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Examining Optimal Sight Distances at Rural Intersections

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16. Abstract (Limit: 250 words)

Decisions made regarding driver sight distance at rural intersections are complex and require considerations for safety, efficiency, and environmental factors. Sight distance, cross-traffic velocity, and vehicle placements significantly affect driver judgment and behavior at these intersections. A series of rural, two-lane thru-STOP simulated intersections with differing sight distances and traffic speeds were created and then validated by county and state engineers. Experimental data from 36 participants in a time-to-collision (TTC) intersection crossing judgment task and a rural highway thru-STOP intersection driving simulation task was analyzed to clarify the influence of rural thru-STOP intersection characteristics on driving performance and decision-making. Results demonstrated that longer sight distances of 1,000 ft. and slower crossing speeds (i.e., 55 mph) were more accommodating for participants attempting to select gaps and cross from the minor road, corresponding with (1) lower mental workload, perceived risk, difficulty, and anxiousness, and (2) better performance in terms of estimated crash rate, and larger TTCs. Second, longer distances of 1,000 ft. appear to aid drivers' responsiveness on the main road approaching an intersection, specifically when another driver on the minor road runs the stop sign. Minor road drivers positioned close to the roadway at the stop sign, compared to standard stop bar placement, tended to help reduce the speed of main road drivers. Overall, results demonstrated a systematic improvement in the performance of both minor and major road drivers with the implementation of a 1,000-foot sight distance at rural thru-STOP intersections.

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Examining Optimal Sight Distances at Rural Intersections

FINAL REPORT

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EXECUTIVE SUMMARY

Of the many challenges of driving a motor vehicle, safely passing through intersections can prove difficult for drivers. While ubiquitous and commonly traveled, prototypical four-way intersections are roadway designs that carry inherent safety concerns because of their complexity. Limited visibility has been tied to drivers choosing smaller oncoming vehicle gaps, increased stop violations, and encroaching into pedestrian crossings at signalized intersections (Yan & Richards, 2010); however, simply increasing sight distance to produce maximum visibility may not result in linear gains in safety. Increasing sight distance has been shown to only improve driver confidence, but not safety at rail crossings (Ward & Wilde, 1996). Perfectly clearing an intersection of occluding objects (e.g., shrubs or trees) may not improve time-to-collision (TTC) judgments either. A laboratory study found subjects estimated longer than actual TTC of far objects with no occlusion, while they estimated closer or occluded objects as shorter than actual TTC (DeLucia, 2004). Establishing a proper lower and upper limit for visibility at rural intersections is important to not only ensure that the visual environment encourages safe driving behavior but also to minimize cost and labor to ensure clearing and grubbing efforts are efficient.

The simulated world developed for this project was comprised of a series of mock-up rural intersections on a typical Minnesota highway segment, with an environment that bears the characteristics of rural roadways such as straight segments, wooded areas, and shoulders, etc. The rural intersections tested in the simulator should provide a representative sample of a real-world intersection in Minnesota, based on engineer feedback. Researchers reached out to state, county, and academic engineers familiar with rural roadways who could provide an expert perspective on the scenario being tested in the driving simulator. The participating engineers performed three validation tasks: (1) sight estimation, (2) representativeness rating, and (3) mainline drive and feedback. The validity test allowed the research team to make iterative changes to the design and presentation of stimuli in the study based on the engineer feedback. The modifications to the vehicle chassis position in relation to the projection screen provided a solution to the more persistent and seemingly non-addressable issues raised in the validity and pilot testing. The result was a more immersive driving experience with fewer barriers to capturing natural driver decision-making at real-world rural intersections. Overall, the expert ratings were high for representativeness, and qualitative feedback was significantly positive.

Experimental data from 36 participants in (1) the time-to-collision (TTC) intersection crossing judgement and (2) the rural highway thru-STOP intersection driving simulation studies were analyzed to inform county and state engineers and researchers regarding the influence of rural thru-STOP intersection characteristics on driving performance and decision-making.

The TTC intersection crossing study featured nine randomly presented thru-STOP intersections with varying sight distances (400-ft., 600-ft., and 1,000-ft.), varying oncoming cross traffic vehicle speeds (55 mph, 65 mph, and 75 mph), and randomly presented cross vehicle types (small or medium vehicles). Each intersection test scenario lasted approximately 3 minutes for a total of 30 minutes for all TTC sessions. Each intersection presented participants with 10 intersection-crossing judgments, with various time headways separating the crossing vehicles (3-sec, 5-sec, 7-sec, 9-sec, and 12-sec), repeated for small and medium vehicle types, and appeared from the left or right. Participants were trained to keep

their foot on the brake pedal and press the accelerator once a gap was presented between two vehicles that was large enough to safely cross. Between each trial block, participants estimated, via paper survey, the extent to which the intersection crossing judgments taxed their mental processes and reported how risky and dangerous they thought the crossing was and the degree to which they felt anxious making the crossing judgments.

The subjective results of the TTC study demonstrated a consistent trend for stress measures including mental workload, perceived risk, perceived difficulty, and anxiousness. Participants generally reported higher stress for 400-ft. and 600-ft. sight distances, compared to 1,000-ft. sight distances. Additionally, participants tended to report significantly lower stress measures for 55 mph, compared to 65 and 75 mph, with no differences between the two higher speed conditions. An interaction was observed for perceived risk, with no differences between speeds reported at the 1,000-ft. sight distance, indicating that participants may become less sensitive to high-speed risks at very long sight distances.

The performance results of the TTC study demonstrated a significantly higher likelihood for participants to take gaps under conditions for which they reported higher levels of stress (i.e., 400 ft. and 600 ft. distances, and 65 mph and 75 mph) and tended to hesitate for a longer period before deciding to cross during these conditions. A significantly greater number of head movements were observed under the shortest sight distance condition (i.e., 400 ft.) compared to longer distances, mirroring the reported levels of stress and observed hesitation prior to executing a crossing decision. Moreover, the final TTC of the accepted gap tended to be significantly shorter and more likely to be estimated as a collision risk (i.e., shorter than 4.5-sec. TTC at time of crossing decision) under these more stressful intersection scenarios. Similar to perceived risk, the estimated collision analysis revealed an interaction between speed and sight distance with the increase in collision risk of high speeds disappearing at the 1,000-ft. sight distance. Overall, slower speeds (i.e., 55 mph) and longer sight distances (i.e., 1000-ft.) imposed less stress on drivers and led to drivers accepting fewer but ultimately longer TTC/safer gaps than the faster, shorter sight distance scenarios.

The rural highway thru-STOP intersection driving simulation study consisted of a 19-mile drive along a two-way, two-lane rural highway that featured 18 thru-STOP intersections with minor roadways every 1 mile and a 60-mph speed limit. The tree lines leading up to the intersections were manipulated to mirror the three different sight distances used in the TTC study for the minor road of the intersection (i.e., 400-ft., 600-ft., and 1,000-ft.). Each intersection randomly presented a scenario from the right or left that may have one of three levels of initial vehicle appearance (i.e., near, far, absent), and two levels of vehicle behavior (intrudes into the intersection, either from stop or running stop; or stationary, either remaining at stop sign or absent entirely). Vehicles stopped at the stop sign were placed either 13 ft. from the outside lane edge for the "near" condition or 36 ft. from the outside lane edge for the "far" condition. Participants were instructed to travel at 60 mph unless an evasive maneuver was required to avoid an intruding car. Additionally, participants were reminded to engage with the arrows task on the LCD screen in the dashboard at a rate that was comfortable but continuous for the duration of their drives.

On approaching the intersection, drivers were more likely to slow their speed, observed with both mean speed and average speed deviation, when a stationary vehicle was present and near the intersection compared to a vehicle stopped far from the intersection or absent. Approach speeds did not significantly differ with sight distance changes for stationary vehicles. Approach speeds significantly differed by sight distance and vehicle proximity for intruding vehicle scenarios. An interaction was observed where short sight distances (i.e., 400 ft. and 600 ft.) resulted in significantly higher approach speeds and smaller speed deviation when a stop-sign-running vehicle entered the intersection compared to those that entered the intersection from a stop (i.e., either near or far proximity). The effect of the poor responsiveness to the stop-sign-running vehicle was not found with the largest sight distance (i.e., 1,000 ft.). Moreover, participants were more likely to brake farther back from the intersection for intruding vehicles after a stop (i.e., either near or far) compared to stop-sign-running vehicle events for the shorter sight distances (i.e., 400 ft. and 600 ft.). However, the effect was reversed for 1,000-ft. sight distances, with participants braking significantly farther back for stop-sign-running vehicles compared to vehicles that intruded from a stop. This improvement in evasive maneuvers for stop-sign-running events at the 1000-ft. sight distance resulted in longer TTCs and was significantly less likely to result in a collision compared to the two shorter sight distances that featured shorter TTCs and higher collision rates for stop-sign-running vehicle conditions.

The research team can draw several broad conclusions from the presented data of relevance to engineers and safety experts responsible for designing and implementing layouts for rural intersections. First, longer sight distances of 1,000 ft. and slower crossing speed (i.e., 55 mph) appear to be particularly helpful for participants on the minor road attempting to take a gap and cross, given (1) lower mental workload, less perceived risk, difficulty, and anxiousness, and (2) better performance in terms of estimated crash rate, larger TTCs, and less hesitancy. Second, longer distances of 1,000 ft. appear to be somewhat helpful for drivers on the main road approaching an intersection, specifically for the circumstances in which another driver on the minor road runs the stop sign, as participants driving through intersections with 1,000-ft. sight distances were better able to react and avoid cars running stop signs. Third, vehicles placed nearer to the intersection appeared to lead participants to drive at somewhat slower speeds than when vehicles were placed farther away from the intersection, suggesting that the proximity of a vehicle to the intersection led to safer driving behaviors by participants travelling on the main road. Engineers should consider placing stop lines closer to the intersection.

CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

1.1.1 Overall Summary

Of the many challenges of driving a motor vehicle, safely passing through intersections can prove difficult for drivers. While ubiquitous and commonly traveled, prototypical four-way intersections are roadway designs that carry inherent safety concerns because of their complexity. The primary purpose and research problem of this project was to investigate the level of visibility appropriate for intersections, specifically rural intersections, while accounting for other factors that may impact safe crossing. Establishing a proper lower and upper limit for visibility at rural intersections is important to not only ensure that the visual environment encourages safe driving behavior but also to minimize cost and labor to ensure clearing and grubbing efforts are efficient. The scope of the research project was on rural intersections using simulation and experimental methods. For this report, we cover the literature and historical background, the simulation builds and experimental design, the validity testing of the simulation builds, the experiments and results, and conclusions. The research team drew several broad conclusions from the presented data of relevance to engineers and safety experts responsible for designing and implementing layouts for rural intersections.

1.2 LITERATURE REVIEW AND HISTORICAL BACKGROUND

1.2.1.1 Overview

Of the many challenges of driving a motor vehicle, safely passing through intersections can prove difficult for drivers. While ubiquitous and commonly traveled, prototypical four-way intersections are roadway designs that carry inherent safety concerns because of their complexity. Drivers must expend cognitive resources in assessing the visuospatial environment of the roadway design, attend to motor vehicles in motion on each leg of the roadway, and execute a decision-making task to safely traverse the intersection. This section reviews roadway intersection sight distance design standards and guidance criteria (i.e. AASHTO), in addition to human perceptual capability and cognitive performance, to establish an understanding of the literature regarding decision sight distance at intersections on the roadway. Findings from this review then guided the task of developing a comprehensive experimental design and research protocol to meet the safety goals of this study.

1.2.1.2 Intersection Crash Factors

Minnesota intersection crashes (four-way, T, and Y intersections) in 2015 accounted for 30% of all fatal crashes and 41% of all serious injury crashes (NHTSA, 2017). National averages of the same year were slightly lower, with 24% of all fatal crashes and 25% of all serious injury crashes occurring at comparable

intersections (NHTSA, 2017). In past reviews, Minnesota's rural intersection crashes have been shown to be similar to nationwide studies examining intersection-related collisions. A safety analysis surveying 34,175 rural Minnesota crashes in 2004 identified an overall intersection crash rate of 29.5% on two-lane roads, with 38.5% being on rural expressway (e.g. 3-legged, 4-way divided expressway) intersections (Preston, Storm, Donath, & Shankwitz, 2004). Investigating the crash report data involving intersection collisions, Preston and colleagues found rural expressways comprised 21% of all crashes, with nearly 19% occurring on rural two-lane roadways. From these observations, the researchers further explored crash report data determine intersection-related collision causalities or Contributing Factors fields in the legacy Minnesota Department of Public Safety crash report, to explain driver behaviors that may have led to the collisions.

Previous research has examined motor vehicle crash statistics and contributing factors at stop sign controlled intersections. Earlier work attempted to describe collisions at intersections into different typologies based on crash characteristics (e.g. right angle, rear-end crashes). Treat and colleagues (1979) investigated intersection-related crash factors in Indiana, which provided a foundation for classifying *contributing factors* of intersection-related crashes, which included human factors errors at a 93% rate for crash contribution, environmental factors (e.g. sight distance), and vehicle equipment failures. The contributing crash factor of "improper lookout", or decision sight distance, was then added to the motor vehicle collision literature of the time, in addition to their other driver-centered crash analyses (Treat et al., 1979).

Drivers' stop sign compliance and crossing behavior at two-way stop signed intersections was evaluated through a meta-analysis by Chovan, Tijerina, Pierowicz, and Hendricks (1994). The study revealed that in a sample of 100 crash reports collected at intersections, 42 involved drivers' failure to stop and 58 involved drivers deciding to unsafely cross the intersection after stopping. Additionally, Chovan and colleagues' examination of intersection crash factors deconstructed driver behavior into drivers' failure to identify oncoming traffic (62%), gap size and perceptual miscalculation (20%), and sight distance restriction (14%). Similarly, Volpe Center researchers observed drivers' inability to detect safe gaps at crossings accounted for four out of five collisions at stop sign controlled intersection crossings (Najm, Smith, & Smith, 2001).

Further work analyzing intersection collision data, including data provided by Chovan and colleagues, underline the significant safety concerns regarding intersection crossing. Drivers' inability to perform sufficient visual searches in order to identify oncoming traffic and estimate safe gaps in traffic appear to increase crash likeliness and severity (Chovan et al., 1994; Geedipally, Patil, & Lord, 2010; Retting, Weinstein, & Solomon, 2003). Visual search requirements increase and subsequently present greater opportunities for error as intersections become more complex with greater numbers of conflict points. Figure 1.1 and Figure 1.2 provide an example of differing numbers of potential collision conflicts at a standard 3-legged, 4-way divided rural expressway intersection compared to a conventional four-legged intersection, the latter which would experience greater incidence of crashes (Harwood, Mason, & Brydia, 2000; Hanna, Flynn, & Tyler, 1976).
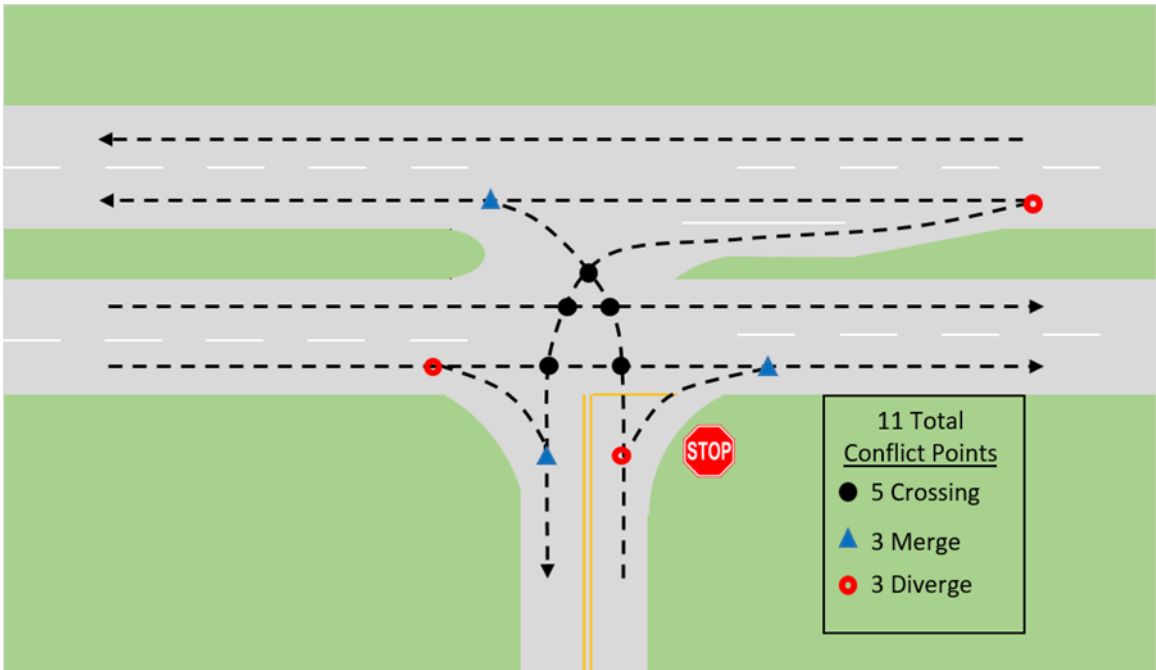
Figure 1.1 Prototypical 3-legged, 4-lane divided rural expressway intersection and potential conflict scenarios. Adapted from Maze, Hochstein, Souleyrette, Preston, & Storm, 2010.
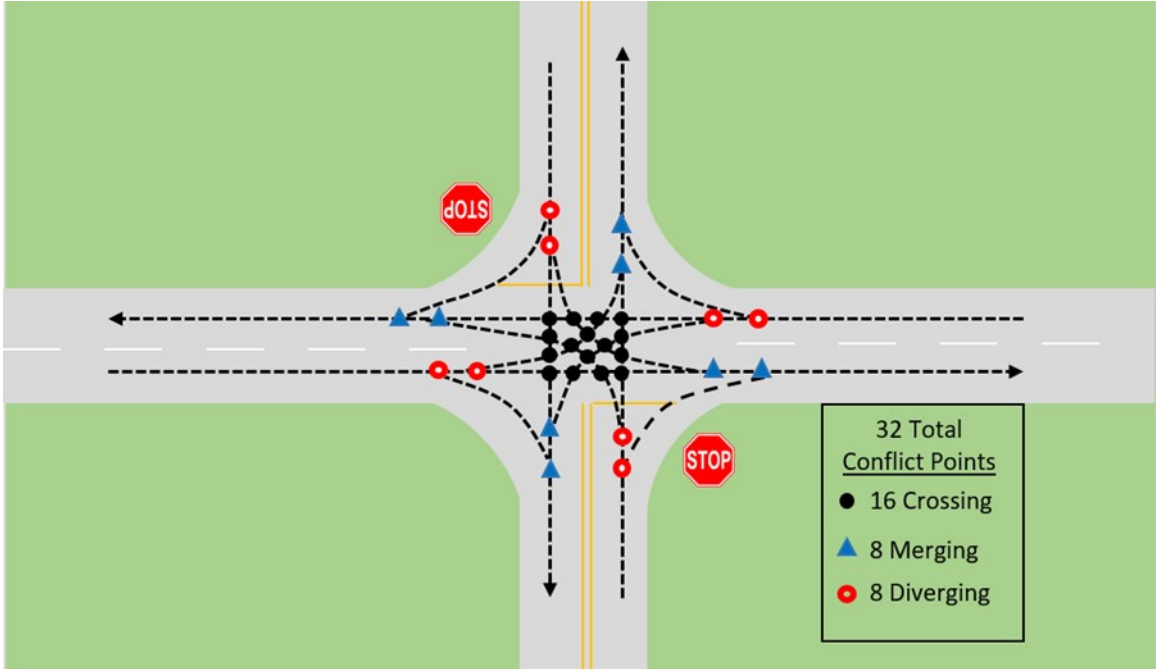
Figure 1.2 Prototypical 4-legged 2-lane undivided rural intersection and potential conflicts scenarios. Adapted from Bared, 2009.

1.2.1.3 Infrastructure design revisions to mitigate intersection crashes

For decades, researchers, transportation safety agencies, and state DOTs have attempted to solve the problems of injury, death, and financial burdens that intersection-related collisions create (Najm et al., 2001). Efforts in mitigating intersection crashes over time have included multiple changes to existing roadway design. One major element associated with lower crash rates was the installation of left turn and right turn lanes (Parker, Flak, Tsuchiyama, Wadenstorer, & Hutcherson, 1983; Hauer, 1988; Harwood et al., 2000). Such modifications do not present a clear improvement in safety because the addition of left turn lanes has been associated in increased crashes in certain situations (Poch & Mannering, 1996). Wider shoulder widths have been found to result in a smaller crash incidence and lower probability of serious crashes (David & Norman, 1976), which are particularly important on 3.0 m (10 ft.) lane widths on low ADT roadways (Zegeer, Stewart, Council & Neuman, 1994). Similarly, acceleration lanes, restricting turning maneuvers, and increased signage have been implemented and have produced mixed results in terms of effectiveness.

Intuitively, solutions to address the problematic causal crash factor of drivers unsafely pulling out into the intersection might appear as simple sign, such as a "Look, Look Again, or Look Both Ways.' Figure 1.3 depicts a conventional 'LOOK' instruction sign as described in the MUTCD. While these types of signs can be commonly found at train crossings on rural roadways, the MUTCD and state variants of the MUTCD do not currently allow for such signage on rural roadways.
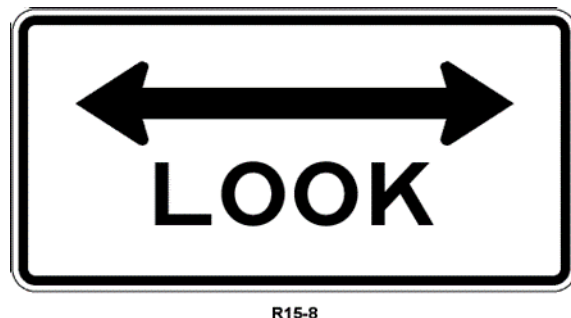
Figure 1.3 MUTCD supplied Look sign for rail intersection applications.

1.2.2 Decision Sight Distance and Roadway Design: Crossing Maneuvers at Rural Intersections

Crash data on intersection crossing collisions at rural thru-stop intersections highlight the impact that roadway infrastructure design has on collision conflicts at those locations (Preston et al., 2004). Previous work has shown that drivers have trouble estimating oncoming traffic speed and distance relative to the intersection when they are making crossing judgments and decisions while at the minor road location (Harwood, Mason, & Brydia, 2000). Providing drivers greater sight distances at intersections has been associated with reduced crash frequency (David & Norman, 1979; Harwood et al., 2000). Further, minor-road approaches that have sufficient commercial truck volumes have been recommended to have

longer sight distance. Horizontal curves have been shown to be significantly associated with higher crash frequency, making it more difficult for a driver to discern the proper travel path of the approaching vehicles. Moreover, vertical curves near intersections have been attributed to crashes due to imposing limited sign distance (Fambro at al., 1989). Accounting for these factors and modifying the environment to provide sight distance based on guidelines informed by this body of work requires engineers to utilize reference manuals, such as the MUTCD, MN MUTCD, or AASHTO "Green Book" (see below).

AASHTO Case IIIB: Intersection Sight Distance (ISD) at intersection crossing scenario. Case IIIA: Stop Control--Crossing Maneuver. ISD for a vehicle on a stop-controlled approach on the minor road to accelerate from a stopped position and cross the major road.

AASHTO's *A Policy on Geometric Design of Highways and Streets*, commonly referred to as the "Green Book", dedicates a significant portion of its content to the design guidelines associated with decision sight distance and human factors considerations of roadway design for the driver. AASHTO defines the criteria of decision sight distance as the "distance required for a driver to detect an unexpected, or otherwise difficult to perceive information source or hazard in a roadway environment that may be visually cluttered, recognize the hazard or its threat potential, select an appropriate speed and path, and initiate and complete the required maneuver safely and efficiently." In other words, AASHTO summarizes the safety related variables present on the roadway, such as traffic, roadway design, and potential collision conflicts, and how they influence or impact human perception and driver decision-making. Due to the complexity of the driving task, compounded by various uncertainties and other factors on the road, drivers may make judgement errors when crossing intersections.

Sight distance, or the driver's ability to see an object (e.g. vehicle roof) at consistent height relative to the roadway, is an important factor to consider. According to AASHTO's Green Book (2001; 2011), the following are general factors for identifying circumstances in which to consider sight distance and decision sight distance:

- Complex roadway, infrastructure, or likely traffic conditions
- Visibility reduced by infrastructure, environment, or visual field to traffic controls
- Vehicle speeds on primary and arterial roadways
- ADT and high traffic density
- Other contributing factors that increase perception-reaction model values

Metric						US Customary					
Design speed (km/h)	Decision sight distance (m)					Design speed (mph)	Decision sight distance (ft)				
	Avoidance maneuver						Avoidance maneuver				
	A	B	C	D	E		A	B	C	D	E
50	70	155	145	170	195	30	220	490	450	535	620
60	95	195	170	205	235	35	275	590	525	625	720
70	115	235	200	235	275	40	330	690	600	715	825
80	140	280	230	270	315	45	395	800	675	800	930
90	170	325	270	315	360	50	465	910	750	890	1030
100	200	370	315	355	400	55	535	1030	865	980	1135
110	235	420	330	380	430	60	610	1150	990	1125	1280
120	265	470	360	415	470	65	695	1275	1050	1220	1365
130	305	525	390	450	510	70	780	1410	1105	1275	1445
						75	875	1545	1180	1365	1545
						80	970	1685	1260	1455	1650

Avoidance Maneuver A: Stop on rural road—t = 3.0 s
Avoidance Maneuver B: Stop on urban road—t = 9.1 s
Avoidance Maneuver C: Speed/path/direction change on rural road—t varies between 10.2 and 11.2 s
Avoidance Maneuver D: Speed/path/direction change on suburban road—t varies between 12.1 and 12.9 s
Avoidance Maneuver E: Speed/path/direction change on urban road—t varies between 14.0 and 14.5 s

Figure 1.4 AASHTO Decision Sight Distance specifications for critical locations on the roadway (AASHTO Green Book, 2001; 2011).

In addition, AASHTO dictates standards and measurements for determining decision sight distance values. Some guidelines, such as specified eye height (1080mm) relative to an object of 600mm, consider the driver's psychophysiological (i.e. vision) capabilities to detect other vehicles or potential hazards on the roadway. For traffic officials to assign an appropriate decision sight distance, AASHTO's 2011 iteration of the Green Book provides the decision sight distance values based upon design speed and time required to perform a predicted driver avoidance maneuver, see Figure 1.4. As described, varying degrees of pre-maneuver time, 3 sec. to 9.1 sec. are prescribed to ensure the driver has enough advance notice of the upcoming roadway conditions, from which to calculate and executive a corrective

action (e.g. brake immediately).
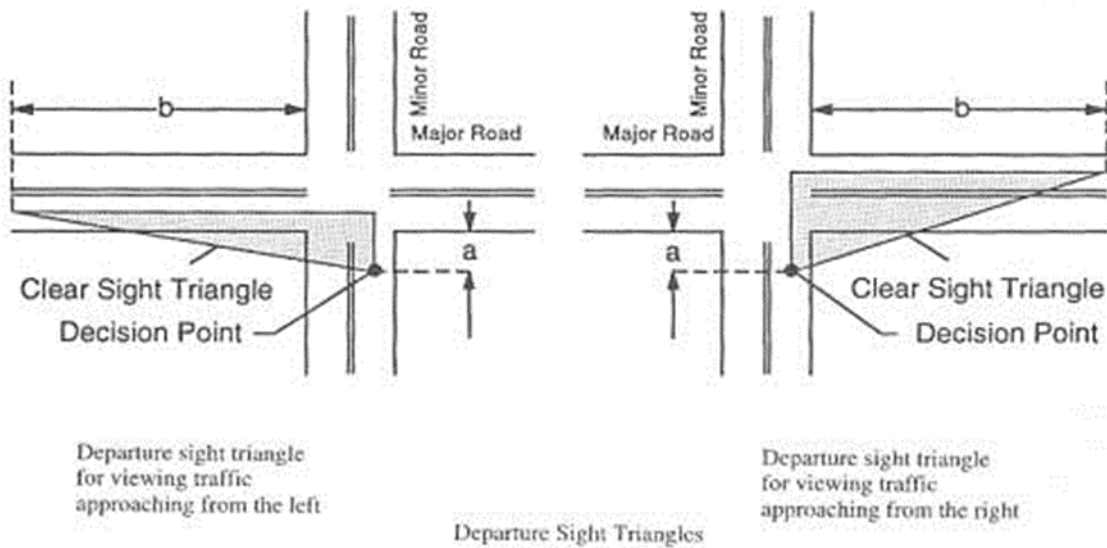
Figure 1.5 AASHTO Intersection Sight Distance Departure Sight Triangle and Decision Point Location (Green Book 2001; 2011).

Federal guidelines on roadway intersection designs within the AASHTO Green Book categorizes varying intersections by case classifications, which vary by a roadway design and driver maneuvers while navigating through the roadway. The Green Book (2001; 2011) details decision sight distance considerations where drivers need to safely perform crossing maneuvers across a major roadway from a minor road stop-controlled location. A primary factor in roadway design to provide ample decision sight distance is explained by the intersection sight triangle in Figure 1.5 that depicts a drivers' field of view at an intersection and the corresponding decision point location on the adjacent major road. The most recent AASHTO guidelines for the departure sight distance triangles are based upon Harwood, Mason, & Brydia's (2000) work performing field observations of driver behavior when discerning gap acceptances at stop-controlled intersections on minor roads (Hardwood, Mason, & Brydia, 2000). A headway of 7.5 sec. is recommended through calculating the sight distance triangle to achieve optimal safety and efficiency in IIIB crossing maneuver circumstances.

Driver visual perception and cognitive considerations

Assuming that providing minor road drivers with the prescribed 7.5 second sight distance of on-coming vehicles on crossing major roads were not only necessary but sufficient to reduce crashes, our roadway safety goals would have been met. Driver behavior and decision-making is not so reliable or predictable, however. Despite presenting drivers with clear views at rural intersections, they still choose unsafe circumstances (e.g., close approaching vehicle) to enter the intersection. Given the persistence of

serious injury and fatal crashes at treated rural THRU-stop intersections, further examination of the visual and cognitive factors that contribute to safety risk and poor driver judgment is needed.

Previous transportation human factors research has evaluated human perceptual capability and the accompanying task hierarchies to complete intersection navigation while driving (Laberge, Creaser, Rakauskas, & Ward, 2006). The HumanFIRST Laboratory's previous work involving Intersection Decision Support applications in rural Minnesota included a task analysis detailing the required driver actions to successfully perform a crossing maneuver at a stop-controlled intersection. The task analyses conducted by Laberge and colleagues illustrate the complexity in performing an intersection crossing maneuver. To cross safely, a driver must perform a sequence of primary actions (e.g. detect traffic-control devices), each consisting of secondary or sub-tasks (e.g. detect stop signs, speed signs) each requiring varying levels of mental effort and visual attention to accomplish. The task analysis outlines the intersection crossing procedure from the driver's viewpoint, beginning at the initial approach of the intersection, the safety and situational assessment of the intersection environment before the crossing action, and the execution of the crossing action. In total, the analysis outlines approximately 26 sub-tasks required to perform the maneuver, including the driver to be attentive and engaged at all times to ensure safety while crossing the intersection.

This work was expanded into a second task analysis highlighting potential human factors errors while performing the intersection crossing maneuver task was also conducted (Laberge et al., 2006). Decision sight distance can account for each task described by the potential error and problematic outcomes listed in the error identification. Errors included failures to detect vehicles or gaps and failure to accurate assess speeds or gaps. Clearly, the driver's ability to view the roadway and each variable in the driving environment, such as instances featuring dense traffic with few adequately sized gaps or driver visibility limited by infrastructure or natural features, is critical to the safe passage through an intersection crossing.

1.2.2.1 Determining factors for intersection crossing decision errors

The work by Laberge et al. highlights a number of errors drivers may make in the course of entering an intersection, including failing to detect traffic, inaccurately estimating actions, velocity, or distance of vehicles, or inaccurately estimating gaps in between vehicles. These errors are easier to understand under circumstances of minimal sight distance, but harder to understand under circumstances of greater sight distance. The primary areas investigated in the present study is how they make time and distance predictions.

1.2.2.2 Driver visual attention while at intersections

Some human factors research studying driving behavior has incorporated eye-tracking technology to evaluate drivers' visual patterns as they perform the task of driving. For example, insufficient visual attention acts as a major contributing factor to collisions at intersection (Werneke & Vollrath, 2012).

Driving experience, or the cumulative time spent performing the driving task, has also been found to influence the ways in which drivers allocate their visual attention while driving. Drivers with more experience have been found to demonstrate visual search behaviors that include a wider range of the visual scene in front of them, when compared to inexperienced or novice drivers (Mourant & Rockwell, 1972). In addition, less experienced drivers appear to focus on one particular area of their visual scene for longer when compared to experienced drivers, which is correlated with an increase in required time to visually process one area of interest or object (e.g. traffic sign, vehicle). An increase in time spent visually focusing, or fixating, on one location when the visual complexity and density of a scene increased has also been observed among inexperienced drivers (Everatt & Underwood, 1992; Mackworth, 1976; Loftus & Mackworth, 1978). Further, less experienced drivers were also observed to utilize less of their horizontal perceptual field when performing a visual search, suggesting that these novice drivers did not have well-developed visual searching skills to aid in discerning hazards associated with demanding driving conditions (Crundall & Underwood, 1998). These studies and their results suggest that newer drivers demonstrate a significantly lower ability to perform safe visual search strategy while driving; a finding that underlines the importance of continued study of how novice drivers use their visual attention at intersections.

1.2.2.3 Driver gap acceptance when choosing to enter the intersection

Driver's cumulative visual perception and judgement making to enter the intersection is ultimately reflected in their gap acceptance, which plays a significant role in rural intersection collisions (Laberge et al., 2006; Preston et al., 2004). Vision is a key component in gap acceptance. Difficulty for drivers choosing to enter the intersection is affected by the variables of visual scenery complexity, obstructed vision at intersections, sight distance limitations upstream and downstream, and insufficient vehicle detection (i.e. did not perceive an incoming vehicle, entered intersection; Chovan et al., 1994; Laberge et al., 2006; Preston et al, 2004). In addition, inadequate or incorrect time to collision distance estimation, oncoming traffic speed underestimation, and gap sizes between approaching vehicles also have been found to negatively impact drivers' intersection crossing safety (Scialfa, Guzy, Leibowitz, Garvey, & Tyrrell, 1991; Hancock & Manser, 1997).

The size-arrival effect described by DeLucia (2013) indicates the difficulty drivers have at intersections making accurate judgments about time-to-collision (TTC) for large or small objects at near or far distances. Large, far objects are assumed to arrive sooner than small, near objects (such as motorcycles, Horswill, Helman, Ardiles, & Wann, 2005). Rural thru-STOP intersections may present a wider range of vehicles from large, commercial or farm vehicles to small motorcyclists. Drivers may underestimate the arrival time to an intersection for smaller vehicles at far distances compared to large motor vehicles at the same intersection.

Limited visibility has been tied to drivers choosing smaller oncoming vehicle gaps, increased stop violations, and encroaching into pedestrian crossings at signalized intersections (Yan & Richards, 2010); however, simply increasing sight distance to produce maximum visibility may not result in linear gains in

safety. Increasing sight distance has been shown to only improve driver confidence, but not safety at rail crossings (Ward & Wilde, 1996). Perfectly clearing an intersection of occluding objects (e.g., shrubs or trees) may not improve time-to-collision (TTC) judgments either. A laboratory study found subjects estimated longer than actual TTC of far objects with no occlusion, while they estimated closer or occluded objects as shorter than actual TTC (DeLucia, 2004). Further, a study of drivers in Japan near rice fields with perfect visibility found poor peripheral detection of vehicles on collision courses with drivers, because the vehicles appeared static (Uchida et al., 2001). While novice drivers are often observed to exhibit behavioral deficits at intersections, older drivers appear to be disproportionately affected by exposure to approaching objects with long TTCs, as they overestimate TTC compared to younger drivers (DeLucia, Bleckley, Meyer, & Bush, 2003).

More recent research investigating drivers' visual behaviors at intersections may further indicate that driver's confidence or risk perception of a roadway may negatively influence their visual scanning and decision-making at intersections. Notably, driving simulation research has observed counterintuitive driving and visual behavior at intersections: drivers were more likely to pull out into an intersection at riskier times while neglecting to sufficiently perform safe visual attention scanning during the lead up to and the execution of the maneuver when the roadway conditions had low traffic volume (Werneke & Vollrath, 2012). In other words, drivers have been observed choosing fewer safe gaps and paying less attention when they encounter intersections without high traffic volumes on the major road.

Finally, the impact of intersection visibility on risk perception and vehicle-to-vehicle trust should be considered, as well. Kinosada and Usui (2015) found that drivers may become riskier in crossing judgments when they assume cross-traffic drivers will slow to avoid them based on their own vulnerability along with no objective indication of such slowing. This phenomenon has been observed among interviewed bicyclists struck by cars who, among those who saw the vehicle before the crash, 92% of the time incorrectly assumed they were seen by the driver of the vehicle who would in turn yield for them (Räsänen & Summala, 1998). It may be the case that drivers entering stop-controlled intersections with high visibility assume they are visible to oncoming traffic, who will slow to accommodate their crossing.

1.2.3 Conclusion

The literature reviewed for this study identified some of the large and varying factors that lead drivers to unsafely cross intersections due to failure to detect the presence of or incorrectly predict the arrival of oncoming vehicles on the crossing lanes. Further, several counterintuitive elements have been identified related to confidence and visibility that suggest simple visibility increases may not necessarily result in linear gains in safety. It may be that the relationship between safety and intersection visibility is curvilinear, in that risk is mitigated with improved visibility but may diminish at high visibility levels. Establishing a proper lower- and upper-limit for visibility at rural intersections is important to not only ensure that the visual environment encourages safe driving behavior, but also minimizes cost and labor to ensure clearing and grubbing efforts are efficient.

CHAPTER 2: SIMULATION BUILD AND EXPERIMENTAL DESIGN

2.1 INTRODUCTION

In the context of improving crossing judgments on rural intersections, while drivers require the necessary information (e.g., distance and speed of oncoming vehicle), increasing the sight distance to spot oncoming vehicles and thereby increasing the time to make judgments may actually have unexpectedly negative effects on accuracy in judging when the oncoming vehicle will arrive at the intersection. The following experimental tasks were designed to:

1) Integrate subject matter expert feedback gained from the validity test into the simulated world and protocol design.
2) Explicitly manipulate speed, distance, and viewing distance, while measuring judgment of TTC and confidence
3) Explore active driving by manipulating viewing distance for participants driving on major roads approaching thru-STOP rural intersections to determine if viewing distance and placement of vehicles on the minor road impacts factors such as willingness to brake or slow down when approaching an intersection.

2.2 DRIVING SIMULATOR AND ENVIRONMENT

The research effort was conducted in the HumanFIRST partial motion-based driving simulator manufactured (see Figure 2.1) by Realtime Technologies, Inc. The simulator consists of a 2013 Ford Fusion full vehicle cab with realistic operation of controls and instrumentation including force feedback on the steering and realistic power assist feel for the brakes. The simulator is powered by the latest generation PCs with the latest generation simulation creation software that provides high fidelity simulation for all sensory channels to generate a realistic presence within the simulated environment. The visual scene is projected through three new, high lumen, high resolution projectors and a seamless, cylindrical screen which will maximize the 210-degree forward horizontal field of view. Complimentary right and left LCD mirrors are embedded into the standard mirror housing of the chassis for an OEM look.

A custom-fitted glass cockpit includes a dashboard cluster panel and 17-inch center stack touchscreen panel allows for testing of in-vehicle displays and feedback similar to the most advanced vehicles on the road today. A custom-fitted glass cockpit includes a dashboard LCD display and center stack touch-screen display that can replicate any configuration of vehicle gauges and display. Auditory feedback pertaining to the driving world is provided by a 3D surround sound system.

Figure 2.1 HumanFIRST immersive driving simulator and practice drive.

The simulated world was comprised of a series of mock-up rural intersections on a typical Minnesota highway segment, with an environment that bears the characteristics of rural roadways such as straight segments, wooded areas, shoulders, etc. The rural intersections tested in the simulator should provide a representative sample of a real-world intersection in Minnesota, based on engineer feedback in the validity test, see Chapter 3.

The roadways were created as a series of thru-STOP intersections. Both legs of the intersections were two-lanes, the main road designed for 60 mph travel speeds. The lane widths were 12 ft. wide, with 4 ft. shoulders, and 14 ft. ditches on either side of the roadway. The pavement was light gray and signs were limited to stop signs.

2.3 EXPERIMENTAL DESIGN

2.3.1 TTC Simulator Study Overview

This study utilized a within-subjects design approach with all participants being exposed to all conditions, which has benefits in terms of statistical power. The design is a 3 × 3 within-subjects design

with three levels of visibility distance (400 ft., 600 ft., 1000 ft.) and three levels of oncoming vehicle speed (55 mph, 65 mph, 75 mph), see Figure 2.2.

Participants were presented a simple practice simulation in which they will be prompted with instructions on the screen regarding the TTC gap acceptance task. They were asked to keep their foot on the brake pedal as they watch a series of black vehicles pass through the intersection from the left. When a safe gap is presented in the practice (denoted by a yellow car clearing the intersection), they were instructed to indicate the gap is large enough to cross by pressing the accelerator pedal (see https://www.youtube.com/watch?v=yNgo-l3_Y4w for video demonstration).

Next, each participant performed a series of six practice drives with the vehicle, which involves crossing intersections, in order to familiarize them with the vehicle and crossing capabilities (see https://www.youtube.com/watch?v=us8r73rD3NQ for video demonstration).
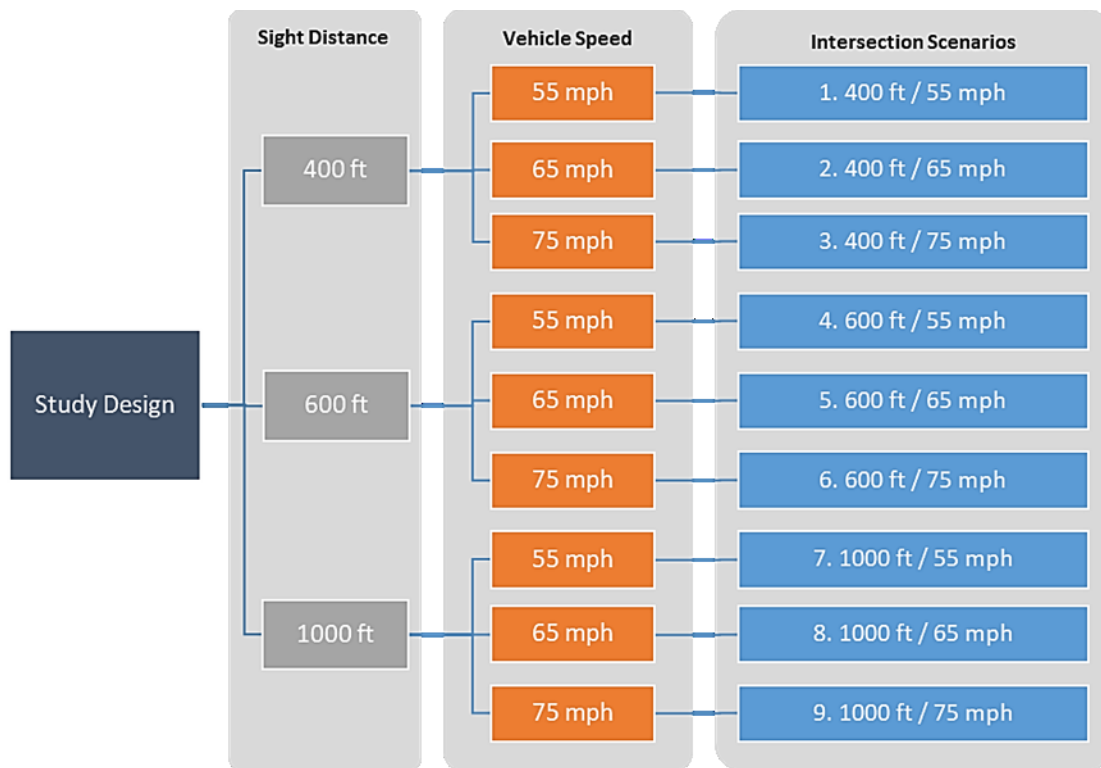
Figure 2.2 TTC study 3x3 experimental design with 9 simulated intersection

For experimental trials, participants waited at simulated intersections with varying degrees of visibility (distance), oncoming vehicle speeds, and oncoming vehicle sizes. Three example demos can be found for the 400 ft./55 mph intersection pairing (https://www.youtube.com/watch?v=qHs6f6-Aqhc), the 600 ft./65 mph intersection pairing (https://www.youtube.com/watch?v=uvHU13pQQ0A), and the 1000 ft./75 mph intersection pairing (https://www.youtube.com/watch?v=cFgJ82SuI7E). The participant watched a series vehicles pass through the intersection from the left and right. The TTC of the vehicles

was either 3 sec, 5 sec, 7 sec, 9 sec, or 12 sec, ordered at random. They pressed the accelerator pedal when they perceived the gap between vehicles is large enough to safely cross the intersection. They were instructed to keep their foot pressed on the brake pedal if the gap appears too short to safety cross.

2.3.2 TTC Simulator Study Procedure

Prior to driving on the simulator, participants were provided with a general background of the study and a detailed explanation of the purpose of their participation. After participants read and signed an informed consent form, they had their vison tested using a standard Snellen Acuity Chart to ensure they met minimum Minnesota regulations for driving (20/40 vision corrected or uncorrected).

Participants completed a Demographic and Driving History Questionnaire (see Appendix B) and a Driving Stress Inventory (Appendix C; Matthews, Desmond, Joyner, Carcary, & Kirby, 1997) that asks questions about their age, years licensed, frequency and type of driving, and other related driving behaviors. Participants were also queried if they have recently been in a crash or near crash at the start of each testing session. Participants will be provided with a general background of the project and a detailed explanation of the purpose of their participation.

Participants completed the two practice drives prior to beginning the experimental condition. For the experimental condition, the presentation order of intersection conditions was randomized. Participants were asked to indicate by pressing the accelerator pedal as soon as they think they can safely cross the intersection but hold their foot to the brake pedal if they do not believe they have sufficient time to safely cross. The participants were asked to make their decisions as they would in the real world, to avoid crashes and adhere to the law.

After each intersection set, participants were asked to rate their safety confidence, their efficiency confidence and their mental workload via the Rating Scale Mental Effort (RSME; Zijlstra, 1993), a global measure of workload to consider whether the crossings were cognitively demanding in general.

2.3.2.1 Main Road Drive Simulator Study Overview

This study utilized a within-subjects design approach with all participants being exposed to all conditions, which has benefits in terms of statistical power. The design is a $3 \times 3 \times 2$ within-subjects design with three levels of viewing distances (near, medium, far), three levels of initial vehicle appearance (near, far, absent), and two levels of vehicle behavior (enters intersection (either from stop or running stop), does not enter (either staying at stop sign or absent).

Sight Distance	Vehicle Position	Vehicle Behavior	Intersection Scenarios
		Enters Intersection	1. 400ft/Near/Enters Intersection
	Near	Does Not Enter	2. 400ft/Near/Does Not Enter
		Enters Intersection	3. 400ft/Far/Enters Intersection
400 ft	Far	Does Not Enter	4. 400ft/Far/Does Not Enter
		Enters--Runs Stop	5. 400ft/Absent/Enters--Runs Stop
	Absent	Absent	6. 400ft/Absent/Absent
		Enters Intersection	7. 600ft/Near/Enters Intersection
	Near	Does Not Enter	8. 600ft/Near/Does Not Enter
		Enters Intersection	9. 600ft/Far/Enters Intersection
600 ft	Far	Does Not Enter	10. 600ft/Far/Does Not Enter
		Enters--Runs Stop	11. 600ft/Absent/Enters--Runs Stop
	Absent	Absent	12. 600ft/Absent/Absent
		Enters Intersection	13. 1000ft/Near/Enters Intersection
	Near	Does Not Enter	14. 1000ft/Near/Does Not Enter
		Enters Intersection	15. 1000ft/Far/Enters Intersection
1000 ft	Far	Does Not Enter	16. 1000ft/Far/Does Not Enter
		Enters--Runs Stop	17. 1000ft/Absent/Enters--Runs Stop
	Absent	Absent	18. 1000ft/Absent/Absent

Study Design

Figure 2.3 Intersection study 3x3x2 experimental design with 18 simulation scenarios.

2.3.2.2 Main Road Drive Simulator Study Procedure

Prior to driving on the simulator, participants were provided with a general background of the study and a detailed explanation of the purpose of their participation. After participants read and signed an informed consent form, they had their vison tested using a standard Snellen Acuity Chart to ensure they met minimum Minnesota regulations for driving (20/40 vision corrected or uncorrected).

Participants completed a Demographic and Driving History Questionnaire (see Appendix B) and a Driving Stress Inventory (Appendix C; Matthews, Desmond, Joyner, Carcary, & Kirby, 1997) that asks questions about their age, years licensed, frequency and type of driving, and other related driving behaviors. Participants were also queried if they have recently been in a crash or near crash at the start of each testing session. Participants were provided with a general background of the project and a detailed explanation of the purpose of their participation.

For experimental trials, participants drove through simulated thru-STOP intersections on the main road (i.e., without a STOP sign) with three levels of visibility (distance) to observe cars placed on the minor

road. Each intersection had a random assignment of visibility, initial vehicle appearance (near intersection, far from intersection, or absent), and vehicle behavior (enters intersection or does not enter). The visibility of the intersection influenced drivers' detection of vehicle that were placed far back or approaching the intersection. For certain trials, the car began to move across the intersection, requiring braking to avoid a collision. At some intersections, no car will be present. This either resulted in no interaction with a vehicle (i.e., completely absent) or a car approached the intersection and will not stop at the stop sign (i.e., runs the stop sign) and will enter the intersection. This created conditions in which drivers will have a hard time predicting if a vehicle is present and if it entered the intersection in front of them based on the set visibility distance and vehicle placement. Participants indicated by pressing the brake pedal when they feel they need to slow down for the vehicle at the intersection. An online demo of the mainline drive can be viewed at; https://www.youtube.com/watch?v=twmsji_KJyI.

After completing all trials, participants completed the Rating Scale Mental Effort (RSME; Zijlstra, 1993) for a global measure of workload to consider whether the crossings were cognitively demanding in general.

2.3.3 Statistical Approach

2.3.3.1 Dependent Variables

A summary of the dependent variables is presented in Table 2.1. The development of dependent variables also draws on measurements used in previous HumanFIRST studies of gap acceptance at intersections.

Table 2.1 Dependent Variables

Study	Measure	Description
Validity	Validity Scale	A Likert from 1 to 7 on how much the simulated intersection resembles the dimensions of a real-world rural intersection
	Distances	Experts will indicate perceived sight distances in either an open entry format or possibly from a multiple choice list
TTC	RSME	Values on the Rating Scale Mental Effort.
	Difficulty	Perceived task difficulty of the task conditions
	Riskiness	Perceived riskiness of the task
	Anxiety	Reported anxiety experienced by the participant as a result of the task conditions
	Pedal Press	Rate of gas pedal presses (e.g., decision to take a gap)
	TTC	Minimum Time to collision (TTC) of the oncoming car to the middle of the intersection when pressing the gas pedal
	Collision Rate	Frequency of collisions: accepting a gap less than 4.5 sec

	Misses	Frequency of rejecting a gap greater or equal to 5 sec
	Hesitancy	Amount of time from gap first appearing and participant choosing to take it
	Head Movements	Total number of head movements for glances to the left and right as measured with a Go Pro camera.
Main Drive	RSME	Values on the Rating Scale Mental Effort.
	Speed (1st ½ mile)	Average speed for the first half mile before the intersection
	Speed deviation (1st ½ mile)	Average speed deviation for the first half mile before the intersection
	Speed (4th ¼ mile)	Averages speed for the 4th quarter mile (including the intersection)
	Speed deviation (4th ¼ mile)	Averages speed deviation for the 4th quarter mile (including the intersection)
	Accelerator Release Distance	First accelerator release distance from intersection with "intruding vehicle"
	Braking Distance	First braking distance from intersection with "intruding vehicle"
	Maximum Heading Error	Maximum heading error (in degrees) on approach or travel through intersection
	Collision Rate	Calculated as the intersection of the dimensions of the participant and simulation vehicles
	Minimum TTC	Minimum time-to-collision (TTC) with intruding vehicles

2.3.4 Validity Test Design and Analysis

The analyses of the validity measures were primarily qualitative and descriptive.

2.3.5 TTC Simulator Study Design and Analysis

The analyses of the driving performance and confidence were carried out using multiple ANOVAs to examine how the safety performance and confidence measured for each factor compares and interacts. Post-hoc analyses will be conducted when appropriate. Subjective measures were analyzed using descriptive statistics, correlations, and regressions on the safety measures and confidence.

2.3.6 Main Road Drive Design and Analysis

The analyses of the driving performance, confidence, and eye tracking were carried out using multiple ANOVAs to examine how the safety performance and confidence measured for each factor compares and interacts. Post-hoc analyses were conducted when appropriate. Subjective measures were analyzed using descriptive statistics, correlations, and regressions on the safety measures and confidence.

2.3.7 Research Hypothesis and Questions

Validity Test Hypotheses. There were no explicit hypotheses here, although the researchers anticipated that the simulated intersections will resemble real rural intersections.

   VT Prediction 1. Scores on similarity measures will be high.

TTC Simulator Study Hypotheses. Based on prior research (DeLucia, 2008; Levulis et al., 2015), we expected that performance should be worse for vehicles with far viewing distances and slower speeds. Furthermore, we expected that confidence will not correspond with actual performance (Hancock & Manser, 1997), and that confidence would be higher for conditions with worse performance, specifically far viewing distances.

   TTC Prediction 1. Collision rate should be higher, safety margins should be lower, and the optical expansion rate should be smaller during participant responses for small, far viewing distance vehicles travelling at slow speeds.

   TTC Prediction 2. Confidence should be high for vehicles travelling at slower speeds, and high for conditions with far viewing distances.

Main Drive Simulator Study Hypotheses. We expected that collision rates will be higher and TTCs will be shorter for far viewing distances and vehicles stopped back.

   MD Prediction 1. Collision rate should be higher, braking distance should be lower, and the average speed should be higher for participants approaching for vehicles stopped back and far viewing distance vehicles.

   MD. Prediction 2. Confidence should be high for vehicles stopped back at intersections, and high for conditions with far viewing distances.

CHAPTER 3: SIGHT DISTANCE VALIDITY TEST

3.1 INTRODUCTION

To determine whether the proposed experimental stimuli and conditions were representative of rural intersections to test the effect of sight distances on gap acceptance and confidence, researchers invited qualified state, county, and academic engineers who were familiar with these intersections. The validity test was conducted in the HumanFIRST immersive driving simulator to expose the subject matter experts to the stimuli and conditions in order to receive their feedback and iteratively design the simulation.

3.1.1 Participants

Researchers reached out to state, county, and academic engineers familiar with rural roadways who could provide an expert perspective on the scenario being tested in the driving simulator. Five engineers participated in the validation test in September 2018. Two additional engineers who could not attend the validation test participated in a pilot test in October 2018. These participating engineers spent an hour of their time experiencing the experimental conditions and providing feedback to the conditions and the questions asked by the researchers. This number of participating engineers, i.e., seven total participants, is reasonable for a validity test of this nature, like sampling sizes of usability and iterative design protocols based on proportion of unique problems found per participant (Nielsen & Landauer, 1993).

3.1.2 Methods

The validity test plan is summarized in Appendix D. The engineers individually came to the driving simulation lab at the Mechanical Engineering building at the University of Minnesota – Twin Cities campus. When they arrived, they were briefed on the general goal of the study. They were asked to perform two practice trials. First, they experienced a practice drive during which they drove across six simulated, rural thru-STOP intersections to get a feel for how the virtual vehicle behaved (e.g., how it handled, how long it would take to cross the intersection, etc.), see Figure 3.1. The second practice task included on-screen instructions and allowed participant to practice pressing the response/gas pedal when they thought the gap between onscreen vehicles was large enough to proceed safely through the simulated intersection.

Figure 3.1 Image of practice drive for crossing thru-STOP intersections.

Once the practice trials were completed, the participating engineers performed three validation tasks: (1) Sight estimation, (2) Representativeness rating, and (3) Mainline drive and feedback.

1. *Sight estimation*. To determine if the sight distances in the simulated world were portrayed realistically, each distance (i.e., 400 ft., 600 ft., and 1000 ft.) was presented in counterbalanced order to the engineer, with cross traffic vehicles traveling at 55 mph, see Figure *3.2*. The true simulated sight distance of the intersection was withheld from the engineers, but they were informed that the travel speed of the vehicles was 55 mph. After they performed the gap judgment task, the engineers were asked to provide an absolute judgement of which distance they believed was presented to them for that trial. Questions about confidence ratings were also verbally posed here.
2. *Representativeness rating*. Each of the experimental conditions for the gap judgment or time-to-contact phase of the study (3 sight distances and 3 speeds of 55 mph, 65 mph, and 75 mph) were presented to the participating engineer. For each condition, the engineer rated how representative the condition was of its real-world counterpart, along with any comments they had.
3. *Mainline drive and feedback*. Time permitting, the engineer would then drive through the main roadway and react to differing car and intersection scenarios, including different sight distances (i.e., 400 ft., 600 ft., and 1000 ft.), cars stopped close to or far away from the intersection, and being present, absent, remaining stopped, or driving through the intersection in front of the engineer's simulated vehicle. Once complete, the engineer was asked to provide feedback on the drive and how it could be improved for the experiment.

20

Figure 3.2. Image of moving pickup truck crossing participant vehicle in the sight estimation test.

3.1.2.1 Materials

The response materials are provided in Appendix E. The responses to the sight estimation validity task was a multiple-choice response, although verbal indication that another distance not listed was preferred was then written down by the research staff. The responses to the representativeness rating portion was done via 7-point Likert scales (i.e., scores ranged 0-6) from "not at all representative" to "completely representative", along with a section for a written response for detailed qualitative feedback. Responses for the mainline drive portion were verbal with notes taken by the HumanFIRST staff.

3.1.3 Results

3.1.3.1 Sight estimation

Overall, the engineers judged the sight distances at similar values to their programmed actual distances. Accuracy in judgement was best at the shortest distance (i.e., 400 ft.) and decreased as the distance increased (see Table 3.1). This inverse relationship matches typical absolute judgement decrements that decrease with increased distance (Wu, Ooi, & He, 2004). The 600 ft. distance was typically perceived correctly or overestimated, by 100 ft. on average. The 1,000 ft. distance was over and under estimated by 180 ft. (absolute) on average.

Table 3.1 Average Sight Distance Estimations

Average Sight Distance Estimation			
Actual distances	**400 ft.**	**600 ft.**	**1000 ft.**
Avg. Perceived distances (*standard deviation)*	420 ft. (*45 ft.*)	700 ft. (*100 ft.*)	1020 ft. (*205 ft.*)

3.1.3.2 Representative rating

The ratings for representativeness were generally high across distances and speeds. The question: "*Overall, how representative was the experimental simulations of real-world rural intersections?*" received an average score of 5.25 (*SD* = 0.5) or slightly better than 'very much'. Ratings were examined across sight distances and across speeds. The lowest representativeness rating for distance, averaged across speeds, was for 400 ft. (see Table 3.2) at an average score of 4.5 (i.e., in between 'significantly' and 'very much' representative of real rural intersections). The remaining distances scored higher in their perceived representativeness.

The ratings for the representativeness of speed, averaged across distances, were slightly lower than for distances, but still averages ranged between 'significantly' and 'very much' for their representativeness of real rural intersections.

Table 3.2 Average Representative Rating by Distance

Average Representative Rating by Distance			
Actual distances	**400 ft.**	**600 ft.**	**1000 ft.**
Avg. Representative Score (*standard deviation*)	4.5 (*1.6*)	5 (*0.8*)	5.1 (*1.1*)

Table 3.3 Average Representative Rating by Speed

Average Representative Rating by Speed			
Actual speeds	**55 mph**	**65 mph**	**75 mph**
Avg. Representative Score (*standard deviation*)	4.9 (*1.0*)	4.8 (*1.1*)	4.8 (*1.5*)

3.1.3.3 Qualitative comments on representativeness

The comments received throughout the process provided a variety of insight into possible ways to enhance the simulation to best design a study that may yield useful and implementable results for state and county engineers to utilize. There were a few themes that the comments tended to center around: mirror/A-pillar sight obstructions, motorcycle visibility, distance representativeness, speed representativeness, and vehicle stop placement.

- **Mirror/A-pillar***:* Several engineers mentioned difficulty tracking vehicles (particularly motorcycles) approaching from the right due to the extent that the mirror and A-pillar occluded the roadway and limited visibility of the motorcycle for a perceived time of 4 sec. This was stated as a factor that increased uncertainty about when it was safe to "go". Ultimately, it was still noted as a reasonable limitation since the simulator chassis is a standard 2013 Ford Fusion

(i.e., no modifications to the chassis have changed the size or shape of the side mirror or A-pillar) and may be representative of many similar modern passenger vehicles.

- **Motorcycle visibility**: In addition to the side mirror issues, the motorcycles were noted as slightly more difficult to see. Other engineers noted that the "*motorcycle speed is hard to perceive*," or might be easier to see if their headlights were on, but the current representation seems like it matches problems experienced by drivers in the real world. Another engineer noted that most motorcycles are black, but felt matching the color to the pickup truck (i.e., white) was appropriate and would not want any color changes to make the motorcycle further blend into its background. The lighting also did not particularly reflect off of either type of vehicle like it would in real life, but was thought to test less than optimal lighting conditions that are representative of a significant portion of the year.
- **Distance representativeness:** The 400 ft. visibility was mentioned as hard to judge for most drivers because "*400 ft. seems large but it isn't*." The 400 ft. distance with faster speeds (e.g, 65 or 75) were deemed "*stressful*" or "*difficult*" to pick gaps and would "*make drivers anxious to cross in real life*." The 1,000 ft. visibility distance was mentioned to be "*comfortable*" and "*adequate for testing large sight distances*", but was noted that we "*could go wider, but this feels pretty wide open*."
- **Speed representativeness:** There were few comments about the 55 mph vehicles, but the faster vehicle speeds (i.e., 65 or 75) did result in engineers commenting that they appeared too slow (particularly in the periphery) or too fast, depending on the engineer. The 75 mph speeds were discussed as rare on most county roads, but useful to include in the study.
- **Vehicle stop placement:** The position of the simulated vehicle at the stop bar was rated as representative of typical stop bar placement, but the inability to move forward or "*crowd the intersection*" did not match how some of the engineers would typically behave. However, it was noted that some drivers will not "*creep*" forward toward the intersection when sight distance is obstructed, so the simulation matches how drivers may make judgments under more difficult conditions.

Overall, the comments about the intersections were positive for how they were "*realistic to real rural intersections*." One engineer stated that the intersections had a, "*really good feel, like you really are at a rural intersection. The realism was way higher than I expected."*

3.1.3.4 Qualitative comments on mainline drive

If time permitted, the engineers were given the opportunity to drive a portion or all the mainline drive. The discussion for the mainline drive was positive for being "very realistic" and suggestions tended to focus on modifying the simulation to increase driver uncertainty, distraction, and road design.

- **Uncertainty:** The first iteration of the mainline drive featured only vehicles approaching from the right. The feedback received was that the vehicles should be present or enter the intersection from the left or right at random. Another discussion was about the consistency of 1-mile segments between intersections that may present too much rhythm and expectancy for

drivers as they approach. Although intentionally omitted from the simulation, one engineer noted that there were no traffic signs regarding the upcoming intersections that is not representative of real roads, but would help to reduce driver expectancies of upcoming intersections to magnify possible sight distance effects.

- **Distraction:** Multiple comments were received about adding aspects that would distract drivers from being overly vigilant for cars entering at the intersections. Some of the suggestions were to add more visual information near the road (i.e., more foliage variety, cows, etc.) or add oncoming traffic. Most engineers thought an in-vehicle distraction task would be appropriate to help "take the brain off of driving."
- **Road Design:** The distance between intersections (i.e., 1 mile) received a good deal of discussion. It was stated that in both Washington and Dakota county cross roads are more often encountered every half mile instead of every mile. The 1 mile segment was suggested to be appropriate to reduce down to .75 or .5 miles between intersections. The road noise was stated to be realistic; however, the steering wheel torque (to the left) did not seem appropriate and needed to be corrected.

3.1.3.5 Qualitative comments on confidence judgments

Engineers were asked to consider how their confidence and efficiency might be best assessed after they had an opportunity to complete a few of the gap acceptance trials. Some engineers stated clearly that they could tell that they had chosen gaps at incorrect times: "*Pretty sure I would have gotten T-boned from the left at least once.*" The confidence questions were suggested to preface the conditions of the simulator and other cars prior to asking drivers: "How confident are you that you made it through all the gaps without being hit." Additionally, efficiency could be assessed by asking, "What percent of gaps that you chose to take did you think you could have safely made it across without being hit?" Notably, some of the interesting effects between confidence and sight distance were spontaneously described, such as, "*It seems the more the sight distance, the harder to know when to pick a gap.*"

3.1.4 Pilot Test

Two additional engineers (one state and one county engineer) participated in a pilot test to review the modifications made to the driving simulation and experimental protocols based on feedback gained from the validity test. They were tested in the same manner as the previous five participants and their feedback was recorded.

Two aspects of the TTC study simulation were raised as a concern in this testing: speed representativeness and A-pillar/side mirror (right) occlusion of the roadway. The approach speed of vehicles from the far left and right distances did not match expectations at higher-level speeds (i.e., 65 and 75 mph), as was similarly discussed by engineers in the validity test. Both engineers felt as though vehicles appeared to move too slowly from far distances, but appeared to pass directly in front of them at a correct speed. One engineer noted that the high speeds and high number of vehicles presented in

the brief amount of time did not match the road design of the simulated intersection (note: although it was understood that this aspect is a necessity of the experimental constraints).

The occlusion of approaching vehicles (particularly for motorcycles) by the right A-pillar and side mirror was raised as a concern of the validity of the simulation, as was also previously raised in the validity test. It was noted that the mainline road in the TTC study should appear slightly elevated compared to the minor crossroad.

No significant issues were raised regarding the mainline study. Both engineers agreed that some parts of the state might have more frequent crossroads than every 1 mile, but that others may not. Adding visual clutter to the mainline road (e.g., driveways, mailboxes, etc.) was discussed as a possible design modification, but engineers agreed that adding an in-vehicle distraction would help to reduce participant expectancies of upcoming crossroads and induce errors experienced by real-world drivers.

3.1.5 Design Modifications

The following changes were made to the initial design of the interface based on validity test feedback.

- The color of all vehicles was made white for both contrast and representativeness.
- Vehicles during the mainline drive were added to appear and intrude from both the left and right directions. Previously they only came from the right.
- Questions about confidence were streamlined into the following:
  - How confident are you that you made it through all the gaps without being hit?
  - What percent of your rejected gaps do you think you could have safely made it across without being hit?
- A distractor task (arrows) will be added to the mainline drive to encourage drivers to divide their attention from the primary task of driving, as the drive was observed to be somewhat boring and drivers would normally occupy their attention during a similar drive in the real world.
- Changes considered but not taken:
  - Moving side mirror to improve right sight distance not possible due to complexity of LED embedded screen. Instead, the visual optics will be re-examined to improve and maximize viewing distance.
  - Reducing mainline drive segment lengths not possible due to driver's ability to see the next intersection at .5 miles. Distractor task introduction should reduce the perceived drive time and boredom.

The following changes were made to the initial design of the interface based on the additional pilot test feedback.

- Move vehicle chassis forward approximately 1.5 meters to be positioned closer to the projection screen.

- o Modifications to chassis position has improved driver viewpoint of the roadway with mainline appearing slightly elevated compared to minor road.
  - o A-pillar with mirror occlusion of the roadway and approaching vehicles is eliminated (see Figure 3.2).
  - o Perception of approach speed of vehicles traveling from left and right at a distance better matches expectations for designed speeds
- Improvements done to visual channel to reduced masking and shadowing of objects
- Center stack computer was upgraded to include in-vehicle distractor task
- Luminance of center stack display reduced for comfortable viewing under ambient low luminance conditions

Figure 3.2 Driver's right-looking perspective of roadway after vehicle chassis moved forward.

3.1.6 Conclusions

The validity test allowed the research team to make iterative changes to the design and presentation of stimuli in the study based on the engineer feedback. The modifications to the vehicle chassis position in relation to the projection screen provided a solution to the more persistent and seemingly non-addressable issues raised in the validity and pilot testing. The result is a more immersive driving experience with fewer barriers to capturing natural driver decision-making at real-world rural intersections.

Overall, the expert ratings were high for representativeness, and qualitative feedback was significantly positive. Based on these results, the design of the experiment task and changes to the stimuli and metrics are considered by the research staff to be ready to proceed to the data collection phase of the study.

CHAPTER 4: EXPERIMENT DATA ANALYSIS

4.1 INTRODUCTION

Experimental data from 36 participants in (1) the time-to-collision (TTC) intersection crossing judgement and (2) the rural highway thru-stop intersection driving simulation studies were analyzed to inform county and state engineers and researchers regarding the influence of rural thru-STOP intersection characteristics on driving performance and decision-making.

The TTC intersection crossing study featured nine randomly presented thru-STOP intersections with varying sight distances (400 ft., 600 ft., and 1000 ft.), varying oncoming cross traffic vehicle speeds (55 mph, 65 mph, and 75 mph), and randomly presented cross vehicle types (small or medium vehicles). Each intersection test scenario lasted approximately 3 minutes for a total of 30 minutes for all TTC sessions. Each intersection presented participants with 10 intersection-crossing judgments, with various time headways separating the crossing vehicles (3 sec, 5 sec, 7 sec, 9 sec, and 12 sec), repeated for small and medium vehicle types, and appeared from the left or right. Participants were trained to keep their foot on the brake pedal and press the accelerator one a gap was presented between two vehicles that was large enough to safely cross. Between each trial block, participants estimated, via paper survey, the extent to which the intersection crossing judgments taxed their mental processes and reported how risky, dangerous, and the degree to which they felt anxious making the crossing judgments.

The subjective results of the TTC study demonstrated a consistent trend for stress measures including mental workload, perceived risk, perceived difficulty, and anxiousness. Participants generally reported higher stress for 400 ft. and 600 ft. sight distances compared to 1000 ft. sight distances. Additionally, participants tended to report significantly lower stress measures for 55 mph compared to 65 and 75 mph, with no differences between the two higher speed conditions. An interaction was observed for perceived risk with no differences between speeds reported at the 1000 ft. sight distance, indicating that participants may become less sensitive to high-speed risks at very long sight distances.

The performance results of the TTC study demonstrated a significantly higher likelihood for participants to take gaps under conditions that they reported higher levels of stress (i.e., 400 ft., 600 ft., 65 mph, and 75 mph) and tended to hesitate for a longer period before deciding to cross during these conditions. A significantly greater number of head movements were observed under the shortest sight distance condition (i.e., 400 ft.) compared to longer distances, mirroring the reported levels of stress and observed hesitation prior to executing a crossing decision. Moreover, the final TTC of the accepted gap tended to be significantly shorter and more likely to be estimated as a collision risk (i.e., shorter that 4.5 sec. TTC at time of crossing decision) under these more stressful intersection scenarios. Similar to perceived risk, the estimated collision analysis revealed an interaction between speed and sight distance with the increase in collision risk of high speeds disappearing at the 1000 ft. sight distance. Overall, slower speeds (i.e., 55 mph) and longer sight distances (i.e., 1000 ft.) imposed less stress on drivers and

led to drivers accepting fewer but ultimately longer TTC/safer gaps than the faster, shorter sight distance scenarios.

The rural highway thru-stop intersection driving simulation study consisted of a 19-mile drive along a two-way, two-lane rural highway that featured 18 thru-STOP intersections with minor roadways every 1-mile and a 60 mph speed limit. The tree lines leading up to the intersections were manipulated to mirror the three different sight distances used in the TTC study for the minor road of the intersection (i.e., 400 ft., 600 ft., and 1,000 ft.). Each intersection randomly presented a scenario from the right or left that may have one of three levels of initial vehicle appearance (i.e., near, far, absent), and two levels of vehicle behavior (intrudes into the intersection (either from stop or running stop) or stationary (either remaining at stop sign or absent entirely)). Vehicles stopped at the stop sign were placed either 13 ft. from the outside lane edge for the "near" condition or 36 ft. from the outside lane edge for the "far" condition. Participants were instructed to travel at 60 mph unless an evasive maneuver was required avoid an intruding car. Additionally, participants were reminded to engage with the arrows task on the LCD screen in the dashboard at a rate that was comfortable but continuous for the duration of their drives.

Upon approach to the intersection, drivers were more likely to slow their speed, observed with both mean speed and average speed deviation, if a stationary vehicle was present and near the intersection compared to vehicle stopped far from the intersection or absent. Approach speeds did not significantly differ with sight distance changes for stationary vehicles. Approach speeds significantly differed by sight distance and vehicle proximity for intruding vehicle scenarios. An interaction was observed where short sight distances (i.e., 400 ft. and 600 ft.) resulted in significantly higher approach speeds and smaller speed deviation when a stop-sign-running vehicle entered the intersection compared to those that entered the intersection from a stop (i.e., either near or far proximity). The effect of the poor responsiveness to the stop-sign-running vehicle was not found with the largest sight distance (i.e., 1000 ft.). Moreover, participants were more likely to brake further back from the intersection for intruding vehicles after a stop (i.e., either near or far) compared to stop-sign-running vehicle events for the shorter sight distances (i.e., 400 ft. and 600 ft.). However, the effect was reversed for 1000 ft. sight distances with participants braking significantly further back for stop-sign-running vehicles compared to vehicles that intruded from a stop. This improvement in evasive maneuvers for stop-sign-running events at the 1000 ft. sight distance resulted in longer TTCs and was significantly less likely to result in a collision compared to the two shorter sight distances that featured shorter TTCs and higher collision rates for stop-sign-running vehicle conditions.

The research team can draw several broad conclusions from the presented data of relevance to engineers and safety experts responsible for designing and implementing layouts for rural intersections. First, longer sight distances of 1000 ft. and slower crossing speed (i.e., 55 mph) appear to be particularly helpful for participants on the minor road attempting to take a gap and cross, given (1) lower mental workload, less perceived risk, difficulty, and anxiousness, and (2) better performance in terms of estimated crash rate, larger TTCs, and less hesitancy. Second, longer distances of 1000 ft. appear to be

somewhat helpful for drivers on the main road approaching an intersection, specifically for the circumstances in which another driver on the minor road runs the stop sign, as participants driving though intersections with 1000 ft. sight distances were better able to react and avoid cars running stop signs. Third, vehicles placed nearer to the intersection appeared to lead participants to drive at somewhat slower speeds than when vehicles were placed further away from the intersection, suggesting that the proximity of a vehicle to the intersection lead to safer driving behaviors by participants travelling on the main road, and engineers should consider placing stop lines closer to the intersection.

Task 6 Data Analysis details extended analyses performed following Task 5 Data Collection deliverable's general overview of participants' demographic information. This deliverable documents the various descriptive and inferential statistical analyses conducted on the experimental data collected in Task 5 from 36 participants in (1) the time to collision (TTC) intersection crossing judgement task scenario and (2) the rural highway thru-stop intersection "mainline" driving simulation studies analyzed. The purpose of this task was to provide quantitative and qualitative results and accompanying scientific discussion to inform county and state engineers regarding the influence of rural thru-STOP intersection characteristics on driving performance and decision-making.
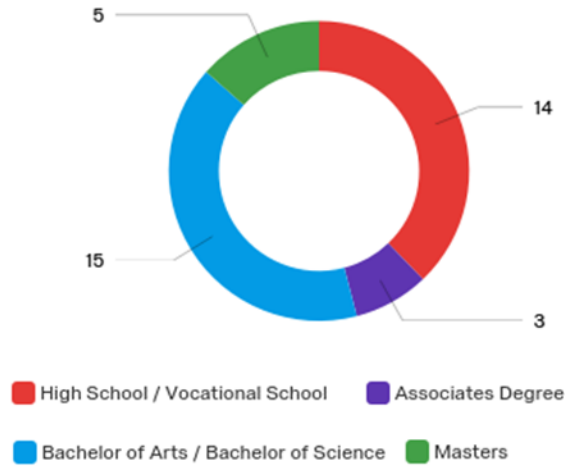
4.1.1.1 Participant Demographics

In total, 36 Minnesota drivers participated in the driving simulation study. Participants had at least two years of licensed driving experience (less than two-year driving experience for teen drivers), a minimum of 4,000 miles driven each year, normal or corrected-to-normal vision (20/40 or better, normal color vision), normal hearing function, and normal cognitive function. Participants were excluded from the study if they have a history of hearing loss that inhibits every day conversation, health problems that affect driving, inner ear or balance problems, history of motion/sea sickness, lingering effects of stroke, tumor, head trauma, or infection, and history of migraines or epileptic seizures.

The participants were recruited from University of Minnesota by posting flyers on and off campus and using advertisements on University websites, social media (Facebook, Twitter, CraigsList and newsletters or magazines. Prior to enrollment in the study, participants were asked questions from a screening questionnaire (see Appendix A) to ensure they meet the age, driving, and visual requirements of the study as well as ensure those prone to motion sickness are not included in the study. Additionally, they were asked if they will be capable and willing to travel to the University of Minnesota East Bank Campus. Participants were paid $50 cash at the time of the simulation, and the experiment lasted approximately 1 hour.

During the beginning of the experimental protocol, researchers prompted participants to provide demographic and technology use information to further identify driver characteristics (see Appendix B). The mean age of participants was 27 years old (*SD* = 6.7). Participant sex distribution was relatively equal, with 17 females and 19 males. Participant level of education varied from High School or

Vocational School (*N* = 14), Associate-level Degree (*N* = 3), Bachelors of Arts or Sciences (*N* = 15), and Masters-level Degrees (*N* = 5), see Figure 4.1. Roughly, half of participants were currently enrolled as students in various degree-seeking programs.


Figure 4.1 Participant Highest Educational Level Demographic.

Mean participant driving experience was 9.6 years (*SD* = 6.5), with a majority reporting they drove Most Days (*N* = 15; 42%), or Every Day (*N* = 12; 33%) during their typical seven-day week. A quarter of participants (*N* = 9) reported driving Sometimes, which indicated roughly 3 days per week, and none said they Never drove. Participants also disclosed their typical yearly miles driven values in the survey, which were binned into five categories of 5000 miles intervals. Five participants reported driving less than 5000 miles per year (13%), ten reported driving 5000-10,000 (27%), fourteen reported between 10,000 and 15,000 miles (38%), one participant reported between 15,000 and 20,000 miles (3%), and seven participants drove over 20,000 miles per annum (19%), see Figure 4.2.
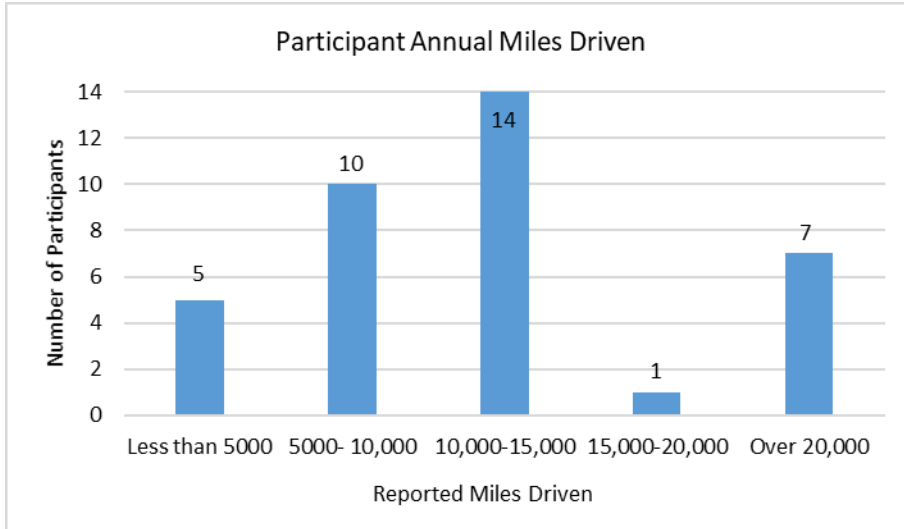
Figure 4.2 Reported Participant Annual Miles Driven.

Participants' road type experience was assessed, which included usages across highways (97%), main roads other than highways (95%), urban roads (86%), and country roads (27%), see Figure 4.3. These results suggest the study sample consisted primarily of urban/metropolitan drivers. Six participants (9%) reported at fault minor traffic incidences within the past three years, while two participants (6%) said they were at fault for a major traffic crash that resulted in more than $1500 of property damage or medical treatment. Additionally, four participants disclosed speeding citations in the past three years.
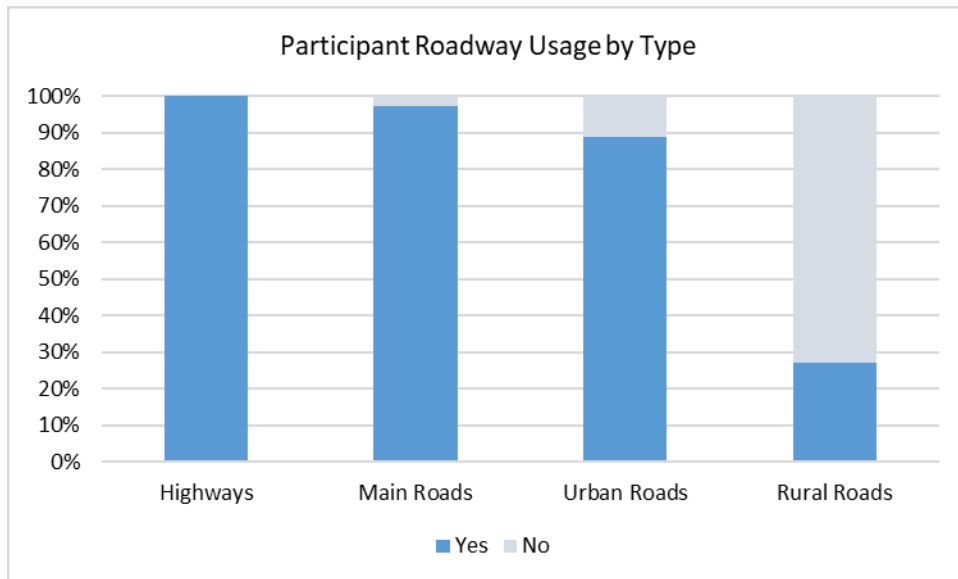
Figure 4.3 Reported Participant Annual Miles Driven.

4.1.2 Dependent Measures

4.1.2.1 TTC Judgement Subjective Measures

The research team utilized a series of subjective questionnaires to assess subjective experience during the TTC judgement task. Mental workload was assessed using the Rating Scale Mental Effort (RSME) questionnaire (Zijlstra, 1993), which is a sensitive measure of mental workload if one is not concerned with diagnosing the type of workload in question (e.g., visual or cognitive), making the RSME particularly useful in the driving context (Verwey & Veltman, 1996), see Appendix F. Other measures were focused on assessment of (1) perceived task difficulty, (2) perceived riskiness of the task, and (3) the anxiety experienced by the participant as a result of the task conditions. These three measures each utilized a single question 7-pt. scale rating from low (1) to high (7), see Appendix G. These questions were adapted from Ward and Wilde (1996).

4.1.2.2 TTC Judgement Performance Measures

The measures presented here include the rate of gas pedal presses (e.g., decision to take a gap), average time-to-contact (TTC) of the oncoming car to the middle of the intersection when pressing the gas pedal, the rate of likely collisions (pressing gas pedal less than 4.5 sec. before oncoming car reaches intersection), rate of misses (initial gap for oncoming vehicle was sufficient for crossing, greater or equal to 5 sec., but pedal was not pressed), hesitancy as measured by the amount of time delay between the initial gap presented by the oncoming vehicle and the time when the accelerator pedal was pressed, and total number of head movements for glances to the left and right as measured with a Go Pro camera.

4.1.3 Mainline Drive Subjective Measures

Mental workload was assessed using the Rating Scale Mental Effort (RSME) questionnaire (Zijlstra, 1993) for the same rationale as that used for the TTC judgement study. The primary concern for the mainline drive study is to see whether the overall drive required some degree of mental workload to perform, and whether participants were mentally engaged in the task and the secondary distractor.

4.1.4 Mainline Drive Performance Measures

The performance measures for the mainline drive study include speed metrics for the first half mile before the intersection and the 4th quarter mile (including the intersection). These speed metrics include the average speed (meters per second) and the average change in speed (i.e., speed deviation). Half of the intersections involved a computer-controlled vehicle "intruding" into the intersection and required the participant to undertake an evasive maneuver(s) to avoid a collision. In these event-based crossings, the following measures were assessed: accelerator release distance, braking distance, maximum heading error (in degrees), collision rate (calculated as the intersection of the dimensions of the participant and simulation vehicles), and minimum time-to-collision (TTC) for that event.

4.2 ANALYSES

4.2.1 TTC Judgement Analyses

A series of 3 × 3 repeated measures ANOVAs of sight distance (400 ft., 600 ft.,1000 ft.) by speed (55 mph, 65 mph, 75 mph) were conducted on the aforementioned subjective measures and performance measures in the TTC judgement study.

4.2.2 Mainline Drive Analyses

The RSME subjective measure in the mainline drive was analyzed with descriptive statistics. The other measures were analyzed with inferential statistics.

6.3.2.1 Stationary vs. Moving analyses

Before considering the speed and event measures separately for stationary and intruding vehicles at the intersections, a confirmatory analysis was conducted to determine if there was a significant difference between moving and stationary vehicles in terms of driver behavior. This will determine whether it is reasonable to consider the two conditions separately, and whether participants were generally reacting as expected to both stationary and moving vehicles.

6.3.2.2 Speed-based vs. Event-based analyses

A series of 3 × 3 repeated measures ANOVAs of sight distance (400 ft., 600 ft.,1000 ft.) by vehicle proximity (near, far, not visible) were conducted separately for stationary and intruding vehicle conditions on the performance measures in the mainline drive study.

4.3 RESULTS

4.3.1 TTC Judgement Results

4.3.1.1 Subjective measures results

For RSME, there was a main effect of distance, Greenhouse-Geisser corrected, $F(1.205, 39.757) = 32.33$, $p < .001$, $\eta^2 = .495$. The 400 ft. distance had significantly higher RSME scores ($M = 40.74$, $SE = 2.53$) than the 600 ft. distance ($M = 32.85$, $SE = 2.03$), and both had significantly greater RSME scores than the 1000 ft. distance ($M = 26.28$, $SE = 2.26$) ($ps < .001$), see figure 4.4. There was a main effect for speed, $F(2, 66) = 6.71$, $p = .002$, $\eta^2 = .169$, with the 55 mph condition having significantly lower RSME scores ($M = 30.28$, $SE = 2.14$) relative to the 65 mph ($M = 35.08$, $SE = 2.27$) and 75 mph ($M = 34.40$, $SE = 2.13$) conditions ($p =.004$, $p = .006$, respectively), see Figure 4.5. There was no distance × speed interaction, $F(4, 132) = 2.10$, $p = .084$, $\eta^2 = .060$.
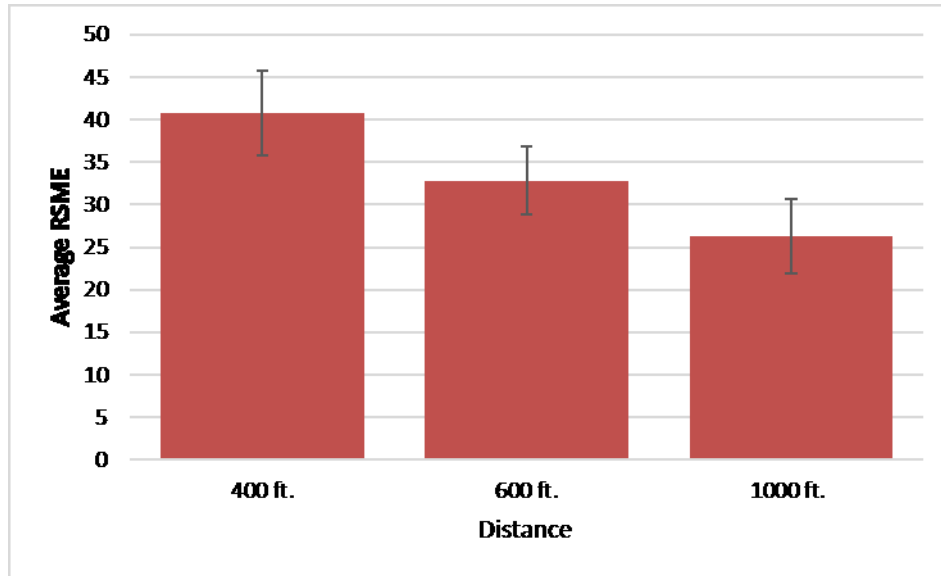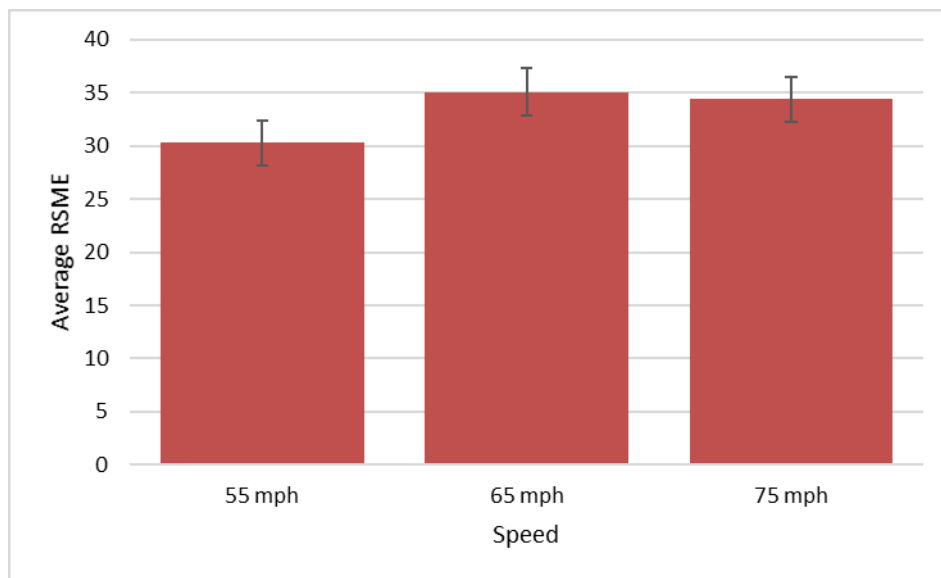
Figure 4.4 Average RSME for distance.

Figure 4.5 Average RMSE for speed.

For perceived difficulty, there was a main effect of distance, Greenhouse-Geisser corrected, $F(1.5, 49.50)$ = 33.69, $p < .001$, $\eta^2 = .505$. The 400 ft. distance had significantly higher perceived difficulty scores ($M = 2.83$, $SE = .14$) than the 600 ft. distance ($M = 2.24$, $SE = .12$), and both had significantly greater difficulty scores than the 1000 ft. distance ($M = 1.81$, $SE = .12$) ($ps < .001$), see Figure 4.6. There was a main effect for speed, $F(2, 66) = 10.30$, $p < .001$, $\eta^2 = .238$, with the 55 mph condition having significantly lower difficulty scores ($M = 2.08$, $SE = .11$) relative to the 65 mph ($M = 2.43$, $SE = .12$) and 75 mph ($M = 2.37$, SE

= .11) conditions (p <.001, p = .002, respectively), see Figure 4.7. There was no distance × speed interaction, Greenhouse-Geisser corrected, $F(2.93, 96.52) = 2.67$, p = .054, η^2 = .075.
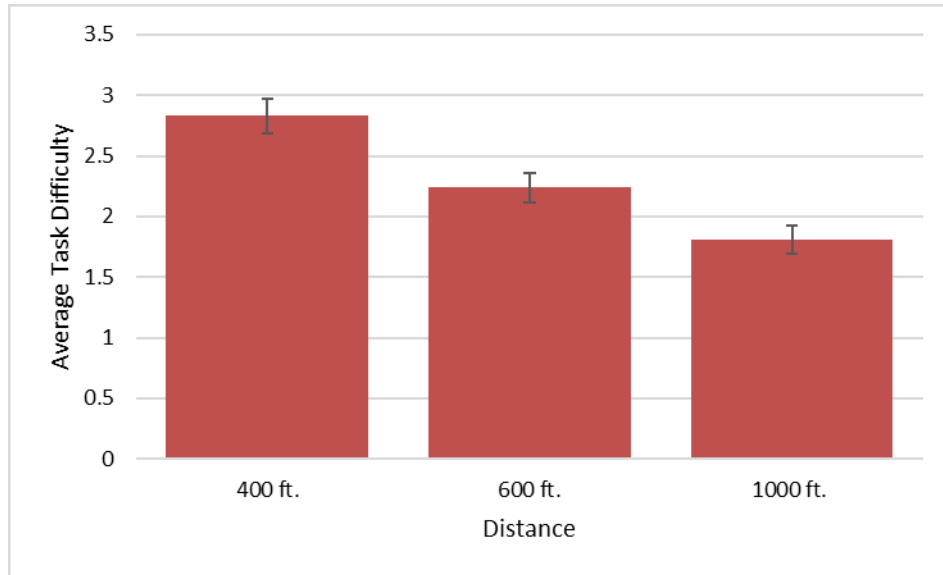

Figure 4.6 Average perceived task difficulty for distance.
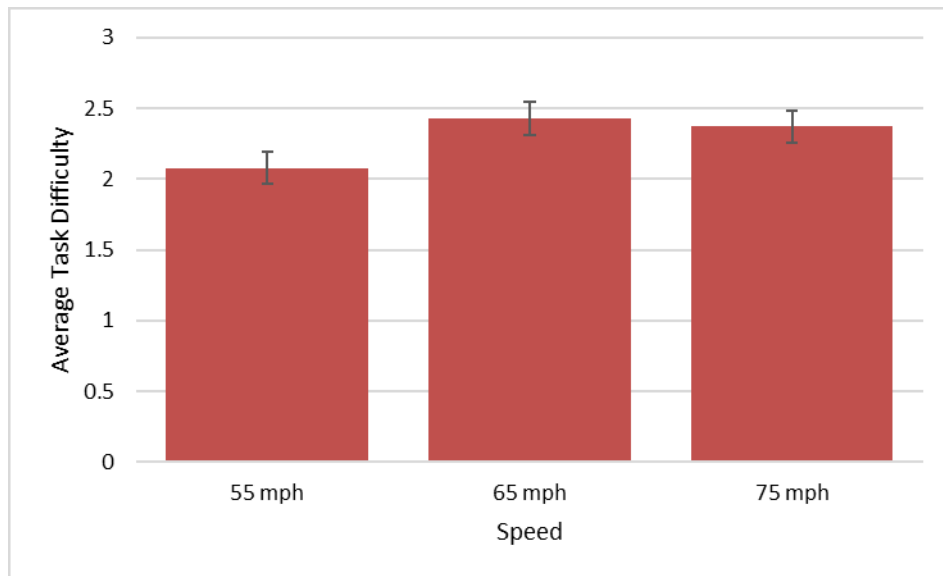
Figure 4.7 Average perceived task difficulty for speed.

For perceived risk, there was a main effect of distance, Greenhouse-Geisser corrected, $F(1.21, 39.94)$ = 29.64, $p < .001$, η^2 = .473. The 400 ft. distance had significantly higher perceived riskiness scores (M = 3.18, SE = .20) than the 600 ft. distance (M = 2.55, SE = .15), and both had significantly greater risk scores than the 1000 ft. distance (M = 2.21, SE = .14) ($ps < .001$). There was a main effect for speed, $F(2, 66)$ = 6.126, p = .004, η^2 = .157, with the 55 mph condition having significantly lower risk scores (M = 2.45, SE =

.16) relative to the 65 mph (M = 2.77, SE = .16) and 75 mph (M = 2.72, SE = .15) conditions (p = .005, p = .009, respectively). There was a distance × speed interaction, $F(4, 132)$ = 2.55, p = .042, η^2 = .072. For the 400 ft. distance and 600 ft. distance, 55 mph speed conditions were perceived as less risky than the 75 mph conditions (paired samples t-tests, p = .014 and p = .017 respectively), but for the 1000 ft. distance, the 55 mph and 75 mph speed conditions did not have a difference in perceived risk (p = .701), see Figure 4.8.
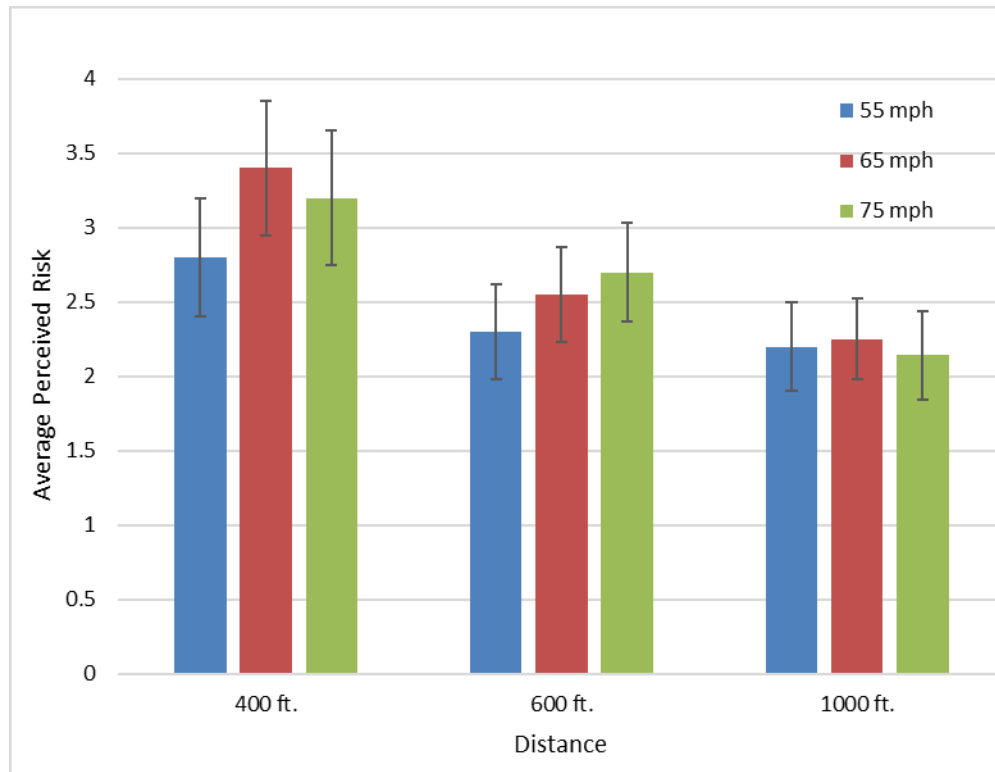
Figure 4.8 Average perceived risk as a function of distance and speed.

For anxiousness, there was a main effect of distance, Greenhouse-Geisser corrected, $F(1.32, 43.39)$ = 28.80, p < .001, η^2 = .466. The 400 ft. distance had significantly higher anxiety scores (M = 2.68, SE = .17) than the 600 ft. distance (M = 2.19, SE = .12), and both had significantly greater anxiousness scores than the 1000 ft. distance (M = 1.79, SE = .12) (ps < .001), see Figure 4.9. There was a main effect for speed, $F(2, 66)$ = 6.82, p = .002, η^2 = .171, with the 55 mph condition having significantly lower anxiousness scores (M = 2.04, SE = .14) relative to the 65 mph (M = 2.30, SE = .12) and 75 mph (M = 2.31, SE = .14) conditions (p = .006, p = .002, respectively), see Figure 4.10. There was no distance × speed interaction, $F(4, 132)$ = 1.60, p = .179, η^2 = .046.
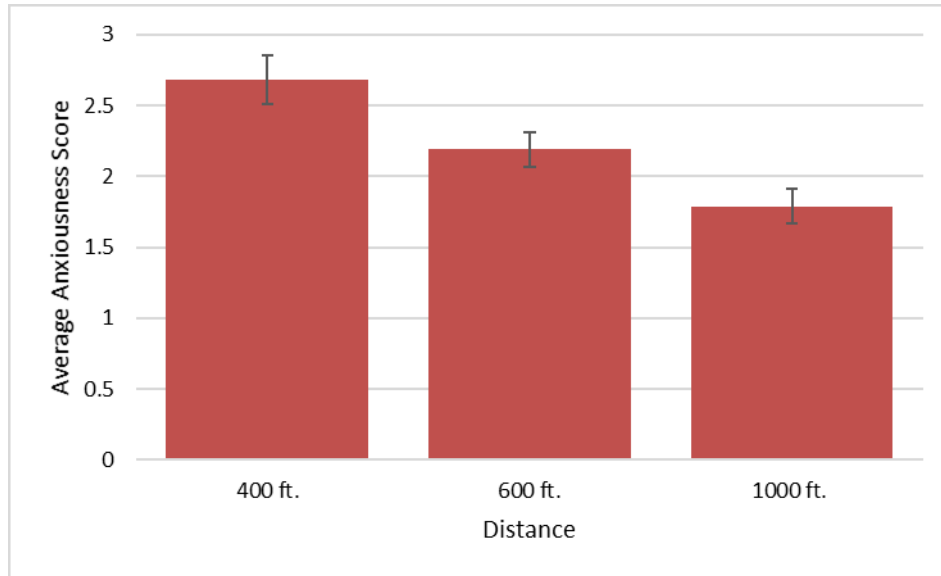
Figure 4.9 Average anxiousness for distance.
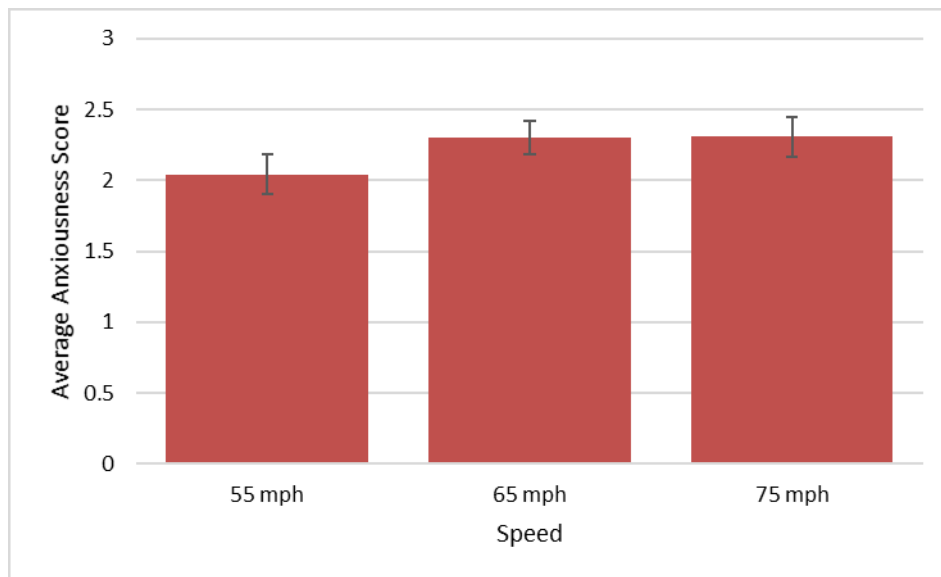
Figure 4.10 Average anxiousness for speed.

4.3.1.2 Performance measures results

For pressed pedal rate, there was a main effect of distance, $F(2, 66) = 66.14$, $p < .001$, $\eta^2 = .667$. The 400 ft. distance had significantly higher pressed pedal rates ($M = .69$, $SE = .02$) than the 600 ft. distance ($M = .61$, $SE = .02$), and both had significantly greater pressed pedal rates than the 1000 ft. distance ($M = .54$, $SE = .02$) ($ps < .001$), see Figure 4.11. There was a main effect for speed, $F(2, 66) = 27.01$, $p < .001$, $\eta^2 = .$

45, with the 55 mph condition having significantly lower pressed pedal rates (M = .57, SE = .02) relative to the 65 mph (M = .62, SE = .02) and 75 mph (M = .65, SE = .02) conditions (ps <.001). The 65 mph and 75 mph conditions were also significantly different (p = .010), see Figure 4.12. There was no distance × speed interaction, Greenhouse-Geisser corrected, F(3.01, 99.41) = 1.12, p = .344, η^2 = .033.

Figure 4.11 Pressed pedal rate for distance.
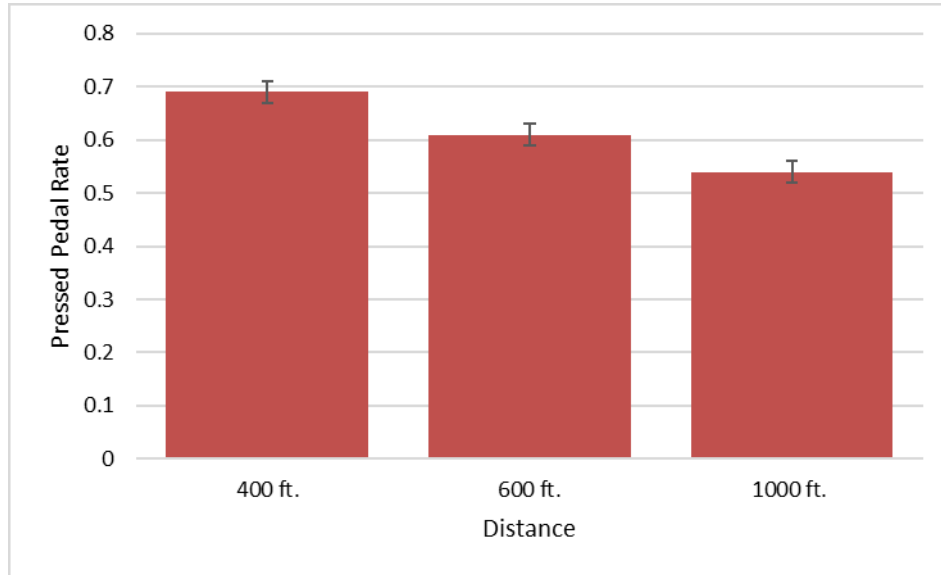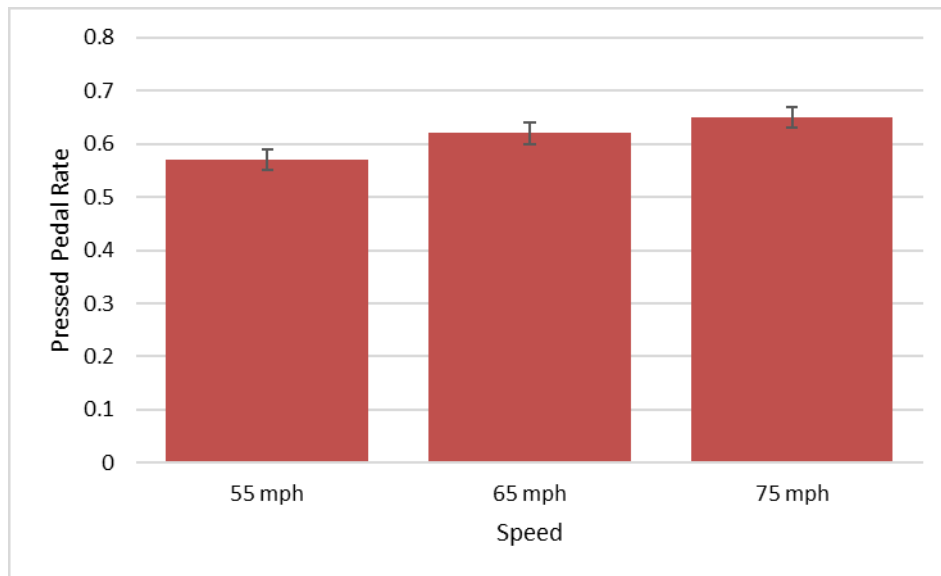

Figure 4.12 Pressed pedal rate for speed.

For average TTC, there was a main effect of distance, Greenhouse-Geisser corrected, F(1.69, 55.64) = 93.81, p < .001, η^2 = .74. The 400 ft. distance had significantly lower TTC averages (M = 7.61, SE = .07) than the 600 ft. distance (M = 8.27, SE = .07), and both had significantly lower TTC averages than the

1000 ft. distance (M = 8.94, SE = .10) (ps < .001), see Figure 4.13. There was a main effect for speed, $F(2, 66)$ = 21.62, p < .001, η^2 = .396, with the 55 mph condition having significantly higher TTC averages (M = 8.59, SE = .09) relative to the 65 mph (M = 8.23, SE = .08) and 75 mph (M = 8.01, SE = .07) conditions (ps <.001). The 65 mph and 75 mph conditions were also significantly different (p = .024), see Figure 4.14. There was no distance × speed interaction, $F(4, 132)$ = 1.82, p = .125, η^2 = .053.
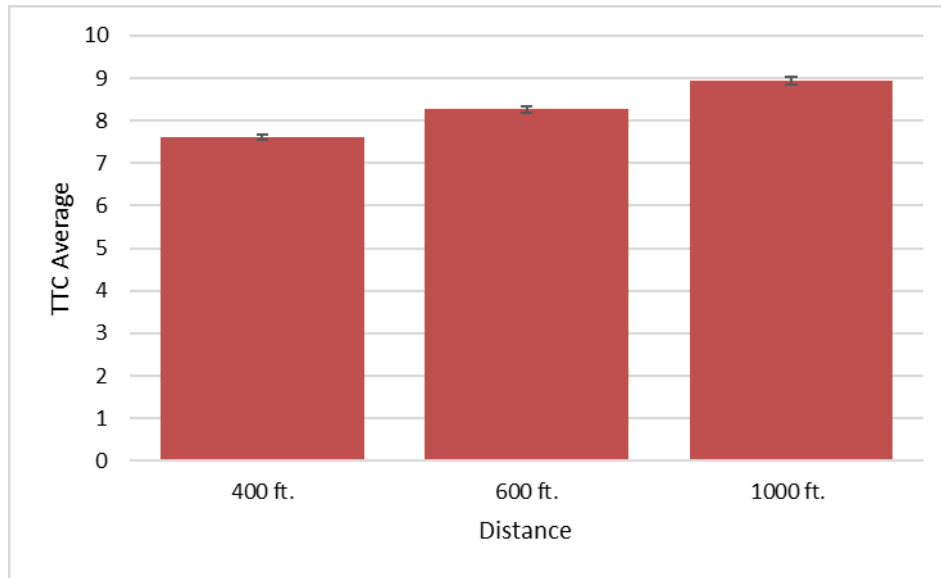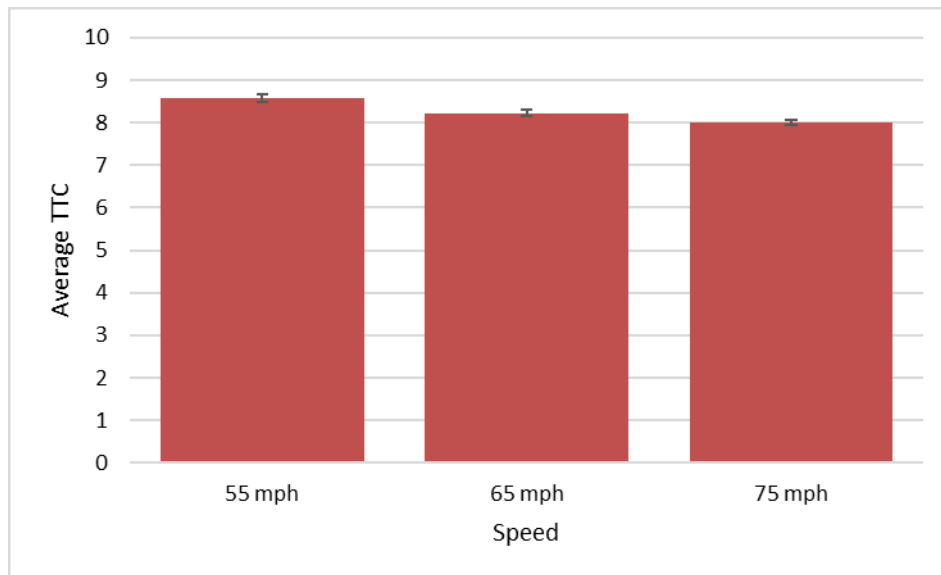

Figure 4.13 Average TTC for distance.

Figure 4.14 Average TTC for speed.

For estimated crash rate, there was a main effect of distance, Greenhouse-Geisser corrected, $F(1.49, 49.16)$ = 70.01, p < .001, η^2 = .68. The 400 ft. distance had significantly higher estimated crashes (M =

.11, *SE* = .01) than the 600 ft. distance (*M* = .03, *SE* = .007), and both had significantly greater estimated crash rates than the 1000 ft. distance (*M* = .009, *SE* = .005) (*ps* < .001). There was a main effect for speed, $F(2, 66) = 10.06$, $p < .001$, $\eta^2 = .234$, with the 55 mph condition having significantly lower estimated crashes (*M* = .03, *SE* = .008) relative to the 65 mph (*M* = .05, *SE* = .008) and 75 mph (*M* = .08, *SE* = .01) conditions (*p* = .013, *p* < .001, respectively). The 65 mph and 75 mph conditions did not significantly differ (*p* = .055). There was a distance × speed interaction, Greenhouse-Geisser corrected, $F(2.10, 98.87) = 4.69$, $p = .004$, $\eta^2 = .124$. For the 400 ft. distance, 55 mph speed conditions were had higher crash rates than the 75 mph conditions (paired samples t-tests, *p* < .001), but for the 1000 ft. distance, the 55 mph and 75 mph speed conditions did not have a difference in crash rate (*p* = .694), see Figure 4.15.
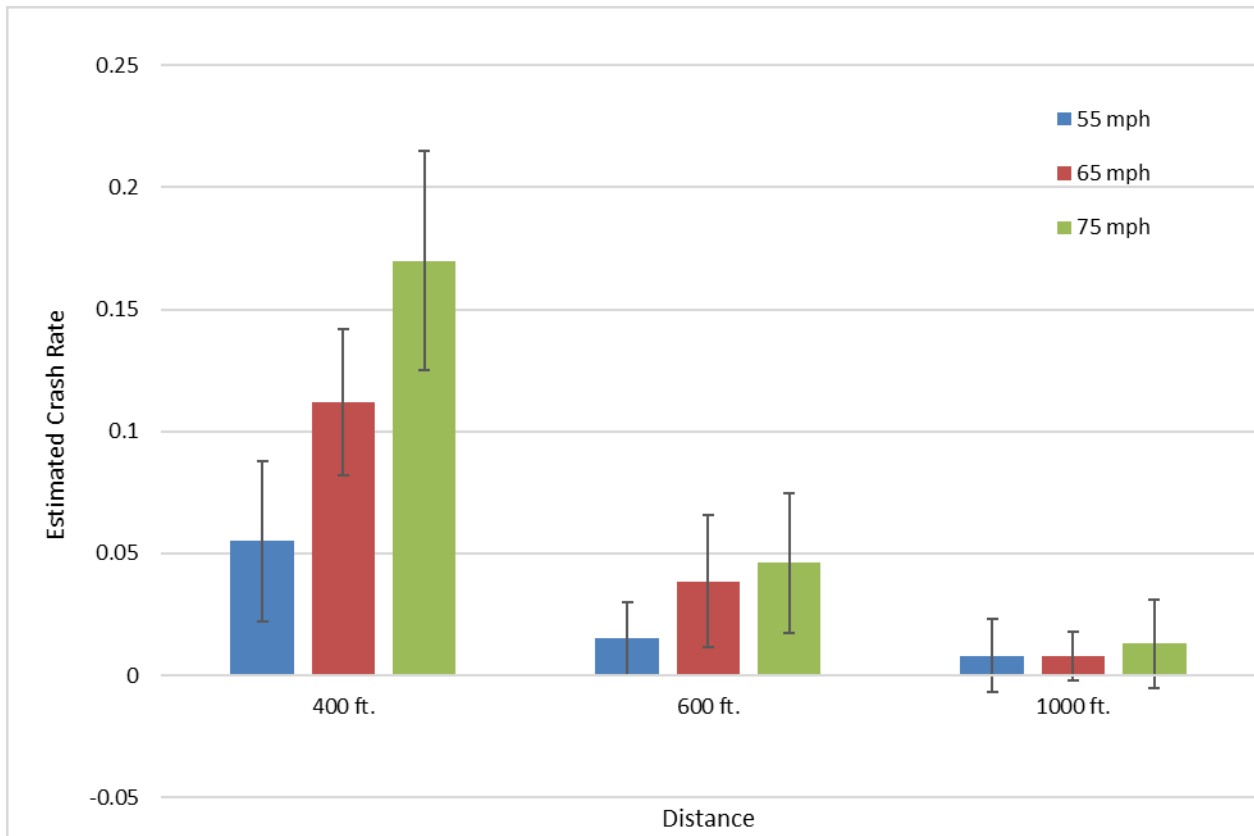
Figure 4.15 Estimated crash rate as a function of distance and speed.

For misses, there was a main effect of distance, $F(2,66) = 59.31$, $p < .001$, $\eta^2 = .643$. The 400 ft. distance had significantly fewer misses (*M* = .11, *SE* = .01) than the 600 ft. distance (*M* = .20, *SE* = .02), and both had significantly fewer misses than the 1000 ft. distance (*M* = .26, *SE* = .02) (*ps* < .001), see Figure 4.16. There was a main effect for speed, $F(2, 66) = 25.48$, $p < .001$, $\eta^2 = . 436$, with the 55 mph condition having significantly higher misses (*M* = .23, *SE* = .016) relative to the 65 mph (*M* = .186, *SE* = .015) and 75 mph (*M* = .155, *SE* = .015) conditions (*ps* <.001). The 65 mph and 75 mph conditions were also

significantly different (p = .012), see Figure 4.17. There was no distance × speed interaction, Greenhouse-Geisser corrected, $F(2.89, 95.25)$ = 1.07, p = .366, η^2 = .031.
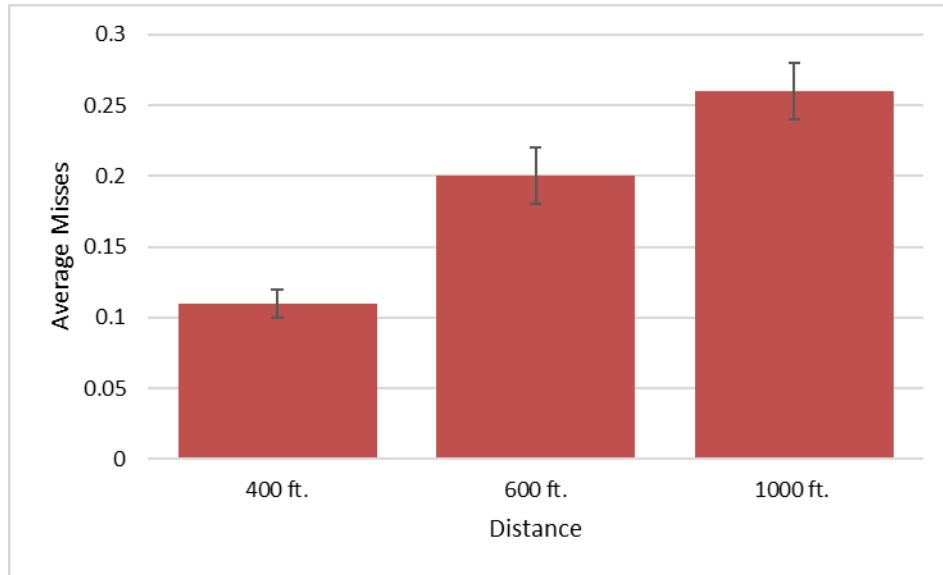
Figure 4.16 Average misses by distance.
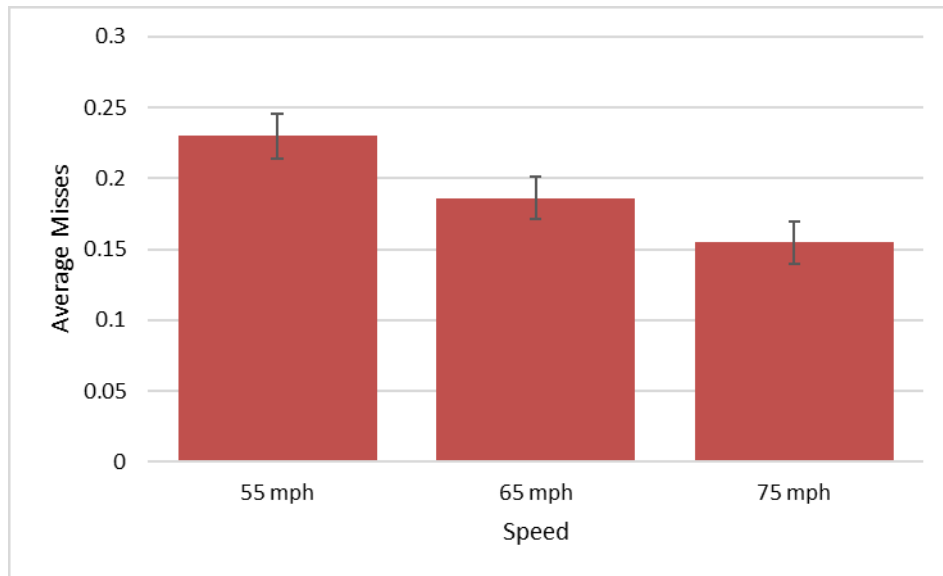
Figure 4.17 Average misses by speed.

For hesitancy, there was a main effect of distance, $F(2,66)$ = 20.29, p < .001, η^2 = .381. The 400 ft. distance had significantly higher hesitancy duration (M = .98, SE = .10) than the 600 ft. distance (M = .81, SE = .09), and both had significantly higher hesitancy duration than the 1000 ft. distance (M = .57, SE = .055) (p = .004, p < .001, p = .002, respectively), see Figure 4.18. There was a main effect for speed, $F(2, 66)$ = 5.38, p = .007, η^2 = . 14, with the 55 mph condition having significantly lower hesitancy duration (M

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= .69, *SE* = .068) relative to the 75 mph (*M* = .89, *SE* = .091) condition (*p*s <.001). The 65 mph condition did not significantly differ from the others (*p*s > .10), see Figure 4.19. There was no distance × speed interaction, Greenhouse-Geisser corrected, *F*(1.81, 59.71) = 2.55, *p* = .092, η^2 = .072.
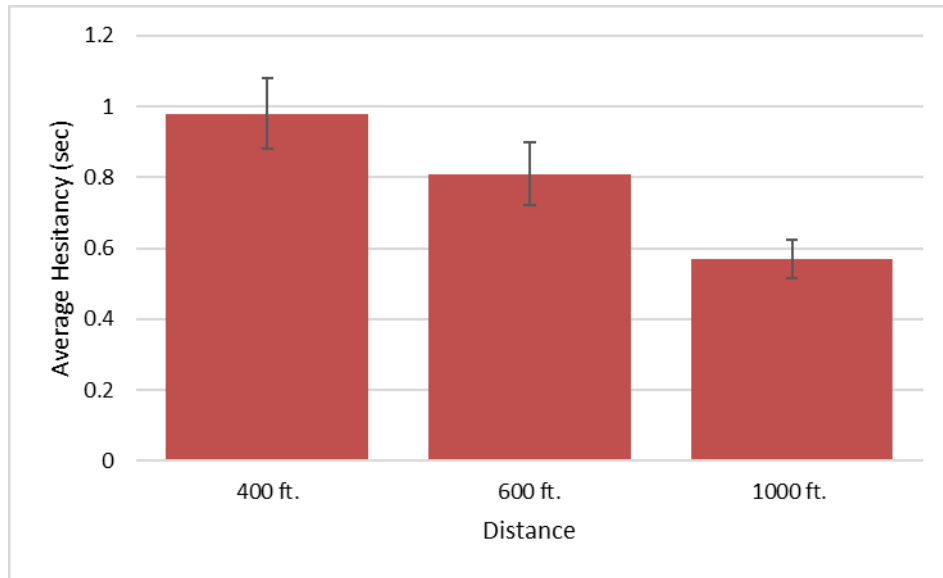
Figure 4.18 Average hesitancy duration by distance.
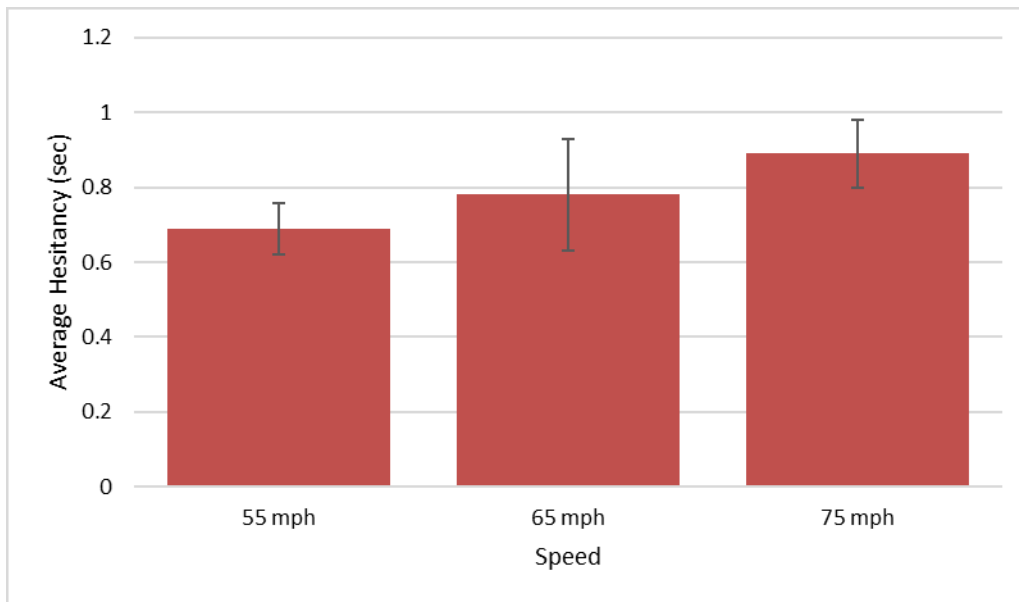
Figure 4.19 Average hesitancy duration by speed.

For head movement or glance counts, there was a main effect of distance, Greenhouse-Geisser corrected, *F*(1.36, 33.88) = 13.34, *p* < .001, η^2 = .348. The 400 ft. distance had significantly higher number of head movements (*M* = 43.89, *SE* = 1.97) than the 600 ft. distance (*M* = 40.03, *SE* = 1.66), and

the 1000 ft. distance (*M* = 38.55, *SE* = 1.72) (*p*s < .001), see Figure 4.20. The 600 ft. and 1000 ft. distance did not differ from each other in terms of head movement count (*p* = .051). There was no main effect for speed, (*F* < 1). There was no distance × speed interaction, (*F* < 1). In order to ensure that glance counts were accurately coded for head movement direction and shifts, two researchers performed coding in the head movement videos. The reliability between each coder's judgments were tested using Intraclass Correlation Coefficients (Bartko, 1966; McGraw & Wong 1996). ICC estimates and their 95% confident intervals were calculated using R's statistical package DescTools (Andri Signorell et mult. al. ,2019) based on a mean-rating (k = 2), absolute-agreement, one-way random effects model. Results indicate that inter-rater reliability was excellent by Intraclass Correlation Coefficients standards; ICC (1) = 1, CI: [0.999 < ICC < 1], suggesting that coders were nearly in perfect agreement on the coding dataset.
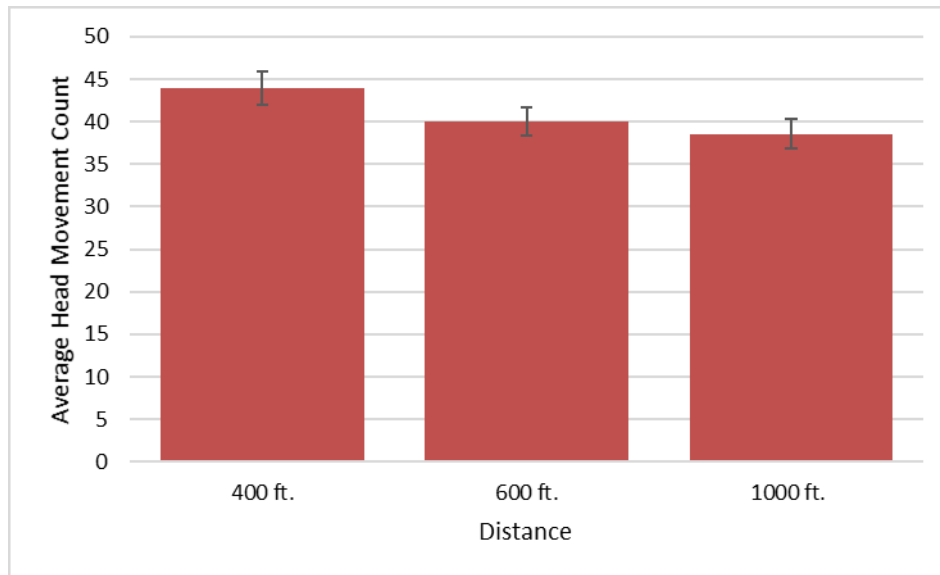
Figure 4.20 Average count of head movements or glances by distance.

4.3.2 Mainline Drive Results

For subjective measures, specifically mental workload as assessed by the RSME, the average for the mainline drive was 55.97 (*SD* = 19.56), which is approximately "rather much effort" on the scale. This demonstrates that the secondary task imposed on drivers sufficiently loaded their mental resources to help to increase the power of the study results.

4.3.2.1 Performance measures results for stationary vs. moving vehicles

For the performance variables of interest, a series of paired samples t-tests were conducted between the stationary and intruding vehicle conditions to confirm that there were expected performance patterns (both differences and no differences) for the measures, see Table 4.1. The results help to validate the driving scenarios to show that participants performed similarly in their speed and speed

deviation in the first half-mile segment prior to the intersection. The remaining variables demonstrate that participants did significantly change their performance (e.g., mean speed, speed deviation, heading, accelerator release, and braking) in response to intruding vehicles compared to stationary conditions as intended by the experiment. The Collisions and TTC minimums were not analyzed here due to there being very few scores recorded for the stationary vehicle condition.

Table 4.1 Comparison of stationary and intruding vehicle conditions

	Stationary Veh. Mean	Stationary Std. Deviation (Std. Error)	Intruding Veh. Mean	Intruding Std. Deviation (Std. Error)	t-value	p-value
Mean Speed 1st Half Mile (mph)	59.61	2.68 (0.47)	59.69	2.69 (0.48)	-2.72	.79
Mean Speed 4th Quarter (mph)	**59.75**	**2.92 (0.52)**	**50.75**	**5.02 (0.89)**	**14.03**	**<.001**
Standard Dev. Speed 1st Half Mile (mph)	5.32	1.42 (0.25)	4.8	1.39 (0.25)	1.38	.179
Standard Dev. Speed 4th Quarter (mph)	**2.47**	**2.01 (0.36)**	**15.46**	**3.96 (0.70)**	**-18.08**	**<.001**
Max Heading Error 4th Quarter (degrees)	**0.149**	**.111 (.02)**	**1.455**	**1.65 (.29)**	**-4.56**	**<.001**
Accelerator Pedal Release Distance (ft.)	**398.47**	**222.75 (42.10)**	**297.99**	**238.09 (44.99)**	**2.75**	**.011**
Brake Press Distance (ft.)	**111.48**	**20 (5.16)**	**80.84**	**25.02 (6.46)**	**4.54**	**<.001**

4.3.2.2 Secondary Task Results

Participants' arrow task performance during the mainline drive was assessed. A total of 608 total engagements with the arrow task, placed on the center stack interface in the driving simulator, were initiated by participants. On average, participants interacted with the arrows task nearly 7 times (M = 6.52, SD = 9.52), suggesting that participants introduced additional mental workload during their driving tasks. Participant mean accuracy during their arrow task trials, or Correct spins divided by Total spins as found in Table 4.2, was 73.8% (SD = 31.8%).

Table 4.2 Descriptive Statistics of secondary task

	Mean RT	Accuracy	Correct spins	Total spins
N observations	608	608	608	608
Mean	6.516	0.7379	1.839	2.474
Std. Deviation	9.522	0.3177	1.366	1.402
Minimum	0.08439	0.000	0.000	1.000
Maximum	138.8	1.000	8.000	8.000
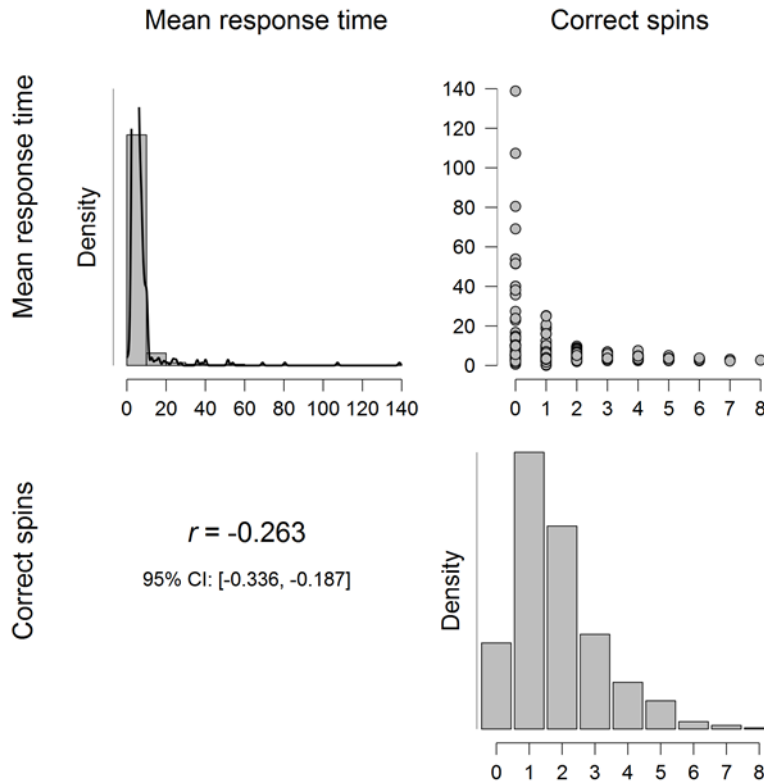
Figure 4.21 Descriptive statistics and correlation coefficients for secondary task.

4.3.2.3 Performance Measures Results for Speed-Based Variables

Each set of analyses first considers stationary vehicles and then intruding (i.e., moving) vehicles. Once dependent measures were divided by vehicle movement, sight distance (i.e., 400 ft., 600 ft., and 1000 ft.) and vehicle proximity (i.e., stopped "near" intersection, "far" from intersection, or "absent") were considered.

For the average speed for the first half mile prior to the intersection for *stationary vehicles*, there was no main effect for distance ($F < 1$), proximity *($F < 1$)*, and no distance × proximity interaction, $F(4, 120) = 1.10$, $p = .360$, $\eta^2 = .035$.

For the average speed for the first half mile prior to the intersection for *intruding vehicles*, there was no main effect for distance, $F(2, 60) = 2.45$, $p = .095$, $\eta^2 = .076$, proximity ($F < 1$), and no distance × proximity interaction, ($F < 1$).

For the standard deviation of speed for the first half mile prior to the intersection for *stationary vehicles*, there was no main effect for distance ($F < 1$), proximity ($F < 1$), and no distance × proximity interaction, ($F < 1$).

For the standard deviation of speed for the first half mile prior to the intersection for *intruding vehicles*, there was no main effect for distance, $F(2, 60) = 2.90$, $p = .062$, $\eta^2 = .088$, proximity (F < 1), and no distance × proximity interaction, ($F < 1$).

For the average speed (in mph) for the 4th quarter mile including the intersection for *stationary vehicles*, there was no main effect for distance (F < 1) and no distance × proximity interaction ($F < 1$). There was a main effect of proximity, $F(2, 60) = 6.99$, $p = .002$, $\eta^2 = .189$. Participants were on average slower for the near proximity condition (M = 58.6, SE = .765) than for the far proximity condition (M = 60.37, SE = .485), p = .006, or the vehicle absent condition (M = 60.55, SE = .58), $p = .005$, see Figure 4.22. The far proximity and vehicle absent conditions were not significantly different ($p = .699$).

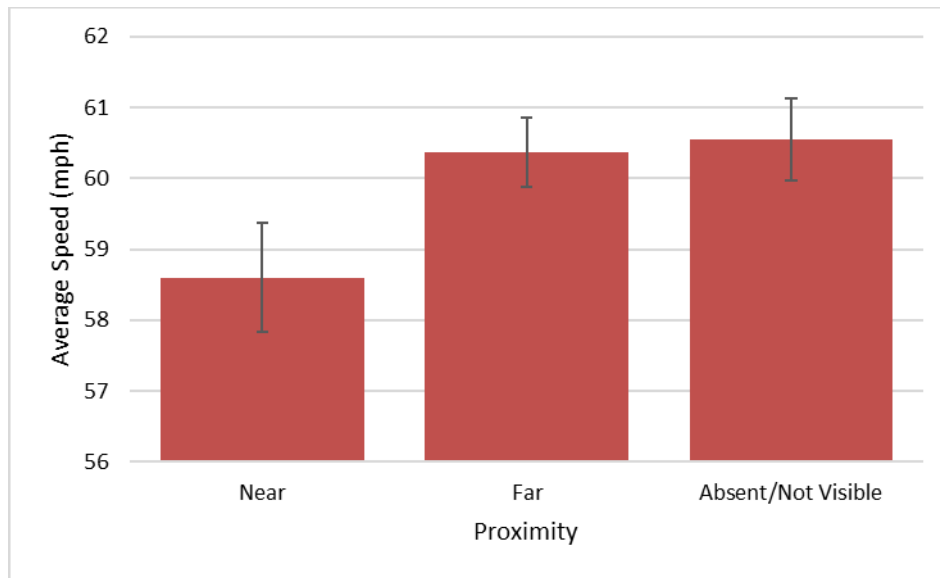**Figure 4.22 Average speed (mph) in the 4th quarter mile for stationary vehicles by proximity.**

For the average speed for the 4th quarter mile including the intersection for *intruding vehicles*, there was a main effect for distance, $F(2, 60) = 6.848$, $p = .002$, $\eta^2 = .186$. The 400 ft. sight distance had higher average speeds (*M* = 51.96, *SE* = 0.955) than the 1000 ft. sight distance condition (*M* = 49.57, *SE* = 1.049), $p < .001$. There were no other significant differences for distance. There was a main effect of proximity, $F(2, 60) = 45.57$, $p < .001$, $\eta^2 = .603$. The near proximity condition (*M* = 47.51, *SE* = 1.0) had average slower speeds than the far proximity condition (*M* = 49.66, *SE* = 1.087), $p = .014$, and the stop-sign-running condition (*M* = 55.27, *SE* = 1.016), $p < .001$, and far proximity and stop-sign-running conditions were significantly different ($p < .001$). There was a distance × proximity interaction, $F(4, 120) = 6.18$, $p < .001$, $\eta^2 = .171$, see Figure 4.23. This interaction is driven by significant differences in speed between the stop-sign-running conditions and both near and far proximity conditions for the shorter sight distances (400 ft., 600 ft.) (*ps* < .001), while there is no significant difference between the stop-sign-running average speeds and the other proximity conditions in the 1000 ft. condition ($p = .234$ and $p = .045$, with Bonferroni corrected alpha of .05/6 or .0083).

Figure 4.23 Average speed (mph) for the 4ᵗʰ quarter mile for moving vehicles as a function of distance and proximity.

For the standard deviation of speed (in mph) for the 4ᵗʰ quarter mile including the intersection for *stationary vehicles*, there was no main effect for distance (F < 1), and no distance × proximity interaction, Greenhouse-Geisser corrected, $F(2.75, 82.40) = 1.81$, $p = .156$, $\eta^2 = .057$. There was a main effect of proximity, Greenhouse-Geisser corrected, $F(1.86, 55.88) = 5.19$, $p = .015$, $\eta^2 = .147$. Speed deviation is higher for the near proximity condition (M = 3.29, SE = .620) than the far proximity condition (M = 2.39, SE = .441), p = .041, and the vehicle absent condition (M = 1.73, SE = .251), $p = .014$, see Figure 4.24. There is no difference between the far and absent conditions ($p = .119$).
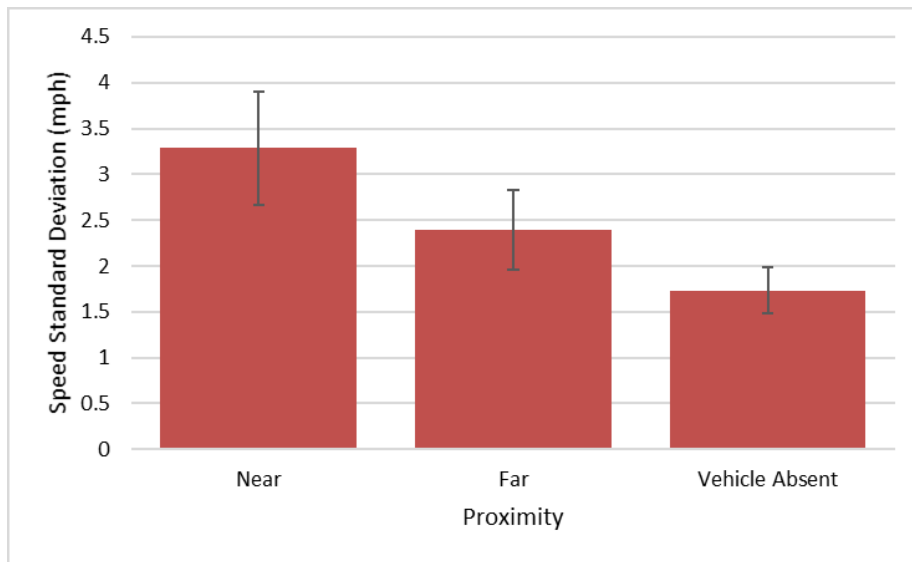
Figure 4.24 Standard deviation of speed (mph) for the 4ᵗʰ quarter mile for stationary vehicles by proximity.

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For the standard deviation of speed for the 4th quarter mile including the intersection for *intruding vehicles*, there was a main effect for distance, Greenhouse-Geisser corrected, $F(1.66, 49.87) = 4.59$, $p = .02$, $\eta^2 = .133$. The 400 ft. sight distance had lower average speed deviation ($M = 14.67$, $SE = 0.76$) than the 1000 ft. sight distance condition ($M = 16.62$, $SE = 0.85$), $p = .005$. There were no other significant differences for distance. There was a main effect of proximity, Greenhouse-Geisser corrected, $F(1.52, 45.45) = 45.29$, $p < .001$, $\eta^2 = .602$. The near proximity condition ($M = 18.70$, $SE = 0.792$) had higher average speed deviation than the far proximity condition ($M = 17.20$, $SE = 0.91$), $p = .014$, and the stop-sign-running condition ($M = 10.83$, $SE = 0.917$), $p < .001$, and far proximity and stop-sign-running conditions were significantly different ($p < .001$). There was a distance × proximity interaction, Greenhouse-Geisser corrected, $F(3.06, 91.92) = 8.00$, $p < .001$, $\eta^2 = .211$, see Figure 4.25. This interaction is driven by significant differences in speed deviations between the stop-sign-running conditions and both near and far proximity conditions for the shorter sight distances (400 ft., 600 ft.) ($ps < .001$), while there is no significant difference between the stop-sign-running average speed deviations and the other proximity conditions in the 1000 ft. condition ($p = .53$ and $p = .073$, with Bonferroni corrected alpha of .05/6 or .0083).
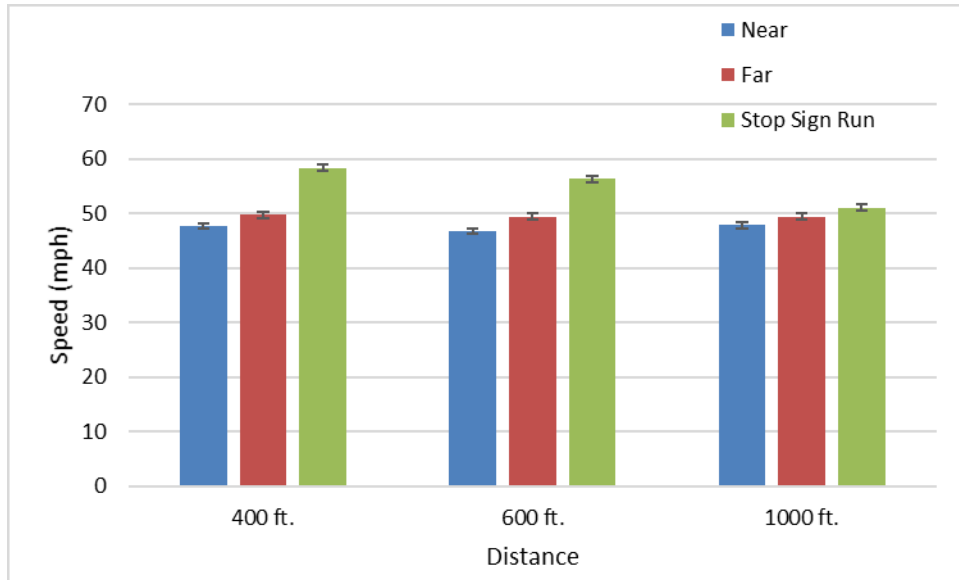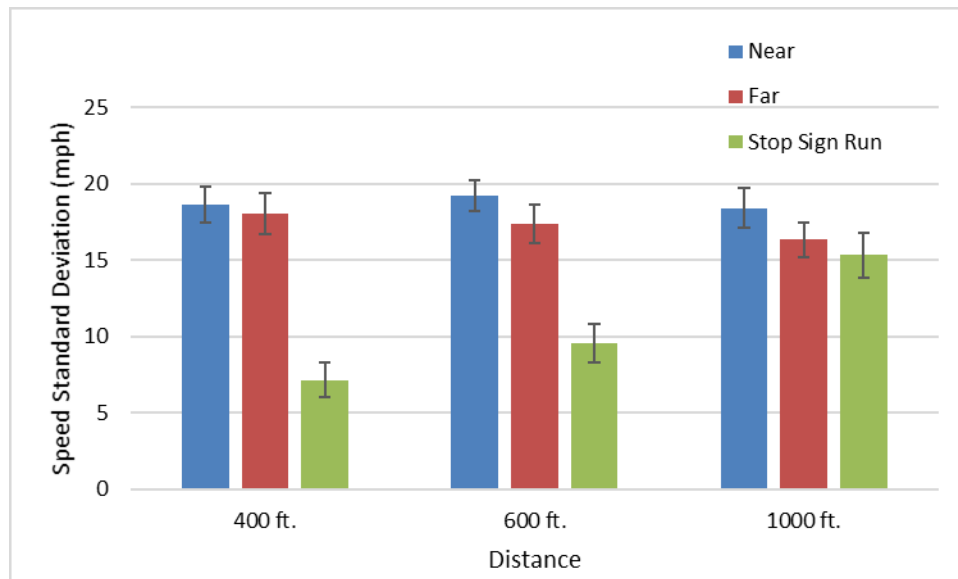

Figure 4.25 Average standard deviation of speed (mph) in the 4th quarter mile for moving vehicles as a function of distance and proximity.

4.3.2.4 Performance measures results for event-based variables

All analyses for events are based on the intruding vehicle condition, as the stationary vehicle condition did not have any events (i.e., intersection intrusions).

For accelerator release time, there was no main effect for distance ($F < 1$), no effect of proximity, $F(2, 52) = 1.04$, $p = .36$, $\eta^2 = .038$, and no distance × proximity interaction, ($F < 1$).

For braking distance, there was a main effect of distance, $F(2,36) = 6.124$, $p = .005$, $\eta^2 = .254$. The 1000 ft. condition ($M = 73.94$, $SE = 3.42$) had a longer braking distance than the 400 ft. ($M = 61.256$, $SE = 3.454$) and 600 ft. ($M = 65.23$, $SE = 2.75$) conditions ($p = .005$ & $p = .021$, respectively). There was no difference between the 400 ft. and 600 ft. conditions ($p = .301$). There was a main effect of proximity, $F(2,36) = 6.375$, $p = .004$, $\eta^2 = .262$. The stop-sign-running condition ($M = 59.97$, $SE = 2.90$) had a smaller braking distance than the near ($M = 72.02$, $SE = 3.72$) and far ($M = 68.43$, $SE = 2.67$) conditions ($p = .002$ & $p = .014$, respectively). There was no difference between the near and far conditions ($p = .362$). There was a distance × proximity interaction, Greenhouse-Geisser corrected, $F(2.91, 52.44) = 13.465$, $p < .001$, $\eta^2 = .428$. The interaction is driven by the differences or trend toward differences between the stop sign run condition and both the near and far conditions for the 400 ft. and 600 ft. distance conditions ($p < .001$, $p = .055$, $p = .006$, $p = .001$), while a difference in the opposite direction is significant or marginally significant for the 1000 ft. condition ($p < .001$, $p = .010$), see Figure 4.26. There is a Bonferroni corrected alpha of .05/6 or .0083.
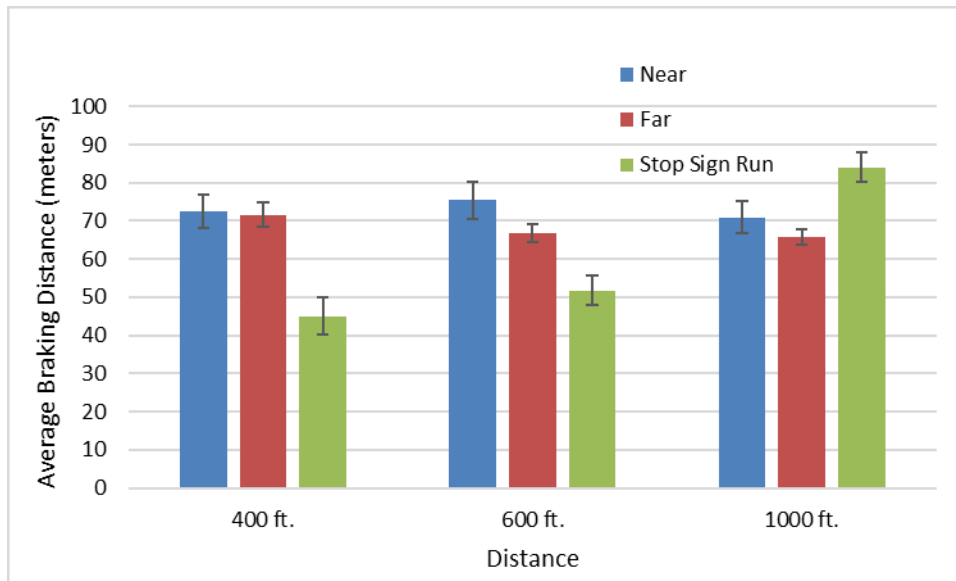
Figure 4.26 Average braking distance (m) for moving vehicles as a function of distance by proximity.

For maximum heading error in degrees for the 4th quarter mile, there was no main effect for distance ($F < 1$), no effect of proximity, Greenhouse-Geisser corrected, $F(1.52, 45.60) = 2.76$, $p = .087$, $\eta^2 = .084$, and no distance × proximity interaction, ($F < 1$).

For minimum time-to-collision (TTC) during the intruding event, there was a main effect of distance, Greenhouse-Geisser corrected, $F(1.38, 30.29) = 9.91$, $p = .002$, $\eta^2 = .311$. The 1000 ft. sight distance condition ($M = 2.03$, $SE = .223$) was significantly larger for minimum TTC than the 400 ft. ($M = 1.27$, $SE = .119$) and 600 ft. ($M = 1.424$, $SE = .119$) conditions ($p = .003$, $p = .002$). There was no difference between the 400 ft. and 600 ft. conditions ($p = .216$). There was no effect of proximity, Greenhouse-Geisser corrected, $F(1.41, 30.999) = 1.997$, $p = .163$, $\eta^2 = .083$. There was a distance × proximity interaction,

Greenhouse-Geisser corrected, $F(1.73, 38.01) = 10.70$, $p < .001$, $\eta^2 = .327$, see Figure 4.27. The interaction was driven by the observation that the stop sign run condition had significantly less TTC minimums than the near and far proximity conditions for the 400 ft. and 600 ft. distances ($ps < .001$). However, there were no minimum TTC differences between the stop sign run condition and the near and far proximity conditions for the 1000 ft. sight distances ($p= .092$, $p = .076$). There is a Bonferroni corrected alpha of .05/6 or .0083.
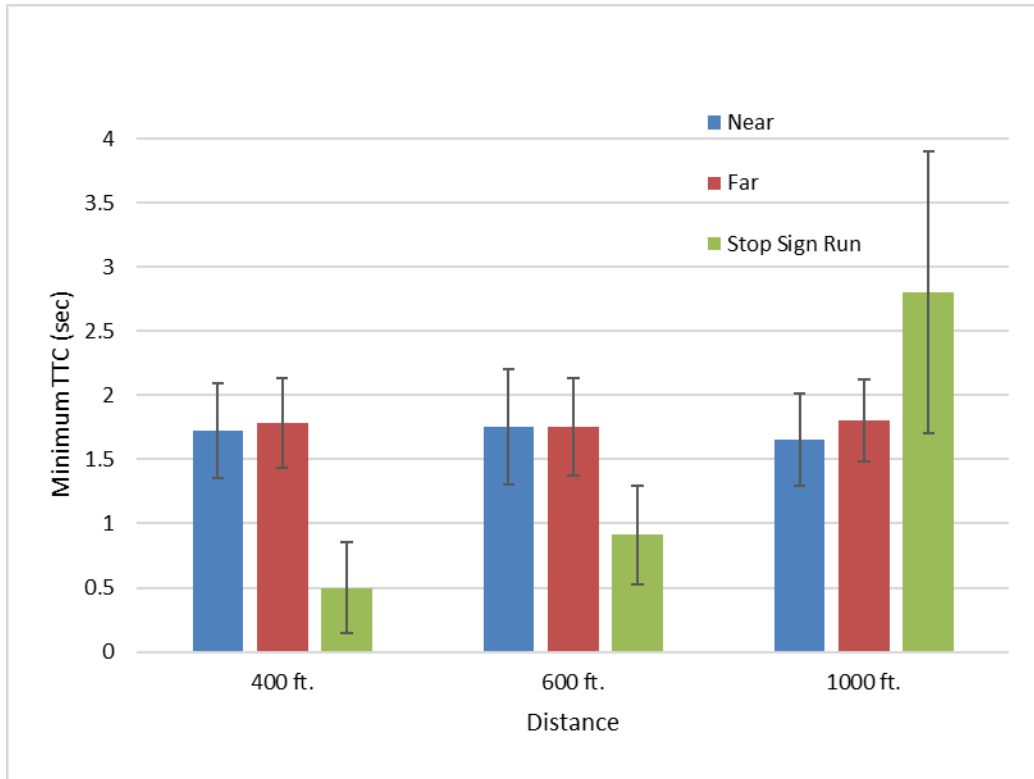
Figure 4.27 Minimum TTC value for moving vehicles as a function of distance and proximity.

For collision rate, there was no main effect for distance, Greenhouse-Geisser corrected, $F(1.29, 38.74) = 1.09$, $p = .320$, $\eta^2 = .035$, no effect of proximity ($F < 1$), and no distance × proximity interaction, Greenhouse-Geisser corrected, $F(2.11, 63.21) = 1.21$, $p = .308$, $\eta^2 = .039$.

An exploratory analysis of collision rate, focusing only on the stop-sign-running condition with a repeated measures ANOVA with three levels of distance (400 ft., 600 ft., 1000 ft.) found a significant effect of distance, $F (2, 60) = 6.77$, $p = .002$, $\eta^2 = .184$, see Figure 4.28. The 1000 ft. condition had a lower collision rate ($M = 2.03$, $SE = 1.35$) than the 400 ft. ($M = 14.87$, $SE = 3.19$), $p < .001$, and 600 ft. ($M = 9.36$, $SE = 1.346$), $p =.019$, conditions ($p < .001$ & $p = .019$ respectively). There was no difference for stop-sign-running proximity between the 400 ft. and 600 ft. conditions ($p = .181$).

Figure 4.28 Collision rate for the stop-sign-running condition by distance.

CHAPTER 5: CONCLUSIONS

5.1 INTRODUCTION

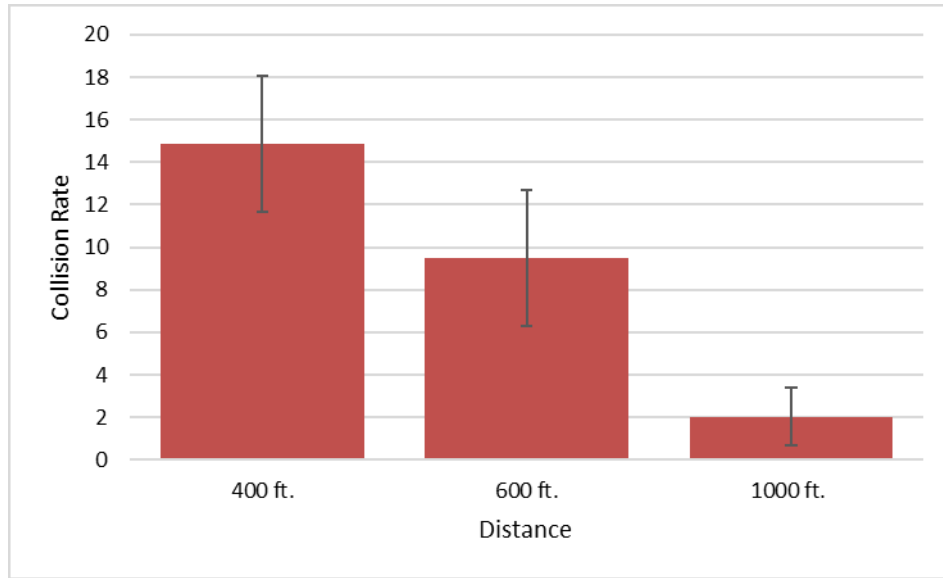The research team conducted a literature review, simulation build, validation test, and two experimental phases to test the efficacy of different decision sight distances at simulated rural intersections. The validation test ensured that the simulation build and experimental phases accurately characterized the experience of crossing and driving through similar rural intersections. For the experimental trials, the study tested driver behavior on both minor and major roads to ensure safety on both facets of the roadway.

Experimental data from 36 participants in a time-to-collision (TTC) intersection crossing judgment task and a rural highway thru-STOP intersection driving simulation task were analyzed to clarify the influence of rural thru-STOP intersection characteristics on driving performance and decision-making. First, longer sight distances of 1,000 ft. and slower crossing speeds (i.e., 55 mph) appear to be helpful for participants on the minor road attempting to take a gap and cross, given (1) lower mental workload, perceived risk, difficulty, and anxiousness, and (2) better performance in terms of estimated crash rate, and larger TTCs. Second, longer distances of 1,000 ft. appear to be somewhat helpful for drivers on the main road approaching an intersection, specifically when another driver on the minor road runs the stop sign.

5.2 EXPERIMENT DATA CONCLUSIONS

The research team can draw several broad conclusions from the presented data of relevance to engineers and safety experts responsible for designing and implementing layouts for rural intersections. First, longer sight distances of 1,000 ft. and slower crossing speed (i.e., 55 mph) appear to be particularly helpful for participants on the minor road attempting to take a gap and cross, given (1) lower mental workload, less perceived risk, difficulty, and anxiousness and (2) better performance in terms of estimated crash rate, larger TTCs, and less hesitancy. The increases in safety were met with some decreased efficiency, as participants were more likely to reject gaps longer than 6.5 sec. that would be considered safe to cross. Participants were more likely to press the pedal in short distances, often after hesitating to make the decision. The observed increases in hesitation at shorter sight distances and higher speeds may suggest that participants may have been too overloaded to efficiently select gaps once presented, and the hesitation results in a loss of safety as the ultimate gap accepted may have become unsafe during the wait. Head gaze movement counts were all higher in the lower sight distances, particularly the 400-ft. condition, even for slower vehicle speeds. The increased head movements could contribute to the increased hesitancy as the additional checking of the roadway costs valuable time prior to the driver selecting to take the, now shortened, gap.

Second, longer distances of 1000 ft. appear to be somewhat helpful for drivers on the main road approaching an intersection, specifically for the circumstances in which another driver on the minor

road runs the stop sign, as participants driving though intersections with 1000-ft. sight distances were better able to react and avoid cars running stop signs. This includes lower average speeds and higher average speed change (st. deviation) during the 4th quarter mile for stop-sign-running conditions given 1,000-ft. sight distance. Furthermore, there was greater average braking distance for that condition relative to the others, along with higher minimum time-to-contact, and fewer estimated crashes.

Third, vehicles placed nearer to the intersection appeared to lead participants to drive at somewhat slower speeds than when vehicles were placed farther away from the intersection, suggesting that the proximity of a vehicle to the intersection led to safer driving behaviors by participants travelling on the main road. Engineers should consider placing stop lines closer to the intersection. These stop lines could even be misaligned with the stop sign placement (given that the intersection geometry may have pushed the stop sign farther away from the roadway) and placed closer to the intersection than the stop sign. Also, a comparison analysis between stationary and moving vehicle conditions demonstrated that participants performed similarly in their speed and speed deviation in the first half-mile segment prior to the intersection, while participants significantly changed their performance (e.g., mean speed, speed deviation, heading, accelerator release, and braking) in response to intruding vehicles compared to stationary conditions, as intended by the experiment.

The primary concern was whether greater sight distances would improve driver subjective confidence while not leading to a corresponding improvement in performance, as some prior research has indicated (Ward & Wilde, 1996). However, at least for the sight distances tested, this appeared not to be the case. Results from both the intersection crossing judgment and rural highway mainline driving task suggest potential safety increases can be found by increasing intersection visibility via increased sight distance clearing on rural highways. While increased sight distance did not directly affect estimated crash rates when vehicles were proximal to the major road, the larger sight distance appeared to mitigate deadly outcomes from infrequent stop-sign-running events. This is particularly promising as stop-sign running from the minor road is thought to be a significant risk in rural thru-STOP intersections (Preston & Storm, 2003).

5.3 COSTS

5.3.1 Costs of clearing/grubbing

Based on our study results for sight distance at the experimental, near stop bar placement, we estimate 34 ft. of grubbing width is required at each leg of the intersection. This is based on the stop bar distance of 36 ft. from road edge, adds 12 ft. for the average length of a car (i.e., provides a margin of safety and error), and subtracts the already cleared 14 ft. for the ditch. This results in 34 ft. x 999.42193 ft. to achieve a 1,000-ft. sight distance (Pythagorean Theorem). The calculated area of the grubbing triangle is 33,980.3456 divided by 2, leading to a square footage of approximately 16,990 sq. ft.

As stated earlier, at the national level, clearing and grubbing can cost $2,000 to $15,500 per acre depending on the width of the road (Bushell, Poole, Zegeer, and Rodriguez, 2013; USDA Forest Service Northern Region Engineering, 2017). In Minnesota, the average cost for grubbing a rural intersection is $3,169 to $4,454 per acre and increases depending on the number of trees or other obstructions that must be cleared (MnDOT, 2018). Here we take the higher value of $4,454 per acre for clearing and grubbing on average. An acre is 43,560 sq. ft. The calculated square footage presented here is 16,990. When divided by 43,560 for an acre, this amounts to 0.390036731. This value multiplied by $4,454 leads to approximately $1,739 for one corner of a rural intersection. For all four corners, clearing and grubbing an intersection *along our suggested sight distance* costs approximately $6,946.

Ongoing maintenance should also be considered as a cost factor of sustaining target sight distances. According to MnDOT, maintenance of rural intersections must be done approximately three times per year, and the starting range is $300 to $500 per intersection. Further, this cost analysis does not include the additional costs of land acquisitions that may be required to obtain the desired sight distances if obstructions are present on private land. Maintenance agreements can be obtained with cooperating adjacent land owners where land acquisitions are not feasible; however, such arrangements would likely increase maintenance operations and costs compared to acquired land. The costs of routine maintenance, land acquisitions, and maintenance agreements on private land are not calculated in this cost benefit analysis due to the greater variability of cost by circumstance.

Preston, Storm, Donath, and Shakwitz (2004) conducted an analysis of crashes at intersections in Minnesota, considering a database of over 3,700 intersections. If we *unreasonably* assume that all of these intersections were rural thru-STOP intersections, then the cost of clearing and grubbing these intersections would be approximately $25,700,200 (i.e., 3,700 multiplied by 6,946), reflecting the ceiling cost for clearing and grubbing all thru-STOP intersections in rural Minnesota.

5.3.2 Costs of rural thru-STOP crashes

The following costs of intersection crashes are estimated based on Council, Zaloshnja, Miller, and Persaud (2005) and updated to reflect inflation for 2019. Given the increased severity of rural crashes (Preston, 2015), we can estimate that each crash costs approximately $157,000 to $300,000 for non-fatal crashes with disabling injuries, and $1,572,000 to $5,069,000 for fatal crashes.

Table 5.1 Costs of Multiple Vehicle Crash at Signed Intersections

Maximum Injury Severity in Crash	Mean Human Cost per Crash	Mean Comprehensive Cost per Crash
No injury	$6,209	$ 7,046
Evident or possible injury	$ 55,958	$ 100,807
Disabling injury	$ 157,965	$ 301,747
Killed	$ 1,572,128	$ 5,069,997

Table 5.1 adapted from Council et al 2005. Crash code was 8, multiple vehicles cross paths at signed intersection (mcp, sign), for speed limits at or above 50 mph. Comprehensive cost includes estimated Monetized Quality-Adjusted Life Years, which represent the value of years of statistical life lived in perfect health. Numbers have been adjusted from the original 2005 values for U.S. dollar inflation to reflect potential 2019 values via a CPI inflation calculator.

For a second estimate, Minnesota's Department of Public Safety's Crash Facts provides National Safety Council estimates of $90,000 for serious injury crashes and $1,542,000 for fatal crashes in 2016, which cost the state $718,446,000 in 2017 for fatal and serious injury crashes alone and over $1.7 billion for all crashes (MnDPS, 2018). Two hundred and twenty (65%) fatal crashes occurred in rural areas in 2018, and 42 fatal crashes occurred at stop sign controlled areas (MnDPS, 2018). Earlier estimates noted that 41.9% of statewide fatal crashes occurred at intersections between 2008 and 2012 (MnDOT, 2014). Therefore, we can assume that if even less than half of the fatal crashes at stop signs occurred at rural locations (20 fatal crashes), this reflects a cost of $30,000,000 to the state, assuming a cost of $1.5 million per crash. Also, 2,709 injury crashes occurred at stop signs, and if even less than half of those occurred at rural intersections (i.e., 1,000), this reflects a cost to Minnesota of between $90,000,000 ($90,000 per crash; MnDPS, 2018) to $157,000,000 ($157,000 per crash; Council et al., 2005), assuming serious injuries occurred, and not measuring the comprehensive cost per crash (see Table 5.1).

5.4 BENEFITS

5.4.1 Benefits via reduced crash rate

We estimate crash rates from our simulated crossing judgment task at two different clearing and grubbing sight distances: 1,000-ft. sight distance as the optimal distance and 600-ft. sight distance as a benchmark. There was an observed .03 crash rate at a 600-ft. sight distance and an observed crash rate of .009 at 1,000-ft. sight distance. For drivers making the decision to cross on the minor road at a thru-STOP intersection, this constitutes a 30% reduction in estimated crashes (i.e., .03x = .009 leads to x = .3).

When considering drivers on the mainline or major road who experienced intruding simulated vehicles run the stop sign, the 1,000-ft. sight distance condition had a lower estimated crash rate (M = 2.03) than the 600-ft. condition (M = 9.36). This leads to an estimated 21% reduction in crash rate (i.e., 9.36x = 2.03 leads to x = .21688) for a stop-sign-running scenario. This would lead to a greater overall reduction in crash rate than 30% as crossing the minor road and avoiding a vehicle running a stop sign represent two interacting threat points at an intersection. Furthermore, the previous analysis does not account for increases in time-to-contact with a 1,000-ft. sight distance relative to a 600-ft. sight distance, which could imply not only a reduced real-world crash rate but also reduced severity.

5.4.2 Benefits via reduced speeding

Speeding is a major issue at rural intersections (Preston, 2015) and is a contributing factor in 5.2% of overall fatal crashes and 2.8% of overall injury crashes (MnDPS, 2018). When the stop bar or stop lines are placed close to the intersection, participants driving on the mainline in our study drove an average of 58.61 mph when approaching an intersection, while those same drivers drove an average of 60.37 mph when the stop bars were placed farther away from the intersection. The recommended near placement of the stop bar to the intersection may help to slow drivers on the mainline and reduce speeding near thru-STOP intersections. Notably, study participants were instructed to drive at a constant 60 mph when not braking, which constrained the range of speed at which they would have normally chosen. The differences between these values may be magnified in real-world conditions where these constraints are absent. Finally, note a precedent for reduced crash risk for moving the stop bar and increasing the visibility of the intersection at the following links:

http://www.cmfclearinghouse.org/detail.cfm?facid=8866
http://www.cmfclearinghouse.org/detail.cfm?facid=8867

5.5 LIMITATIONS AND FUTURE DIRECTIONS

While the current findings suggest that reported stress and performance correspond, providing disputing evidence against Ward and Wilde (1996), this study only tested sight distances of up to 1,000 ft. It is possible that farther sight distances, which are present on some rural intersections, may lead to a situation in which driver's subjective experience of safety may not correspond with his or her actual safety margins. Additional intermediate distances should also be considered. Since little difference was found between the 400-ft. and 600-ft. sight distances, but significant behavior changes were observed at 1000-ft. sight distances, it is unknown what incremental gains may be found at 800-ft. sight distances. Future studies should examine if 800 ft. is an acceptable sight distance to obtain similar safety gains as observed with a 1,000-ft. sight distance.

Second, this study only considered straight roads and clear conditions, and it is possible that watching oncoming vehicles in different road geometries (e.g., curved roadways or highly skewed intersections or nighttime or snowy weather conditions) will lead to a different pattern of results. Such high-risk intersections and sub-optimal environmental or weather conditions could also be paired with increased or perfect visibility to further examine potential interactions between perceived risk and performance. However, presenting skewed intersections in a driving simulator that does not provide 360 degrees of viewing is difficult to capture the most problematic segments of the intersection and may need to be combined with controlled field testing.

Additionally, the sample included in this study was homogeneous given the mean age was 27 years old with a standard deviation of 6.7 years. While the limited age range of the study sample helped to increase the study power, it may not indicate whether the recommended sight distances equally apply to more at-risk demographic groups. Future work should include novice teen drivers and older drivers

(i.e., age 65 and older) to determine if the recommendations should be modified when considering a broader fleet of drivers. Expectations of approaching vehicles, particularly at higher speeds, might be different for drivers with less experience. Novice drivers' known differences in search strategies might reveal additional differences in head movements in gap acceptance decision-making. Further, older drivers may have different levels of hesitancy or misses due to more conservative tendencies in gap acceptance or may respond more cautiously in the mainline scenarios than younger drivers who tend to be more risk prone. Such future investigations may solidify the recommended sight distances by showing a larger change in mainline driver speeds based on stopped vehicle position or avoidance of non-stop-sign-running entering vehicles.

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APPENDIX A: SCREENING QUESTIONNAIRE

This questionnaire will be administered during the recruitment process to determine eligibility for participation.

1. What is your age?
   - EXCLUDE IF NOT 18-45
2. Have you had a U.S. driver's license for at least two years?
   - EXCLUDE IF NO
3. Do you drive a minimum of 4,000 miles each year?
   - EXCLUDE IF NO
4. Do you have at least 20/40 visual acuity, either corrected (contact lens only) or uncorrected? (i.e. persons that use corrective lenses which improve their vision to 20/40 may participate)
   - EXCLUDE IF NO
5. Do you have normal color vision?
   - EXCLUDE IF NO
6. Do you have any history of hearing loss which inhibits every day conversation?
   - EXCLUDE IF YES
7. Do you have any health problems that affect your driving?
   - EXCLUDE IF YES
8. Do you experience inner ear problems, dizziness, vertigo, or balance problems?
   - EXCLUDE IF YES
9. Do you have a history of motion sickness or sea sickness? (e.g., back seat of car, boats, amusement park rides, etc)
   - EXCLUDE IF YES
10. Are you suffering from any lingering effects of stroke, tumor, head trauma, or infection?
    - EXCLUDE IF YES
11. Do you or have you ever suffered from epileptic seizures?
    - EXCLUDE IF YES
12. Do you have a history of migraines?
    - EXCLUDE IF YES

APPENDIX B: DRIVING HISTORY QUESTIONNAIRE

This questionnaire asks you to indicate some details about your driving history and related information. Please tick one box for each question.

1. Your age: _____ years

2. Your sex: ☐

          Male   ☐
          Female ☐

3. What is your highest educational level completed?

    ☐   High School / Vocational School
    ☐   Associates Degree
    ☐   Bachelor of Arts / Bachelor of Science
    ☐   Masters
    ☐   PhD

4. Are you currently taking any college level classes?

          Yes   ☐
          No   ☐
          ☐

5. Please state your occupation:_____

6. Please state the **year** when you obtained your full driving license: _____

7. About how often do you drive nowadays?

      ☐   ☐   ☐   ☐   ☐
   Never   Hardly Ever   Sometimes   Most Days   Every Day

8. Estimate roughly how many miles you personally have driven in the past year:
    ☐   Less than 5000 miles
    ☐   5000-10,000 miles
    ☐   10,000-15,000 miles
    ☐   15,000-20,000 miles
    ☐   Over 20,000 miles

9. About how often do you drive to and from your place of work?

      ☐   ☐   ☐   ☐   ☐
   Never   Hardly Ever   Sometimes   Most Days   Every Day

Do you drive frequently on…	Yes	No
10. Highways?	☐	☐
11. Main Roads other than Highways?	☐	☐
12. Urban Roads?	☐	☐
13. Country Roads?	☐	☐

14. During the last three years, how many <u>minor</u> traffic crashes have you been involved in where you were at fault? A minor crash is one in which no-one required medical treatment, AND costs of damage to vehicles and property were less than $1500.

       Number of minor accidents _____ (if none, write 0)

15. During the last three years, how many <u>major</u> traffic crashes have you been involved in where you were at fault? A major crash is one in which EITHER someone required medical treatment, OR costs of damage to vehicles and property were greater than $1500, or both.

       Number of major accidents _____ (if none, write 0)

16. During the last three years, have you ever been convicted for:

	Yes	No
a. Speeding	☐	☐
b. Distracted, careless, or dangerous driving	☐	☐
c. Driving under the influence of alcohol/drugs	☐	☐

17. What type of vehicle do you drive most often?

Motorcycle	☐
Passenger Car	☐
Motorcycle	☐
Sport utility vehicle	☐
Van or Minivan	☐
Other, briefly describe:	_____

APPENDIX C: DRIVER STRESS INVENTORY

This questionnaire lists a number of errors and violations that people have experienced or observed while driving. For each item, you are required to indicate how often, if at all, this kind of thing has happened to you-- say, over a period of about the last year. You do this by circling ONE of the numbers to the right of each item. These numbers range from 0-5, and have the following meanings:

0=NEVER, 1=HARDLY EVER, 2=OCCASIONALLY, 3=QUITE OFTEN, 4=FREQUENTLY, 5=NEARLY ALL THE TIME.

It is, of course, impossible for you to give precise answers: we are only interested in your general impressions. So don't spend too long thinking about each item. Simply give your best guess as quickly as possible by CIRCLING the number you think most appropriate.

1. Deliberately disregard the speed limits late at night or very early in the morning.

0   1   2   3   4   5

2. Drive especially close or 'flash' the car in front as a signal for that driver to go faster or get out of your way

0   1   2   3   4   5

3. Exceed the speed limit in residential areas

0   1   2   3   4   5

4. Angered by another driver's behavior, you chase them with the intention of giving him/her a piece of your mind

0   1   2   3   4   5

5. Drive with only 'half-an-eye' on the road while looking at a map, changing a cassette or radio channel, fixing make up, dialing car phone, etc.

0   1   2   3   4   5

6. Take a chance and drive through a red light

0   1   2   3   4   5

7. Stuck behind a slow-moving vehicle on a two-lane highway, you are driven by frustration to try to pass in a no-passing zone

0 1 2 3 4 5

8. Intending to drive to destination A, you 'wake up' to find yourself en route to B, where the latter is the more usual journey

0 1 2 3 4 5

9. Try to pass without first checking your mirror, and then get honked at by the car behind which has already begun its passing maneuver

0 1 2 3 4 5

10. Disregard red lights when driving late at night along empty roads

0 1 2 3 4 5

11. Get involved in unofficial 'races' with other drivers

0 1 2 3 4 5

12. Misjudge your crossing interval when turning left and narrowly miss collision

0 1 2 3 4 5

13. Exceed the speed limit on highways

0 1 2 3 4 5

14. Fail to check your mirror before pulling out, changing lanes, turning, etc

0 1 2 3 4 5

15. Distracted or preoccupied, realize belatedly that the vehicle ahead has slowed, and have to slam on the brakes to avoid a collision

0 1 2 3 4 5

APPENDIX D: SIGHT DISTANCE VALIDITY TEST PLAN

Description: Researchers will conduct a validity test of the presented sight distances in the simulation to ensure that the specified simulated sight distances are matched with participants' perceptions. Simulations may be compared to real world videos or images of intersection visibilities. Any discrepancies will be accounted for through simulation modifications.

Deliverable: A video and available in-person demonstration to the TAP of the simulated drives and experimental tasks for each experiment will be conducted as the deliverable.

To test and validate:

1. *What is the estimate of this sight distance?*

    Distances of 1. 400 ft., 2. 600 ft., 3. 1000 ft., counterbalanced.

    Participants choose distance they believe the simulation is presenting

    Out of 5-10 choices

2. *Speeds and Distances Representativeness*

    Speeds of 1. 55 mph, 2. 65 mph, 3. 75 mph

    For EACH sight distance and speed combination (9 combinations)

    7 pt. scale for representativeness to rural intersections

    Qualitative comments

3. *Real world similarity to rural intersections*

    7 pt. scale for representativeness overall to rural intersections

    Qualitative comments

4. *General qualitative comments on similarity, speeds, distances, and other thoughts*

APPENDIX E: VALIDITY TEST RESPONSE SHEET

Sight Distance Estimation

1. What do you estimate the visible distance or sight distance to be for this trial?
    a. 100 ft.
    b. 200 ft.
    c. 400 ft.
    d. 600 ft.
    e. 800 ft.
    f. 1000 ft.
    g. 1200 ft.
    h. 1400 ft.

2. What do you estimate the visible distance or sight distance to be for this trial?
    a. 100 ft.
    b. 200 ft.
    c. 400 ft.
    d. 600 ft.
    e. 800 ft.
    f. 1000 ft.
    g. 1200 ft.
    h. 1400 ft.

3. What do you estimate the visible distance or sight distance to be for this trial?
    a. 100 ft.
    b. 200 ft.
    c. 400 ft.
    d. 600 ft.
    e. 800 ft.
    f. 1000 ft.
    g. 1200 ft.
    h. 1400 ft.

Representativeness of Speeds

1. *For the presented speed of 55 mph at 400 ft. sight distance, please indicate how representative it is of real rural intersections of 55 mph at 400 ft. sight distance.*

Not at all	Very little	Somewhat	Moderately	Significantly	Very much	Completely
O	O	O	O	O	O	O

      1a. Do you have any comments you'd like to make?

2. *For the presented speed of 65 mph at 400 ft. sight distance, please indicate how representative it is of real rural intersections of 65 mph at 400 ft. sight distance.*

Not at all	Very little	Somewhat	Moderately	Significantly	Very much	Completely
O	O	O	O	O	O	O

      2a. Do you have any comments you'd like to make?

3. *For the presented speed of 75 mph at 400 ft. sight distance, please indicate how representative it is of real rural intersections of 75 mph at 400 ft. sight distance.*

Not at all	Very little	Somewhat	Moderately	Significantly	Very much	Completely
O	O	O	O	O	O	O

      3a. Do you have any comments you'd like to make?

4. *For the presented speed of 55 mph at 600 ft. sight distance, please indicate how representative it is of real rural intersections of 55 mph at 600 ft. sight distance.*

Not at all	Very little	Somewhat	Moderately	Significantly	Very much	Completely
O	O	O	O	O	O	O

      4a. Do you have any comments you'd like to make?

5. *For the presented speed of 65 mph at 600 ft. sight distance, please indicate how representative it is of real rural intersections of 65 mph at 600 ft. sight distance.*

Not at all	Very little	Somewhat	Moderately	Significantly	Very much	Completely
O	O	O	O	O	O	O

      5a. Do you have any comments you'd like to make?

6. *For the presented speed of 75 mph at 600 ft. sight distance, please indicate how representative it is of real rural intersections of 75 mph at 600 ft. sight distance.*

Not at all	Very little	Somewhat	Moderately	Significantly	Very much	Completely
O	O	O	O	O	O	O

      6a. Do you have any comments you'd like to make?

7. *For the presented speed of 55 mph at 1000 ft. sight distance, please indicate how representative it is of real rural intersections of 55 mph at 1000 ft. sight distance.*

Not at all	Very little	Somewhat	Moderately	Significantly	Very much	Completely
O	O	O	O	O	O	O

      7a. Do you have any comments you'd like to make?

8. *For the presented speed of 65 mph at 1000 ft. sight distance, please indicate how representative it is of real rural intersections of 65 mph at 1000 ft. sight distance.*

Not at all	Very little	Somewhat	Moderately	Significantly	Very much	Completely
O	O	O	O	O	O	O

      8a. Do you have any comments you'd like to make?

9. *For the presented speed of 75 mph at 1000 ft. sight distance, please indicate how representative it is of real rural intersections of 75 mph at 1000 ft. sight distance.*

Not at all	Very little	Somewhat	Moderately	Significantly	Very much	Completely
O	O	O	O	O	O	O

      9a. Do you have any comments you'd like to make?

Overall Real-World Similarity to Rural Intersections
1. *Overall, how representative was the experimental simulations of real-world rural intersections?*

Not at all	Very little	Somewhat	Moderately	Significantly	Very much	Completely
O	O	O	O	O	O	O

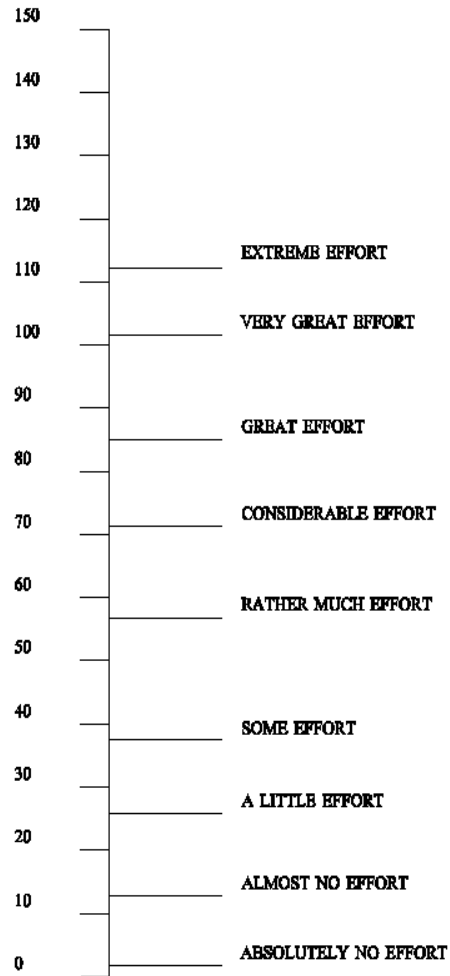   1a. Do you have any comments you'd like to make?

Do you have any general comments or thoughts on similarity, speed, sight distances, and other issues related to driving, perception, and safety in these scenarios?

APPENDIX F: RSME

Rating Scale Mental Effort

Please indicate, by marking the vertical axis below, how
much effort it took for you to complete the task you've just finished

```
150 —
140 —
130 —
120 —
110 — ———— EXTREME EFFORT
100 — ———— VERY GREAT EFFORT
 90 —
 80 — ———— GREAT EFFORT
 70 — ———— CONSIDERABLE EFFORT
 60 —
 50 — ———— RATHER MUCH EFFORT
 40 — ———— SOME EFFORT
 30 — ———— A LITTLE EFFORT
 20 —
 10 — ———— ALMOST NO EFFORT
  0 — ———— ABSOLUTELY NO EFFORT
```

APPENDIX G: CONFIDENCE QUESTIONS

1. How difficult was it to detect vehicles as they approached this intersection?

Not at all Difficult	Minimally Difficult	Somewhat Difficult	Moderately Difficult	Quite Difficult	Significantly Difficult	Extremely Difficult
O	O	O	O	O	O	O

2. How risky do you believe it is to drive a car across this intersection?

Not at all Risky	Minimally Risky	Somewhat Risky	Moderately Risky	Quite Risky	Significantly Risky	Extremely Risky
O	O	O	O	O	O	O

3. How anxious would you feel driving a car across this intersection?

Not at all Anxious	Minimally Anxious	Somewhat Anxious	Moderately Anxious	Quite Anxious	Significantly Anxious	Extremely Anxious
O	O	O	O	O	O	O