the number of points where vehicles cross paths and decreases the potential for angle crashes ● Eliminates left-turn movements from the main intersection, allowing fewer traffic signal phases, which reduces delay and increases capacity

2.2. Corridor-Level Design Consistency Considerations

In view of the potential operation and safety benefits of AIIs, it is very likely that further corridor-level deployment of AII designs will be put into practice. For instance, Reid et al. *(13)* suggested employing corridor-wide MUT access strategies and management considerations to properties along the median street to promote safe and efficient access to these properties. Nevertheless, to the best of the research team's knowledge, to date there are no guidelines or research related to the geometry consistency of AII designs. Very limited information is available regarding the signing and public information of using AII designs along a corridor, apart from Thompson and Hummer *(16)* who conducted an expert interview and concluded that AII designs can be implemented safely through the use of signing plans and efficient public information campaigns.

Some previous efforts have been made to evaluate the geometric design consistency in terms of roadway horizontal and/or vertical alignments as well as the impacts of geometric design consistency on safety. For instance, in the early 1980s, Messer *(17)* presented a methodology for evaluating and improving the geometric design consistency of rural highways based on conceptual modeling, analysis of driver behavior principles, and empirical data. Factors that contribute to potential geometric inconsistencies were summarized, including basic feature type, design attributes, sight distance, separation distance, operating speed, and driver familiarity. Similarly, Hassan et al. *(18)* compiled different measures for evaluating geometric design consistency to identify their potential applicability and any required future research. These consistency measures are operating speed, vehicle stability, alignment indices, and driver workload. While both studies emphasized the importance of incorporating the concept of design consistency into roadway design, they also pointed out that there is still no standard procedure for designers to evaluate the design consistency of new or existing alignments.

In 2003, the Transportation Research Board (TRB) published guidelines on geometric design consistency for high-speed rural two-lane roadways *(19)*, where design consistency was defined as "*the conformance of a highway's geometric and operational features with driver expectancy.*" The primary objective of the research was to investigate the impacts of roadway geometric design elements (e.g., lane width reductions, lane drops, and driveways) on speed consistency through literature review and expert interviews. A rules-based consistency checklist was developed to notify designers and engineers when the potential for driver expectancy violations is present. The rules cover the following specific areas: cross section, horizontal and vertical alignments, railroad grade crossings, narrow bridges, driveways, preview sight distance, climbing and passing lanes, and frequency of decisions.

Since then, a number of studies have been conducted to assess the effect of geometric design consistency on traffic safety, such as Ng and Sayed *(20)* who developed a generalized linear regression model to quantify the relationship between design consistency and road safety using the accident and geometric design database of two-lane rural highways. Modeling results show that the safety performance of an alignment improved when design consistency was considered. Watters and O'Mahony *(21)* also suggested using geometric design consistency studies to identify inconsistent sections on highways, which can then be targeted for improvement. Based on the modeling of operating speed on different roadway geometric makeups and historical crash data, a relationship was found between geometric design consistency and crash risk. This can be used to pinpoint locations on highways where accidents could conceivably be higher. Cafiso and La Cava *(22)* employed the maximum speed differential between two successive elements and between the average section speed, and the minimum single element speed as driving performance indicators to identify road alignment design inconsistencies. Based on a naturalistic driving experiment, this research suggested that speed consistency variables and relation design parameters could be used as indirect measurements of design consistency, which could eventually aid in the evaluation of road safety performance and infrastructure improvement projects.

2.3. Human Factor Considerations for AII Design

2.3.1. Driver Tasks When Approaching Intersections

In a real-world setting, the overall driving task consists of control, guidance, and navigation tasks *(23)*. To successfully execute a vehicle maneuver through an intersection, the driver must receive and recognize available information, make a decision, and execute the desired action. The FHWA "*Human Factors Issues in Intersection Safety*" lists typical steps a driver must execute when approaching an intersection *(23)*, based on which, this paper illustrates the driver's decision process in Figure 1.

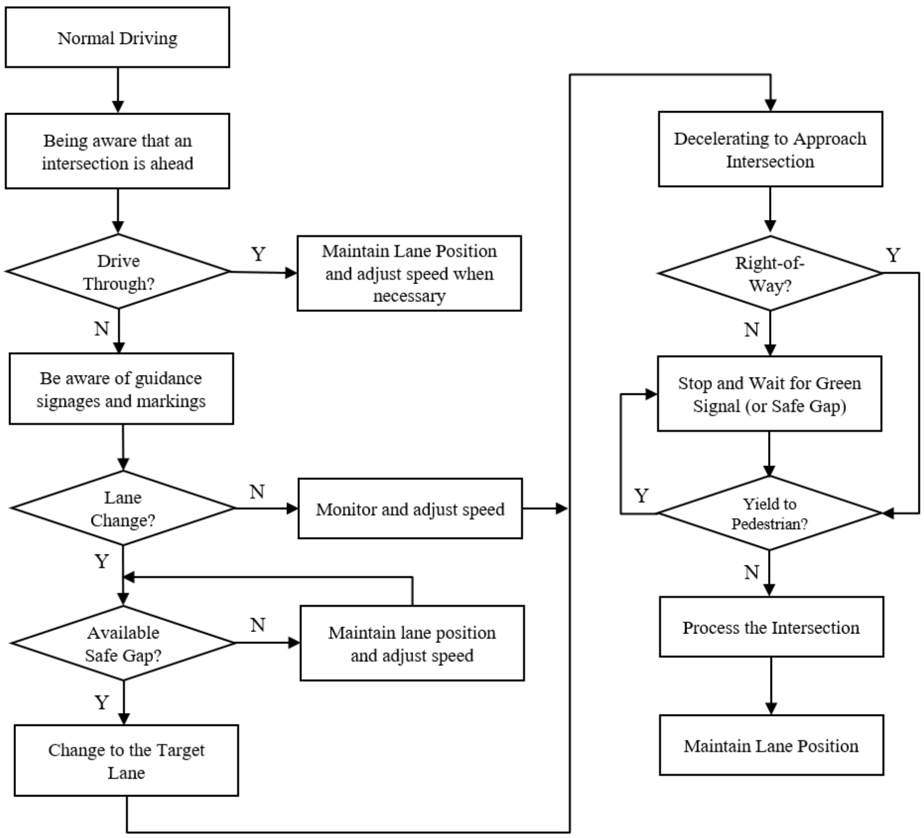


Figure 1. Decision process when a driver approaching an intersection

According to the National Highway Traffic Safety Administration (NHTSA) statistical data *(24)*, more than 90 percent of motor vehicle crashes were caused by or primarily caused by human error. Therefore, roadway design considering human factors, such as drivers' ability to safely navigate while driving through an intersection, has become increasingly important for the intersection geometric, signing, and marking design process. This is particularly critical when designing an alternative intersection, which aims to minimize the potential distractions introduced by the unconventional geometric features and guide information. In this regard, this section overviews three aspects: driver cognition capability, impacts of signing and marking on driver behavior, and human factor considerations for AII design.

2.3.2. Impacts of Signing and Marking on Driver Behavior

In current practice, the most commonly used methodologies for assessing the impacts of signing and marking on driver behavior are based on: empirical analysis of field-collected driver behavior data, on-road testing with static visual stimuli, and driving simulation experiments. In general, empirical observational studies have shown little difference in driver performance under various roadway signage conditions in terms of unusual behaviors with a focus on specific service signs. Nevertheless, the lack of experimental control of roadway conditions, traffic conditions and individual driver and vehicle capabilities in such studies leaves doubt as to the actual effects of signage configuration, location, etc. on driver visual behavior and performance.

In testing with static stimuli, sign images have been presented to participants, in the absence of any driving task demands, and target identification accuracy has been assessed *(25)*. This type of research represents a quick and preliminary form of assessment of sign configuration and content effects on driver responses. In general, the results cannot be guaranteed to extend or apply to real driving circumstances due to the absence of any driving task demands on participants in visually searching sign imagery. This type of research likely has the least utility of all three general types of signage studies as a basis for actual design.

In comparison, driving simulation experiments provide advantages of both observational and stimulus-based research. Simulations allow for realistic representations of roadway configurations and driving demands, leading to visual behaviors that are similar to those occurring on actual roadways and in use of real signage. Such studies also provide for a high degree of control in testing of specific sign configuration and content conditions and support collection of high-resolution data on driver behaviors and vehicle performance under various driving workload demands (e.g., hazard or work zone navigation). In general, prior simulator research *(25,26)* indicates little difference among service sign configurations in terms of driver visual attention and vehicle control performance. However, some more recent simulator-based research has indicated differences in visual demands of various signage types, including guide signs vs. specific service panels with varying logo counts *(27)*. Nevertheless, the method by which this work calculated glance durations to various types of signs is questionable in that multiple fixations were interspersed within glances to a sign and it is not clear whether all fixations were to the target sign or other areas of the driving environment or vehicle.

2.3.3. Driver Cognitive Capability

Since driving is primarily a visual task and navigating an alternative intersection can present considerable visual demand, identifying how excessive visual demand can be determined is appropriate. An early study conducted by *Green (28)* revealed that crash probability increases linearly with eyes-off-the-road time, the product of mean glance duration, the number of glances per trial, and frequency of use. To be more specific, there are four typical factors that dictate driver visual processing of signage: the pace of sign/information presentation, the presence or absence of obstructions to sign viewing, the formatting of a sign (e.g., size, illuminance, colors, shapes), and the information quantity (e.g., bits). In reality, driver's recognition and understanding of the guide information tends to be affected by a number of factors, including but not limited to: road environment, traffic signs' physical attributes, a driver's personal attributes, etc. For instance, *Dutta et al. (29)* employed a driving simulator to analyze different factors that might impact the comprehension of multiple phase messages presented on Variable Message Signs (VMS), such as traffic condition, road geometry features, the content of a message, the frequency and direction of lane changes, etc. The results revealed that a message tended to be more effective when the message was presented for a relatively short duration and repeated twice during the time in which it was visible.

In addition, the levels of cognitive capability to process information differ between experienced and inexperienced drivers. *Patten et al. (30)* explored the relationship between cognitive workload and driver experience through a secondary task method and found that inexperienced drivers had on average approximately 250 milliseconds (ms) longer reaction times to a peripheral stimulus, than experienced drivers. Therefore, increased training and experience with AII designs may benefit drivers in handling new or unexpected traffic situations. In 2015, the FHWA published "*Information as a Source of Distraction*", which aimed at determining the types of information that can be displayed within the right-of-way without adversely affecting drivers' attention to their driving task *(31)*. It was found that there were differences in visual demands of various signage types including guide signs and specific service panels with varying logo counts. In addition, research findings supported that the current Manual on Uniform Traffic Control Devices (MUTCD) standards for supplemental guide signs did not introduce distraction to drivers, and suggested that the design of guide signs should not exceed the current MUTCD standard of no more than six logos per sign and no more than four signs with minimum separations of 800 ft. Similarly, *Shao et al. (32)* collected drivers' visual demands from an experiment with over 50 subjects, results demonstrated that the information threshold of a guide sign was six locations per information, and information efficiency significantly reduced when messages were overloaded.

3. Focus Group

A focus group is a group interview that involves a small number of participants, discussing a topic individually and collectively. Their answers and reactions to specific researcher-posed questions are collected *(33)*. Focus groups have been proved to be an effective tool in gathering qualitative data in the transportation research such as the potential impacts of a certain traffic control strategy on driver behavior *(34-36)*, or the public's attitudes to new transportation technologies *(37-39)*. A focus group gathers participants together to discuss the issue either under a guided manner (i.e., moderator questions), or in an open format (i.e., group discussions), or both guided and open. In comparison with the traditional anonymous questionnaire survey approach, data from focus groups are derived from a dynamic information changing process since a participant's opinion might be influenced by the insights provided by other participants *(33)*. This procedure enables participants to bring up ideas and come to new insights and priorities based on the combined knowledge of the group *(40)*. Moreover, researchers can learn more about participants attitudes by asking follow-up questions and by observing their body language, facial expression, and tone of voice *(41)*.

3.1. Purpose

The purposes of the focus groups were to gain a better understanding of drivers' familiarity and attitude with alternative intersection designs, and how they anticipate they would navigate through them for different movements when approaching an individual alternative intersection and when driving through a sequence of alternative intersections. Moreover, through open discussions, the research team worked to determine what roadway signs or other clues are useful for drivers, determining where these signs should be, and what features they like (and don't like) about the corridor-level deployment of alternative intersection designs.

3.2. Data Collection

This research collected video data along the NC55 RCI corridor in Holly Springs, North Carolina. A sketch of the NC55 RCI corridor is illustrated in Figure 2. The total length of the study corridor is approximately 3 miles, which contains 4 RCI intersections, a Reverse RCI intersection, and a conventional intersection. The videos were presented to the participants as visual illustrations of the potential scenarios they might encounter while navigating this RCI corridor or a similar corridor.

The research team first identified the routes (Origin-Destination pairs, O-D) that can reasonably represent travelers' trip purposes, such as from a residential area to a business, an industrial area, or a gas station. Six reasonable routes were identified for videotaping, as shown in Figure 2. Then, the research team conducted field trips to record these routes. The filming was conducted during workday non-peak periods in July 2020. A high-resolution wide-angle camera was mounted on the top of the subject vehicle to capture a full view of the roadway, including roadside traffic signs, pavement markings, and the surrounding traffic flow condition. The driver was instructed to drive following the posted speed limit on the right-most lane and make appropriate lane-change(s) based on the actual traffic condition.

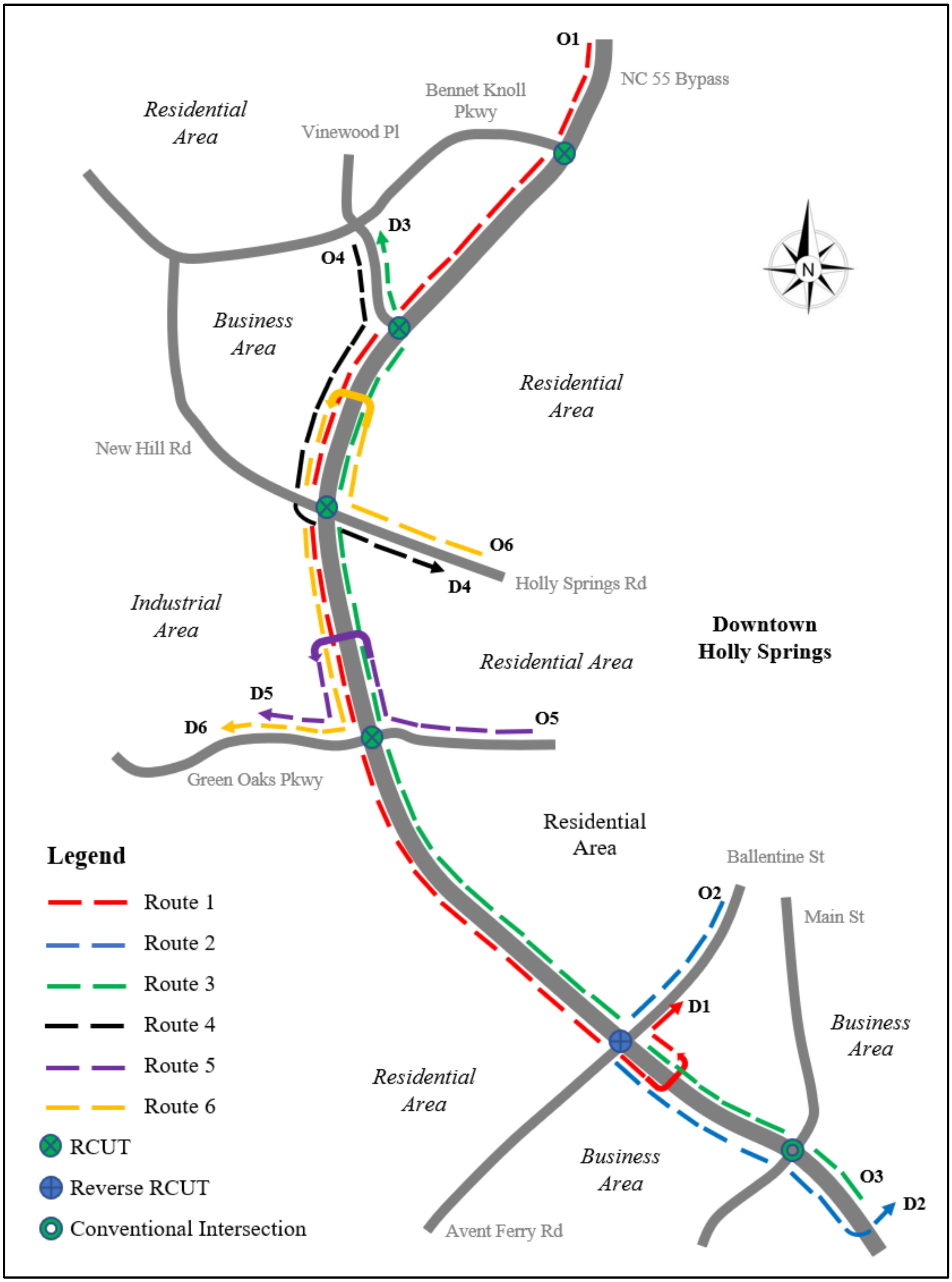


Figure 2. Data collection routes for focus group study

A brief description of each route is presented as follows:

Route 1: Reverse RCI major street left turn (Highway 55/Avent Ferry Road)

This is a bypass trip on NC55. The driver travels on NC55 south, passes a series of RCI intersection, and makes a left-turn at Avent Ferry Road to a service area. The driver must drive past the Reverse RCI intersection, turn from the double U-turn lanes, travel back alongNC55 north, and then take a right onto Avent Ferry Road.

Route 2: Reverse RCI minor street left turn (Avent Ferry Road/Highway 55)

This route departs from a residential area to a business area. The driver traveling on Avent Ferry Road, needs to make a left turn onto NC55. The Reverse RCI intersection does not allow drivers to go straight on Avent Ferry Road, but they can go left onto NC55, similar to a conventional intersection.

Route 3: RCI major left turn (Highway 55/Bennet Knoll Parkway)

This route departs from a business area to another business area. The driver travels on NC55 north, passes a series of RCI intersections, then turns left at a RCI intersection onto Bennet Knoll Parkway.

Route 4: RCI minor street right turn following by RCI major street left turn (Vinewood Place/Highway 55/Holly Springs Road)

This route departs from a business area to a residential area. The driver comes from a street in a shopping center, turns right, drives on NC55 and turns left at an RCI intersection.

Route 5: RCI minor street through (West Ballantine/Highway 55/Green Oaks Parkway)

This route departs from a residential area to the Holly Springs Industrial Park. The driver "crosses" NC55 from minor street by turning right ont NC55 north, performing a U-turn to travel back along NC55 south, and then turning right again onto what would have been a straight continuation of the minor street.

Route 6: RCI minor street left turn following by RCI major street right turn (Holly Springs Road/Highway 55/Green Oaks Parkway)

This route departs from a residential area to the Holly Springs Industrial Park. The driver drives on Holly Springs Road, turns right onto NC55 north, makes a U-turn to NC55 south, then travels through the RCI intersection, and makes a right turn to Green Oaks Parkway.

3.3. Focus Groups Structure

3.3.1. Focus Group Format

Since this research was conducted in the age of COVID-19 pandemic, the focus groups were conducted virtually through the Adobe Connect on-line meeting software and occasionally Zoom software due to technical issues.

Prior to the focus groups, the research team edited the videos and inserted survey questions within the video or in alignment with the video. Other presentation materials, such as aerial maps or photos of alternative signage were also prepared by means of PowerPoint slides. Then, the research team beta-tested the setup using the Adobe Connect software within the research team; a demo of the developed focus groups materials was presented to the NCDOT panel members for their review, comment, and approval. The shared components of the on-line focus group included the main presentation screen that allows the facilitator to show videos of vehicles traveling through intersections, and on-screen survey or polling questions to allow participants to submit their feedback anonymously. The focus group questions included a video presentation question section and an open discussion section. Video presentation questions mainly related to driver behavior (e.g., "Which lane should you be in to reach your destination?"); the open discussion questions were flexible, aimed at collecting participants' concerns and opinions on navigating a corridor with RCI intersections. Responses were measured on a 5-point Likert scale (e.g., Strongly Unfamiliar/Least Comfortable to Strongly Familiar/Most Comfortable). Accordingly, the evaluation results were converted to a 1-5 score, where 1 corresponds to very low evaluation and 5 to very high evaluation. Other member(s) of the research team were available for addressing any questions not mentioned by the facilitator or requiring clarifications. Each focus group session was recorded for note-taking purpose only.

The general structure of the developed focus groups study is briefly described as follows. After a background introduction, the participants were shown six videos (plus a demonstration video) of the six routes along NC Highway 55 in Holly Springs, NC, filmed from the vantage point of the driver using an externally mounted camera. As each video progressed, participants were instructed to act as if they were driving and looking at the road and the surroundings like they normally did. One to six times during each video, the video was paused, and participants were asked to choose which lane they would prefer to be in to reach their destination, through an anonymous poll (as shown in Figure 3). Participants were informed that there were no wrong answers, and the purpose of the focus group was to know what they think when driving on a RCI corridor. After watching all the videos, there was an open discussion on their concerns and thoughts on RCI intersections.

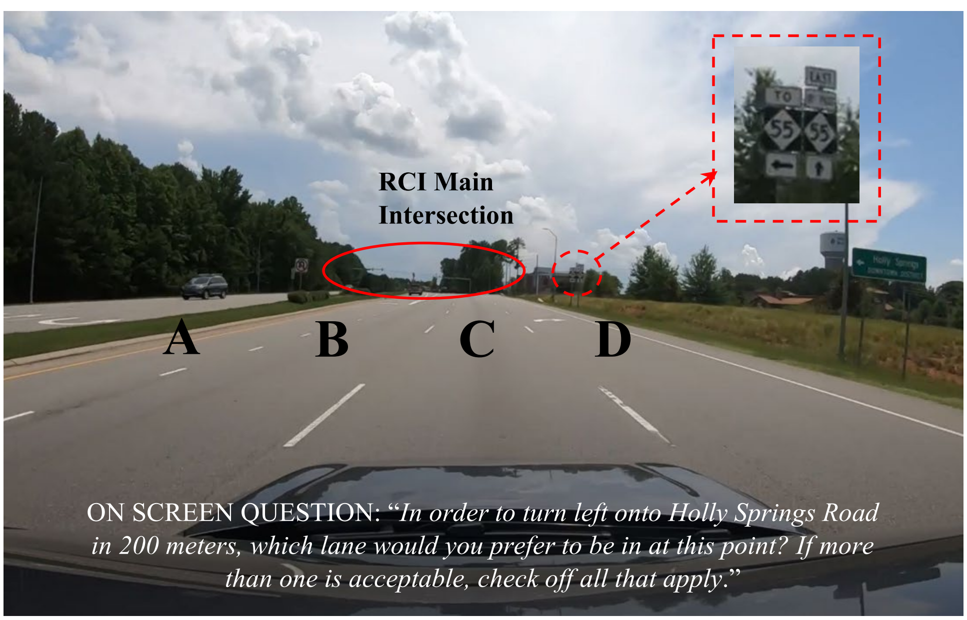


Figure 3. Video presentation example used in the focus group studies

3.3.2. Participants

To compare drivers who had some experience with the innovative RCI intersections to those unfamiliar with them, this research conducted two parallel sets of focus groups. One set, *familiar* focus groups, mainly focused on drivers living in the vicinity (i.e., Holly Springs residents) or those often driving through the NC55 Bypass. The other set, referred to as *unfamiliar* focus groups, involved drivers from other cities or towns in North Carolina.

Qualified participants had to possess a valid U.S. driver license and be at least 18 years old. Moreover, since the focus groups were conducted virtually, participants needed a computer or a similar device with a good internet connection, camera, and microphone. Participants were recruited via recruitment flyers posted on social media apps such as the Facebook and the Nextdoor. The recruitment flyer contained a brief description of the research purpose, a description of participants' roles in the focus group study, and a prescreening questionnaire that assembled candidates' demographic information such as gender, age group, ethnicity, driving experience, etc., which aimed at selecting a diverse set of participants for focus group participation.

A total of 17 participants were recruited, including 8 females and 9 males. The majority of participants were mid-aged (25-34 years old: 5; 35-44 years old: 6; 45-54 years old: 1); 2 were young drivers aged below 24 years, and 3 were senior drivers aged 65 years and above. Among the 17 participants, 7 had bachelor's degrees, 8 had master's degrees, 1 had a professional degree, and 1 had a technical degree.

3.3.3. Focus Group Procedure

A total of four focus groups were conducted. The focus groups were conducted on November 8, 2020 and November 18, 2020 for participants who were familiar with the area (Holly Springs residents), and on January 19, 2021 and January 22, 2021 for non-Holly Springs residents. Focus group meetings were scheduled on weekends or evenings to accommodate the participation of different groups of participants.

For each scheduled focus group session, the facilitator sent reminder emails to participants approximately two days prior to the session detailing access procedures; participants were advised, based on their time flexibility, to log onto the Adobe Connect interface with a member of the research team to test their equipment and software (e.g., internet connection, microphone, speaker, camera, etc.). Once participants joined the session, the facilitator introduced the research team, explained the objectives of the research project, outlined their role in the research and the necessity of their feedback, went over the agenda of the session, and explained how the Adobe Connect worked. Upon understanding all the information provided, if the participant agreed to contribute to the data collection procedure, a consent form was provided, and their signatures, which they signed electronically.

The focus group started with a practice video, to illustrated how the videos would work. This video was of a conventional intersection and the facilitator asked participants example questions about turning left or turning right. Then, the facilitator presented the 6 actual videos in sequence to the participants. For each route, the video was paused at various decision points and the participants were asked to choose (through the anonymous online survey) which lane they think they should be traveling in to complete the action requested (e.g., turning left). At the end of each video, the participants were asked to rate how confusing this type of intersection was, and how comfortable they felt when "driving" on this route. The facilitator then reviewed the route with the participants and discussed what helped them make their decisions at various points and how easy they felt the route was to navigate. Participants were also asked to rate how confusing this type of intersection was, and how comfortable when driving on this route. At the conclusion of all the videos, the facilitator led a final discussion about any relevant issues not discussed.

For each of the AII routes, the facilitator led an open-ended discussion on several topics, including, but not limited to, the following topics:

- What were the key factors that made them decide which lane they should be in at each decision-making point?
- What additional information would they want to help them make their decisions?
- When and why did they decide to make their lane shifts?
- How much did they use the roadway signs/markings and how useful were the traffic signs/markings?
- Should there be a sign (either a text sign or a graphical sign or both) alerting drivers to the type of interchange?
- What were the main difficulties for the different AIIs?
- Do they ever plan their routes based on how easy it is to turn on or off a street? For instance, if they need to turn left off a busy street, would they try to come from a different direction so that they could turn right off it?

Finally, the research team documented the key discussion points and participants' constructive feedback (both positive and negative). A thank you email was sent to focus group participants the day after their session, and each participant received a 30-dollar e-gift card as their compensation.

3.4. Results

Participants' feedbacks to the survey questions were collected and analyzed, include participants' perceptions of their familiarity of RCI intersections (Figure 4) and comfort when driving on a RCI corridor (Figure 5).

A summary of the results of the survey questions for each route individually (Table 1), and detailed descriptions of participants' feedbacks on each route are presented below.

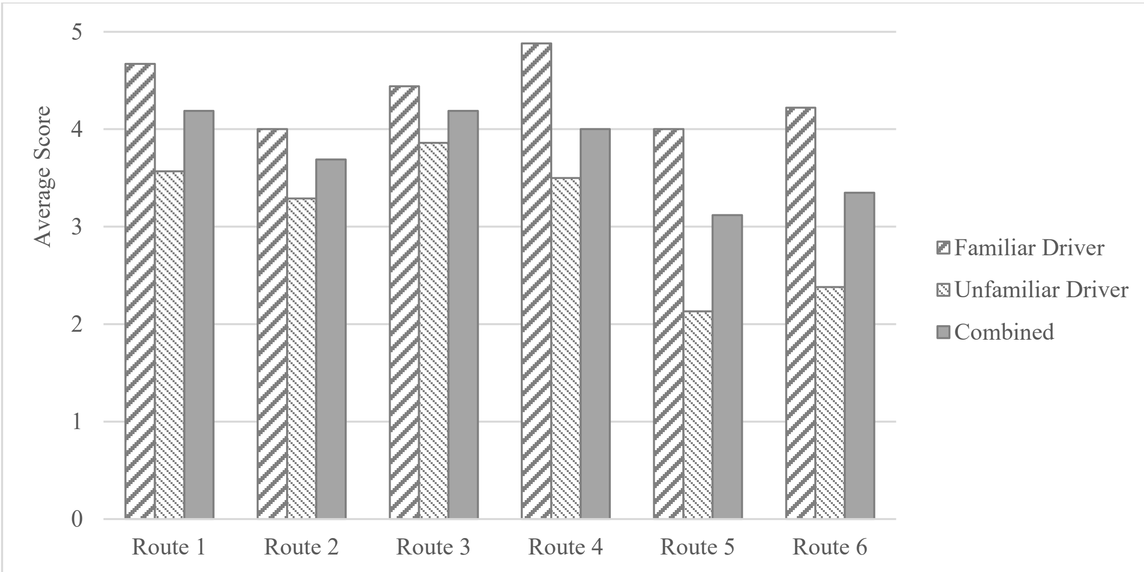


Figure 4. Familiarity of RCI Intersections

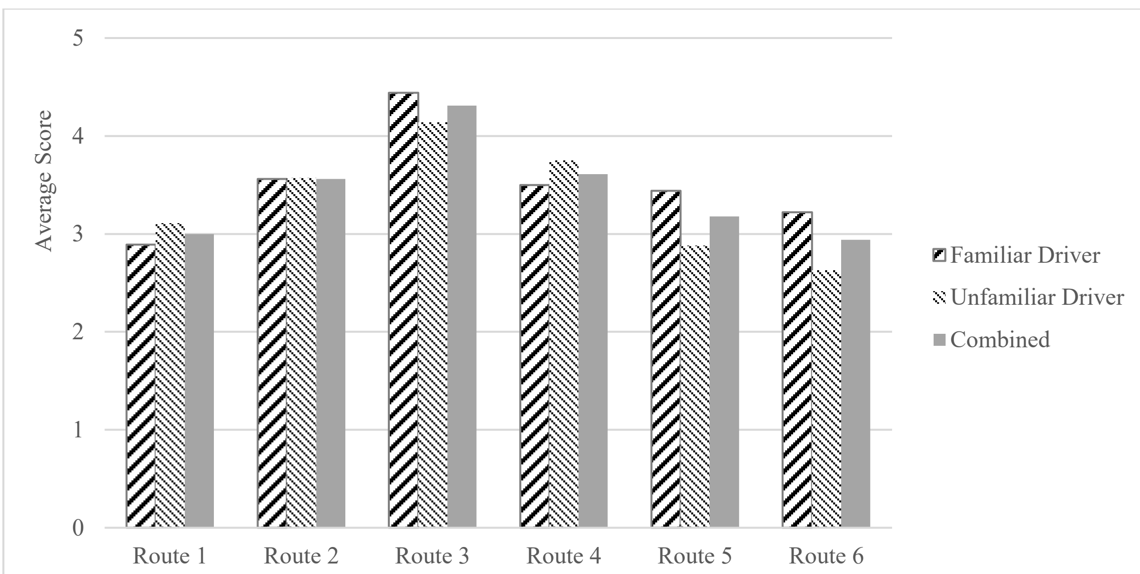


Figure 5. Comfort when Driving on a RCI Corridor

3.4.1. Questionnaires

This summary begins with tables showing the results of the survey questions for all the routes, before going over each route individually, and then summarizes the overall findings. It should be noted that there are many instances where drivers would choose the same lane whether the intersection was traditional or innovative; for example, a driver should get into the left lane in case they wanted to turn left at a traditional intersection or if they needed to drive past the intersection and then perform a U-turn.

Route 1: Reverse RCI major street left turn (Highway 55/Avent Ferry Road)

For this route, the familiar and unfamiliar participants generally both chose the correct lanes to be in, as shown in Table 4. When reaching the destination intersection and seeing the "No U-turn" sign, two of the unfamiliar participants claimed they were not sure what to do next.

The familiar participants were, as expected, more familiar with this type of intersection (4.67 average for them compared to 3.57 for the unfamiliar participants). However, they were actually less comfortable with it than the unfamiliar participants were (2.89 to 3.11). Some of them spoke about there being so many different types of innovative intersections, that they were often not sure which type to expect. The unfamiliar group, on the other hand, said the intersection was annoying, but the choices were obvious once they saw they could not turn right.

Table 4. Participants' Lane Selection at Various Decision-Making Locations - Route 1

Decision-Making Location	Cohort	A	B	C	D	Not Sure	Multiple
200 Meters Before Intersection	F	9					
	U	7	1				1
	Both	16	1				1
At Intersection (A = Straight, B = Turn Left, C = Turn Right	F	8					
	U	6	1			2	
	Both	14	1			2	
Past Intersection, Approaching U-turn	F	3	6				
	U	7					
	Both	10	6				
Choices at 2 Lane U-turn	F	1	9				1
	U	2	5				1
	Both	3	14				2
After U-turn, Reapproaching Intersection	F	1	8				
	U	1	5				
	Both	2	13				
100 Meters from Intersection	F		1	8			
	U			7		1	
	Both		1	15		1	

Note: F = Familiar Driver; U = Unfamiliar Driver; Gray coloring shows the most correct answer, if there is one. Due to technical or other uncontrollable issues (such as the poll ending before all the participants submitted their responses), the number of total answers for some questions may vary.

Route 2: Reverse RCI minor street left turn (Avent Ferry Road/Highway 55)

There was only one decision point for participants to make for this route and only half of the familiar participants chose the correct lane, while three quarters of the unfamiliar participants did. The choice was the "common sense" choice, that is turn left to go left, but half of the familiar group thought the intersection was more restrictive than it was, as shown in Table 5. Again, they were familiar with the innovative intersections, but did not know where every specific one was.

The familiar group was, again, more familiar with the type of intersection (4.44 to 3.86), but had the same level of comfort as the other group (3.56 to 3.57).

Table 5. Participants' Lane Selection at Various Decision-Making Locations - Route 2

Decision-Making Location	Cohort	A	B	C	D	Not Sure	Multiple
100 Meters from Intersection, at sign	F	4	4	1			
	U	6	2			2	1
	Both	10	6	1		2	1

Note: F = Familiar Driver; U = Unfamiliar Driver; Gray coloring shows the most correct answer, if there is one. Due to technical or other uncontrollable issues (such as the poll ending before all the participants submitted their responses), the number of total answers for some questions may vary.

Route 3: RCI major left turn (Highway 55/Bennet Knoll Parkway

In Route 3, for the second decision-making question, five out of the nine familiar participants chose the wrong lane, while only two of eight unfamiliar participants did, as shown in Table 6. In the discussion, those making the wrong decision said they thought were going to have to drive past and then do a U-turn. This was partly due to the fact that they had just driven past a U-turn intersection coming from the other direction and partly due to the fact that there was not clear signage of where to go.

Again, the familiar participants were more familiar (4.44 to 3.86) and slightly more comfortable (4.44 to 4.14).

Table 6. Participants' Lane Selection at Various Decision-Making Locations - Route 3

Decision-Making Location	Cohort	A	B	C	D	Not Sure	Multiple
500 Meters Before Intersection	F	9					
	U	6	1			1	1
	Both	15	1			1	1
Approaching Left Turn Lanes	F	4	5				
	U	6	2				
	Both	10	7				

Note: F = Familiar Driver; U = Unfamiliar Driver; Gray coloring shows the most correct answer, if there is one. Due to technical or other uncontrollable issues (such as the poll ending before all the participants submitted their responses), the number of total answers for some questions may vary.

Route 4: RCI minor street right turn following by RCI major street left turn (Vinewood Place/Highway 55/Holly Springs Road)

As shown in Table 7, For the first decision question, the participants had to choose whether to turn right from the right-most lane or the left-most lane (there were no other choices possible, and both were right-turn lanes). All of the familiar participants chose to turn right from the left-most lane, while half the unfamiliar participants did, with the rest choosing the right-lane or said they were not sure or both. During the discussion, the familiar group spoke more about having to do a relatively quick left turn after turning right and so wanted to be in the outside lane; this shows that their familiarity with the route affected their decision-making. Some of the unfamiliar group said this, but others spoke of it being easier to turn right from the right lane; this perhaps implies that they wanted to make the immediate turn easier and then deal with the next turn when they got there.

The familiar group showed more familiarity (4.44 to 3.50), but were actually less comfortable (3.50 to 3.75) than the unfamiliar group. Some of them again said how they expected to not be allowed to turn left at Holly Springs Road (like in Route 1 where they had to go past the intersection to turn left) and thus were somewhat surprised.

Table 7. Participants' Lane Selection at Various Decision-Making Locations - Route 4

Decision-Making Location	Cohort	A	B	C	D	Not Sure	Multiple
Approaching Two Right Turn Lanes	F	9					
	U	4	3			3	2
	Both	13	3			3	2
Approaching Left Turn Lanes	F	7	1				
	U	5	5				1
	Both	12	6				1

Note: F = Familiar Driver; U = Unfamiliar Driver; Gray coloring shows the most correct answer, if there is one. Due to technical or other uncontrollable issues (such as the poll ending before all the participants submitted their responses), the number of total answers for some questions may vary.

Route 5: RCI minor street through (West Ballantine/Highway 55/Green Oaks Parkway)

When approaching an intersection where they wanted to go straight, but were forced to choose between two right-turn lanes, seven of nine familiar participants chose the left-most right-turn lane, most explaining they did so in order to make their merge into the subsequent U-turn lane easier; the two others chose the right lane, as shown in Table 8. Three of the eight unfamiliar participants also chose that lane, but the remaining five said they were not sure, although most said they were expecting there to be a trick.

This intersection had the lowest familiarity levels for both groups (4.00 and 2.13) and also low comfort levels (3.44 and 2.88). The unfamiliar group said they were confused at the start, but the prior routes had given them some clues about what they would probably have to do.

Table 8. Participants' Lane Selection at Various Decision-Making Locations - Route 5

Decision-Making Location	Cohort	A	B	C	D	Not Sure	Multiple
Approaching Two Right Turn Lanes	F	7	2				1
	U	3				5	
	Both	10	2			5	1
After U-turn, Approaching Intersection from Major Road	F			1	7		
	U				8		
	Both			1	15		

Note: F = Familiar Driver; U = Unfamiliar Driver; Gray coloring shows the most correct answer, if there is one. Due to technical or other uncontrollable issues (such as the poll ending before all the participants submitted their responses), the number of total answers for some questions may vary.

Route 6: RCI minor street left turn following by RCI major street right turn (Holly Springs Road/Highway 55/Green Oaks Parkway)

As shown in Table 9, the first decision question was similar to that of Route 5; that is, all vehicles have to turn right, even if they want to go left or straight. All of the familiar participants chose the left most turn-lane, and seven of eight unfamiliar participants also chose that lane, with the other person saying "not sure"; they said that they now understood better what to do, since they had just used a similar intersection in Route 5.

This was also shown in their familiarity scores, where the familiar group was much more familiar (4.22 to 2.38) and comfortable (3.22 to 2.63). The unfamiliar group said they were more sure what to do at the beginning, as it was similar to Route 5, but then got confused as it began to differ slightly from the earlier route.

Table 9. Participants' Lane Selection at Various Decision-Making Locations - Route 6

Decision-Making Location	**Cohort**	**A**	**B**	**C**	**D**	**Not Sure**	**Multiple**
Approaching Two Right Turn Lanes	F	8					
	U	7				2	1
	Both	15				2	1
Approaching U-turn Lanes on Major Road	F	8					
	U	8	2			2	3
	Both	16	2			2	3
Choices at 2 Lane U-turn	F		8			1	
	U	3	5				
	Both	3	13			1	
Approaching First Intersection	F			6	1	1	
	U			4	4		
	Both			10	5	1	

Note: F = Familiar Driver; U = Unfamiliar Driver; Gray coloring shows the most correct answer, if there is one. Due to technical or other uncontrollable issues (such as the poll ending before all the participants submitted their responses), the number of total answers for some questions may vary.

3.4.2. Open Discussions

In addition to the designated questions, the focus groups also contained an open discussion after watching each route, where participants provided supplementary answers to the designated questions and their concerns about RCI intersections. In general, the discussed questions can be categorized into three categories: 1) driver confusion when navigating a RCI intersection, 2) effectiveness of traffic signages and markings, and 3) effects of previous intersection configuration on the current intersection.

3.4.2.1 Driver Confusion

- The familiar groups talked about how the innovative intersections in Holly Springs were confusing for the first few times or first few weeks (i.e., after they were constructed or when the participants moved to the area). They said that while driving they were more ready for any intersection in the area to be non-traditional.
- In fact, the familiar participants spoke about how they continue to confuse themselves when approaching an intersection even when they have driven through it before. Since there are many different types and they do not always have the location of each one

memorized, sometimes they expect it to be one type and they start to perform the wrong maneuver (e.g., turning right to do a U-turn, when they could have turned left directly).

- Several of the unfamiliar participants said that it was usually possible to guess the right choices in the videos, but that it would be more confusing if, for example, in order to turn left from a major road, they had to turn right and loop back.

3.4.2.2 Traffic Signages and Markings

- Both groups wanted more signs and to have them earlier. They complained that few, if any, signs told them what they needed to actually do, when turning through a non-traditional intersection.
- They found pavement markings useful, especially if they were well before the turn and some of them wanted overhead signs.
- Both groups felt white signs with arrows were more useful than green “destination” signs (e.g., “Holly Springs Village”). Some of the unfamiliar participants complained that destination signs or signs with “north” or “south” descriptions were not useful if you were new to the area.

3.4.2.3 Observations of Previous Intersections

- The familiar group did not pay particular notice to the types of intersections that they passed. They already were aware of the fact that there were alternative intersections along the route and so mostly paid attention to orient themselves as to where they were traveling.
- For the first scenario, which was also the longest and passed the most different types of intersections, only one member of the unfamiliar group noticed that there were alternative intersections, noting that some had turns out of the median. The others generally said that they were watching the traffic and looking for signs.
- As they watched more videos, the familiar group said they did not pay that much more attention to the intersections they passed, since they already knew they were non-traditional in varying ways. The unfamiliar participants, on the other hand, did begin to pay more attention. This was not always directly helpful, since the destination was sometimes different from the ones they passed, but they did say they were more prepared to adapt to novel situations. A couple of them said that if they were actually driving, they would probably slow down and try to drive in a pocket with fewer cars near them.
- Despite having done U-turns from major roads in earlier scenarios, when the unfamiliar group was forced to turn left or straight from a minor road by turning right and doing a U-turn they were confused and uncomfortable.

4. Driving Simulator Experiment

4.1. Experimental Goals

The purpose of the driving simulator experiment was to investigate drivers' performance when navigating alternative intersection corridors. Specifically, the experiment seeks to answer the following questions: 1) Are there any issues navigating any of the specific alternative intersection combinations regardless of the corridor type? 2) Do drivers have a different reaction for a specific pair of subsequent intersections if the corridor is consistent (i.e., a standard or RCI corridor) vs. a unique corridor design? and 3) Is there any learned behavior once drivers have been through one or more unique combinations/pairs?

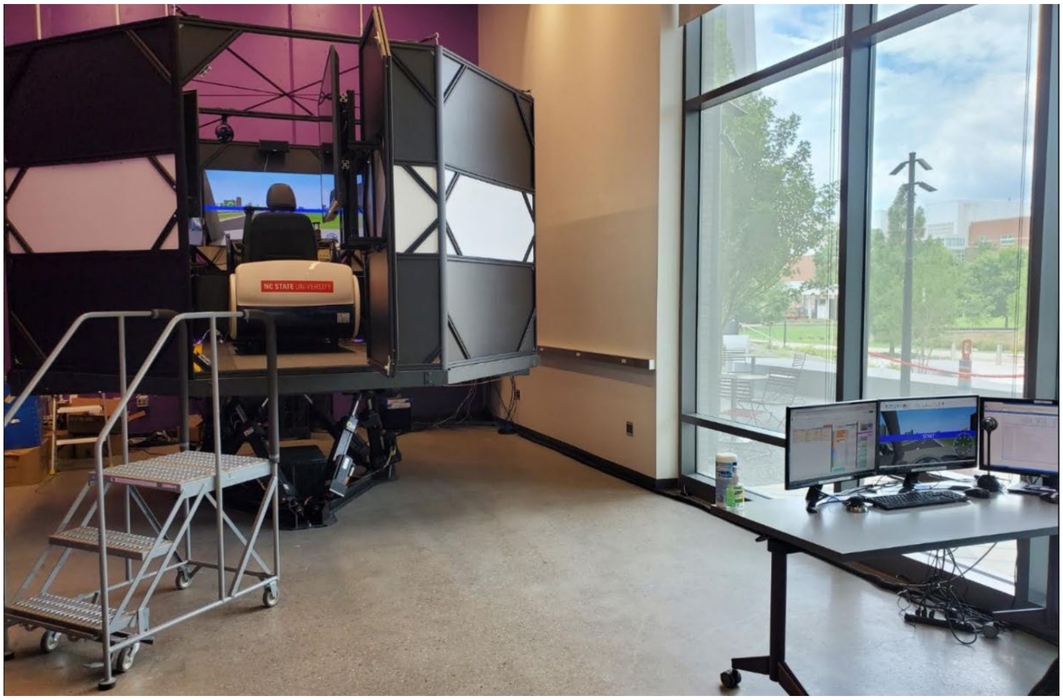
4.2. Participants

For this driving simulation experiment, a total of 48 participants were included which had both 20/20 vision (naturally or corrected) and a valid driver's license. The participants were recruited via recruitment flyers posted around the NCSU campus and ads in social media application such as NextDoor and Facebook. Potential participants submitted an online screen survey and lab visit request according to information on the posted flyers or websites. Participants who passed the screening were contacted by the research coordinator via email with his or her scheduled lab visit date and time, consent form, COVID-19 addendum, as well as logistical information regarding his or her visit such as directions, parking, and the day-of screening. After reading and signing the consent form, the participant was asked to complete a questionnaire survey about the status of their driver license, age, driving experience, visual acuity, etc.

Participants were compensated at a rate of $20 per hour. The participants were divided into four groups, according to age (young driver 18-24 years and middle-aged driver 25-64 years) and gender (male and female), with 12 drivers for each group. Since the experiment was conducted during the COVID-19 pandemic period, per the approved IRB, this research effort did not recruit vulnerable people such as senior driver (65 years and elder).

4.3. Apparatus

A high-fidelity, full motion, driving simulator (shown in Figure 6) was used to investigate driver behavior when driving on alternative intersection corridors. During the driving simulator experiment, drivers interacted with a full-size steering wheel, simulated accelerator, brake pedal, two mirrors, and dashboard. By operating the steering wheel, drivers could control the car to maintain lane-keeping and lane-changing; by controlling the accelerator and brake pedals, they could also adjust the speed of the car. Surrounding the cockpit, there were eight 55-inch monitors that provided drivers with a 360-degree road view to mimic real-world driving environments. The cockpit was mounted on a Moog motion base, which allows a maximum payload weight of 900 kg (2,000 lb.).



(a) Overview of the Lab

(b) Driving Simulator Cab

Figure 6. The NCSU Driving Simulator Lab

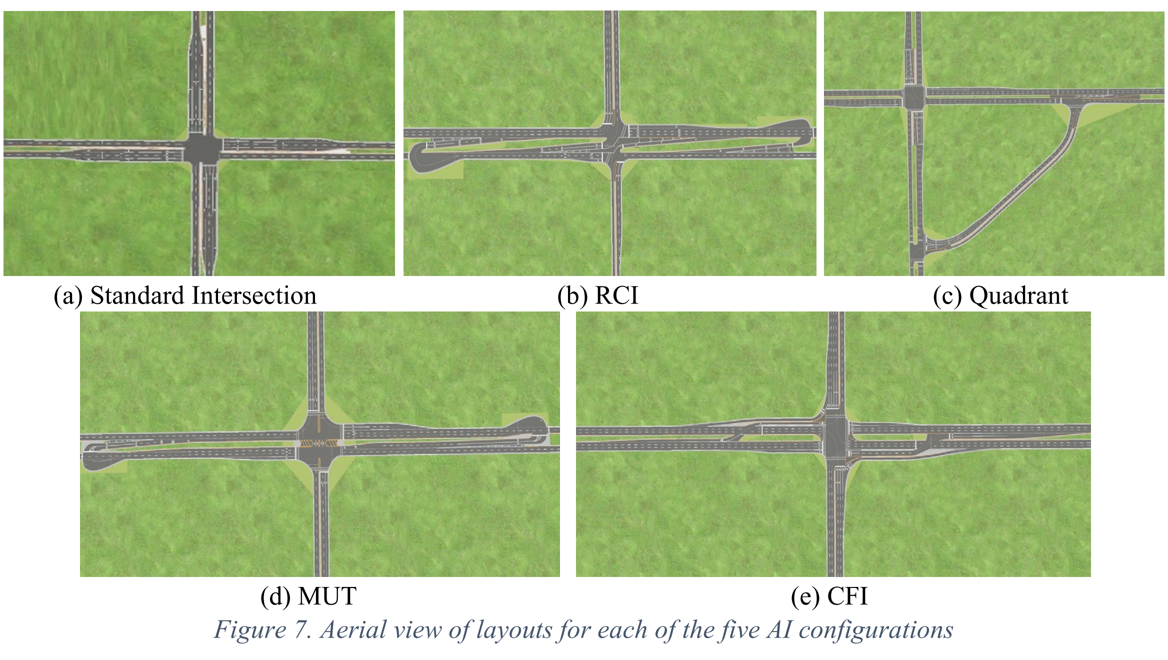
4.4. Experimental Design

4.4.1. Design Elements

The driving simulator experiment was designed to investigate the effects of various alternative intersection pairs on driver behavior, and to see if drivers have a different reaction for a specific pair if the corridor is consistent or contains unique alternative intersection configurations. Three corridor treatments were proposed: a standard corridor, a RCI corridor, and a corridor with unique combinations of various alternative intersections.

During a driving simulator experiment trial, participants were asked to navigate an urban corridor that contained 12 signalized intersections. For consistency, the spacing between adjacent intersections were fixed at 0.25 mile (1320 feet). The major roads were designed as 3 lanes per direction, and the minor roads had 2 lanes per direction. For all road segments, the speed limit was set at 45 mph (although participants were able to exceed this), and the traffic lights were left green in the direction of travel such that drivers arrive at each signal on green. In addition, no vehicles drove in the same direction of travel as the subject vehicle. The purpose of each of these constraints was to provide the least amount of information possible to the driver, leaving them to rely on the geometric and signage information given to them as they approached intersections.

The intersections include both the traditional 4-leg intersection and various AII designs such as the Reduced Conflict Intersection (RCI), the Median U-Turn (MUT) intersection, the Continuous Flow Intersection (CFI), and the Quadrant Roadway (QR) intersection as shown in Figure 7. Turning movements within these designs consisted of major and minor lefts as well as minor through movements, and these movements were reduced to combinations which had a unique combination of turns. For example, minor left turns in RCI and MUT intersections follow the same pattern of right turn followed by U-turn; therefore, only one such movement was included in the experiment design.



(a) Standard Intersection (b) RCI (c) Quadrant

(d) MUT (e) CFI

Figure 7. Aerial view of layouts for each of the five AI configurations

The combinations of intersection pairs were pre-determined to cover a variety of the background intersections (i.e., the previous intersection) and the experiment intersection. Traffic guidance signage and pavement markings were simulated in each experimental trial to facilitate participants navigating the corridor.

This research defined tested movement(s) for each of the intersections. The experimental movements include: (a) Standard intersection main street left turn, (b) RCI side street through movement, (c) MUT (or Reverse RCI) main street left turn, (d) MUT (or RCI) side street left turn, (e) QR intersection main street left turn, and (f) CFI main street left turn. Figure 8 presents graphical illustrations of the tested movements.

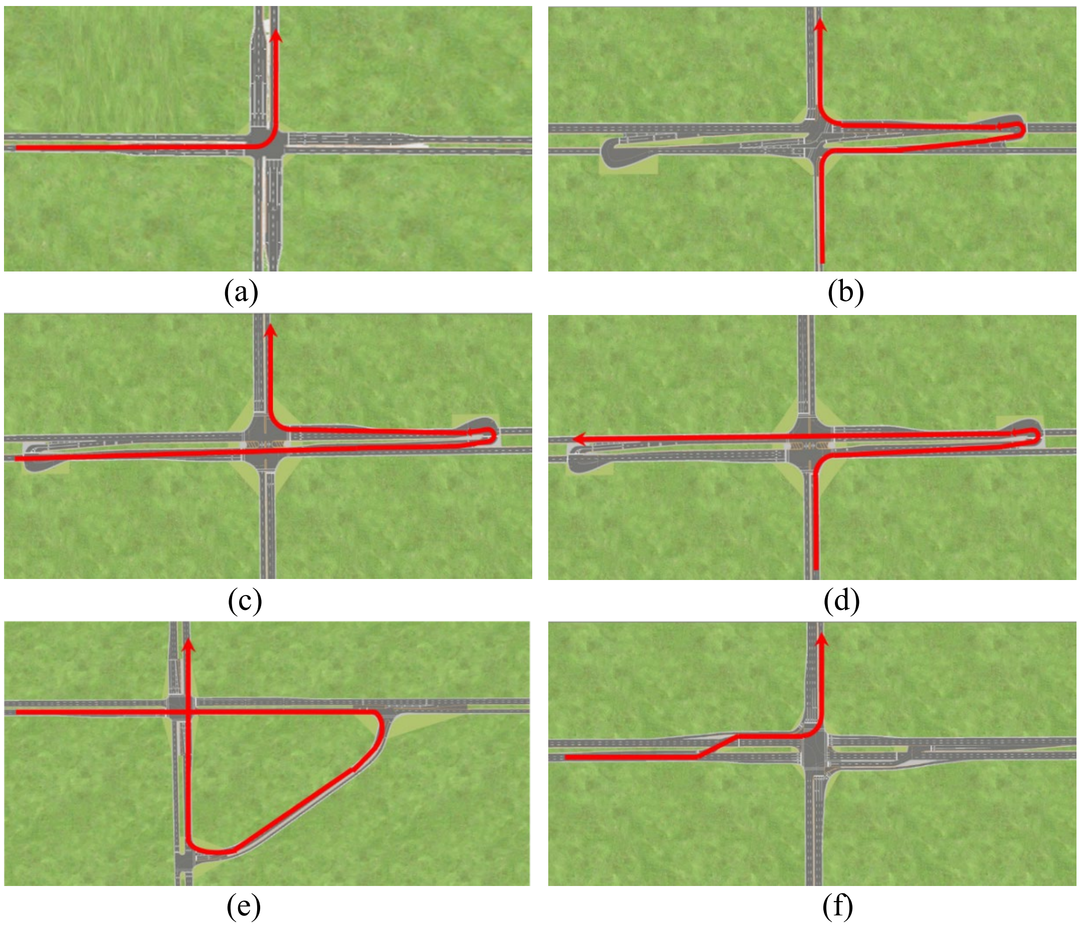
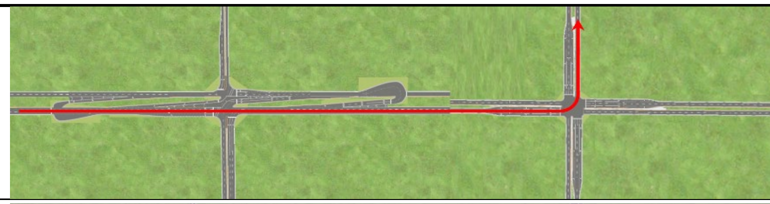
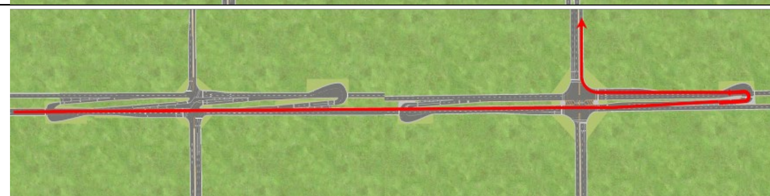
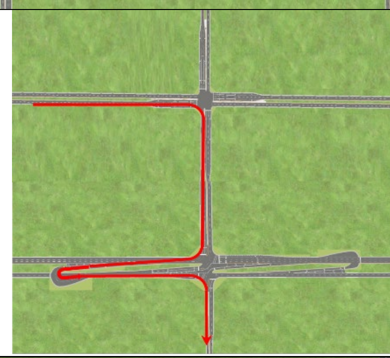
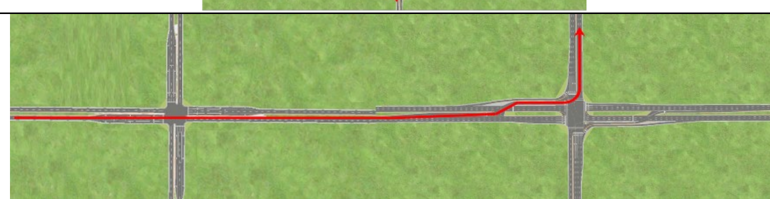
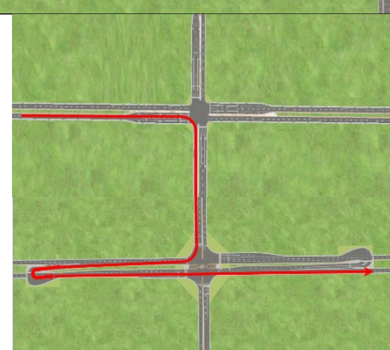
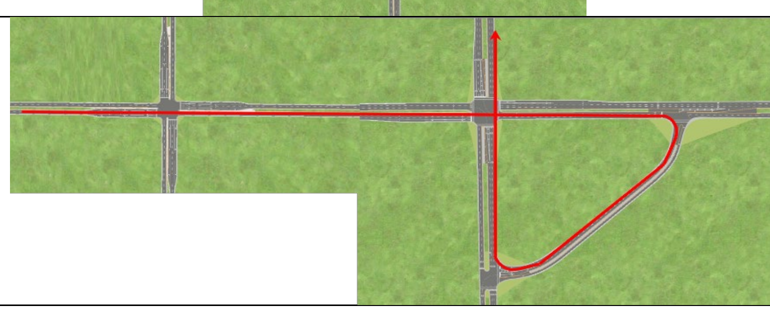
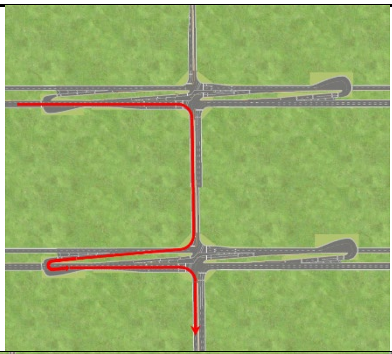
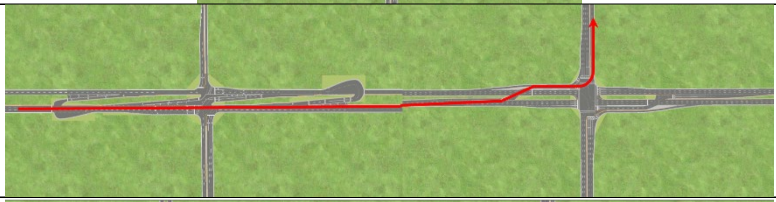
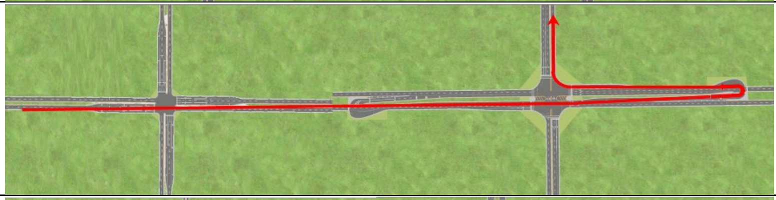
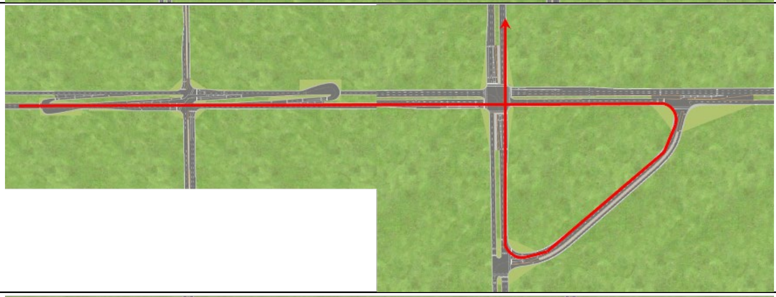
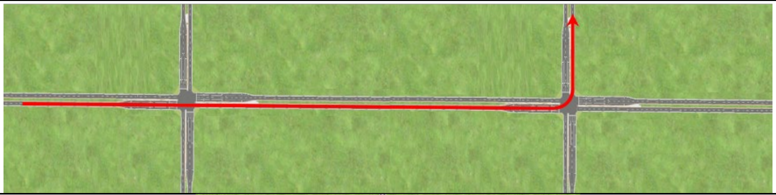
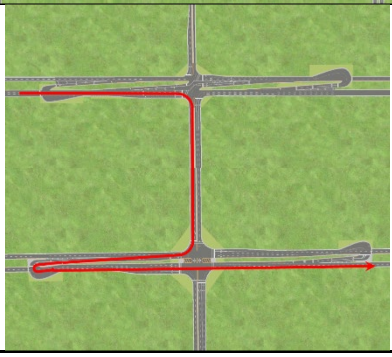


Figure 8. Graphical Illustration of Test Intersection Movements

A total of 12 intersection pairs were designed, where each intersection pair contains a test intersection and a preceding intersection. These intersection pairs were determined to cover the most typical and practical combination of alternative intersections. Detailed descriptions of each intersection pair and paired movements, as well as graphical illustrations of the paired movements, are listed in Table 10.

Table 10. List of the Tested Alternative Intersection Pairs

Pair #	Paired Intersections	Paired Movements	Graphical Illustration of the tested AI Pair
1	RCI & Standard	RCI TH & Standard LT	
2	RCI & MUT	RCI TH & MUT LT	
3	Standard & RCI	Standard RT & RCI Side TH	
4	Standard & CFI	Standard TH & CFI LT	
5	Standard & MUT	Standard RT & MUT Side LT	
6	Standard & QR	Standard TH & Quad LT	

Pair #	Paired Intersections	Paired Movements	Graphical Illustration of the tested AI Pair
7	RCI & RCI	RCI RT & RCI Side TH	
8	RCI & CFI	RCI TH & CFI LT	
9	Standard & MUT	Standard TH & MUT LT	
10	RCI & QR	RCI TH & Quad LT	
11	Standard & Standard	Standard TH & Standard LT	
12	RCI & MUT	RCI RT & MUT Side LT	

4.4.2. Simulation Experiments

The driving simulator experiment looked at individual intersection pairs along the three corridor types. To ease drivers' recognition load prior to approaching the tested intersection, the driving simulator experiments were designed to have at least 2 through or right movements (i.e., conventional movements) between each studied data collection point (i.e., tested intersection). So, this research determined that each tested intersection is associated with a randomized preceding intersection and a background intersection that represents the three predetermined corridor treatments (i.e., RCI corridor, standard corridor, and unique combinations).

For each of the three corridor treatments, the 12 tested intersections were separated into 3 with 4 intersection pairs per trial. This results in a total of 9 simulator experiments. A detailed list of the 9 simulator experiments is presented in Table 11 below, where the red rows refer to the background intersection, blue rows represent for the preceding intersection, and green rows indicate the tested intersection.

A graphical illustration of a simulator experiment (Experiment #1) is demonstrated in Figure 9, where the red arrows indicate the designated route of this experiment, and yellow boxes refer to the intersection pairs. The circled numbers are intersection numbers that correlate to the first column in Table 11. Graphical illustrations of all the experiments are attached in the Appendix.

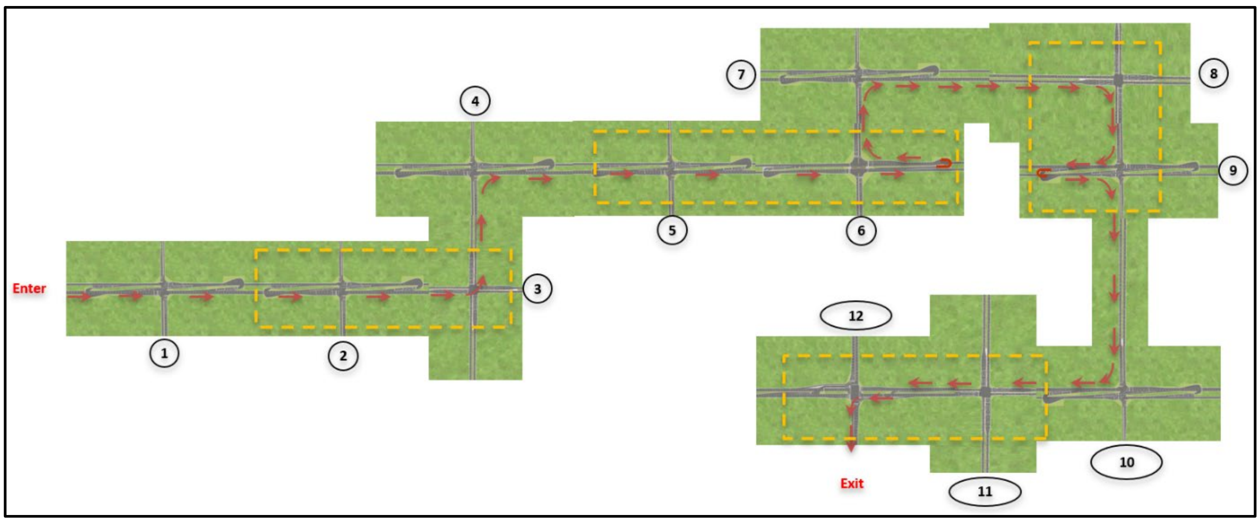


Figure 9. Graphical Illustration of Experiment #1

Table 11. List of the Designed Simulation Experiments

Intersection #	Pair #	Experiment #1 RCI Corridor	Experiment #2 Standard Corridor	Experiment #3 Unique Combinations
Enter	n/a	Start	Start	Start
1	n/a	RCI Main Thru	Standard Main Thru	RCI Main Thru
2	1	RCI Main Thru	RCI Main Thru	RCI Main Thru
3		Standard Left	Standard Left	Standard Left
4	n/a	RCI Side RT	Standard Side RT	CFI Side RT
5	2	RCI Main Thru	RCI Main Thru	RCI Main Thru
6		MUT Main Left	MUT Main Left	MUT Main Left
7	n/a	RCI Side RT	Standard Side RT	Rev-RCI Side RT
8	3	Standard Left	Standard Left	Standard Left
9		RCI Side Thru	RCI Side Thru	RCI Side Thru
10	n/a	RCI Side RT	Standard Side RT	Standard Side RT
11	4	Standard Thru	Standard Thru	Standard Thru
12		CFI Main Left	CFI Main Left	CFI Main Left
Exit	n/a	End	End	End

Intersection #	Pair #	Experiment #4 RCI Corridor	Experiment #5 Standard Corridor	Experiment #6 Unique Combinations
Enter	n/a	Start	Start	Start
1	n/a	RCI Main Thru	Standard Main Thru	Quad Main Thru
2	5	Standard RT	Standard RT	Standard RT
3		MUT Side Left	MUT Side Left	MUT Side Left
4	n/a	RCI Main TH	Standard Main TH	MUT Main TH
5	6	Standard Thru	Standard Thru	Standard Thru
6		Quad Main Left	Quad Main Left	Quad Main Left
7	n/a	RCI Side RT	Standard Side RT	RCI Side RT
8	7	RCI Main RT	RCI Main RT	RCI Main RT
9		RCI Side Thru	RCI Side Thru	RCI Side Thru
10	n/a	RCI Main RT	Standard Side RT	CFI Side RT
11	8	RCI Main Thru	RCI Main Thru	RCI Main Thru
12		CFI Main Left	CFI Main Left	CFI Main Left
Exit	n/a	End	End	End

Intersection #	Pair #	Experiment #7 RCI Corridor	Experiment #8 Standard Corridor	Experiment #9 Unique Combinations
Enter	n/a	Start	Start	Start
1	n/a	RCI Main Thru	Standard Main Thru	Rev RCI Main Thru
2	9	Standard Thru	Standard Thru	Standard Thru
3		MUT Main Left	MUT Main Left	MUT Main Left
4	n/a	RCI Side RT	Standard Side RT	Standard Side RT
5	10	RCI Main Thru	RCI Main Thru	RCI Main Thru
6		Quad Main Left	Quad Main Left	Quad Main Left
7	n/a	RCI Side RT	Standard Side RT	Quad Side RT
8	11	Standard Thru	Standard Thru	Standard Thru
9		Standard Left	Standard Left	Standard Left
10	n/a	RCI Side RT	Standard Side RT	MUT Side RT
11	12	RCI Main RT	RCI Main RT	RCI Main RT
12		MUT Side Left	MUT Side Left	MUT Side Left
Exit	n/a	End	End	End

4.5. Performance Measures

4.5.1. Failure to Complete Instructed Movement

Since an alternative intersection design redirects one or multiple movements, this research selected "failure to complete the instructed movement" (or failed movement, FM) as the critical performance measure. For instance, as shown in Figure 10, the tested movement is a minor street through movement (red route), where drivers need to turn right, go further downstream on major road and then make a U-turn, and finally, make a right turn to complete the desired movement.

The potential failed movements to the tested movement include 1) a driver makes a right turn, then goes straight downstream on the major road without making the U-turn (orange route); 2) a driver makes a turn right, goes further downstream on major road to correctly make a U-turn, and then goes straight on the major road without making the right turn (blue route). Each failed movement was manually documented during the during simulator experiment for further analysis.

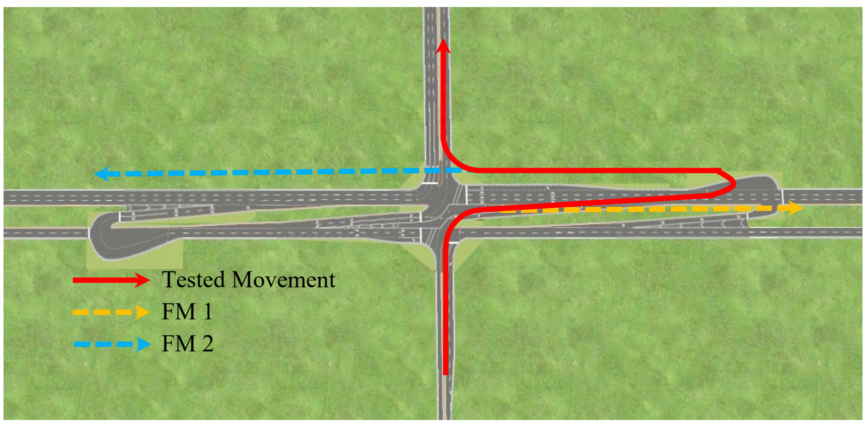


Figure 10. Failed Movements to the tested RCI Minor Street Through Movement

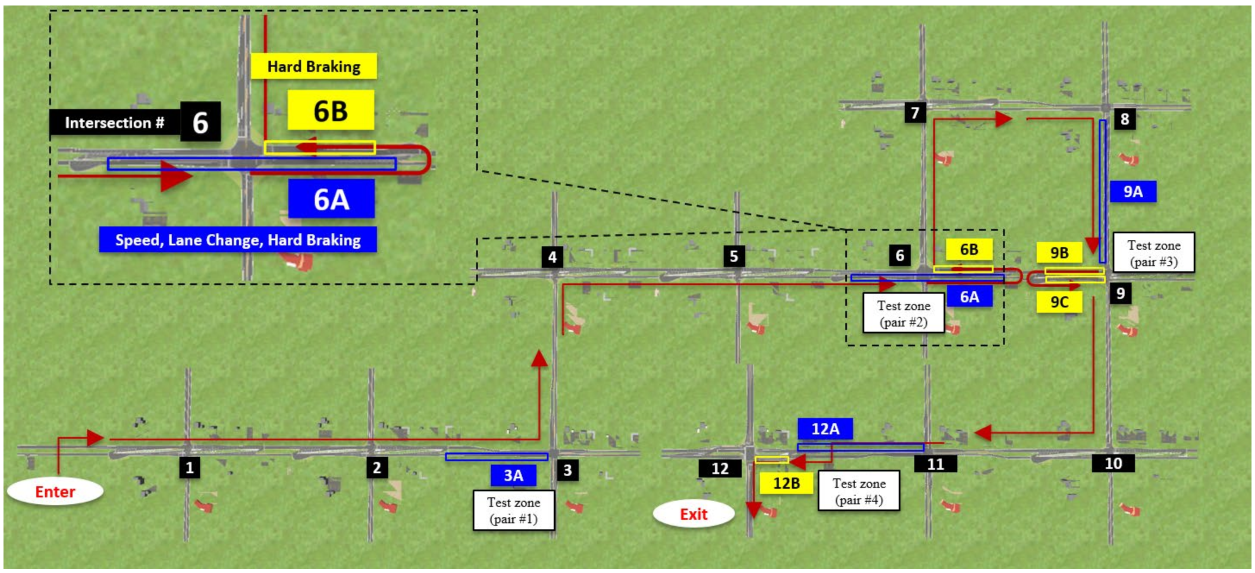
4.5.2. Driver Behavior

In addition to the critical performance measure, this research effort also identified three driver behavior related performance measures: 1) driving speed and speed variances; 2) number of lane changes and distance to complete lane change(s); and 3) number of hard braking events. These performance measures were automatically recorded by the simulator for the entire route, and the research team manually extracted the driver behavior data for the designated test zones. Specifically, methodologies for collecting and extracting the three performance measures are described as follows:

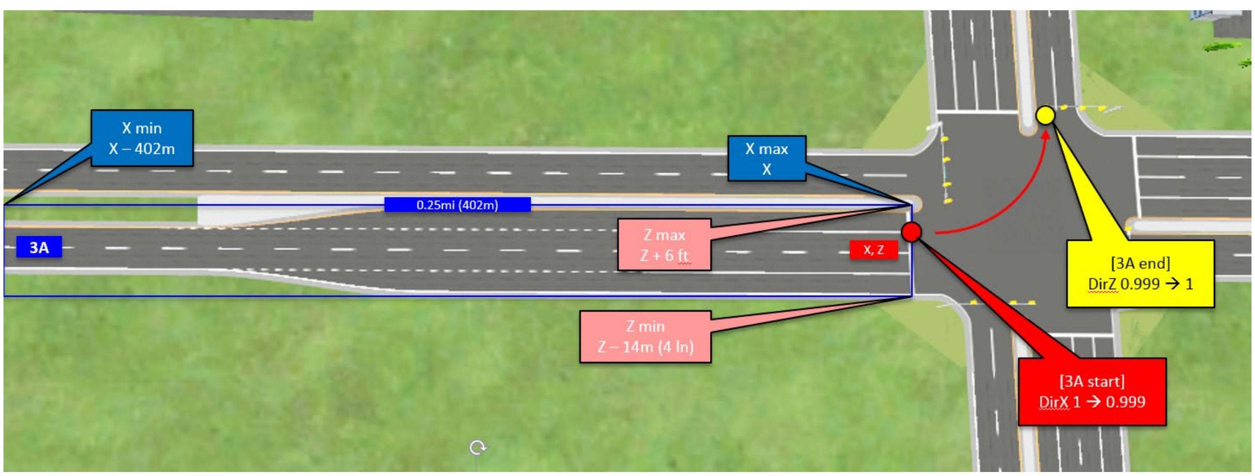
- Simulator log files provide speed information every 0.1 seconds, calculating both maximum and average speed within a test zone after converting the unit of kmh to mph.
- The vehicle's information on where it was located in which lane is provided automatically by the simulator's log file. Therefore, the number of lane changes can be calculated manually by the zone of interest.
- Log files also provide two acceleration (m/s^2) values (X and Z axis), so the total acceleration value can be calculated based on both axes by using the root mean square

equation. A hard braking event was considered when the total acceleration value is more than 4 m/s^2 (app. 13.12 ft/s^2).

An example of the test zones (blue and yellow rectangles within the intersection zone of interest) is illustrated in Figure 11a, where all the three driver behavior performance measures were analyzed for the blue test zone (approaching the main intersection), and only hard braking was analyzed for the yellow test zone. A test zone area is a virtual area determined based on road length and width. Length of the test zone is a quarter mile from the intersection stop bar (i.e., red dot in Figure 11b), and the width of the test zone is determined based on the number of lanes (12 feet per lane) plus a 6-feet buffer distance. So, the width of the test zone that contains 4 lanes in Figure 11b is 54 feet. Details of the test zones for each experiment are presented in the Appendix.



(a)



(b)

Figure 11. Driver Behavior Test Zones for Experiment #1

4.6. Experiment Procedure

An overview of the driving simulator experiment design is illustrated in Figure 12. The driving simulator experiment started with the Institutional Review Board (IRB) protocol development and approval. Upon gaining approval from the North Carolina State University IRB office, the research team started recruiting participants.

On the day of the lab visit, the participant was screened for COVID-19 symptoms or contact. Upon arrival at the NCSU driving simulator lab, an experimenter first provided the participant with a detailed lab orientation, including the purpose of the research, experiment procedure, simulator safety protocols and potential risks, etc. Following this, experimenters introduced to participants to the functions of each component of the driving simulator and how to operate the vehicle cab (i.e., steering wheel, throttle, brake pedals, signal lights, etc.), and the tasks they were required to perform during the test trials.

In the training session, participants were asked to complete one simulated drive on an urban road with slight curves with a speed limit 45mph. Duringr the training session, a Simulator Sickness Questionnaire (SSQ) was administrated to assess a participant's risk of developing motion sickness-like symptoms. Participants were informed that they can quit the experiment at any time for any reason.

After driving simulator screening and training, each participant completed a total of 9 experiment trials, each of which lasted approximately 10 minutes. Traffic guidance signs and pavement markings were simulated in each experimental trial to facilitate participants navigating the corridor. The 9 experiment trials were randomly separated into 3 groups with 3 trials per group. After every 3 trials, an SSQ was administered to identify any changes in participant health state (i.e., simulator sickness level). If a participant demonstrated simulator sickness symptoms above baseline responses, he or she would be provided with an additional 20-minute rest period. If symptoms persist, the participation would be terminated and would be compensated for any time provided.

After the participant finished all the 9 experiment trials, there was an interview on the participant's general opinion of the simulation scenarios he or she had just experienced. The interview was designed as an open discussion format, such as reason(s) for a failed movement. These stated reasons were considered when reviewing the performance measure data and can provide additional context to the results.

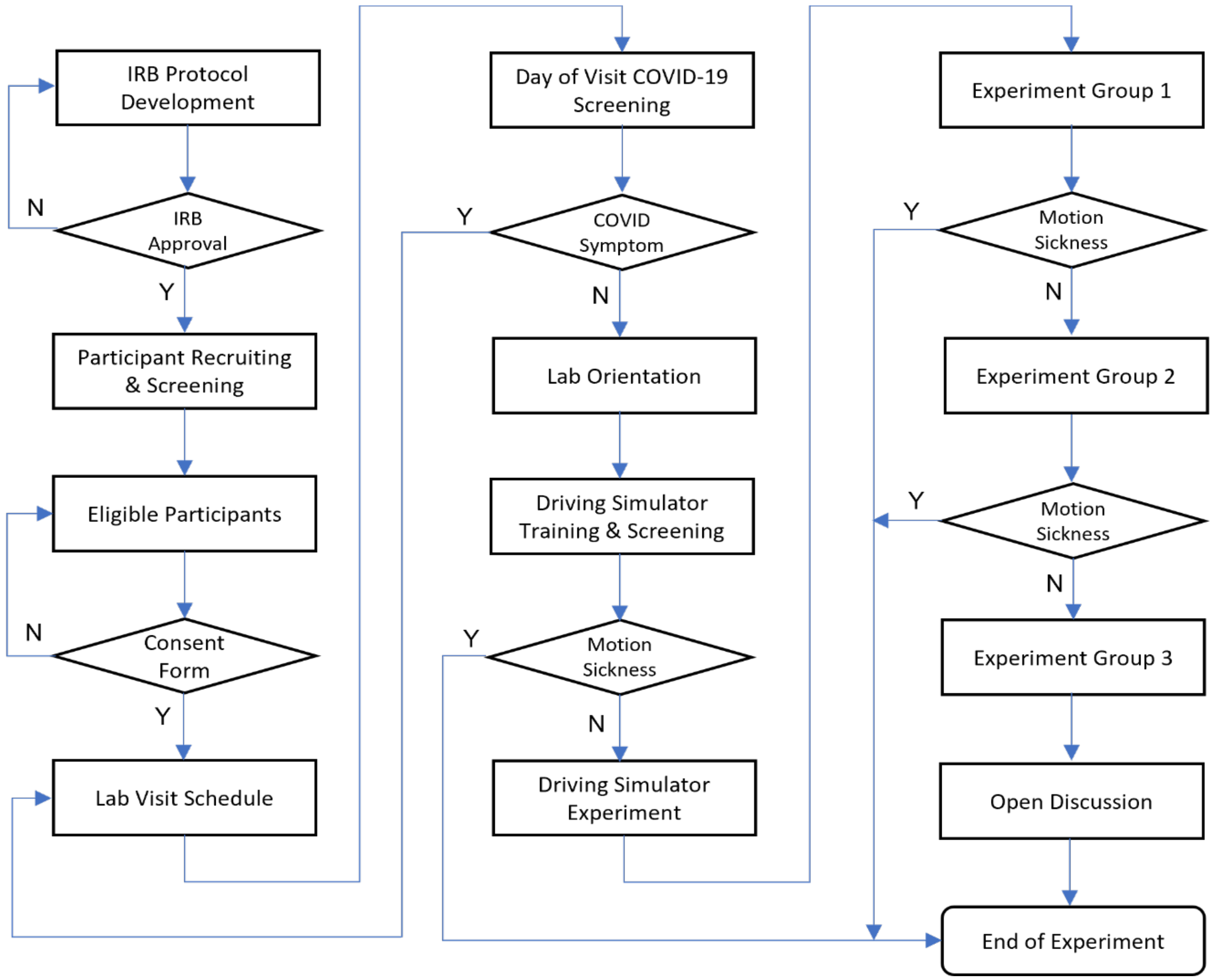


Figure 12. Driving Simulator Experiment Flow Chart

5. Results

This analysis focused on four response measures, including failed movements (FMs), average approach speed (AAS), maximum approach speed (MAS), hard braking events (HBEs), and approach lane changes (ALCs). For each response, there were four predictor variables included in the data analyses, including the test intersection configuration (TIC), the preceding intersection configuration (PIC), traffic corridor configuration (TCC), and the test trial order (TTO).

As documented in the methods section, the experiment involved 48 participants grouped according to age, including young (< 22 years) and middle-aged drivers (23-64 years). This sample produced 1728 test observations. Preliminary statistical analyses on the influence of age on the various driving response measures revealed no significant difference between young and middle-aged drivers in terms of FMs, AS, HBEs and ALCs. Similarly, there were no significant differences in outcomes among female and male drivers within the convenience sample. Consequently, age and gender were not included as covariates in any final statistical model used to assess intersection configuration effects on driver performance.

In addition to the quantitative data collected, each participant was asked to review failed movements after the experiment. Participants stated multiple reasons for failures including Unclear Instruction, Unclear Sign, Missed Sign, Lost Focus, and Confused by Intersection Geometric Design. While stated reasons were collected, these are provided in this report as solely contextual reports as the stated reason cannot be directly confirmed through the experiment data collection.

Table 12 shows the abbreviations used in the following results sections, and Tables 13 and 14 shows the general summary of analysis results for all response variables.

Table 12. Abbreviations used by this research

Abbreviation	Full Description
AAS	Average Approach Speed
ALC	Approach Lane Change
HBE	Hard-braking Event
HBE-A	Hard-braking Event - Type A
HBE-B	Hard-braking Event - Type B
HBE-C	Hard-braking Event - Type C
MAS	Maximum Approach Speed
PIC	Preceding Intersection Configuration
TCC	Traffic Corridor Configuration
TIC	Test Intersection Configuration
TTO	Test Trial Order
FM	Failed Movement

Table 13. Summary of Analysis Results for PIC and TIC

Response Measure	Independent Variable	
	PIC	TIC
FM	Sign. (p=0.03); RCI > Standard.	Sign. (p<0.0001); MUT SLT > Quad. MLT & Standard.
AAS	NS.	Sign. (p<0.0001); MUT SLT < all others; RCI ST > all others.
MAS	Sign. (p<0.0001); RCI > Standard (but weak plot).	NS.
HBE	NS.	Sign. (p<0.0001); Quad. MLT & MUT SLT > Standard MLT.
HBE-A	NS.	Sign. (p<0.0001); MUT MLT > all others.
HBE-B	NS.	Sign. (p<0.0001); Quad. MLT > all others.
HBE-C	NS.	N/A (no C-segment at some TICs).
ALC	Sign. (p<0.0001); Standard > RCI.	Sign. (p<0.0001); All diff. from all others; Standard MLT=max.; Quad. MLT=min.

Table 14. Summary of Analysis Results for TTO and TTC

Response Measure	Independent Variable	
	TTO	TTC
FM	Sign. (p<0.0001); T1=max; T2=min.	NS.
AAS	Sign. (p<0.0001); T1=min; T9=max.	NS.
MAS	Sign. (p<0.0001); T1=min; T9=max.	NS.
HBE	NS.	NS.
HBE-A	NS.	NS.
HBE-B	NS.	NS.
HBE-C	NS.	Sign. (p<0.0001); Standard > Unique & RCI.
ALC	NS.	NS.

5.1. Failed Movements

All FM observations were coded as a binary response, including errors and error-free driving. We examined FMs at both the test intersections and upstream (preceding) intersections. For upstream FMs, the TCC (traffic corridor configuration) and the TTO (test trial order) were considered to be potentially influential factors. For FMs at test intersections, we were concerned with the influence of the PIC (preceding interchange configuration) and the TIC (test interchange configuration).

5.1.1. Failed Movements at Upstream Intersections

Figure 13 presents the number of FMs by experiment trial number (TTO; Plate (a)) and the TCC (Plate (b)) are shown in Figure 13. Error-free trials are represented in "blue", which means that there was no FM at the upstream intersection. The "orange" bar segments represent the number of experiment trials in which an error/FM occurred at the upstream intersection. It can be observed from Figure 13(a) that Trial 1 produced the highest number of FMs among the nine experiment trials with even more observations than the sum of FMs across the other eight test trials. This observation is in-line with the expectation that in the first test trial, participants need to acquaint themselves with the simulated interchange designs, possibly leading to more FMs. The second highest numbers of FMs occurred in Trials 3 and 6 both with four FMs among 1728 test trials. Other trials produced little or no FMs (two or fewer observations per trial), possibly due to drivers being more adapted to experiment conditions. As illustrated in Figure 13b, the FMs observed for the different TCCs was similar – "unique" corridors produced 16 errors, "standard" corridors produced 13 errors, and "RCI" corridors produced 10 errors).

We applied the Pearson's Chi-Squared test to identify any association of the experiment trial order (TTO) and TCC with the large-sample binary FM response. Results are shown in Figure 14. Referring to the x-axis of each graph, the "Yes" column identifies test trials in which a FM occurred. The "No" column identifies those trials in which no FM was observed. As shown in Figure 14a, the TTO was significantly associated with upstream FMs with $\chi^2 = 95.86$ and $p < 0.0001$. In addition, the analysis reveals that the first trial produced the highest percentage of FMs. However, as shown in Figure 14b, FMs were not significantly different among the TCCs ($\chi^2 = 1.42$, $p = 0.49$).

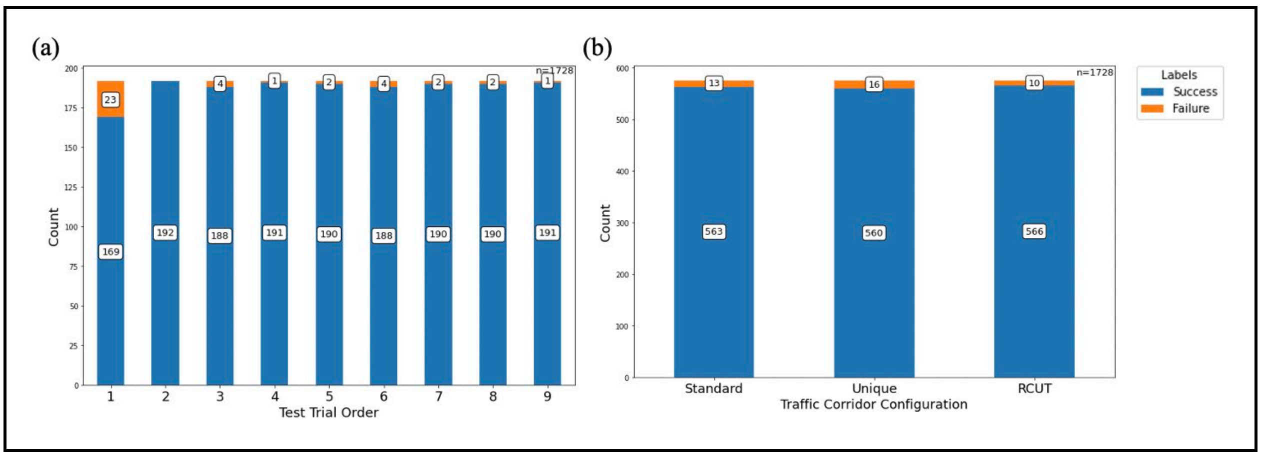


Figure 13. Failed movements at upstream intersections: (a) by TTO; (b) by TCC

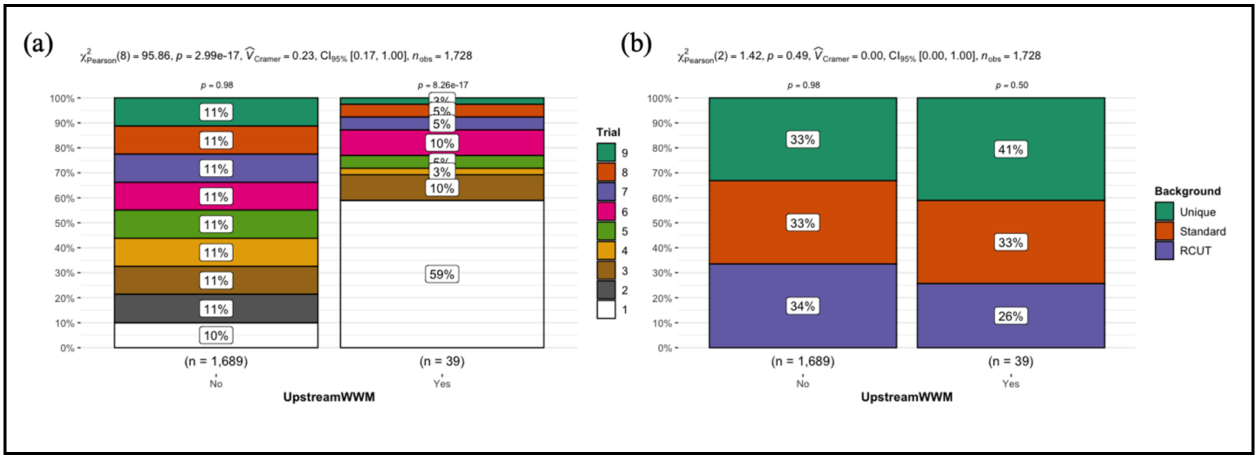


Figure 14. Pearson's Chi-Squared test for FMs at upstream intersections: (a) by TTO; (b) by TCC

5.1.2. Failed Movements at Test Intersections

In addition to FMs at upstream intersections, we also analyzed the occurrence of FMs at test intersections. Results are shown in Figure 15. Figure 15a reveals fewer FMs across TICs when preceded by a standard intersection vs. and RCI preceding intersection. Specifically, there were 38 FMs following a standard intersection and 59 FMs following a RCI intersection. Figure 15b shows the number of FMs by TIC. Participants were most likely to have FM at a MUT side left turn intersection (26 observations), followed by a RCI side through (23 occurrences) and the MUT main left turn intersection (22 occurrences). In contrast, there were only three FMs that occurred at the quadrant main left turn and six FMs for the standard main left turn intersection.

Pearson's Chi-Squared Tests were applied to make inferences on underlying factors in the FM response. From Figure 16, it can be observed that the PIC type was significantly associated with FM occurrence ($\chi^2 = 4.82,\ p = 0.03$) and the RCI preceding intersection type produced the most FMs (61% of the total FMs). The TIC was also associated with the occurrence of FMs ($\chi^2 = 29.81$, $p < 0.0001$). The Quadrant main left turn accounted for 3% of the total FMs and the Standard intersection configuration realized 6% of the total FMs. These rates were the lowest among TICs. The MUT side left turn intersection produced 27% of the total FMs, which was more than any other tested intersection.

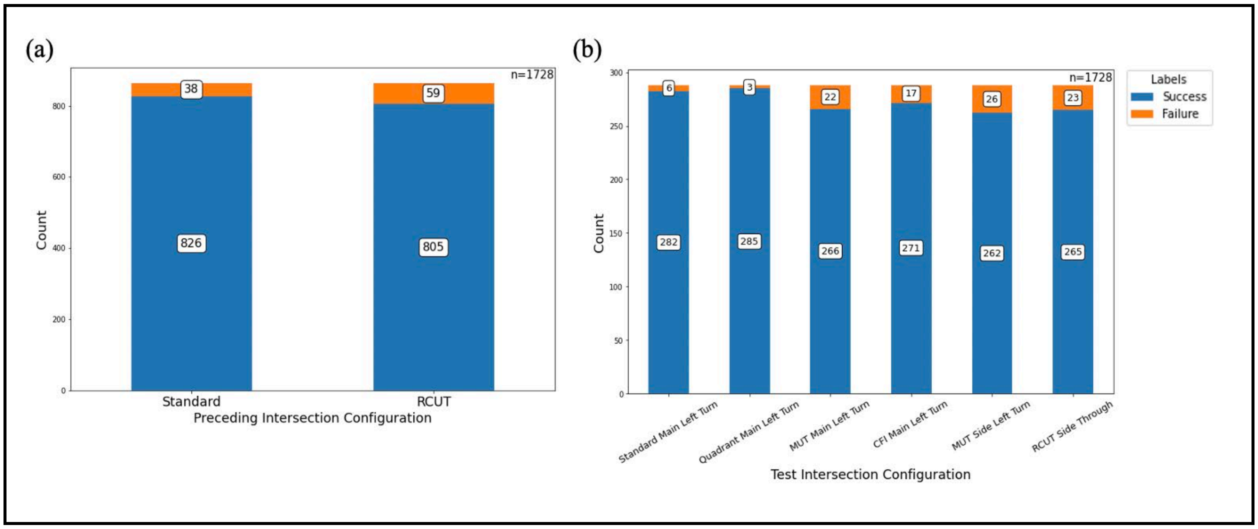


Figure 15. Number of Failed movements: (a) by PIC; (b) by TIC

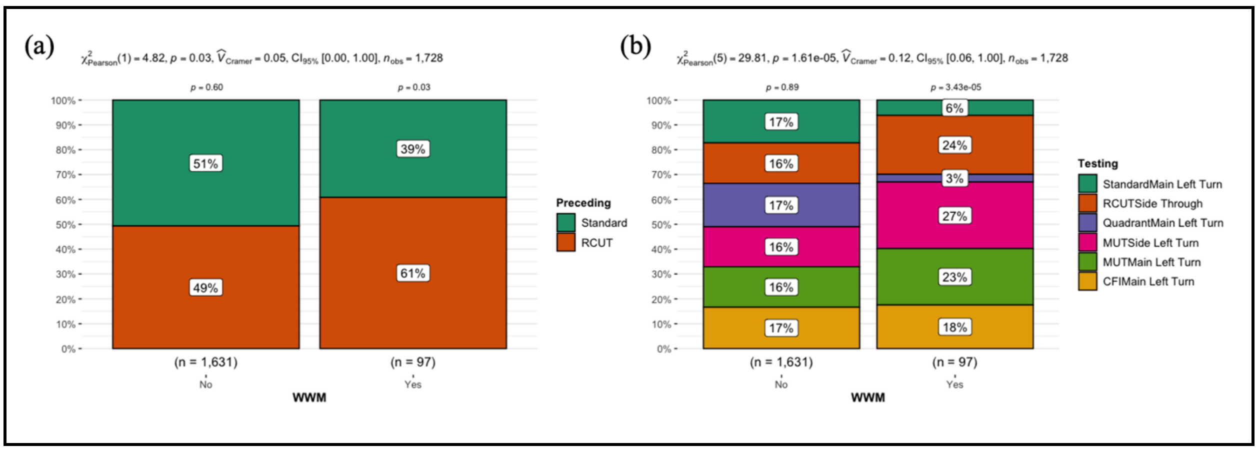


Figure 16. Pearson's Chi-Squared test for FMs: (a) by PIC; (b) by TIC

Beyond these analyses, we also used contingency tables to determine whether there was any interaction of the PIC and TIC in the occurrence of FMs. As shown in Table 15, when the Standard intersection preceded a test intersection, the total FMs (38) were less than when the RCI was the preceding intersection (59). For both the Standard and RCI preceding intersection conditions, drivers had fewer FMs at upstream Standard and quadrant main left turn test intersections. There was only 1 FM in 144 experiment trials involving a quadrant main left turn test intersection, when preceded by a RCI intersection. Similarly, there was only 1 FM at a Standard main left turn test intersection when preceded by a standard intersection. When the preceding intersection was a RCI, and the TIC was a MUT main left turn or side left turn, drivers produced the most FMs (29 (=15+14) occurrences, in total, across TICs).

Table 15. Contingency table of interaction between TIC and PIC on FMs.

Test Intersection Movement	Preceding Intersection			
	Standard		RCI	
	No	Yes	No	Yes
Standard Main Left Turn	143 (99.3%)	1 (0.7%)	139 (93.2%)	5 (3.5%)
Quadrant Main Left Turn	142 (98.6%)	2 (1.4%)	143 (99.3%)	1 (0.7%)
MUT Main Left Turn	137 (95.1%)	7 (4.9%)	129 (89.6%)	15 (10.4%)
CFI Main Left Turn	139 (96.5%)	5 (3.5%)	132 (91.7%)	12 (8.3%)
MUT Side Left Turn	132 (91.7%)	12 (8.3%)	130 (90.3%)	14 (9.7%)
RCI Side Through	133 (92.4%)	11 (7.6%)	132 (91.7%)	12 (8.3%)
Total	826 (95.6%)	38 (4.4%)	805 (93.2%)	59 (6.8%)

5.2. Approach Speed

5.2.1. Average Approach Speed

Figures 17a-d show the mean AAS values for the different PICs, TICs, TTOs, and TCCs. The greatest differences in mean AAS appeared to occur for the TICs and TTOs, with almost no differences among the PICs and TCCs. Specifically, Figure 17b, shows that the MUT side left turn produced the lowest mean AAS (35.13 mph) among the TICs, while the highest mean AAS occurred for the RCI side through (43.07 mph). The Standard, Quadrant, MUT and CFI main left turns appeared to produce similar mean AAS values, which were in the range between 40.5 mph and 41.5 mph. Figure 17c illustrates that the mean AAS for participants tended to increase with the number of trials completed. Trial 9 (the final test trial) produced the maximum mean AAS of 42.46 mph, while Trial 1 produced the minimum mean AAS at 36.93 mph. Here, it should be noted that even the highest mean AAS value was less than the 45-mph speed limit. Based on these observations, despite participant simulator training in advance of test trials, we speculated that participants became more accustomed to the simulated driving across test trial, resulting in a gradual increase in their AAS.

To draw inferences on the AAS response measure, we applied the Kruskal-Wallis non-parametric test. Table 16 reveals that all PICs and TCCs had the same median AAS and, therefore, the AAS observations originated from the same distribution and there were no statistically significant differences among the configurations. However, at least one configuration among the TICs ($\chi^2 = 229.95, p < 0.0001$) was different from all others. In addition, the TTO manipulation also had a significant effect ($\chi^2 = 92.26, p < 0.0001$) on AAS.

To further identify which TIC(s) produced a different median AS value, we applied Dunn's test along with a stepwise multiple comparison adjustment method (Benjamini-Hochberg). Table 17 presents the Dunn's pairwise comparison z-test statistic (top number in table cell) with the p-value for each test statistic (bottom number in each cell). Based on Dunn's test results, we can conclude that the MUT side left turn and RCI side through were significantly different from the other test intersections in terms of AAS, as all the pairwise test p-values revealed approximately no likelihood of observing a more extreme test statistic.

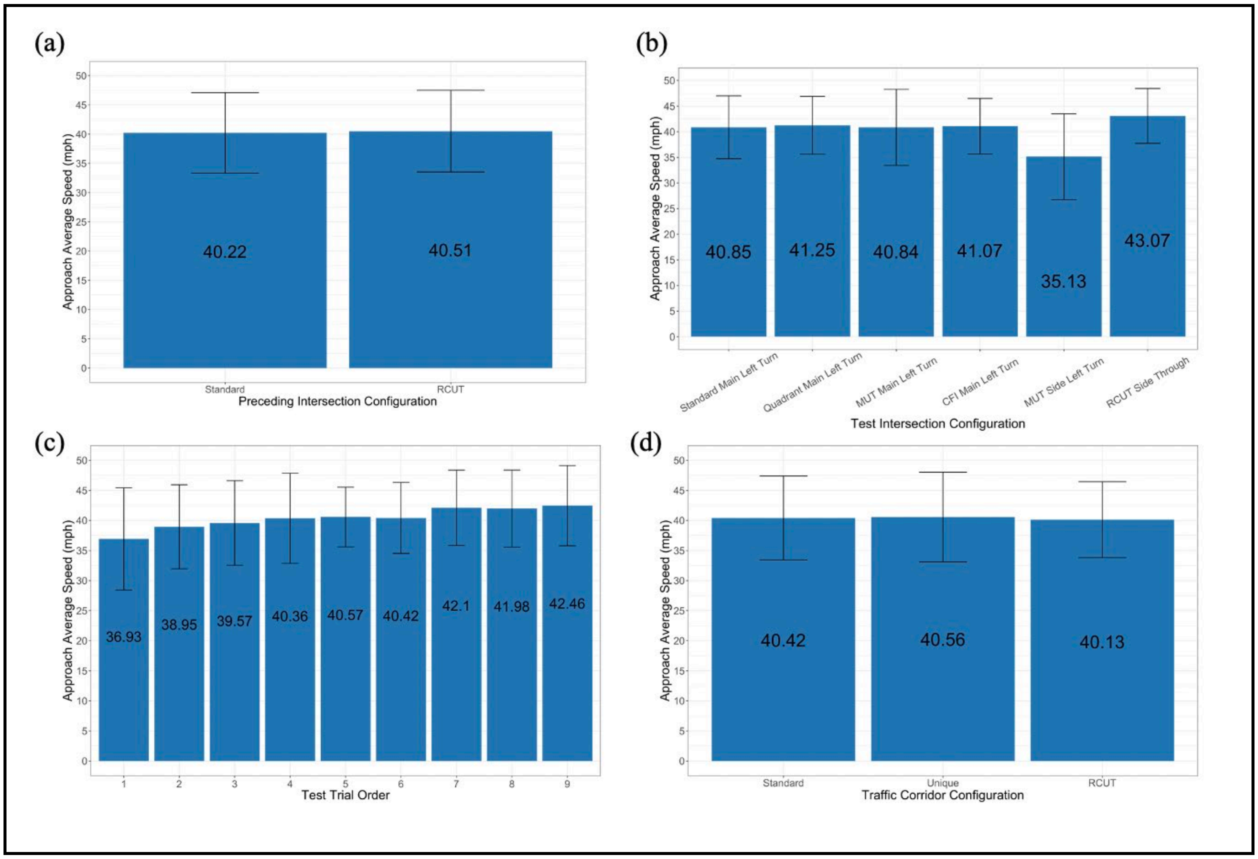


Figure 17. Mean Average Approach Speeds by (a) PIC, (b) TIC, (c) TTO, (d) TCC

Table 16. Kruskal-Wallis test results for AAS response.

AAS by Category	χ^2	df	p-value
Preceding Intersection Configuration	1.25	1	0.26
Test Intersection Configuration	229.95	5	< 0.0001
Test Trial Order	92.26	8	< 0.0001
Traffic Corridor Configuration	0.72	2	0.70

Table 17. Dunn's test result on AAS for each TIC.

Col Mean- Row Mean	CFI Main Left Turn	MUT Main Left Turn	MUT Side Left Turn	Quadrant Main Left Turn	RCI Side Through
MUT Main Left Turn	-0.58 0.30				
MUT Side Left Turn	9.55 <0.0001*	10.13 <0.0001*			
Quadrant Main Left Turn	-0.60 0.32	-0.02 0.49	-10.15 <0.0001*		
RCI Side Through	-4.94 <0.0001*	-4.37 <0.0001*	-14.50 <0.0001*	-4.35 < 0.0001 *	
Standard Main Left Turn	1.76 0.05	2.34 0.01*	-7.79 <0.0001*	2.36 0.01*	6.70 <0.0001*

5.2.2. Maximum Approach Speed

In addition to AAS, we also examined participant maximum approach speed (MAS) to intersections. Figures 18a-d present the mean MAS values for the different PIC, TIC, TTO and TCC conditions.

Given that participants were instructed to limit their speed to 45 mph, maximum speed did not appear to differ substantially across the settings of the independent variables, except for the TTO. The mean MAS revealed the same trend as the mean AAS across test trials; that is, the mean AMS increased with trial number. As with the AAS response, Trial 9 produced the greatest mean MAS (49.86 mph) while Trial 1 had the smallest mean MAS (45.21 mph). Aside from participants becoming more familiar with simulated driving across the test trials, it is possible that driver fatigue and expiration of patience, due to the overall length of the experiment, might have contributed to an increase in MAS.

The Kruskal-Wallis test was applied for statistical inferences on the MAS response. Results are presented in Table 18. Similar to the results of AAS, MAS varied significantly among the experiment trials ($\chi^2 = 88.52$, $p < 0.0001$), but there was no difference in MAS among participants in different TCCs ($\chi^2 = 0.03, p = 0.98$). Notably, in contrast to AAS, MAS varied significantly among the different PICs ($\chi^2 = 9.78$, $p < 0.0001$), including the Standard intersection and RCI intersection; but among the different TICs, the MAS of participants did not significantly differ ($\chi^2 = 5.17, p = 0.40$). Overall, participant's AAC was mainly affected by TICs and TTOs, while MAC was mainly influenced by PICs and TTOs.

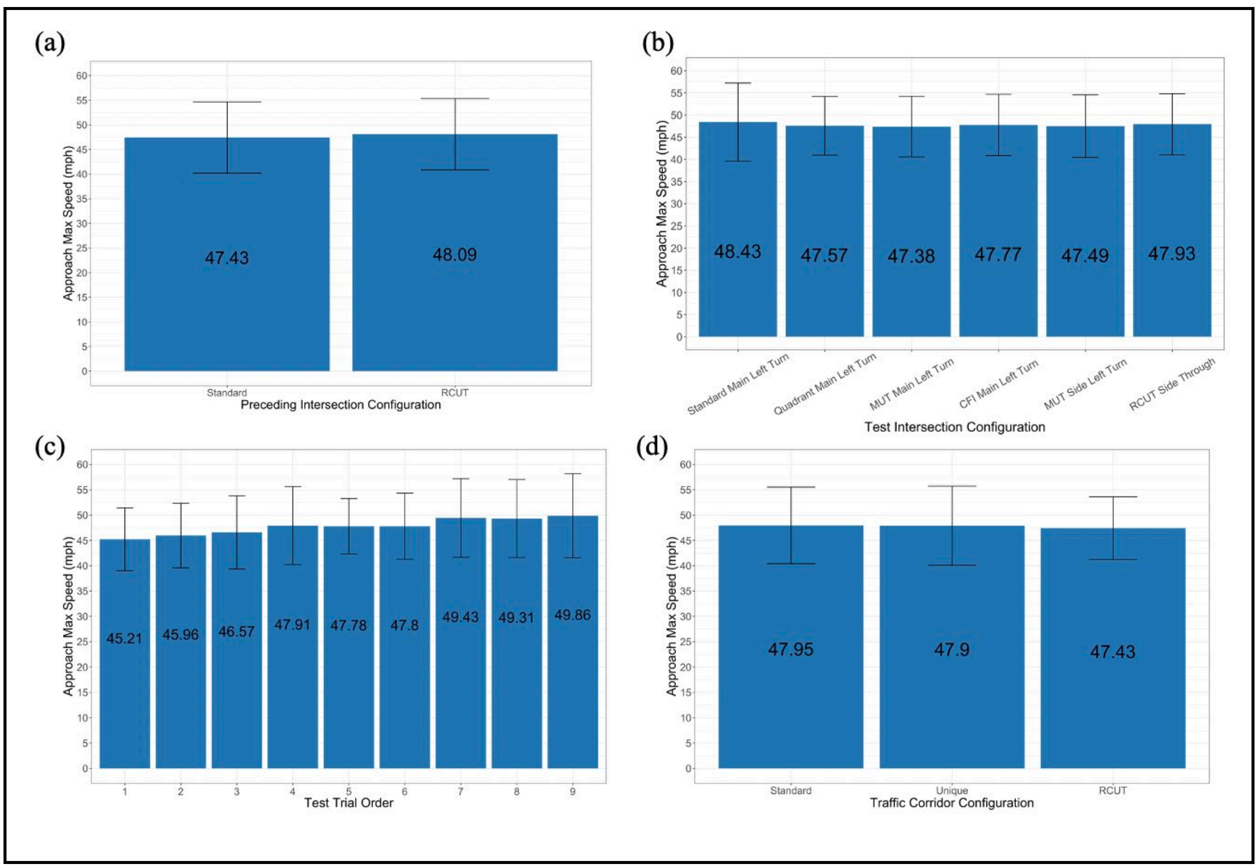


Figure 18. Mean Maximum Approach Speed by (a) PIC, (b) TIC, (c) TTO, (d) TCC

Table 18. Kruskal-Wallis test results on MAS.

MAS by Category	χ^2	df	p-value
Preceding Intersection Configuration	9.78	1	< 0.0001
Test Intersection Configuration	5.17	5	0.40
Test Trial Order	88.52	8	< 0.0001
Traffic Corridor Configuration	0.03	2	0.98

5.3. Hard Braking Events

Figures 19a-d show the number of trials with or without HBEs under different PIC, TIC, TTO and TCC conditions. The total number of trials analyzed for each factor was consistent with our prior analyses on approach speeds and FMs (1728). Figure 19a reveals little difference between the Standard PIC with 280 HBEs and the RCI PIC with 270 HBEs. However, Figure 19b shows that there were higher numbers of trials with HBEs for the Quadrant main left turn TIC (185 occurrences), the MUT side left turn (153 HBEs) and the RCI side through (104 HBEs) in comparison to the standard, MUT and CFI main left turn TICs with 29, 41 and 38 events, accordingly. As shown in Figure 19c, the occurrence of HBEs was relatively consistent across the nine experiment trials. In addition, it can be observed in Figure 19d that the number of trials with HBEs for the standard (190 trials) and unique (195 trials) TCCs were higher and similar than for the RCI TCC with 165 HBE for the experiment.

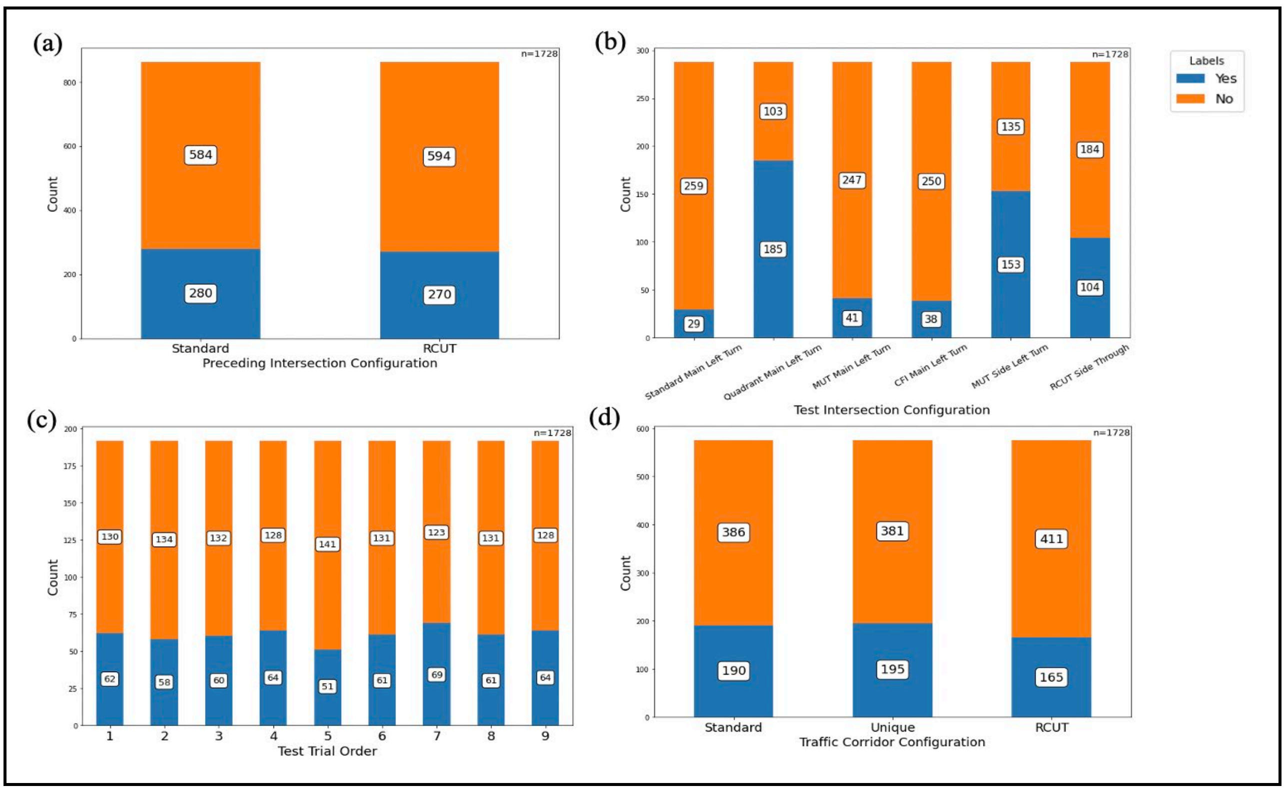


Figure 19. Number of trials with or without HBEs for different (a) PICs, (b) TICs, (c) TTOs, (d) TCCs

A Pearson's Chi-Squared Test was applied to the large sample of binary HBE responses. Figure 20 presents the test results. Referring to the x-axis for the plots, the columns labeled "0" present the percentage of trials without HBEs and the columns labeled "1" present the percentage of trials in which HBEs occurred. As shown in Figures 20a,c,d, the PICs, TTOs and TCCs were not significant predictors of the occurrence of HBEs. However, Figure 20b reveals significant differences among the TICs in terms of HBEs ($\chi^2 = 354.70, p < 0.0001$). Specifically, we found that the Quadrant main left turn and MUT side left turn accounted for 34% and 28% of the total number of HBE trials, respectively. In contrast, the Standard main left turn, with which participants were most familiar, produced the fewest trials with HBEs. It is possible that the elevated number of HBE trials for the Quadrant main left turn and MUT side left turn is attributable to limited participant familiarity with these intersection configurations.

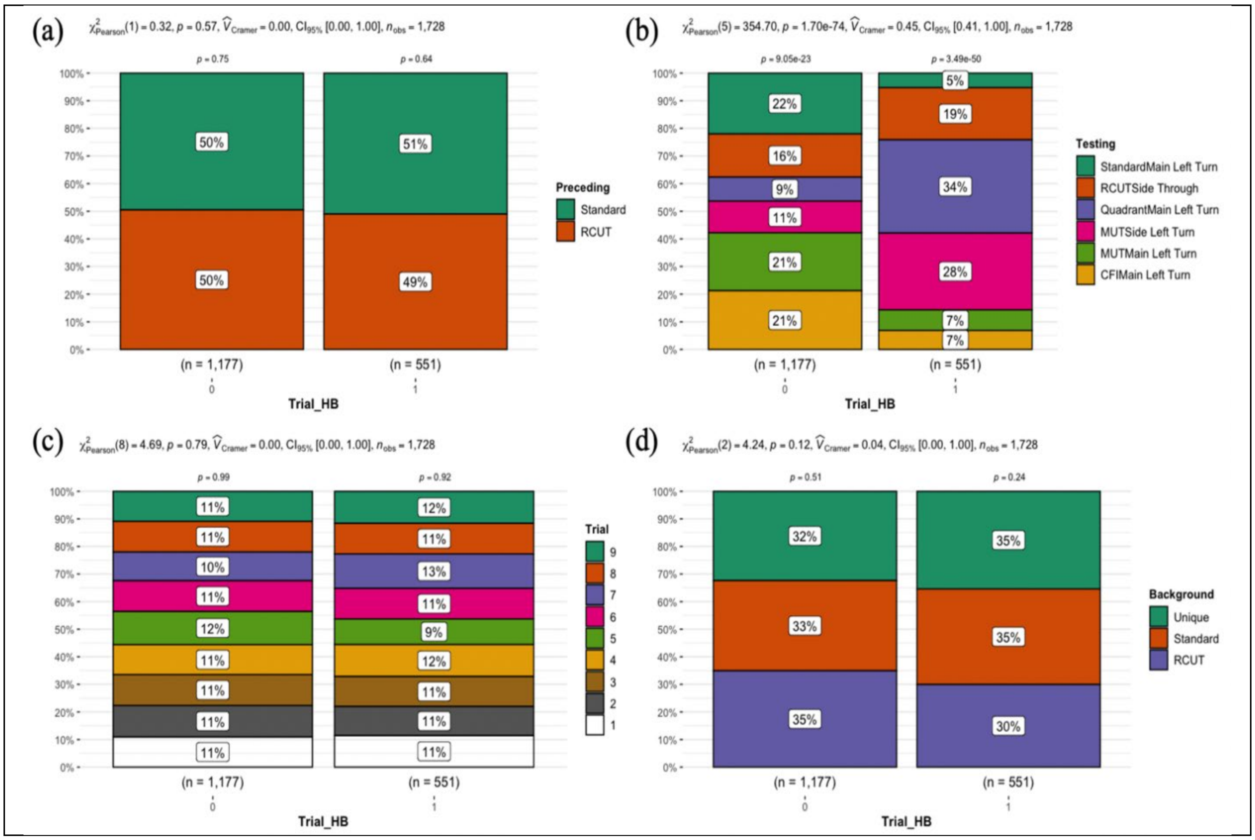


Figure 20. Pearson's Chi-Squared Test on number of trials with or without HBEs for different (a) PICs, (b) TICs, (c) TTOs, (d) TCCs

As further exploration of HBEs under specific experimental settings, we identified specific types of HBEs, including A, B and C (refer to Section 4.5.2), and counted the number of occurrences of each type across experimental trials. We then conducted additional statistical analyses to identify any significant relationships between the PIC, TIC, TTO and TCC conditions with the numbers of trials in which HBE-A, B and C occurred. Figures 21a-d show the number of trials with each type of HBE under the different PIC, TIC, TTO and TCC conditions. The "blue" bar segments indicate the number of trials with HBE-A observations, the "orange" bar segments reveal the number of trials with HBE-B observations, and the "green" bar segments reveal the number of trials with HBE-C observations.

Based on the experiment design, each trial included A and B segments; however, not all trials had a C segment. Consequently, only trials with either HBE-A or HBE-B observations were comparable; i.e., the “blue” and “orange” bars presented in Figure 21. It should be noted that the number of trials with A and B segments was consistent across the settings of the various independent variables. Hence, between-setting comparisons of HBE-A and HBE-B counts were possible for each factor. However, for the TIC manipulation, not all intersections included a C-segment and, therefore, comparisons of HBE-C counts could not be made among the TIC settings.

Figure 21a reveals that the Standard PIC produced slightly more HBE-A, HBE-B and HBE-C occurrences, as compared with the RCI. Related to this, for both the Standard and RCI PICs, the number of trials with HBE-A was not substantially different from the number of trials with HBE-B. In contrast, Figure 21b reveals substantial differences in the number of HBE-A and HBE-B occurrences among the various TICs. Specifically, the Standard main left turn appeared to produce the fewest occurrences of HBE-A (28 trials) and HBE-B (1trial). The standard main left turn appeared to support superior driver performance, as compared to all other test intersections. Opposite to this observation, the MUT side left turn produced the most trials with HBE-A occurrences (135), while the Quadrant main left turn produced the most trials with HBE-A occurrences (173). By graphical comparison, both the MUT main left turn and CFI main left turn appeared to yield fewer HBE-A and HBE-B occurrences.

Referring to Figure 21c, among all the trials in the experiment order, Trial 1 appeared to produce the greatest number of HBE-A occurrences (43), while Trial 6 yielded the greatest number of HBE-B occurrences (43). Regarding the influence of the TCC on HBEs, HBE-A and HBE-B occurrences appeared to be nearly equally distributed among the three traffic corridor types. Type C HBEs appeared to predominately occur for the standard TCC (22 events) and the unique TCC (16 events).

Pearson’s Chi-Squared tests were applied to identify any statistical differences in the types of HBEs (A, B and C) among the settings of the four independent variables. Referring to Figures 22-25 and the frequency plots, “blue” bar segments indicate the occurrence of HBE-A occurrences, “orange” bar segments represent HBE-B occurrences, and “green” bar segments represent HBE-C occurrences. From Figures 22, 23 and 24, it can be observed that both the PIC and the TTO were not significantly associated with HBE-A, B or C occurrences. In contrast, the TIC was significantly influential in HBE-A ($\chi^2 = 229.15, p < 0.0001$) and HBE-B occurrences ($\chi^2 = 490.49, p < 0.0001$), as revealed in Figures 23. The MUT main left turn produced significantly more trials with HBE-A occurrences (47% of all tests) and the Quadrant main left turn produced significantly more trials with HBE-B occurrences (59% of all trials). In addition, as can be observed from Figure 25, the TCC was significantly influential in HBE-C occurrences ($\chi^2 = 9.14, p = 0.01$). The standard TCC produced significantly more trials with HBE-C occurrences (50% of all trials).

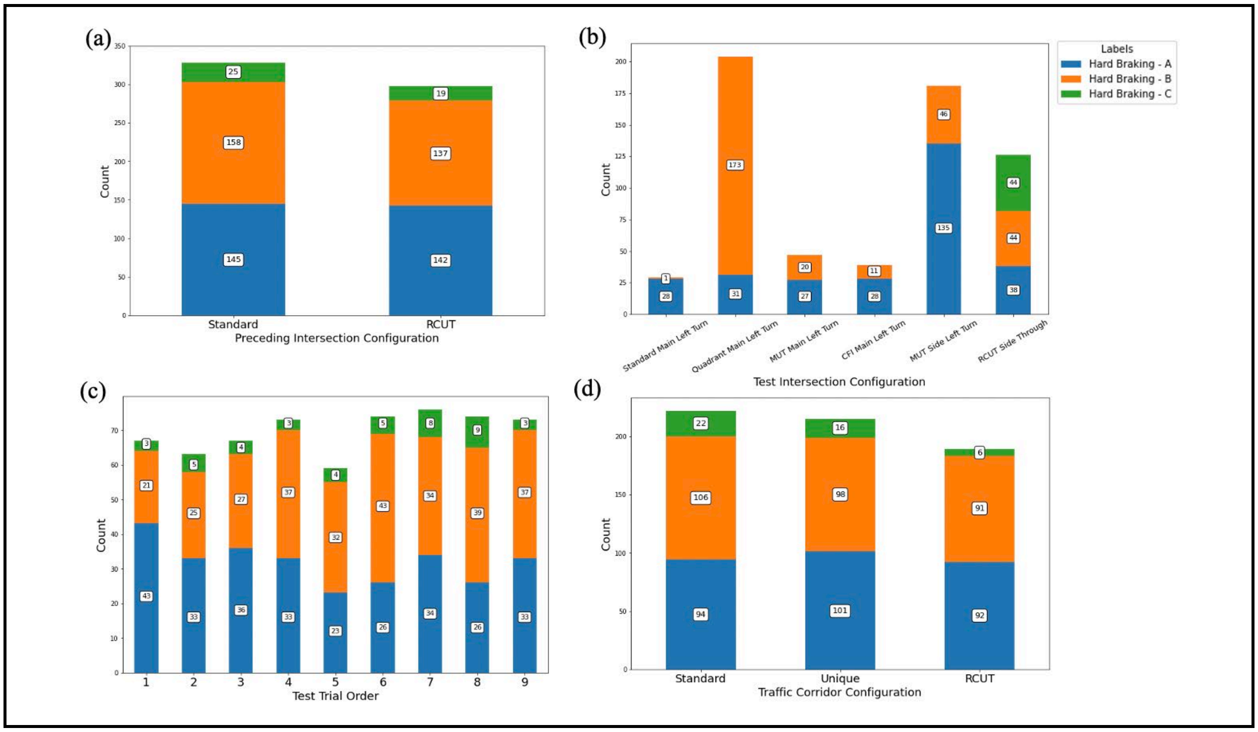


Figure 21. Number of trials with each type of HBE for different(a) PICs, (b) TICs, (c) TTOs, (d) TCCs

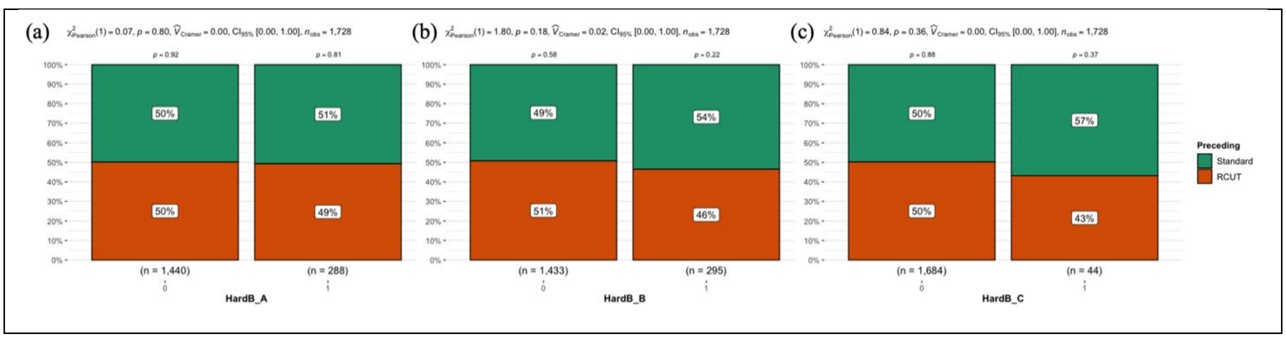


Figure 22. Pearson's Chi-Squared Test results different PICs (a) HBE-A occurrences, (a) HBE-B occurrences, (c) HBE-C occurrences

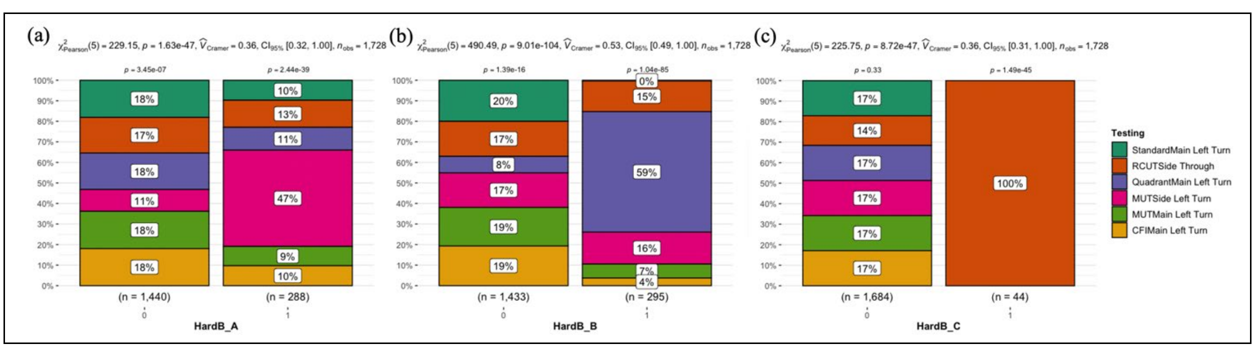


Figure 23. Pearson's Chi-Squared Test results different TICs (a) HBE-A occurrences, (a) HBE-B occurrences, (c) HBE-C occurrences

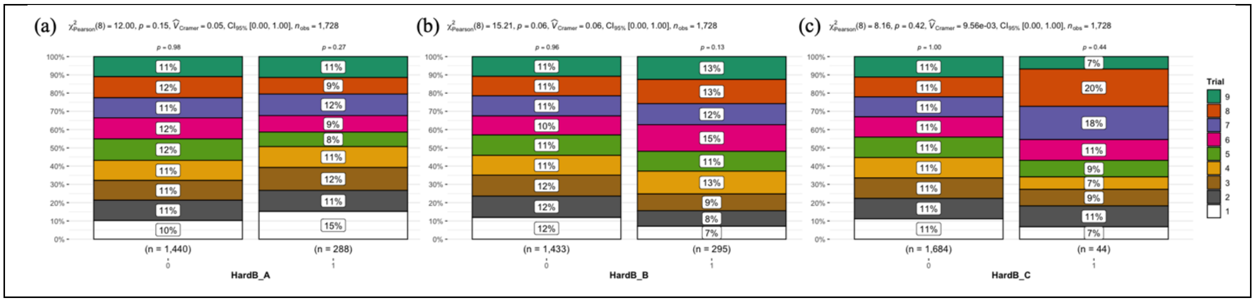


Figure 24. Pearson's Chi-Squared Test results different TTOs (a) HBE-A occurrences, (a) HBE-B occurrences, (c) HBE-C occurrences

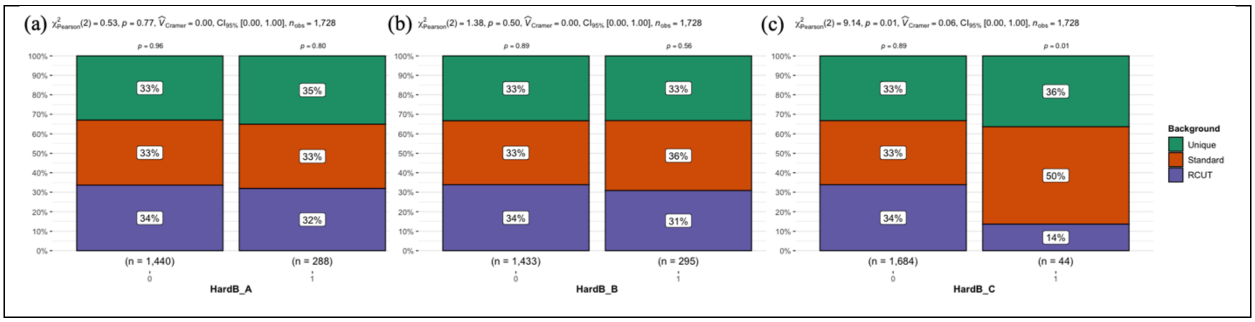


Figure 25. Pearson's Chi-Squared Test results for different TCCs (a) HBE-A occurrences, (a) HBE-B occurrences, (c) HBE-C occurrences

5.4. Approach Lane Change

Across all experiment test trials, drivers executed 2947 ALCs (approach lane changes). The ALC response was a discrete quantitative measure of the total number of times that a participant changed lanes during an experiment. Figures 26a-d reveal the number of ALCs by PIC, TIC, TTO, and TCC.

In Figure 26a the number of ALCs for the Standard and RCI PICs were substantially different (1727 and 1217, respectively) with the Standard PIC producing more ALCs than the RCI. The Standard PIC accounted for approximately 59% of all ALCs during the experiment. As shown in Figure 26b, the Standard main left turn TIC appeared to produce the highest number of ALCs of any TIC with a total of 913 changes. The MUT side left turn followed the standard with 852 ALCs and the CFI main left turn had the next highest number of changes at 633. The MUT main left turn (332 times) and the RCI side through (209 times) produced substantially lower ALCs. Surprisingly, ALCs occurred only 5 times for the Quadrant main left turn TIC.

The number of ALCs occurring in each test trial, according to the experiment order, is illustrated in Figure 26c. Results revealed that participants produced the greatest count of ALCs in Trial 5 (351 changes) and Trial 2 (346 changes); whereas, Trial 9 produced the least number of ALCs with a total of 317 changes. In general, the number of ALCs by trial appeared to be evenly distributed.

It can be seen in Figure 26d that ALCs frequently occurred in the RCI TCC with 1017 changes, followed by the unique TCC (986 ALCs) and the standard TCC (941 ALCs). There was also no observed difference in the number of ALCs among these three TCC types.

Finally, the Kruskal-Waillis test was applied to identify any statistical differences in ALCs among the settings of independent variables. As can be seen in Table 19, there were significant differences in ALC counts among the PICs ($\chi^2 = 90.41, p < 0.0001$) and the TICs types ($\chi^2 = 1107.1, p < 0.0001$). Specifically, the Standard PIC produced significantly more ALCs than the RCI PIC. Furthermore, at least one TIC was significantly different from all others in terms of ALC count. Dunn's test was applied for pairwise comparisons of the TICs, as shown in Table 20. Results revealed that all TICs were different from each other in terms of ALC counts, as detailed above.

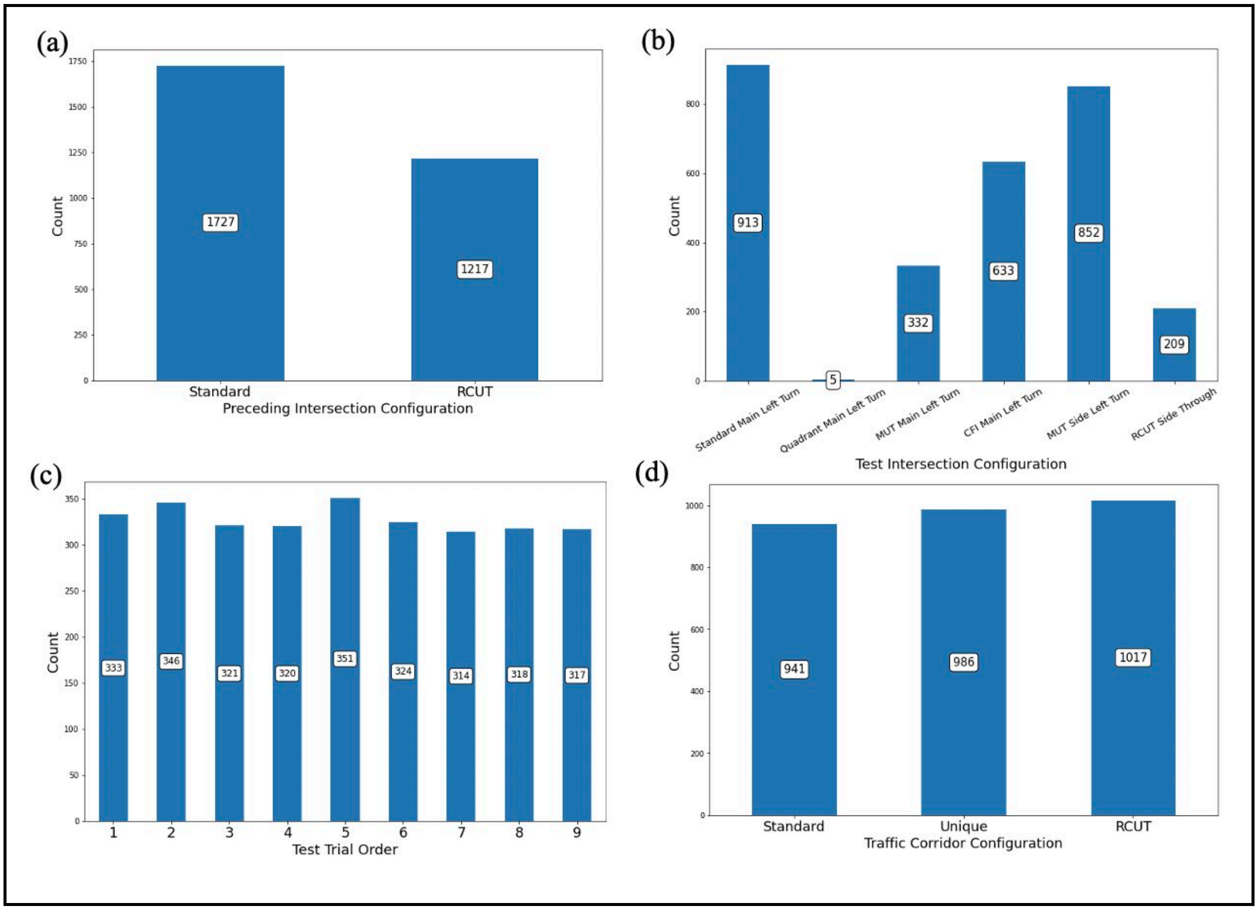


Figure 26. Approach lane changes by (a) PIC, (b) TIC, (c) TTO, (d) TCC

Table 19. Kruskal-Wallis test results on the ALC response.

ALC by Category	χ^2	df	p-value
Preceding Intersection Configuration	90.41	1	< 0.0001
Test Intersection Configuration	1107.1	5	< 0.0001
Test Trial Order	3.09	8	0.93
Traffic Corridor Configuration	1.51	2	0.47

Table 20. Dunn's test results for comparison of ALCs among TIC settings (z-test statistic; p-value).

Col Mean- Row Mean	CFI Main Left Turn	MUT Main Left Turn	MUT Side Left Turn	Quadrant Main Left Turn	RCI Side Through
MUT Main Left Turn	8.70 < 0.0001*				
MUT Side Left Turn	-4.45 < 0.0001*	-13.15 < 0.0001*			
Quadrant Main Left Turn	20.11 < 0.0001*	11.41 < 0.0001*	24.56 < 0.0001*		
RCI Side Through	12.77 < 0.0001*	4.07 < 0.0001*	17.22 < 0.0001*	-7.33 < 0.0001*	
Standard Main Left Turn	-6.70 < 0.0001*	-15.40 < 0.0001*	-2.25 < 0.0001*	-26.81 < 0.0001*	-19.47 < 0.0001*

6. Summary and Findings

When driving on an urban corridor that has intersections, drivers need time and space to observe design differences, identify the correct movement to accommodate their route, and finally change lanes, merge, or diverge as needed. Since the geometric configuration of an alternative intersection design is usually different from a traditional intersection, the presence of an unconventional design tends to bring additional workload to the driver, especially when one is unfamiliar with the corridor.

In current practice, there have been various alternative intersection designs deployed or planned in the nation's roadway systems, including but not limited to the Median U-Turn intersections (MUT), Reduced Conflict Intersections (RCI), Continuous Flow Intersections (CFI), Quadrant Roadways (QR), etc. The different operational features of each alternative intersection design (as compared to a standard intersection) introduce additional workloads for navigating a corridor that contains various alternative intersection designs, and corridors with multiple intersections are often converted to identical alternative intersection designs to reduce complexity. Therefore, it is critical for transportation agencies to understand the effect of various alternative intersection designs on driver behavior and how drivers react to successive alternative intersection combinations. Understanding the design constraints of alternative intersection pairs will allow transportation agencies to continue to innovate and more efficiently implement alternative intersection designs to maximize their operational and safety benefits, as the ideal design for each intersection is often not identical along a corridor.

This research, based on focus group interviews and a driving simulator experiment, investigated driver's understanding of alternative intersection designs and their ability to manage navigation and control of vehicle. Major findings from this research are listed below.

6.1. Findings from Focus Group Study

Through online questionnaire surveys and open discussions, this research found that drivers who are familiar with alternative intersection designs were more ready for any intersection in a corridor to be non-traditional because of their prior experience, but they may still be confused when approaching an intersection because there are many different alternative intersection types, and they didn't always have the location of each one memorized. In comparison, several of the unfamiliar drivers indicated that they were generally able to guess the right lane to be in, but would still be confused if they had to turn right then loop back to complete a left turn.

Both familiar and unfamiliar groups wanted more signs and/or markings and to have them earlier; participants generally reported that pavement markings were useful, especially if they were placed early, and some of the participants wanted overhead signs. Moreover, some of the unfamiliar participants complained that destination signs or signs with "North" or "South" descriptions were not useful if a driver is new to the area. This calls for adequately designing and placing guide signs and markings to provide drivers with advanced warning of the potential changes in traffic patterns introduced by unconventional geometric features. It is also necessary to provide sufficient spacing between adjacent intersections to allow drivers to have more reaction time when recognizing the alternative intersection configuration and making adequate lane-selection maneuvers.

6.2. Findings from Driving Simulator Experiment

The driving simulator experiment aimed to answer the three questions proposed by this research: 1) Are there any issues navigating any of the specific alternative intersection combinations regardless of the corridor type? 2) Do drivers have a different reaction for a specific pair of subsequent intersections if the corridor is consistent (i.e., a standard or RCI corridor) vs. a unique corridor design? and 3) Is there any learned behavior once drivers have been through one or more unique combinations/pairs?

Based on the driver behavior data collected from 48 participants, major findings from the driving simulator experiment are presented below:

General Findings:

- Preliminary statistical analyses on the influence of age on the various driving response measures revealed no significant difference between young and middle-aged drivers in terms of failed movements (FMs), approach speed (AS), hard-braking event (HBEs) and approach lane changes (ALCs). Similarly, there were no significant differences in outcomes among female and male drivers within the convenience sample. Consequently, age and gender were not included as covariates in any final statistical model used to assess intersection configuration effects on driver performance.
- Drivers were asked if they knew of reasons why they failed any movements. They stated reasons including Unclear Instruction, Unclear Sign, Missed Sign, Lost Focus and Confused by Intersection Geometric Design. While stated reasons were collected, these are provided in this report as solely contextual reports as the stated reason cannot be directly confirmed through the experiment data collection.

Question # 1: Are there any issues navigating any of the specific alternative intersection combinations regardless of the corridor type?

- It was found that participants were most likely to have FMs at a MUT side left turn intersection (26 observations), a RCI side through (23 occurrences), and MUT main left turn intersection (22 occurrences). In contrast, there were only three FMs that occurred at the quadrant main left turn and six FMs for the standard main left turn intersection.
- When the preceding intersection was a RCI, and the TIC was a MUT main left turn or side left turn, drivers produced the most FMs (29) occurrences, in total, across TICs.
- For both the Standard and RCI preceding intersection conditions, drivers had fewer FMs at Standard and quadrant main left turn test intersections, indicating that these configurations do not seem to impede decision making. There was only 1 FM in 144 experiment trials involving a quadrant main left turn test intersection, when preceded by a RCI intersection.
- In general, preceding intersection type was significantly associated with FM occurrence and the RCI preceding intersection type produced the most FMs (61% of the total FMs). These primarily occurred when the test intersection was a CFI or MUT and seems to indicate poor decision making at these two test intersections when preceeded by a u-turn at an RCI.
- The testing intersection was also associated with the occurrence of FMs. The Quadrant main left turn accounted for 3% of the total FMs and the Standard intersection

configuration realized 6% of the total FMs. These rates were the lowest among TICs. The MUT side left turn intersection produced 27% of the total FMs, which was more than any other tested intersection.

Question # 2: Do drivers have a different reaction for a specific pair of subsequent intersections if the corridor is consistent vs. a unique corridor design?

- The number of failed movements for the RCI, standard, and unique corridors are 46, 48, and 43, respectively. This indicates that in general, no significant difference in the number of failed movement was found between the three corridor types.
- In terms of intersection pairs, this research effort found that there were fewer FMs across TICs when preceded by a standard intersection vs. a preceding RCI intersection. Specifically, there were 38 FMs following a standard intersection and 59 FMs following a RCI intersection.

Question # 3: Is there any learned behavior once drivers have been through one or more unique combinations/pairs?

- This research effort found that more than half of the failed movements (54.7%) occurred during the participants' first trial. This trend disappeared in subsequent trials, indicating that this is related to the driver's familiarity with the driving simulator itself rather than any specific design.
- Overall, the number of FMs displays a slight but not statistically significant decreasing trend with increased number of trials they have experienced as they became more familiar with the traffic operational features at alternative intersections.

7. References

1. Hummer, J.E., Reid, J.D. *Unconventional Left-Turn Alternatives for Urban and Suburban Arterials: An Update*. TRB Circular E-C019: Urban Street Symposium, 2000, pp.1-17.
2. Hughes, W., Jagannathan, R., Sengupta, D., Humman, J. *Alternative Intersections/Interchanges: Informational Report (AIIR)*. Report No. FHWA-HRT-09-060, U.S. Department of Transportation, Washington, D.C., 2010.
3. Schroeder, B., C. Cunningham, B. Ray, A. Daleiden, P. Jenior, and J. Knudsen. *Diverging Diamond Interchange Informational Guide*. Publication No. FHWA-SA-14-067, Federal Highway Administration, Washington, D.C., 2014.
4. Steyn, H., Z. Bugg, B. Ray, A. Daleiden, P. Jenior, and J. Knudsen. *Displaced Left Turn Intersection Informational Guide*. Publication No. FHWA-SA-14-068, Federal Highway Administration, Washington, D.C., 2014.
5. Reid, J., L. Sutherland, B. Ray, A. Daleiden, P. Jenior, and J. Knudsen. *Median U-Turn Informational Guide*. Publication No. FHWA-SA-14-069, Federal Highway Administration, Washington, D.C., 2014.
6. Hummer, J., B. Ray, A. Daleiden, P. Jenior, and J. Knudsen. *Restricted Crossing U-Turn Informational Guide*. Publication No. FHWA-SA-14-070, Federal Highway Administration, Washington, D.C., 2014.
7. Shumaker, M.L., Hummer, J.E., Huntsinger, L.F. Barriers to implementation of unconventional intersection designs: A survey of transportation professionals. *Public Works Management and Policy*, Vol.18(3), 2012, pp.244-262.
8. FHWA. *Human Factors Issues in Intersection Safety*. Publication No. FHWA-SA-10-005, Federal Highway Administration, Washington, D.C., 2009.
9. Fitzpatrick, K., Wooldridge, M.D., Blaschke, J.D. *Urban Intersection Design Guide: Volume 1 – Guidelines*. Report No. FHWA/TX-05/0-4365-P2 Vol.1, Texas Department of Transportation, Austin, TX, 2005.
10. Wilbur Smith Associates. *Innovative Intersections: Overview and Implementation Guidelines*. High Volume Intersection Study, Vol. I, Community Planning Association of Southwest Idaho, 2008.
11. Schroeder, B., C. Cunningham, B. Ray, A. Daleiden, P. Jenior, and J. Knudsen. *Diverging Diamond Interchange Informational Guide*. Publication No. FHWA-SA-14-067, Federal Highway Administration, Washington, D.C., 2014.
12. Steyn, H., Z. Bugg, B. Ray, A. Daleiden, P. Jenior, and J. Knudsen. *Displaced Left Turn Intersection Informational Guide*. Publication No. FHWA-SA-14-068, Federal Highway Administration, Washington, D.C., 2014.
13. Reid, J., L. Sutherland, B. Ray, A. Daleiden, P. Jenior, and J. Knudsen. *Median U-Turn Informational Guide*. Publication No. FHWA-SA-14-069, Federal Highway Administration, Washington, D.C., 2014.
14. Hummer, J., B. Ray, A. Daleiden, P. Jenior, and J. Knudsen. *Restricted Crossing U-Turn Informational Guide*. Publication No. FHWA-SA-14-070, Federal Highway Administration, Washington, D.C., 2014.
15. Reid, J.D., Hummer, J. *Quadrant Roadway Intersection Informational Guide*. Publication No. FHWA-SA-19-029, Federal Highway Administration, Washington, D.C., 2019.
16. Thompson, C.D., Hummer, J.E. *Guidance on the Safety Implementation of Unconventional Arterial Designs*. Southeastern Transportation Center, University of Tennessee, Knoxville, TN, 2001.
17. Messer, C.J. Methodology for Evaluating Geometric Design Consistency. *Transportation Research Record*, No.757, 1980, pp.7-14.
18. Hassan, Y., Sayed, T., Tabernero, V. Establishing Practical Approach for Design Consistency Evaluation. *Journal of Transportation Engineering*, Vol.127(4), 2001, pp.295-302.

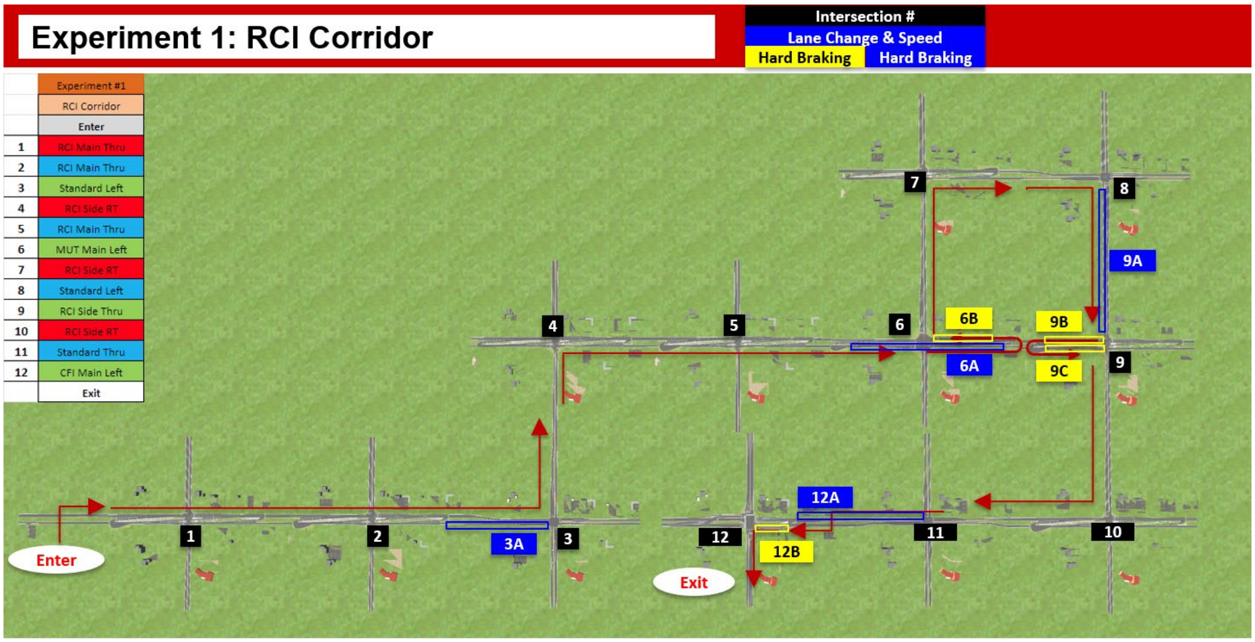
19. Wooldridge, M.D., Fitzpatrick, K., Harwood, D.W., et al. *Geometric Design Consistency on High-Speed Rural Two-Lane Roadways*. NCHRP Report 502, Transportation Research Board, Washington, D.C., 2003.
20. Ng, J.C.W., Sayed, T. Effect of Geometric Design Consistency on Road Safety. *Canadian Journal of Civil Engineering*, Vol.31, 2004, pp.218-227.
21. Watters, P., O'Mahony, M. *The Relationship between Geometric Design Consistency and Safety on Rural Single Carriageways in Ireland*. European Transport Conference, Leiden, Netherlands, 2007.
22. Cafiso, S., La Cava, G. Driving Performance, Alignment Consistency, and Road Safety: Real-World Experiment. *Transportation Research Record*, No.2102, 2009, pp.1-8.
23. FHWA. *Human Factors Issues in Intersection Safety*. Publication No. FHWA-SA-10-005, Federal Highway Administration, Washington, D.C., 2009.
24. NHTSA. *Traffic Safety Facts: Crash Status – A Brief Statistical Summary*. Report No. DOT-HS-812-115, U.S. Department of Transportation, Washington, D.C., 2015.
25. Dagnall, E.E., Katz, B.J., Bertola, M.A., Shurbutt, J., Business logo signing evaluation of the number of logo panels on specific service signs. *Transportation Research Record*, No.2365, 2013, pp.82-89.
26. Zahabi, M., Pankok, C., Kaber, D.B., Machado, P., Lau, M.Y., Hummer, J., Rasdorf, W. On-Road Visual Sign Salience, Driver Attention Allocation, and Target Detection Accuracy. *Transportation Research Record*, No.2663, 2017, pp.40-47.
27. Kaber, D., Pankok Jr., C., Corbett, B., Ma, W., Hummer, J., Rasdorf, W. Driver Behavior in use of Guide and Logo Signs under Distraction and Complex Roadway Conditions. *Applied Ergonomics*, Vol.47, 2015, pp.99-106.
28. Green, P. *Visual and Task Demands of Driver Information Systems*. Report No. UMTRI-98-6, Society of Automotive Engineers, Warrendale, PA, 1999.
29. Dutta, A., Fisher, D. L., Noyce, D.A. Use a Driving simulator to evaluate and optimize factors affecting understandability of variable message signs. Transportation Research Part F, Vol.7, 2004, pp.209-227.
30. Patten, C.J.D., Kircher, A., Ostlund, J., et al. Driver experience and cognitive workload in different traffic environments. *Accident Analysis and Prevention*, Vol.38, 2006, pp.887-894.
31. Inman, V.W., Bertola, M.A., Philips, B. H. *Information as a Source of Distraction*. Publication No. FHWA-HRT-15-027, Federal Highway Administration, Washington, D.C., 2015.
32. Shao, H.P., Mu, W., Ye, Y.X. A quantitative model for the validity of Guide Sign Information at Intersection. *Journal of Transportation Systems Engineering and Information Technology*, Vol.17(4), 2017, pp.70-75.
33. Krueger, R.A., Casey, M.A. *Focus Groups: A Practical Guide for Applied Research*. SAGE Publications, London, 2014.
34. Ullman, B.R., Dudek, C.L., Trout, N.D. Amber Alert and Major Catastrophe Messages on Dynamic Message Signs: Focus Group Studies in Texas. *Transportation Research Record*, Vol.1959(1), 2006, pp.114-121.
35. Kondyli, A., Elefteriadou, L. Driver Behavior at Freeway-Ramp Merging Areas: Focus Group Findings. *Transportation Research Record*, Vol.2124(1), 2009, pp.157-166.
36. Alluri, P., Gan, A., Saha, D., Fernandez, L.O. Evaluation of Signage Alternatives for Express Lane Facilities: Focus Group Study. *Transportation Research Record*, Vol.2616(1), 2017, pp.114-121.
37. Irizarry, J., Kim, S., Johnson, E., Lee, K. *Potential Unmanned Aircraft Systems Based Operations within a Department of Transportation: Findings from a Focus Group Study*. Proceedings of the 53rd Associated Schools of Construction (ASC) Annual International Conference, Seattle, WA, 2017, pp.669-679.
38. Kester, J., De Rubens, G.Z., Sovacool, B.K., Noel, L. Public perceptions of electric vehicles and vehicle-to-grid (V2G): Insights from a Nordic focus group study. *Transportation Research Part D*, Vol.74, 2019, pp.277-293.

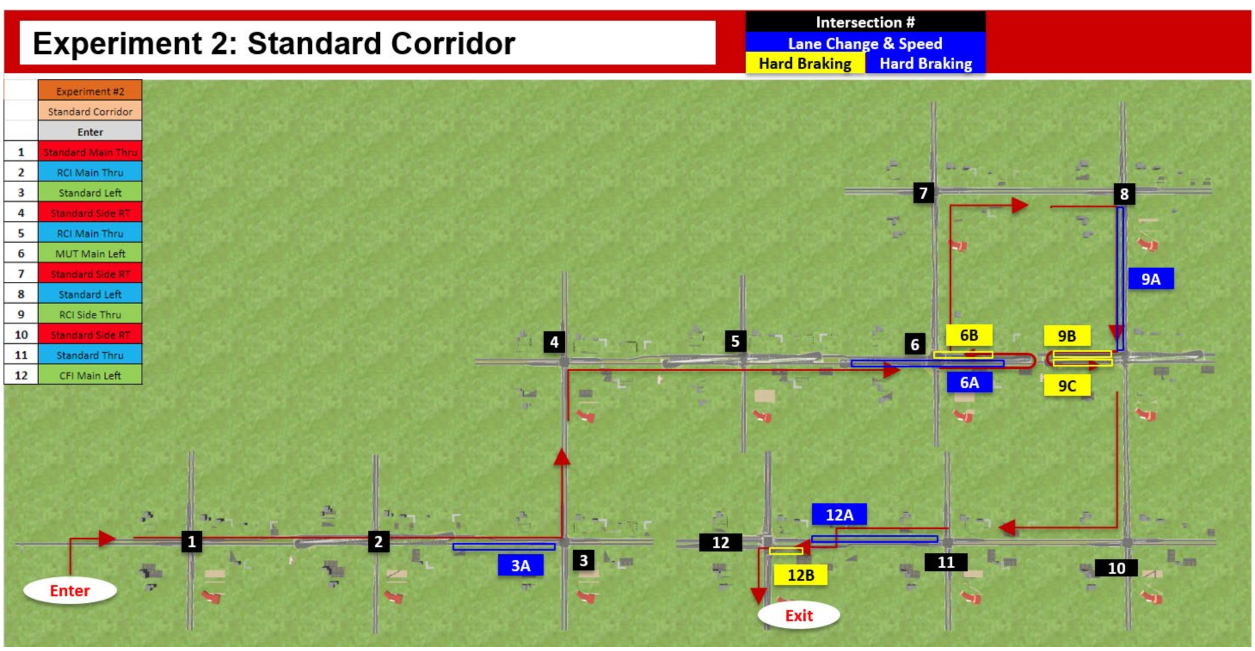
39. Norton, T.A., Ruhl, M., Armitage, T., Matthews, B., Miles, J. Cross-National Focus Group Response to Autonomous Vehicles. *Transportation Research Record*, 2021, https://doi.org/10.1177/0361198121992363.
40. Kitzinger, J. The methodology of Focus Groups: the importance of interaction between research participants. *Sociology of Health & Illness*, Vol.16, 1994, pp.103-121.
41. Wissinger, L.M., Hummer, J.E., Milazzo, J.S. Using Focus Groups to Investigate Issues of Red Light Running. *Transportation Research Record*, Vol.1734(1), 2000, pp.38-45.
42. Shumaker, M.L., Hummer, J.E., Huntsinger, L.F. Barriers to implementation of unconventional intersection designs: A survey of transportation professionals. *Public Works Management and Policy*, Vol.18(3), 2012, pp.244-262.
43. Fitch, G.M., Lee, S.E., Klauer, S., Hankey, J., Sudweeks, J., and Dingus, T. Analysis of Lane-Change Crashes and Near-Crashes. Report No. DOT-HS-811-147, National Highway Traffic Safety Administration, Washington, D.C., 2009.

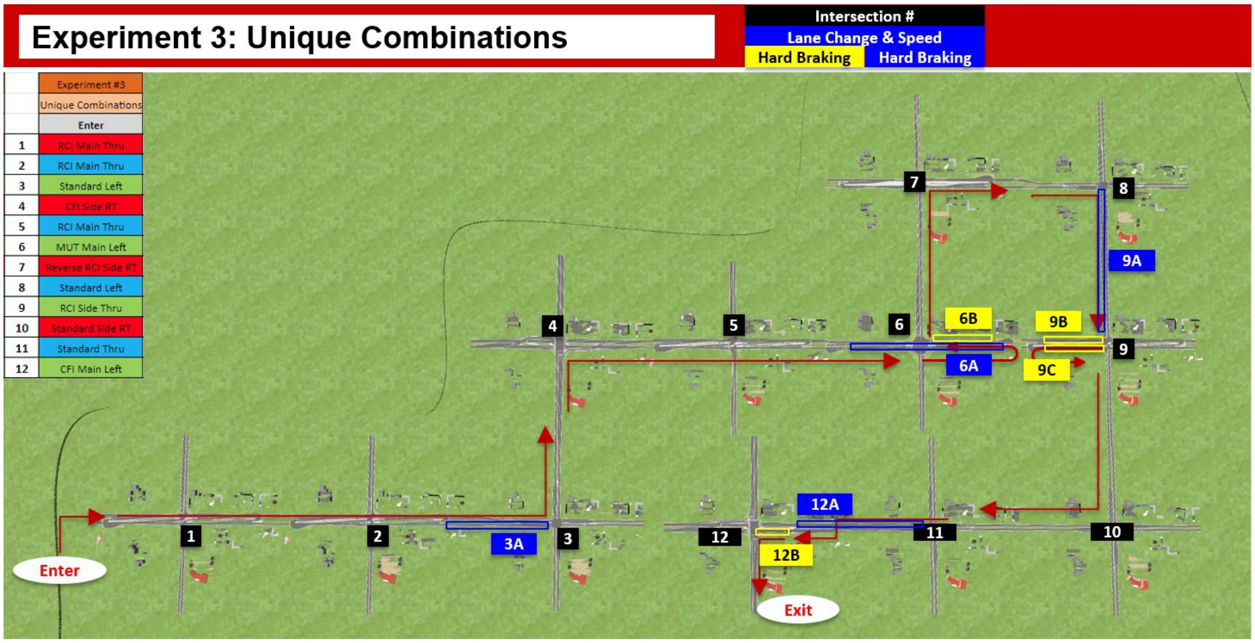
8. Appendix

Test zone plan view for data extraction

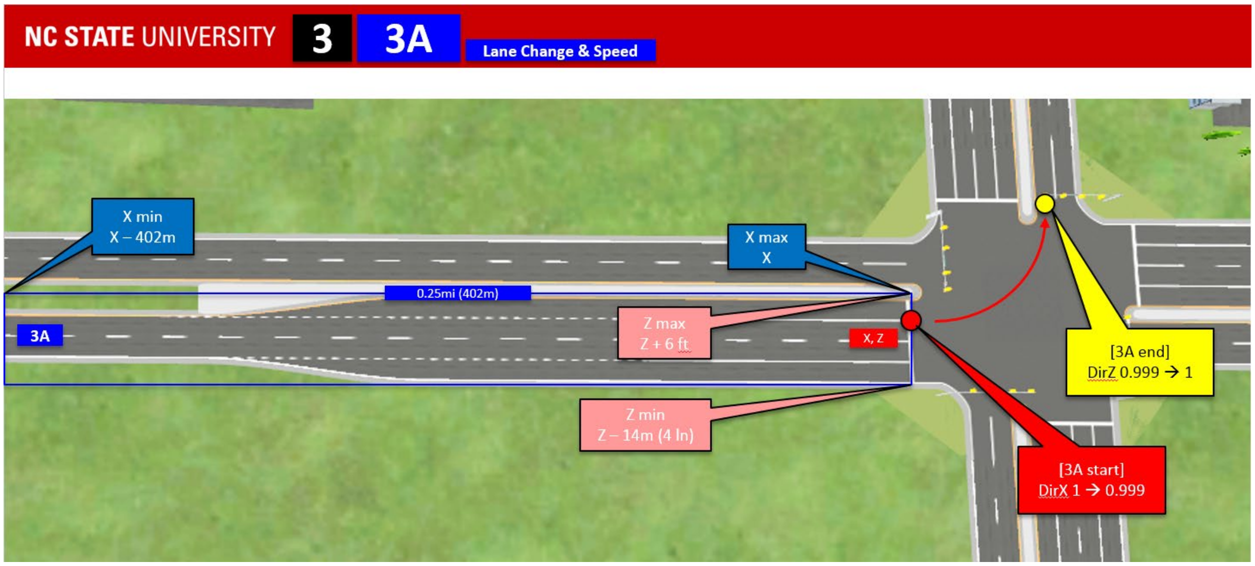
8.1. Experiments 1,2,3 Plan View

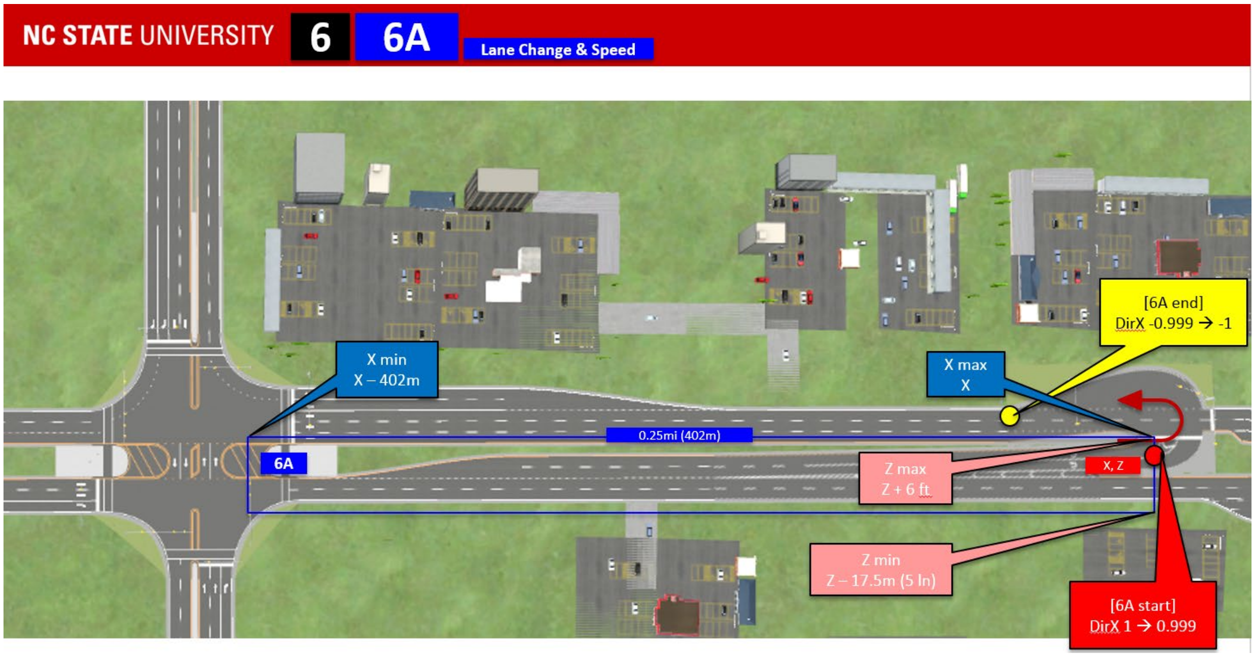


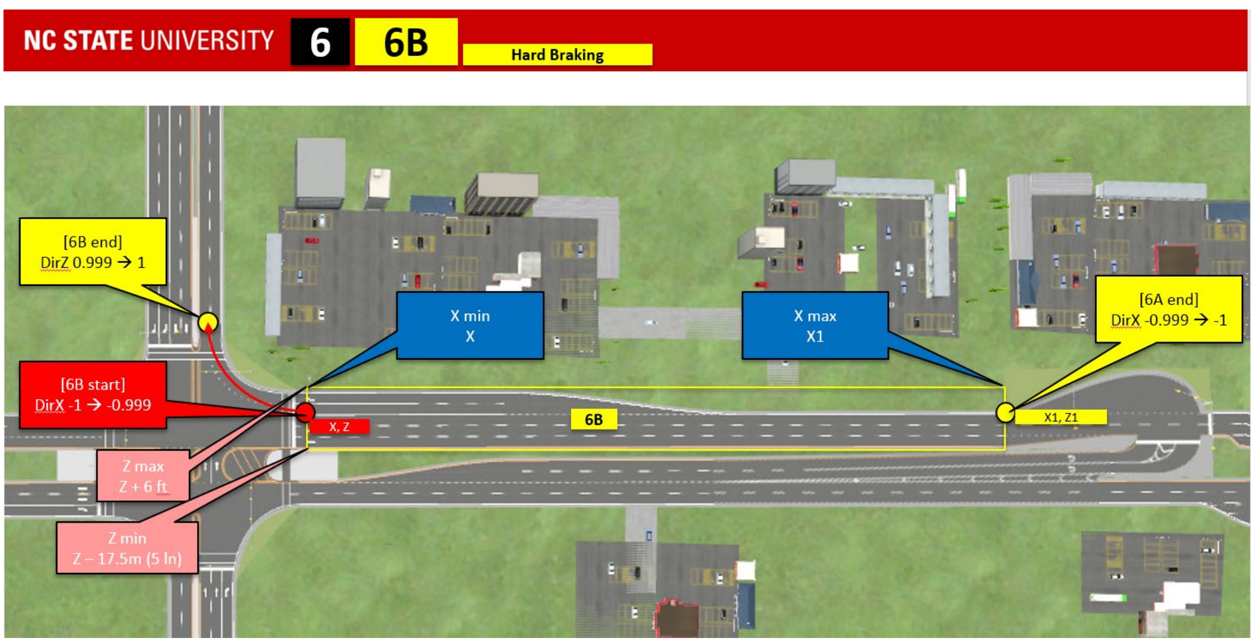


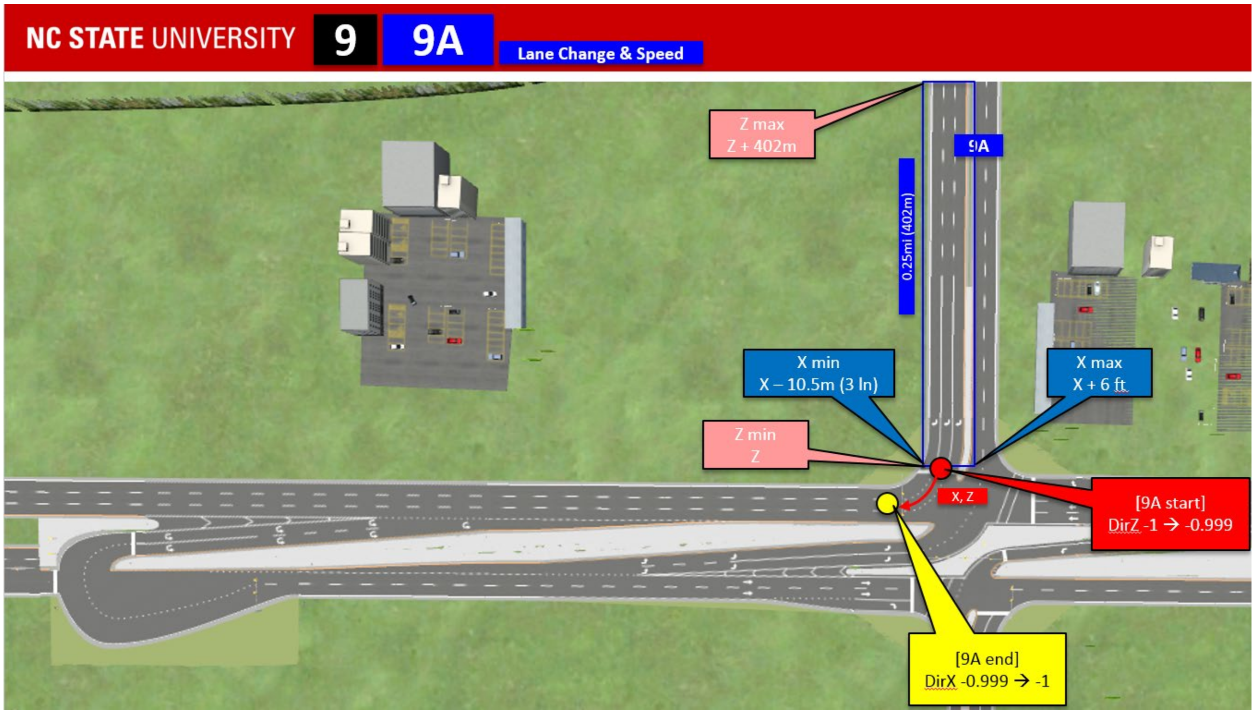


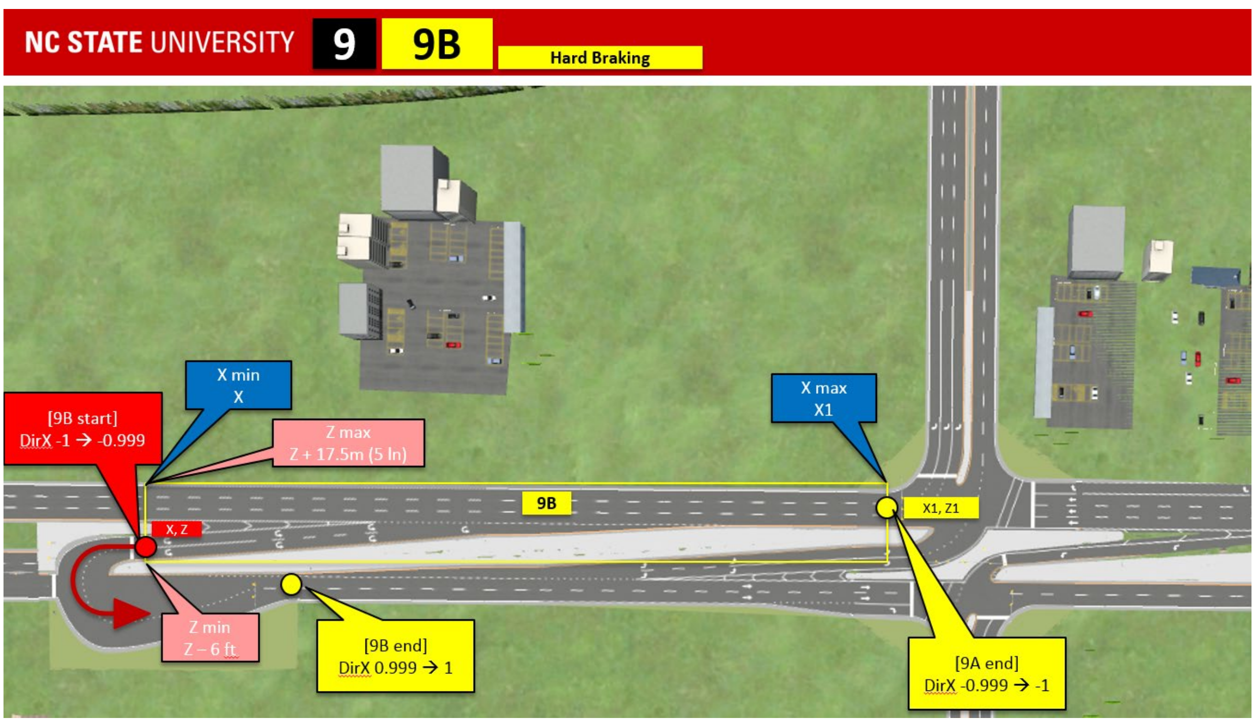
8.2. Experiments 1,2,3 Detection Zones

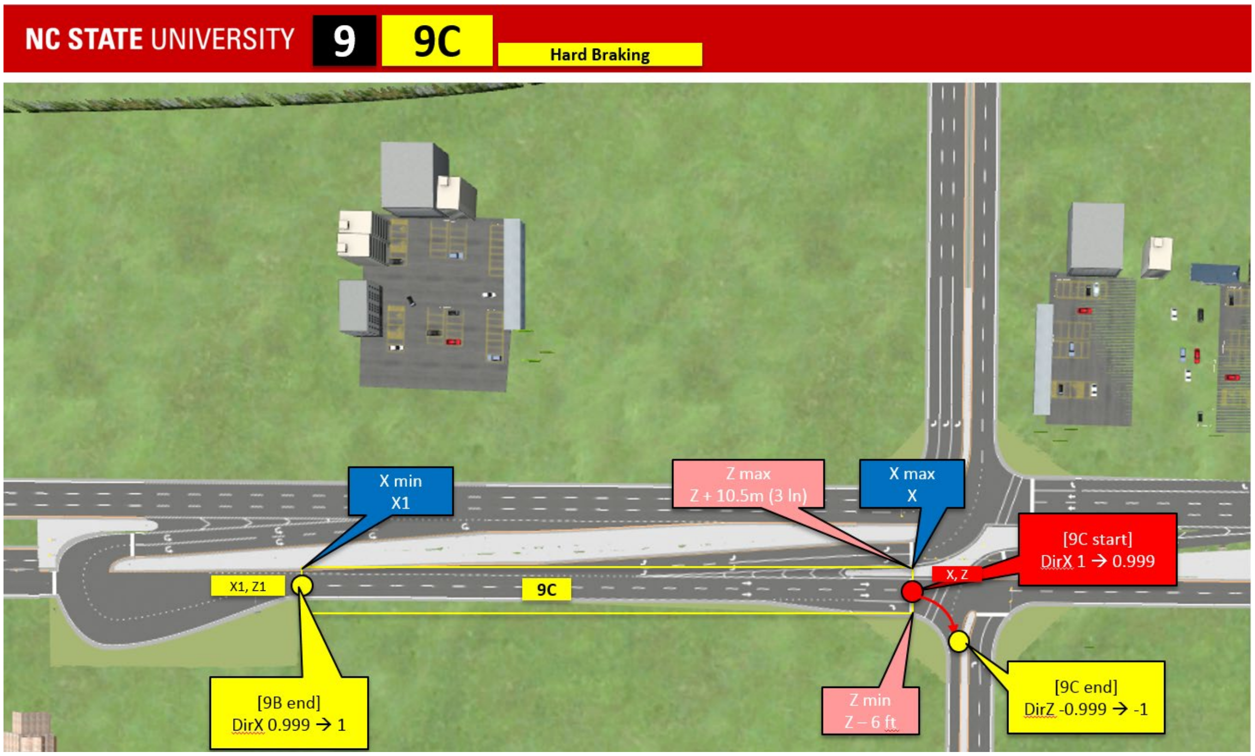


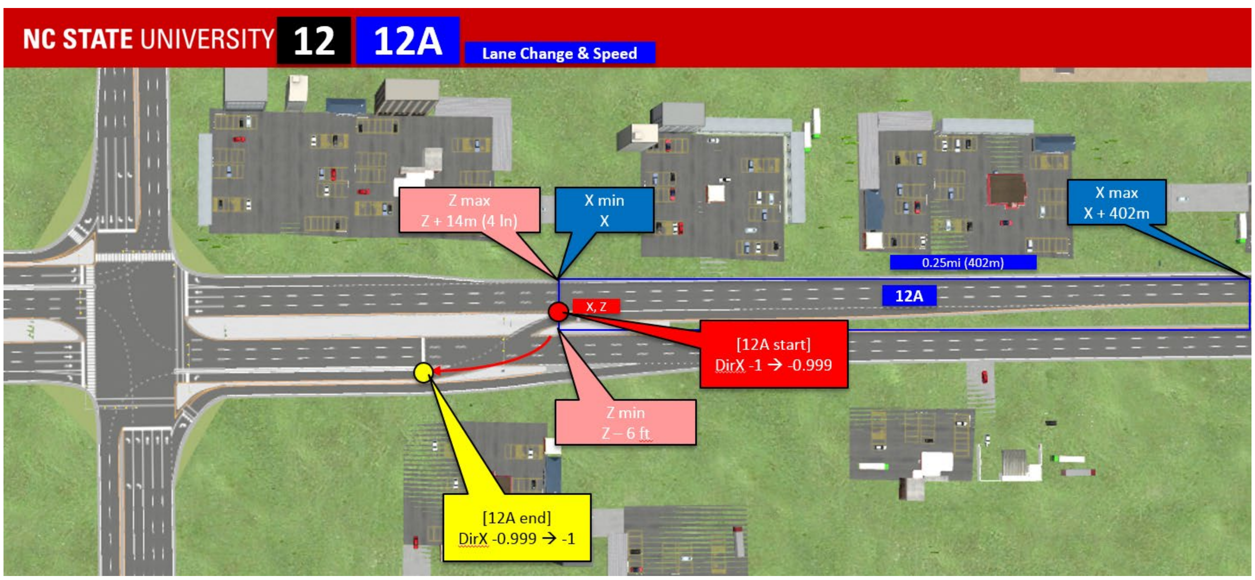

NC STATE UNIVERSITY
6
6A
Lane Change & Speed
X min
X – 402m
X max
X
[6A end]
DirX -0.999 → -1
0.25mi (402m)
6A
Z max
Z + 6 ft
X, Z
Z min
Z – 17.5m (5 ln)
[6A start]
DirX 1 → 0.999

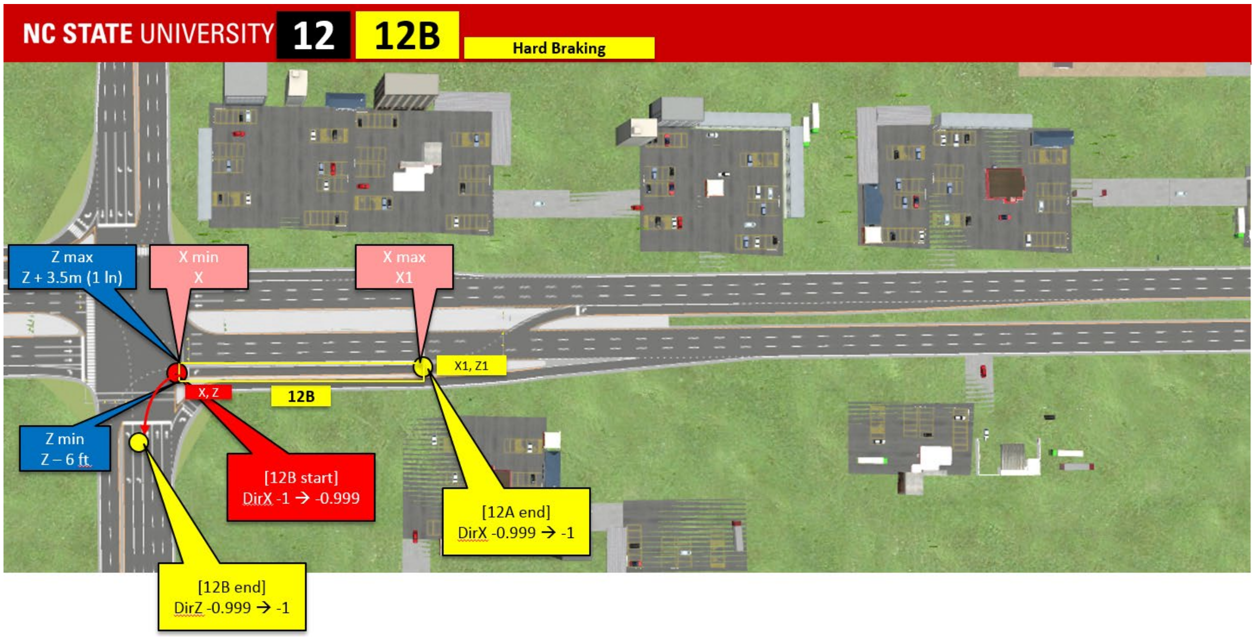

NC STATE UNIVERSITY
6
6B
Hard Braking
[6B end]
DirZ 0.999 → 1
X min
X
X max
X1
[6A end]
DirX -0.999 → -1
[6B start]
DirX -1 → -0.999
X, Z
6B
X1, Z1
Z max
Z + 6 ft
Z min
Z – 17.5m (5 ln)


NC STATE UNIVERSITY
9
9A
Lane Change & Speed
Z max
Z + 402m
9A
0.25mi (402m)
X min
X – 10.5m (3 ln)
X max
X + 6 ft
Z min
Z
X, Z
[9A start]
DirZ -1 → -0.999
[9A end]
DirX -0.999 → -1

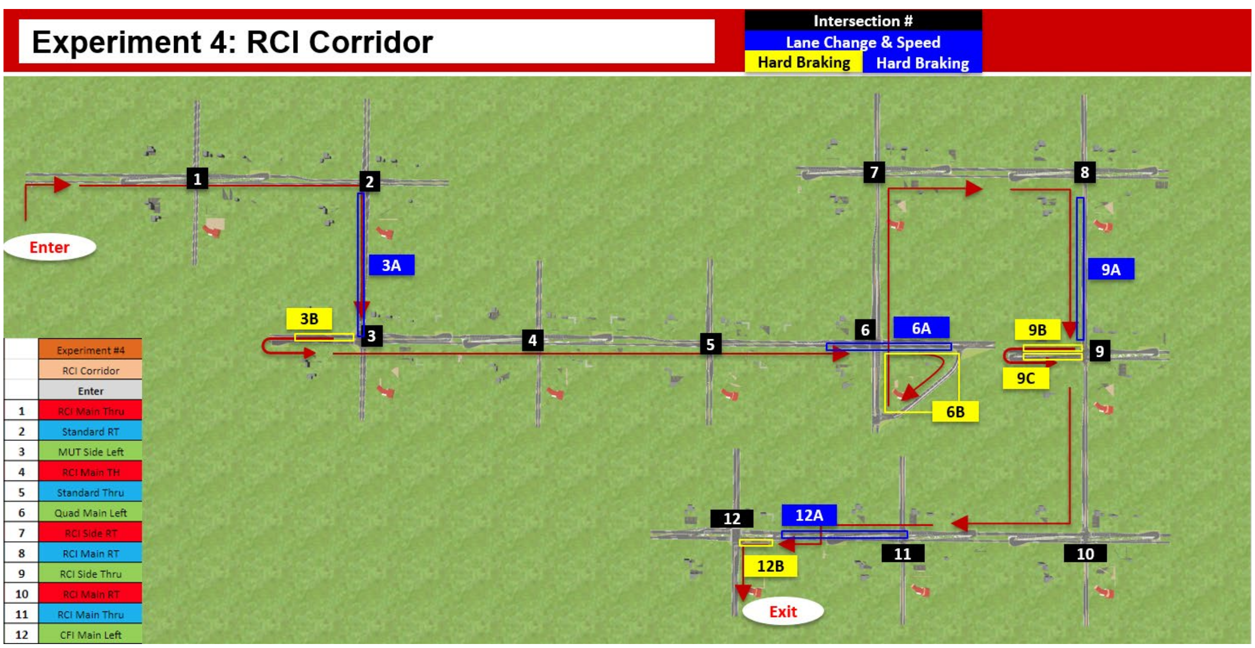

NC STATE UNIVERSITY
9
9B
Hard Braking
X min
X
[9B start]
DirX -1 → -0.999
Z max
Z + 17.5m (5 ln)
X max
X1
9B
X1, Z1
X, Z
Z min
Z – 6 ft
[9B end]
DirX 0.999 → 1
[9A end]
DirX -0.999 → -1

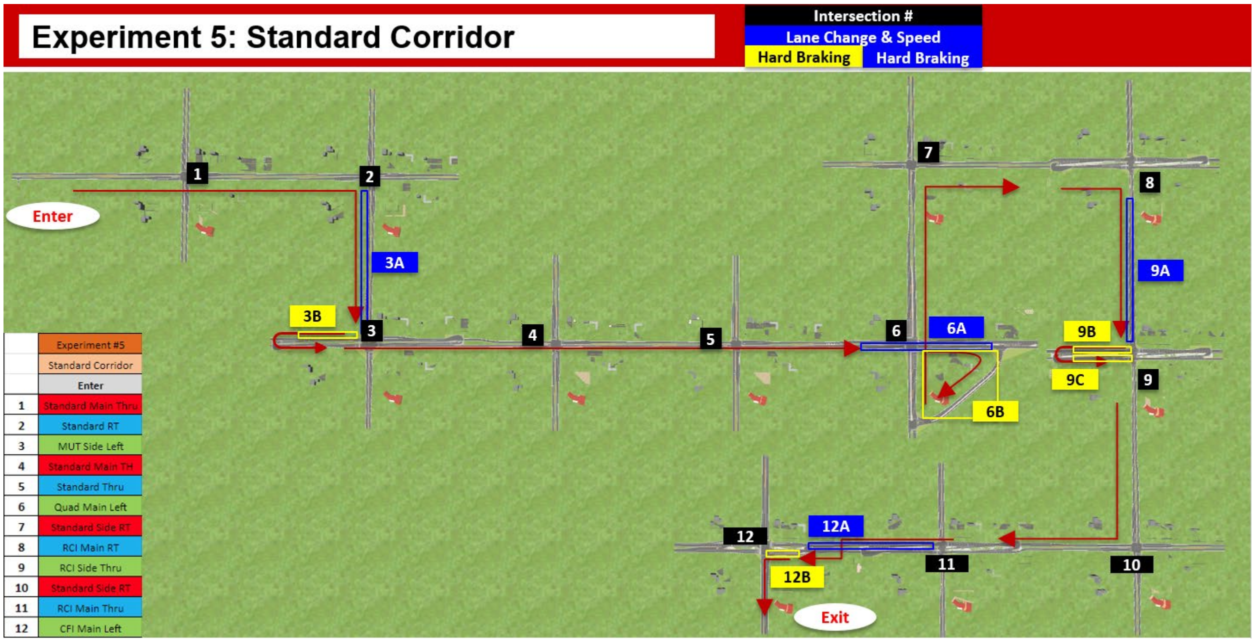

NC STATE UNIVERSITY
9
9C
Hard Braking
X min
X1
Z max
Z + 10.5m (3 ln)
X max
X
[9C start]
DirX 1 → 0.999
X, Z
X1, Z1
9C
[9B end]
DirX 0.999 → 1
Z min
Z – 6 ft
[9C end]
DirZ -0.999 → -1

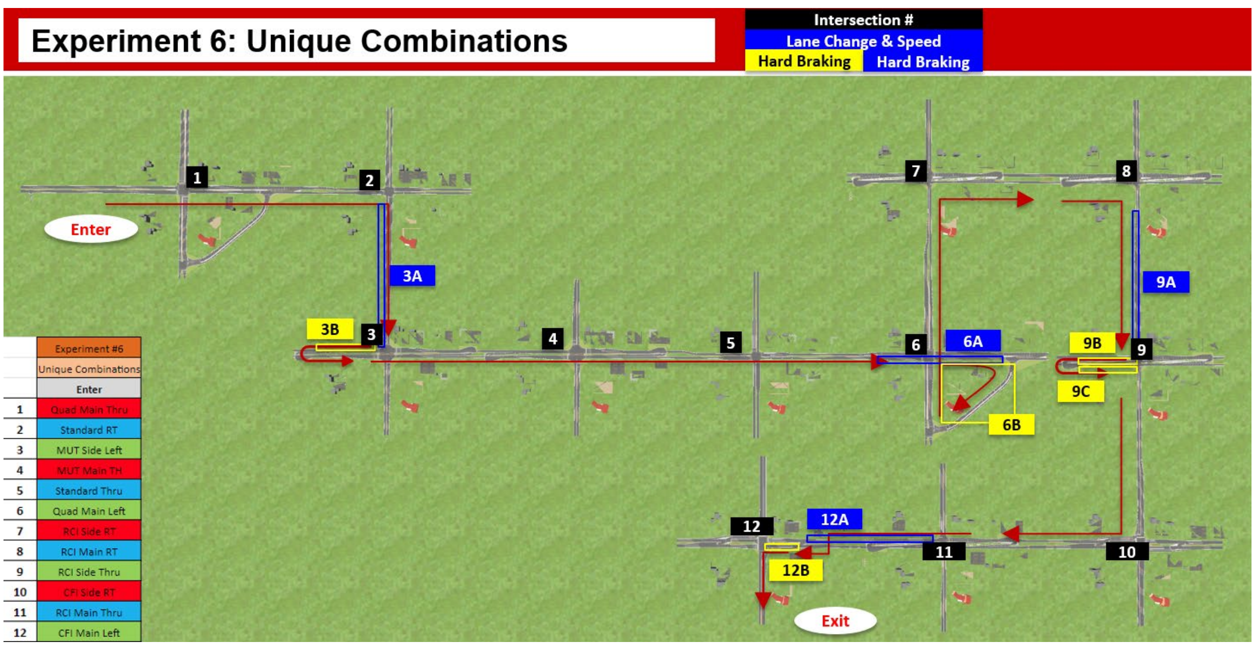

NC STATE UNIVERSITY
12
12A
Lane Change & Speed
Z max
Z + 14m (4 ln)
X min
X
X max
X + 402m
0.25mi (402m)
12A
X, Z
[12A start]
DirX -1 → -0.999
Z min
Z – 6 ft
[12A end]
DirX -0.999 → -1



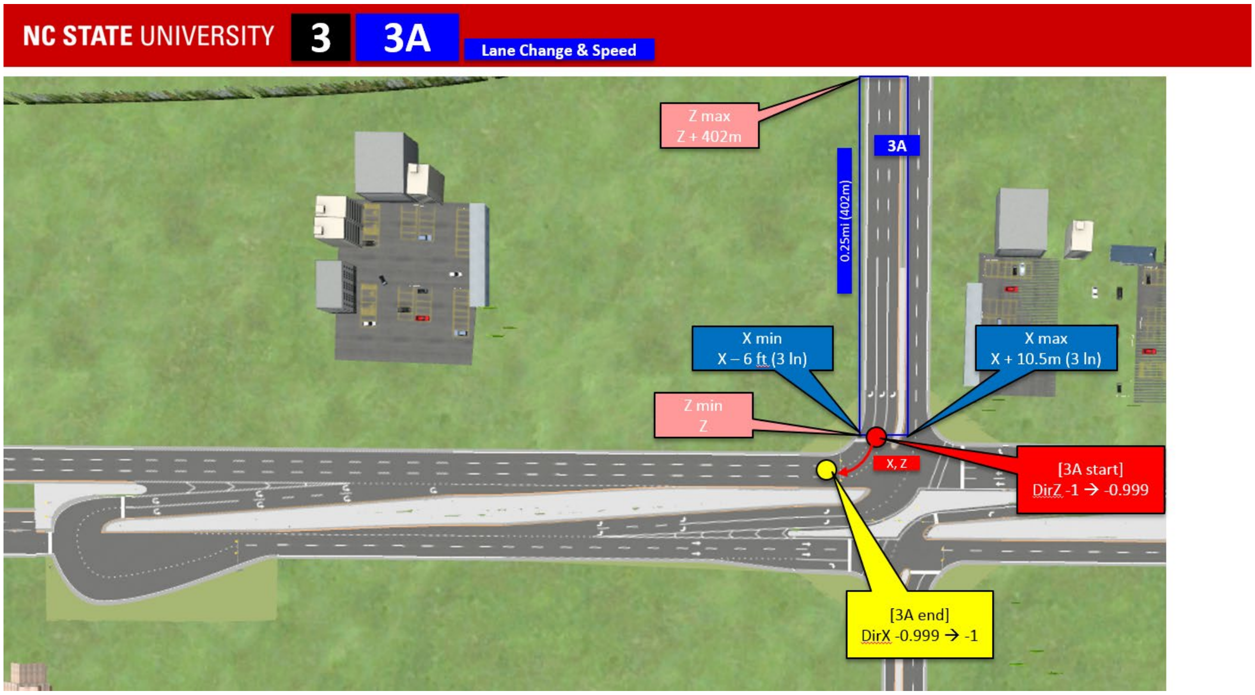
8.3. Experiments 4,5,6 Plan View

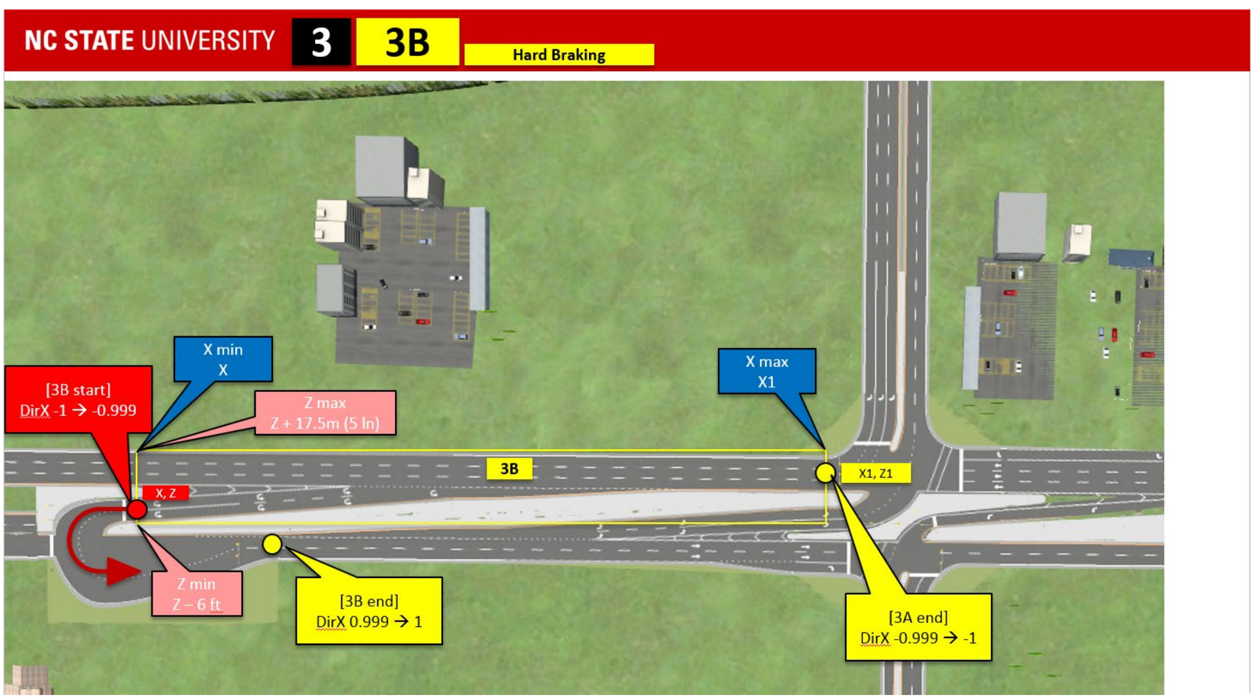


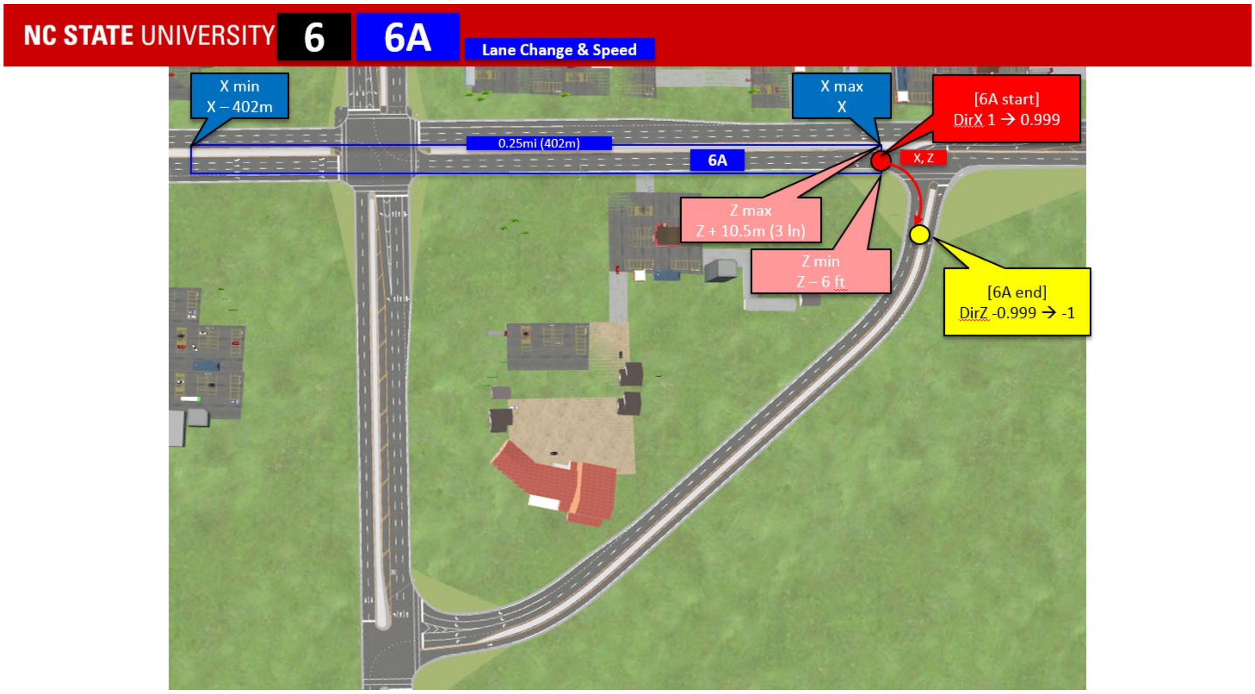

Experiment 5: Standard Corridor
Intersection #
Lane Change & Speed
Hard Braking
Hard Braking
Enter
1
2
3A
3B
3
4
5
6
6A
6B
7
8
9A
9B
9C
9
10
11
12
12A
12B
Exit
Experiment #5
Standard Corridor
Enter
1 Standard Main Thru
2 Standard RT
3 MUT Side Left
4 Standard Main TH
5 Standard Thru
6 Quad Main Left
7 Standard Side RT
8 RCI Main RT
9 RCI Side Thru
10 Standard Side RT
11 RCI Main Thru
12 CFI Main Left

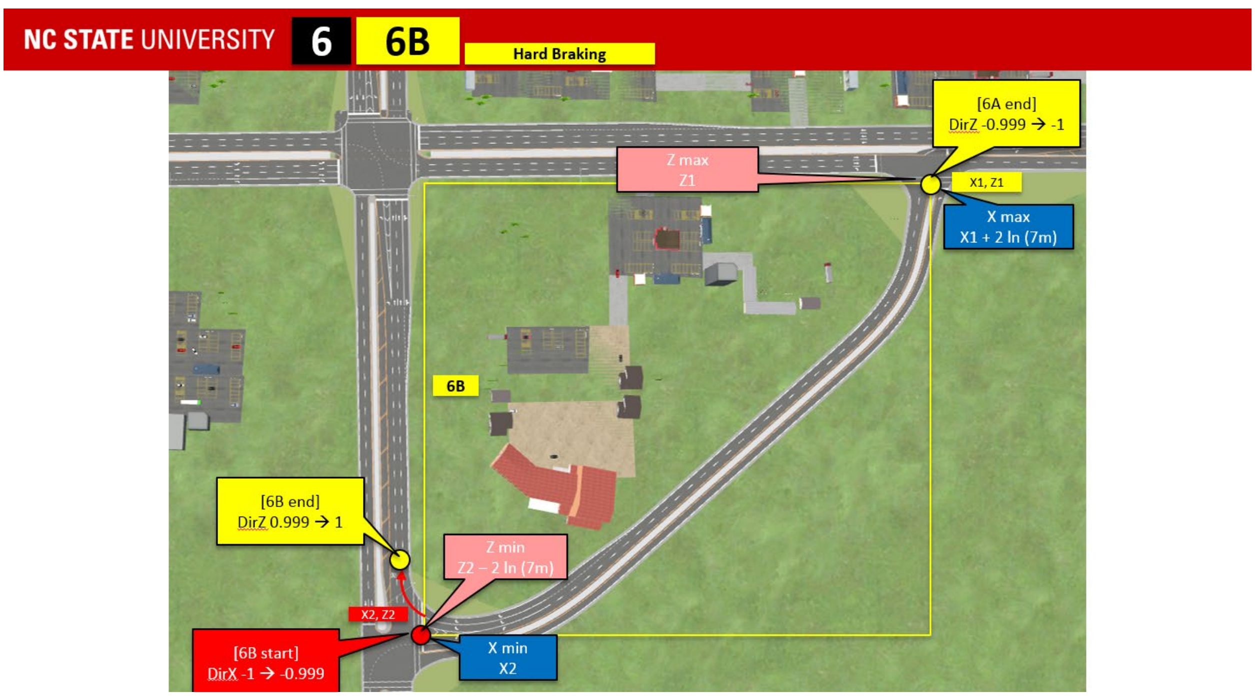

Experiment 6: Unique Combinations
Intersection #
Lane Change & Speed
Hard Braking
Hard Braking
Enter
1
2
3A
3B
3
4
5
6
6A
6B
7
8
9A
9B
9C
9
10
11
12
12A
12B
Exit
Experiment #6
Unique Combinations
Enter
1 Quad Main Thru
2 Standard RT
3 MUT Side Left
4 MUT Main TH
5 Standard Thru
6 Quad Main Left
7 RCI Side RT
8 RCI Main RT
9 RCI Side Thru
10 CFI Side RT
11 RCI Main Thru
12 CFI Main Left

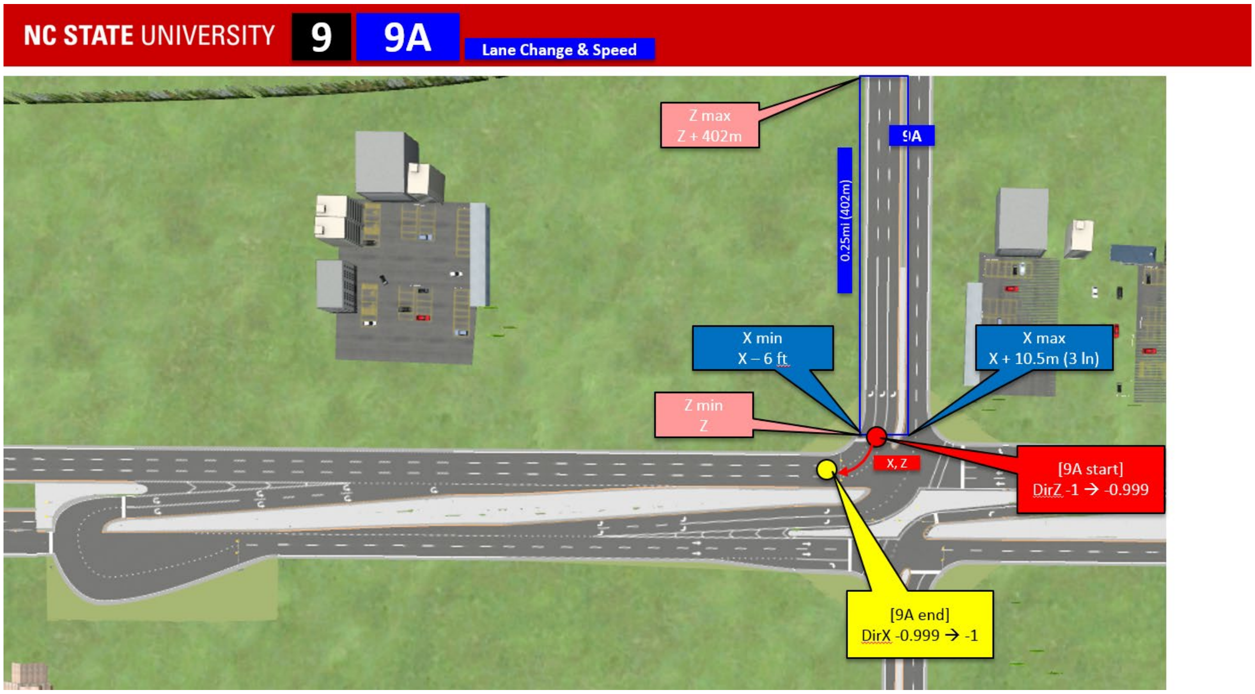
8.4. Experiments 4,5,6 Detection Zones

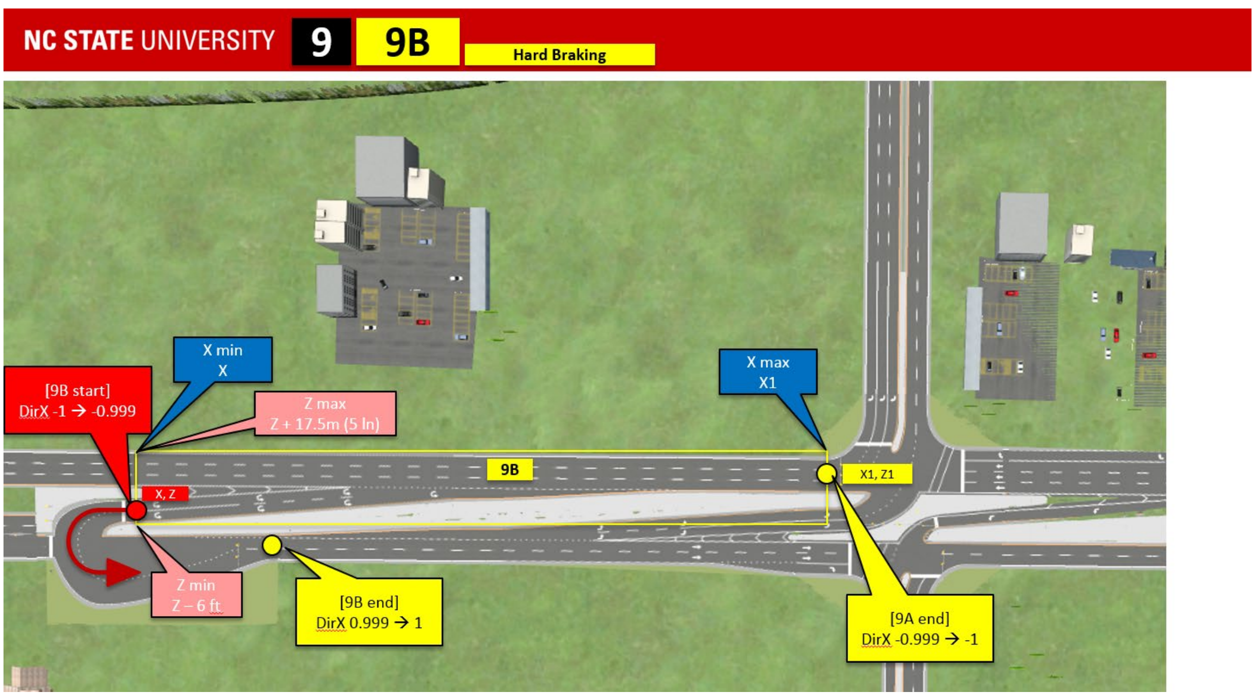


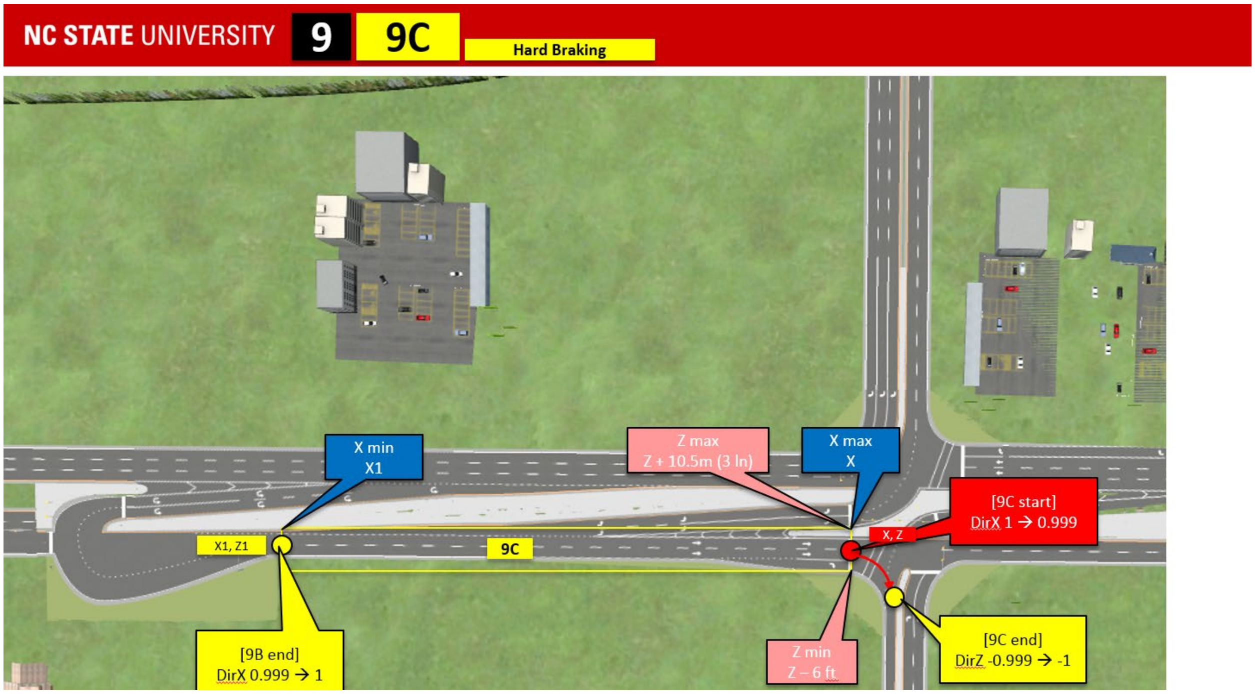


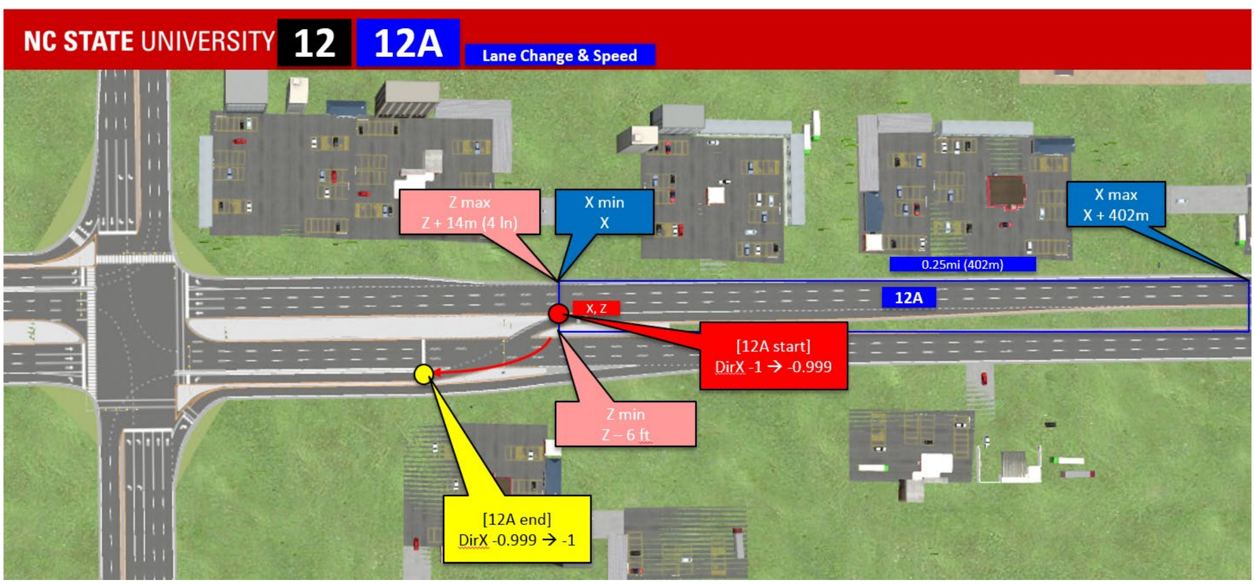

NC STATE UNIVERSITY
6
6A
Lane Change & Speed
X min
X – 402m
X max
X
[6A start]
DirX 1 → 0.999
0.25mi (402m)
6A
X, Z
Z max
Z + 10.5m (3 ln)
Z min
Z – 6 ft
[6A end]
DirZ -0.999 → -1

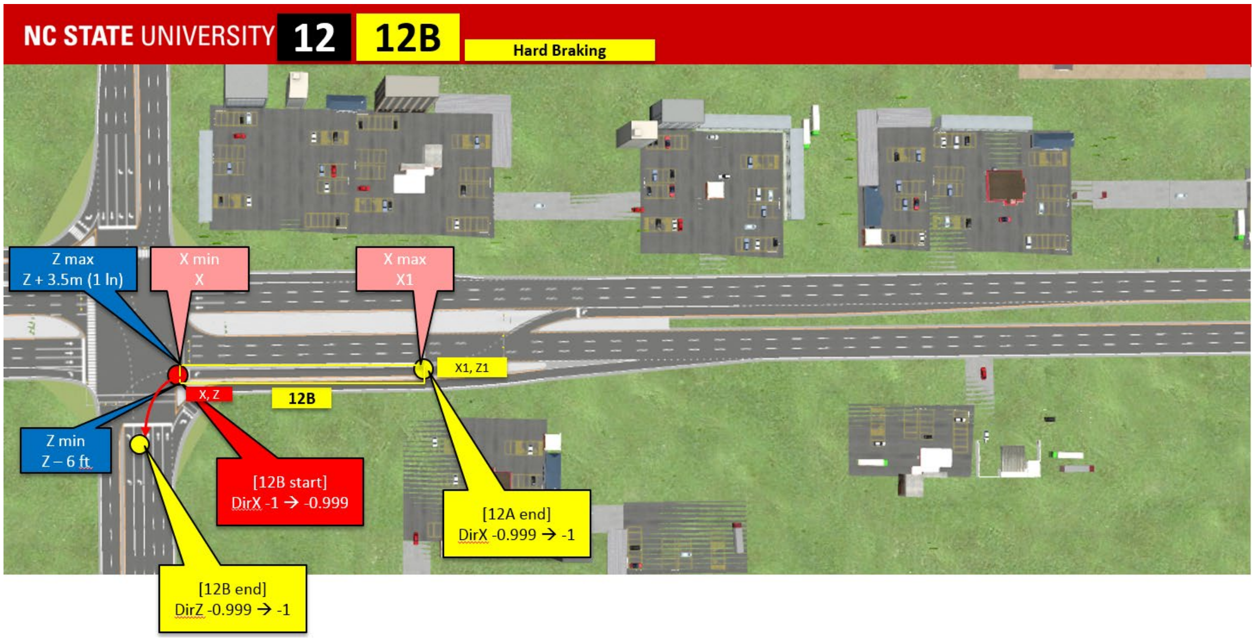

NC STATE UNIVERSITY
6
6B
Hard Braking
[6A end]
DirZ -0.999 → -1
Z max
Z1
X1, Z1
X max
X1 + 2 ln (7m)
6B
[6B end]
DirZ 0.999 → 1
Z min
Z2 – 2 ln (7m)
X2, Z2
[6B start]
DirX -1 → -0.999
X min
X2


NC STATE UNIVERSITY
9
9A
Lane Change & Speed
Z max
Z + 402m
9A
0.25mi (402m)
X min
X – 6 ft
X max
X + 10.5m (3 ln)
Z min
Z
X, Z
[9A start]
DirZ -1 → -0.999
[9A end]
DirX -0.999 → -1

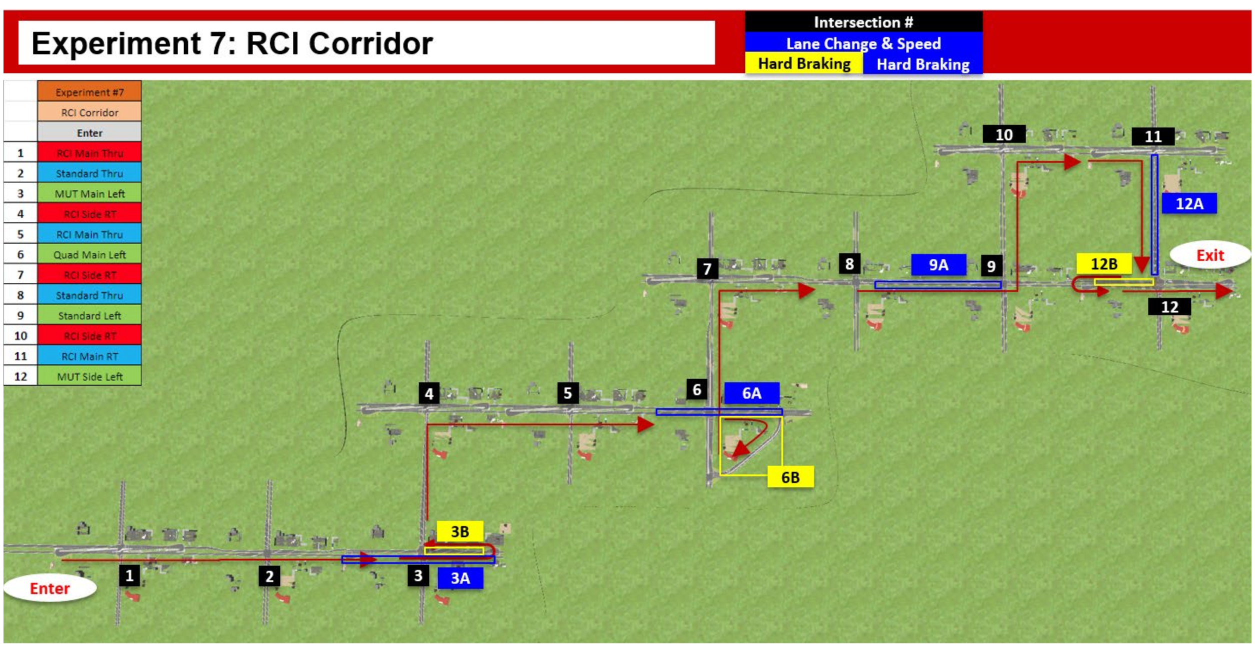

NC STATE UNIVERSITY
9
9B
Hard Braking
X min
X
[9B start]
DirX -1 → -0.999
Z max
Z + 17.5m (5 ln)
X max
X1
9B
X, Z
X1, Z1
Z min
Z – 6 ft
[9B end]
DirX 0.999 → 1
[9A end]
DirX -0.999 → -1

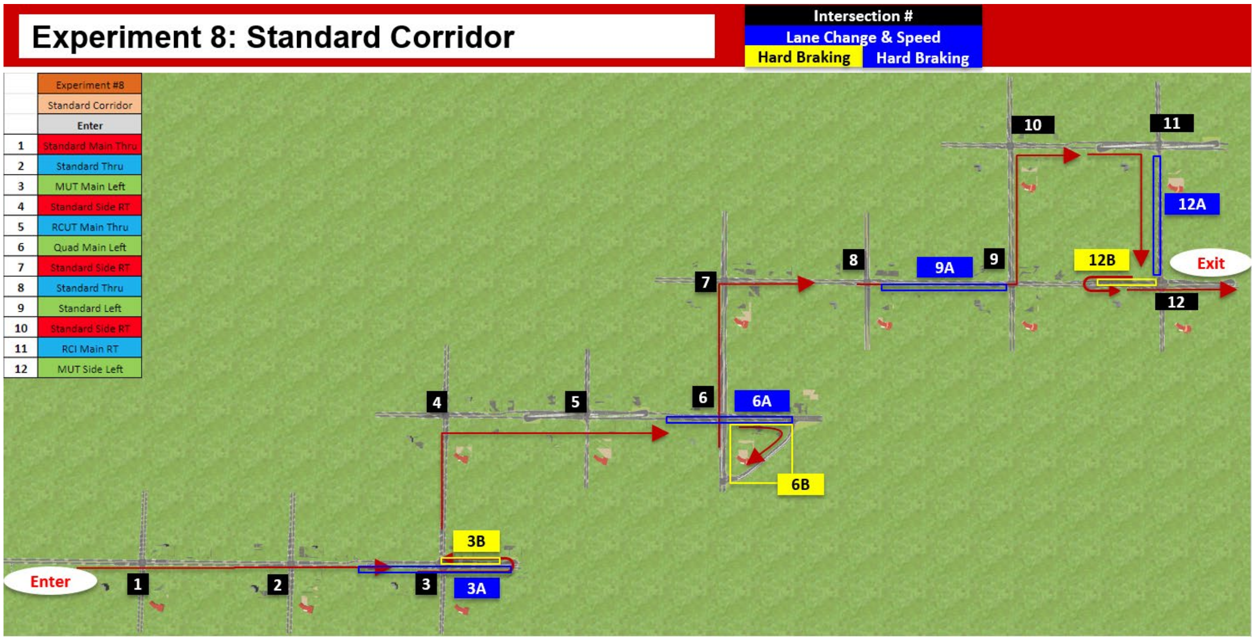

NC STATE UNIVERSITY
9
9C
Hard Braking
X min
X1
Z max
Z + 10.5m (3 ln)
X max
X
[9C start]
DirX 1 → 0.999
X, Z
X1, Z1
9C
[9B end]
DirX 0.999 → 1
Z min
Z – 6 ft
[9C end]
DirZ -0.999 → -1

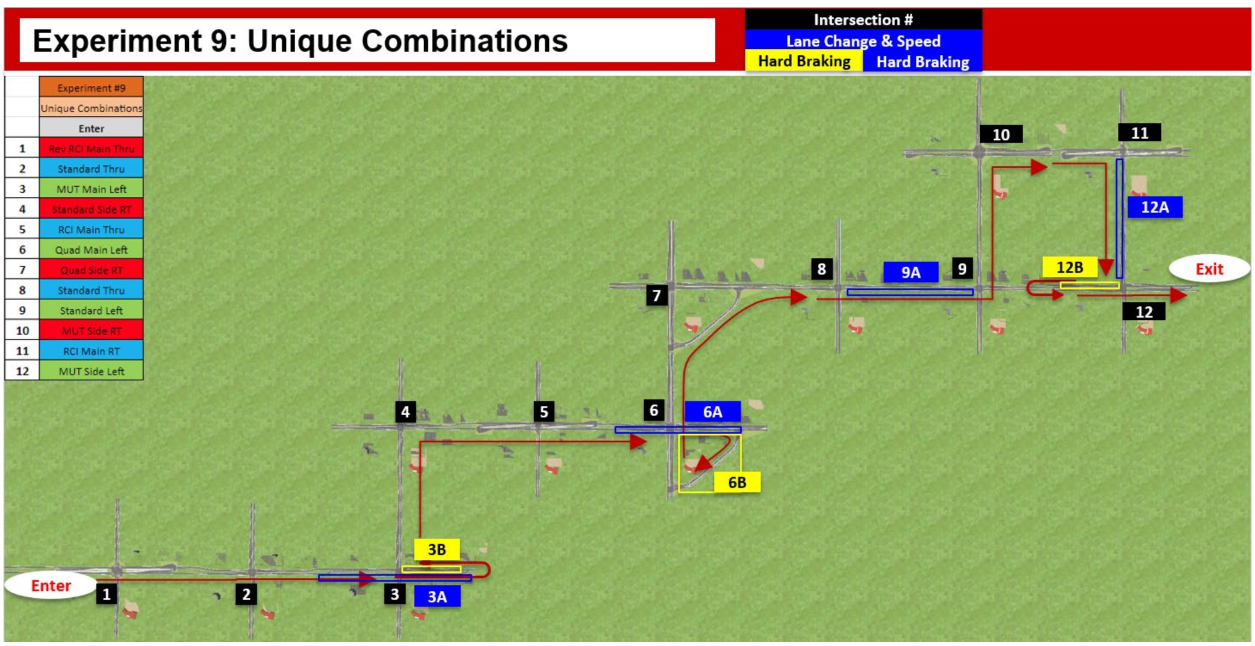

NC STATE UNIVERSITY
12
12A
Lane Change & Speed
Z max
Z + 14m (4 ln)
X min
X
X max
X + 402m
0.25mi (402m)
12A
X, Z
[12A start]
DirX -1 → -0.999
Z min
Z – 6 ft
[12A end]
DirX -0.999 → -1



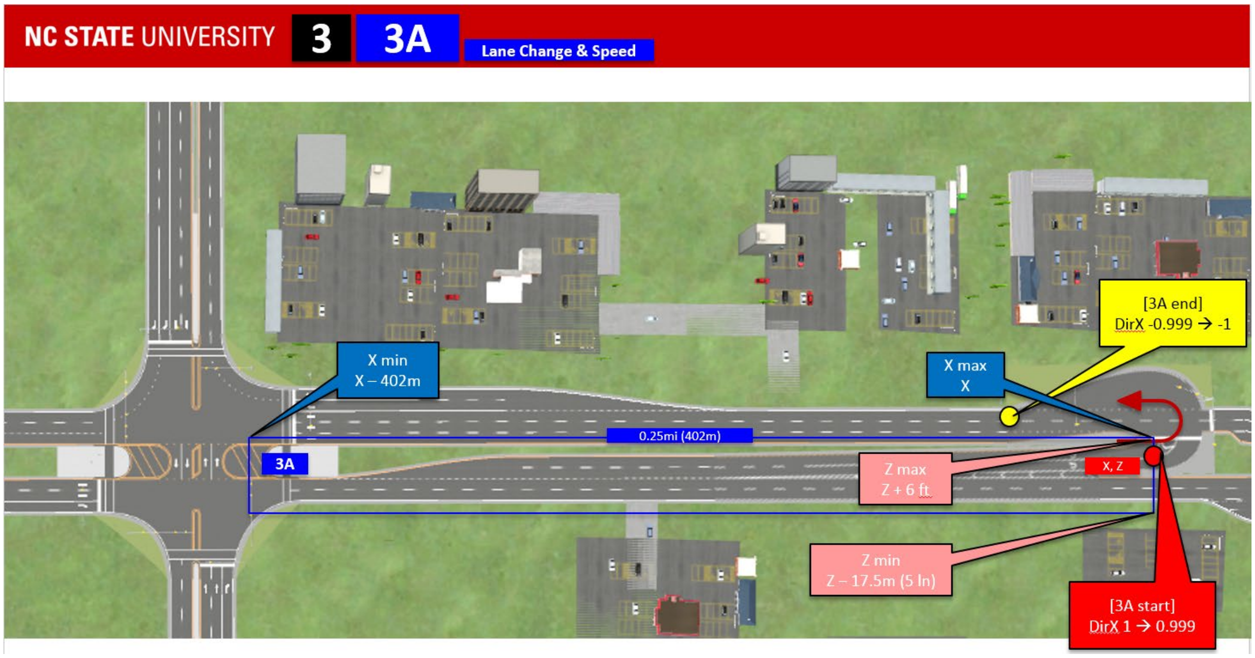
8.5. Experiments 7,8,9 Plan View

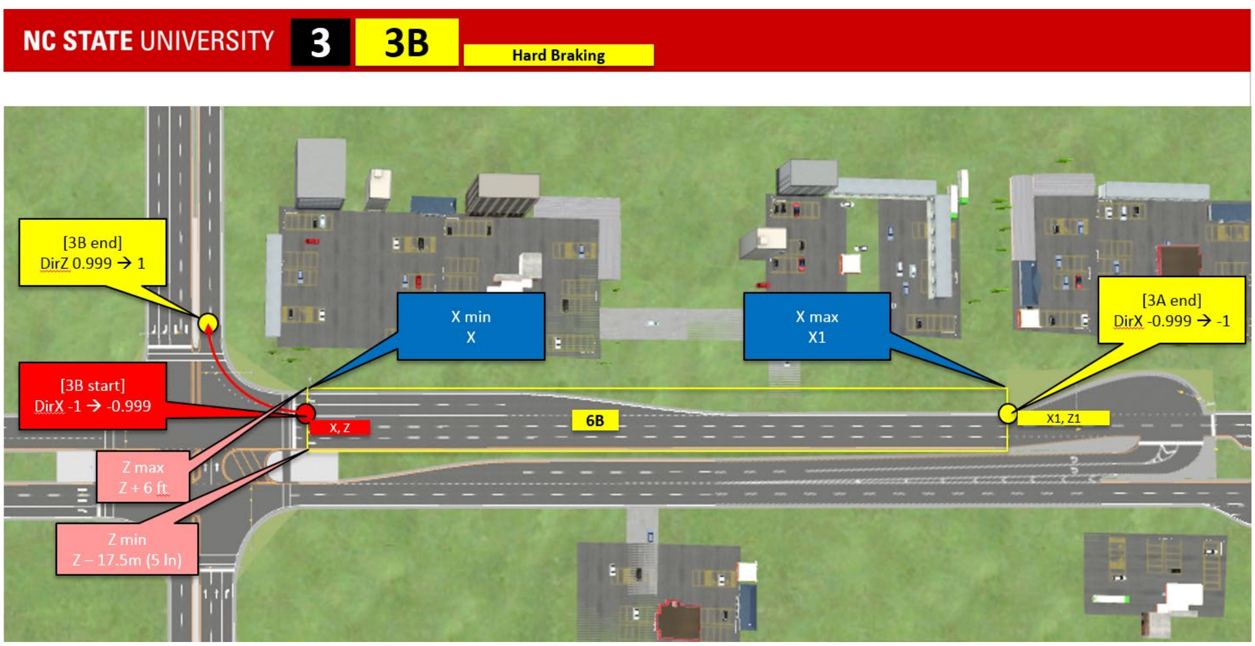


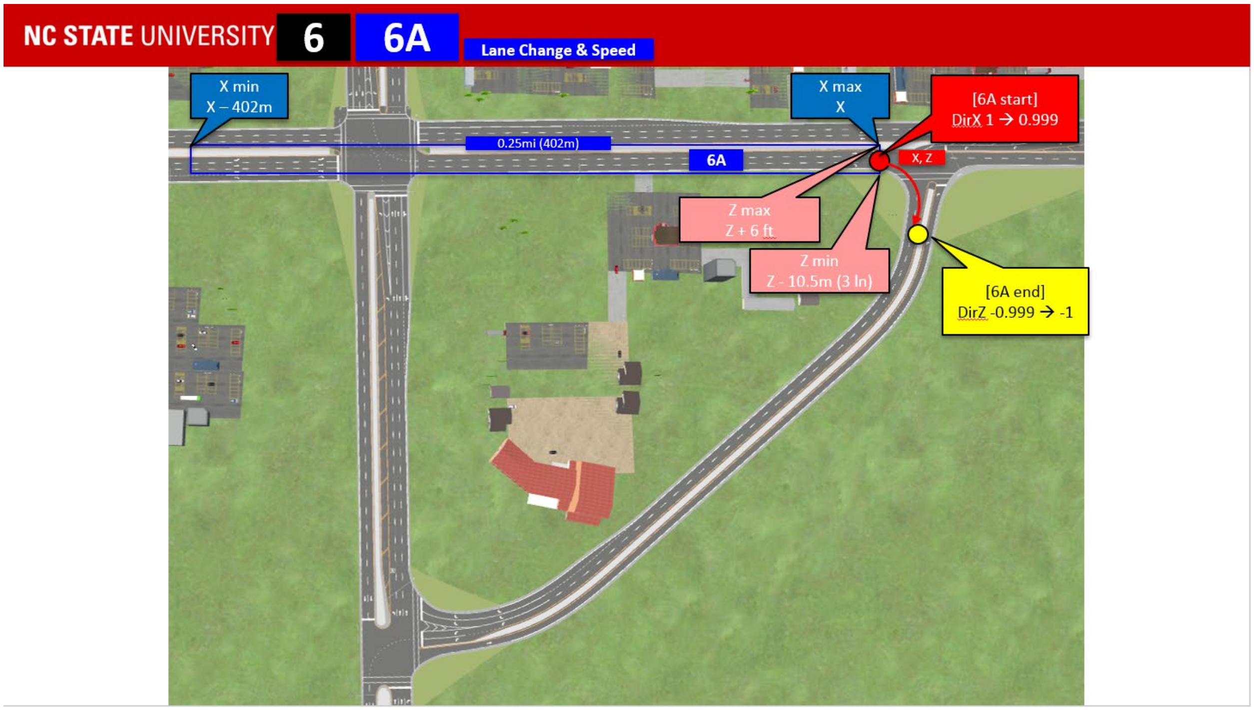


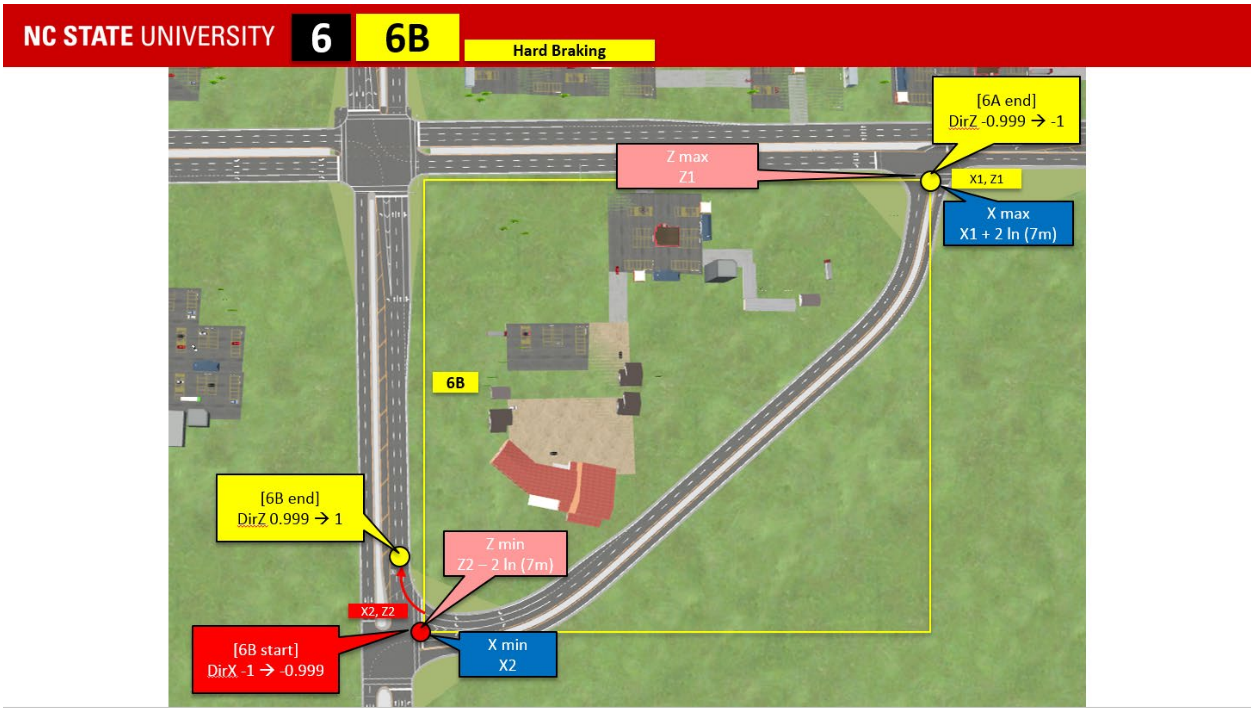


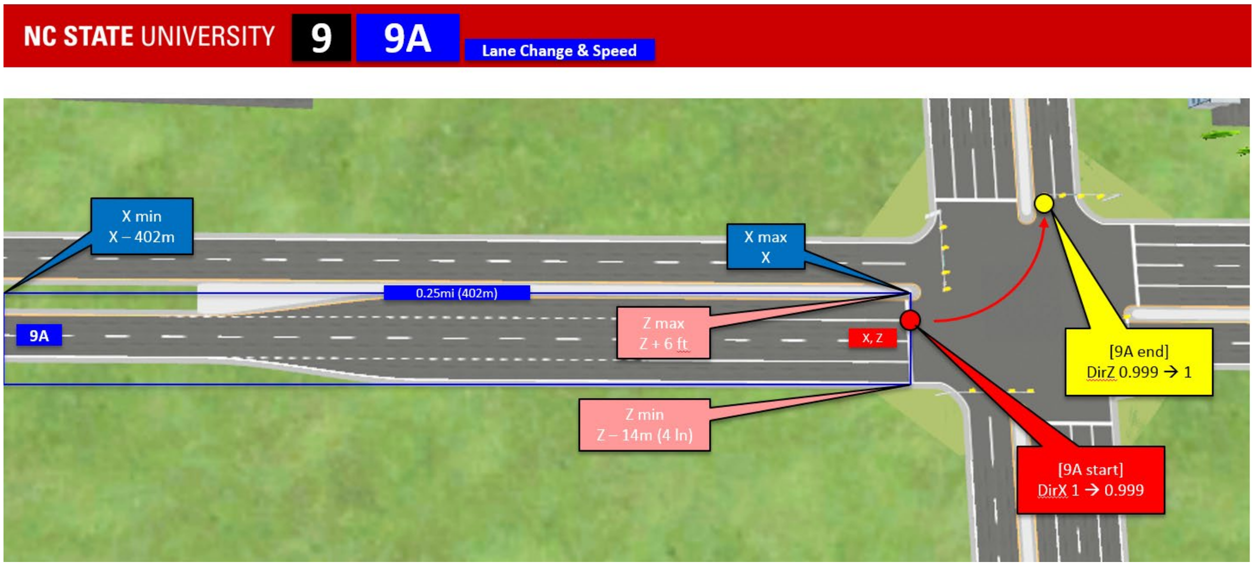
8.6. Experiments 7,8,9 Detection Zones

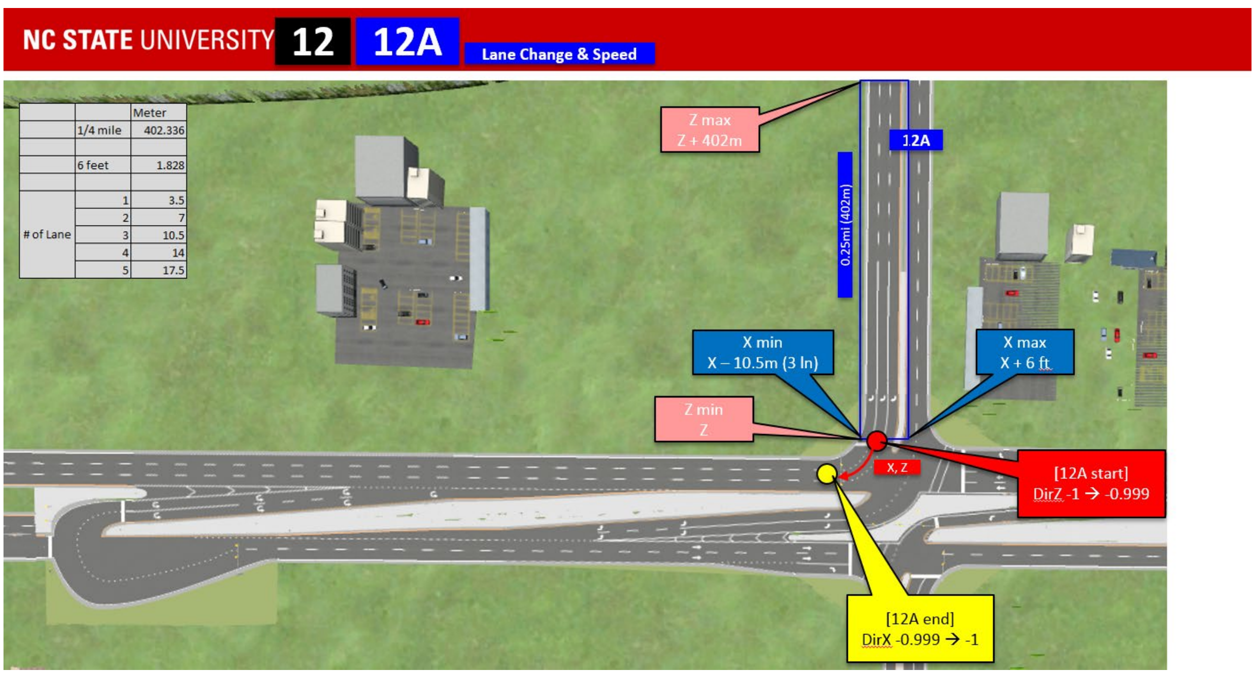

NC STATE UNIVERSITY
3
3A
Lane Change & Speed
X min
X – 402m
0.25mi (402m)
3A
X max
X
[3A end]
DirX -0.999 → -1
Z max
Z + 6 ft
X, Z
Z min
Z – 17.5m (5 ln)
[3A start]
DirX 1 → 0.999

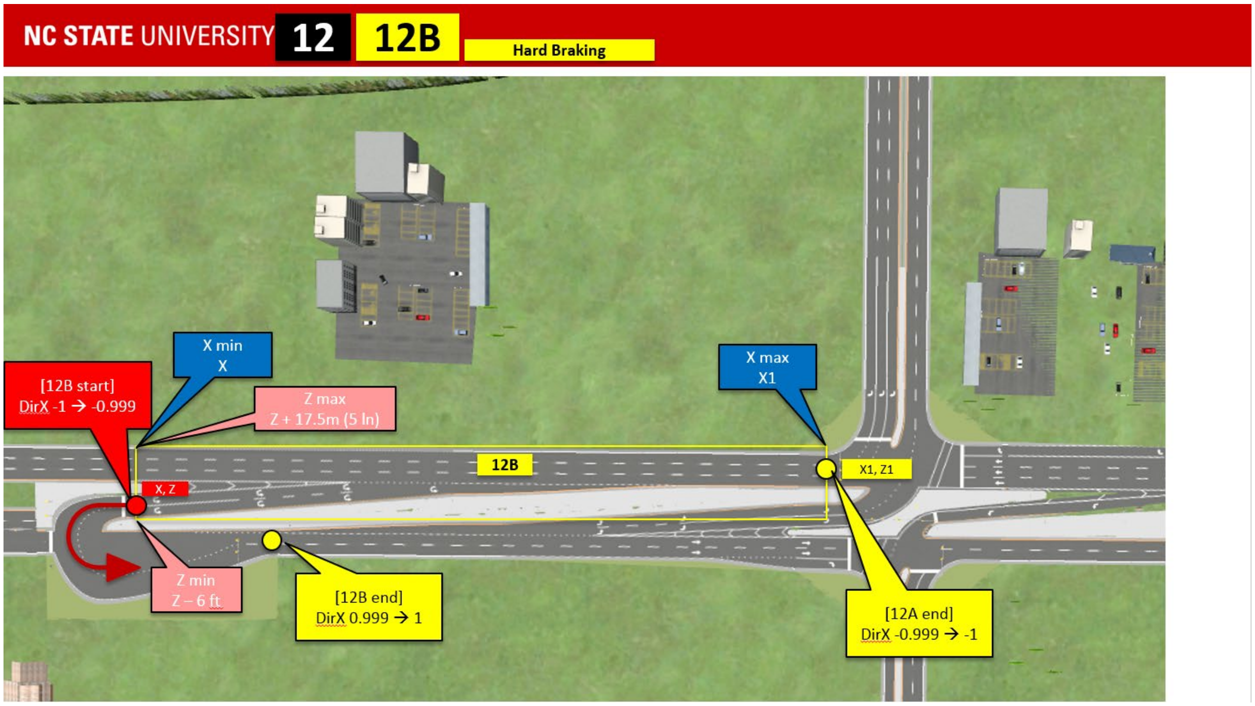

NC STATE UNIVERSITY
3
3B
Hard Braking
[3B end]
DirZ 0.999 → 1
X min
X
X max
X1
[3A end]
DirX -0.999 → -1
[3B start]
DirX -1 → -0.999
X, Z
6B
X1, Z1
Z max
Z + 6 ft
Z min
Z – 17.5m (5 ln)


NC STATE UNIVERSITY
6
6A
Lane Change & Speed
X min
X – 402m
0.25mi (402m)
6A
X max
X
[6A start]
DirX 1 → 0.999
X, Z
Z max
Z + 6 ft
Z min
Z - 10.5m (3 ln)
[6A end]
DirZ -0.999 → -1


NC STATE UNIVERSITY
6
6B
Hard Braking
[6A end]
DirZ -0.999 → -1
Z max
Z1
X1, Z1
X max
X1 + 2 ln (7m)
6B
[6B end]
DirZ 0.999 → 1
Z min
Z2 – 2 ln (7m)
X2, Z2
[6B start]
DirX -1 → -0.999
X min
X2


NC STATE UNIVERSITY
9
9A
Lane Change & Speed
X min
X – 402m
X max
X
0.25mi (402m)
9A
Z max
Z + 6 ft
X, Z
[9A end]
DirZ 0.999 → 1
Z min
Z – 14m (4 ln)
[9A start]
DirX 1 → 0.999


NC STATE UNIVERSITY
12
12A
Lane Change & Speed
Meter
1/4 mile 402.336
6 feet 1.828
# of Lane
1 3.5
2 7
3 10.5
4 14
5 17.5
Z max
Z + 402m
12A
0.25mi (402m)
X min
X – 10.5m (3 ln)
X max
X + 6 ft
Z min
Z
X, Z
[12A start]
DirZ -1 → -0.999
[12A end]
DirX -0.999 → -1


NC STATE UNIVERSITY
12
12B
Hard Braking
X min
X
[12B start]
DirX -1 → -0.999
Z max
Z + 17.5m (5 ln)
X max
X1
12B
X, Z
X1, Z1
Z min
Z – 6 ft
[12B end]
DirX 0.999 → 1
[12A end]
DirX -0.999 → -1