UNIVERSITY OF MINNESOTA

Rural Intersection Conflict Warning System Evaluation and Design Investigation

Final Report

Disi Tian
Nichole L. Morris
David Libby

HumanFIRST Laboratory
Department of Mechanical Engineering
University of Minnesota

CTS 18-10

CENTER FOR
TRANSPORTATION STUDIES

UNIVERSITY OF MINNESOTA

Technical Report Documentation Page

1. Report No. CTS 18-10	2.	3. Recipients Accession No.
4. Title and Subtitle Rural Intersection Conflict Warning System Evaluation and Design Investigation		5. Report Date October 2018 6.
7. Author(s) Disi Tian, Nichole Morris, David Libby		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Mechanical Engineering HumanFIRST Laboratory University of Minnesota 111 Church Street SE Minneapolis, MN 55455		10. Project/Task/Work Unit No. CTS#2016045 11. Contract (C) or Grant (G) No. (C) 99008 (WO) 225
12. Sponsoring Organization Name and Address Center for Transportation Studies University of Minnesota 200 Transportation and Safety Building 511 Washington Ave. SE Minneapolis, MN 55455		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes http://www.cts.umn.edu/Publications/ResearchReports/		

16. Abstract (Limit: 250 words)

The Rural Intersection Collision Warning System (i.e., RICWS) has been deployed across the state of Minnesota to provide real-time traffic information to motorists to assist them with identifying sufficient vehicle gaps at thru-STOP intersections. However, since its implementation, a number of complaints have been received from local road users in regard to the signs. To identify the human factors issues with the current RICWS sign and to propose safe and efficient alternatives to its use, multiple rounds of usability tests were conducted with Minnesota county engineers and local road users to assist iterative design modifications as well as evaluate the effectives of each sign's ability to accurately convey information regarding each of its three states. Three alternative design options were developed and tested along with the original RICWS sign via a driving simulator. A total of 120 participants, including novice teenage drivers (16-18 years old), middle-aged drivers (35-50 years old) and older drivers (65-77 years old), were recruited and were then asked to drive through a sequence of rural thru-STOP controlled intersections, with and without the intervention. The objectives were to evaluate the safety effectiveness and efficiency of different RICWS sign options to promote safe gap acceptance at different types of rural intersections (i.e., varying levels of mainstream traffic volume and intersection visibility). The research findings revealed an overall safety benefit of the intervention; however, potential risks were also identified associated with its deployment. It was also observed that drivers' perceptions did not all match their actual driving behaviors.

17. Document Analysis/Descriptors Human factors, transportation safety, rural thru-STOP controlled intersections, conflict warning system, high risk drivers		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 127	22. Price

Rural Intersection Conflict Warning System Evaluation and Design Investigation

FINAL REPORT

Prepared by:

Disi Tian
Nichole L. Morris
David Libby

Department of Mechanical Engineering
University of Minnesota

October 2018

Published by:

Minnesota Department of Transportation
Research Services & Library
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions from the HumanFIRST research team, including previous employee Jennifer Cooper for her assistance in developing and conducting the usability tests of this project; Jacob Achtemeier and David Libby for their efforts in facilitating data collection for the driving simulator study and final editing. This project was funded under MnDOT Contract Number 99008, Work Order Number 225. It could not be accomplished without all the valuable inputs and guidance from the MnDOT Technical Advisory Panel, including Ray Starr, Daniel J. Rowe, Kenneth Hansen, Derek Leuer, Victor Lund, Nancy Klema, Heather Lott, and Josie Tayse. The authors would also want to thank Dr. Susan G. Gerberich, Dr. Hyun Kim and Mr. Andy Ryan from the Department of Environmental Health Sciences at the University of Minnesota for their advice in for performing data analysis, as well as Peter Easterlund, for his indispensable work of simulator programming and data extraction.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ADT: Average Daily Traffic

CI: Confidence Interval

M: Mean

MPH: Miles per Hour

N: Sample Size

OR: Odds Ratio

RICWS: Rural Intersection Conflict Warning System

RR: Risk Ratio

SD: Standard Deviation

SE: Standard Error

TH: Time Headway

TTC: Time-to-Collision

EXECUTIVE SUMMARY

The Rural Intersection Conflict Warning System (i.e., RICWS) has been deployed across Minnesota to provide real-time traffic information to motorists to inform drivers on the minor road when it is not safe to enter the intersection to prevent serious injury and fatal right-angle crashes. To date, approximately 52 RICWS intersections have been implemented in Minnesota to promote safe travel at these intersections. However, complaints have been received from local road users. The objectives of this project were to: (1) to conduct a human factors analysis of the current RICWS sign and identify what features may be problematic for proper interpretation of its message; (2) examine alternative designs through iterative usability studies to identify candidate signs; (3) and test candidate signs in a driving simulator to ensure proper interpretation of the sign message and safe gap acceptance for passing through the stimulated intersection.

Minnesota county engineers were surveyed regarding their experiences from local road users about current RICWS signs. The majority of feedback received from drivers were negative (e.g., sign is "distracting" or "always flashing/not functioning"). In addition, many county engineers incorrectly interpreted the functionality of the system (i.e., its malfunctioning state).

Human-centered iterative design and computer screen-based usability tests were conducted to produce three sets of candidate signs to test in a driving simulation study. The primary goal of the driving simulator study (N=120 participants) was to evaluate the safety effectiveness and efficiency of candidate RICWS signs (original sign included) at rural thru-STOP intersections. This project investigated driver risks, visual search performance and attitudes toward the RICWS signs among teenage drivers (i.e., 16 to 18 years old), middle-aged drivers (i.e., 35 to 50 years old), and older drivers (i.e., 65 to 77 years old). The moderation effects of driver's age group, traffic volume, and visibility of the intersection on the overall system effect were also investigated.

All the RICWS sign options, except for Sign F, were effective in enhancing drivers' gap acceptance performance, with multiple study outcomes indicating significant results compared to baseline. However, drivers were less likely to comply with stop signs at intersections with adequate sight distance. This was most salient for the original RICWS sign (i.e., Sign C), under the low-traffic-volume condition. Furthermore, the risk of stop sign violations was found to be the greatest when the system malfunctioned (i.e., "sign-off" state).

Middle-aged drivers demonstrated the best gap acceptance performance with use of the RICWS systems; however, teenage drivers did not appear to be significantly assisted by the RICWS. Older drivers tended to have a significantly reduced risk of accepting critical gaps (i.e., less than 6.5 seconds time-to-collision (TTC)), but were also less efficient in using the system (i.e., rejecting non-critical gaps greater than 6.5 seconds TTC). Drivers' gap acceptance was significantly enhanced by the intervention at intersections with inadequate sight distance. With respect to visual attention, drivers of all sign groups (except for Sign B) checked traffic less frequently with the presence of the intervention.

Based on the results, Sign G might demonstrate comparable safety benefits but less potential risks compared to the original RICWS sign. Specifically, certain design elements (i.e., action word or icon) are recommended for consideration in follow-up field evaluations and future implementations. Notably, the

safety impacts of Sign G might have been diminished due to the relatively clustered layout of the current design, which could have influenced the legibility of messages in the simulated environment. This might have introduced difficulty, particularly with older drivers, in acquiring and processing useful information from Sign G. An enlarged version of Sign G should be considered in future field tests.

The overall benefits of this study were to gain a better understanding of issues with the current RICWS sign and to propose safe and efficient alternatives to its use. The findings may have a broader practical implication for design, development and implementation of effective intersection countermeasures targeted for local road users, as well as non-local road users from rural, suburban and urban areas in Minnesota. The results are also expected to contribute to future preventive efforts for mitigating risks of serious and fatal intersection crashes among all road users, including the most vulnerable driver populations (e.g., teen and older drivers).

CHAPTER 1: RISK FACTOR IDENTIFICATION

1.1 INTRODUCTION

Rural intersections serve as an intrinsic component of the public transportation network that connects interstate trunk highways, state highways, and local roads in rural Minnesota; however, they have also been consistently susceptible to high numbers of serious and fatal injuries over the past years (Preston & Storm, 2003; and 2004). In previous studies, a number of factors have been documented to be associated with increased risks of crash occurrences and more severe injuries at these intersections. Identifications of these risk factors present an essential first step toward building fundamental knowledge for prioritizing actions to reduce crash and injury outcomes at these high-risk intersections, as well as recommend guidelines for development and evaluation of innovative prevention strategies in current and future practices.

With recent advancements in sensor technologies, there has been an increased use of intelligent transportation systems (ITS) deployed by transportation agencies and local road planners to promote safe travel at rural intersections. Specifically, to date, approximately 52 Rural Intersection Conflict Warning System (RICWS) signs have been implemented across Minnesota to aid motorists in detecting unsafe gaps and assist in making better judgments at rural thru-STOP intersections. To develop safe and efficient alternatives to the current RICWS sign, a comprehensive literature review is provided in the following section, which aims to 1) understand factors for increased crash risks at intersections, especially with an emphasis on driver characteristics and other relevant factors; 2) include the most recent understanding of drivers' gap acceptance performance, visual and cognitive processes that guide sign recognition and decision making at rural intersections; 3) identify the underlying relationships between drivers' perceptions and attitudes toward ITS (e.g., RICWS), and their actual use of the system; 4) and summarize methodologies and important findings for assessing current alternative intersection countermeasures and solutions in other states and countries.

1.2 DRIVER BEHAVIOR FACTORS

1.2.1 Driver Characteristics

Driver's age acts as one of the major contributing factors that can affect crash risk at intersections. Due to the deteriorations in perceptual and motor capabilities associated with aging (Owsley, Stalvey, Wells, & Sloane, 1999; McDowd, & Shaw, 2000; Caird, Edwards, Creaser, & Horrey, 2005; Bao & Boyle, 2008), older drivers have long been considered one of the most vulnerable driver populations of concern, particularly under the complicated and highly demanding driving environment of an intersection (DeLucia, Bleckley, Meyer, & Bush, 2003; Caird et al., 2005). Using the Fatality Analysis Reporting System (FARS), a recent analysis of all U.S. intersection-related two-vehicle crashes over a four-year period from 2011 through 2014 revealed that older drivers, 55 years old and older, were more likely to be overrepresented in fatal at-fault crashes that occurred at intersections. Moreover, it was also documented that older drivers, 85 years old and older were found to have the highest death rates resulting from intersection crashes (i.e., 9.9 per 100,000 licensed drivers annually, compared to an average estimation of 5.7 per 100,000 licensed drivers across all ages) (Lombardi, Horrey, & Courtney, 2017). This result was also consistent with an earlier study that the risk of being involved in a fatal intersection crash for older drivers increased as they aged (Preusser et al., 1998). Specifically, the most prevalent two types of errors made by older drivers in their attempts to negotiate intersections were recognized as "looked-but-failed-to-see," as well as failure to determine adequate gaps between vehicles (Braitman, Kirley, Ferguson, & Chaudhary, 2007; Cicchino & Mccartt, 2015).

Younger drivers, on the other hand, were suggested to outperform their older counterparts when encountering these intersections', they generally tended to make more accurate judgments about oncoming traffic, exhibited less errors, and responded much faster to traffic, etc. (Ho, Scialfa, Caird, & Graw, 2001; DeLucia et al., 2003; Bao & Boyle, 2008). However, young drivers were also documented to be less compliant to the stop signs (Yagil, 2001; Bao & Boyle, 2008) and their likelihood to commit traffic violations was positively affected by certain personal traits, as well as other driving-induced psychological and situational factors (Yagil, 2001). This is noteworthy because stop signs regulate most intersections in rural Minnesota, therefore, failure to comply with them may potentially increase the likelihood of crashes and causalities at these intersections. Nevertheless, there is little consensus among researchers regarding the exact age range that denotes "young drivers", especially in terms of which age range would demonstrate a stark contrast in cognitive and physical functioning from other driver age groups. Because of this limitation in research uniformity, these results could sometimes be biased or misinterpreted due to inappropriate selection of comparison age group(s). In many experimental studies, younger drivers were typically recognized as less than 35 years of age (e.g., with some exceptions where the upper limit of the age range is set as high as 50 to 55 years old). However, the lower cut-off points of these age ranges significantly vary, ranging from 18 to 25 years old.

Furthermore, it is important to note that novice teenage drivers may be associated with an elevated risk of involvement in a motor vehicle crash, especially when driving at night (Williams, 2003) and under the influences of peer passengers (Simons-Morton, Lerner, & Singer, 2005; Ouimet et al., 2010). Due to their immaturity and lack of experience (Williams, 2003; Dahl, 2008; Steinberg, 2008), teenage drivers were more likely to be motivated by "thrill-seeking" impulses (Arnett, 1996; Steinberg, 2008), and demonstrated more excessive speeding and other risky events, particularly during the early phase of independent driving (Lee, Simons-Morton, Klauer, Ouimet, & Dingus, 2011; Simons-Morton, Zhang, Jackson, & Albert, 2012; Simons-Morton, Cheon, Guo, & Albert, 2013). Besides, it is also well-known that teenage drivers were more prone to reckless driving (Arnett, 1996), and that they were more vulnerable to distractors (Williams, 2003; Neyens & Boyle, 2008) presented in the vehicle or on roadways. Notably, Lombardi et al. (2017) also provided the most updated evidence that teenage drivers less than 20 years of age were identified to have a greater likelihood of being the at-fault driver in fatal two-vehicle crashes, specifically, pertaining to intersections. In addition, the annual fatality rate among teenage drivers ranked as the second highest among all drivers, equivalent to approximately 8.9 per 100,000 licensed drivers in these intersection-related collisions (Lombardi et al., 2017). Given all of the factors that may be attributable to the pronounced crash risk, novice teenage drivers are vulnerable road users who might be in need of assistance for adapting safe intersection crossing or turning maneuvers. However, there has been very limited research conducted on the intersection risks for novice teenage drivers, as well as their decision-making processes, especially at high-risk, rural stop-controlled intersections.

1.2.2 Driver Gap Acceptance Performance

A variety of factors can influence motorists' gap acceptance performance at intersections and subsequently their abilities to cross or enter into traffic in time to avoid a collision. Specifically, it is observed that older drivers were more prone to use poorer judgments of the speeds of other vehicles (Scialfa, Guzy, Leibowitz, Garvey, & Tyrrell, 1991), brake much slower on approaching the intersection (Bao & Boyle, 2008), and were more likely to be mentally overloaded (Cantin, Lavallière, Simoneau, & Teasdale, 2009). Additionally, problems with vision loss and other physical functions among older drivers may further diminish their abilities to detect and respond to traffic as rapidly as their younger counterparts (Scialfa et al, 1991; Caird & Hancock, 1994; and 2002). In addition to the age difference, a number of studies also suggest that the sizes of gaps selected by drivers may also be significantly affected by their time spent at the intersection, vehicle characteristics such as vehicle size, speed and color (Hancock, Caird, Shekhar, & Vercruyssen, 1991; Alexander, Barham, & Black, 2000), as well as other intersection and roadway factors (Cooper & Zhang, 2002; Bao & Boyle, 2008; Louveton, Bootsma, Guerin, Berthelon, & Montagne, 2012). Traffic volume, in particular, has been considered a substantial moderator that may have a significant impact on drivers' decisions to accept or reject certain gaps (Bao & Boyle, 2008; Dotzauer et al., 2015). Enhancements of proper gap detection and gap acceptance performance at high-risk, rural thru-STOP intersections might require considerations of multiple risk factors, as well as their possible interactions.

1.2.3 Driver Visual Search Performance

Similarly, age also plays an important role in determining drivers' capabilities to develop effective and efficient visual searching strategies at intersections. Results of previous research suggest that older drivers tended to underutilize visual searching, use more fixations on sign acquisitions, spend more time processing useful information, and generally have problems detecting unexpected changes in the environment that are less relevant to the concurrent tasks (Ho et al., 2001; Caird et al., 2005; Caird, Chisholm, & Lockhart, 2008; Becic, Manser, Drucker, & Donath, 2013; Romoser, Pollatsek, Fisher, & Williams, 2013; Rusch et al., 2016). Consistently, Bao and Boyle (2009) conducted an on-road experiment of sixty drivers from different age groups to examine their visual scanning locations and percentages of durations at two median-divided intersections. The findings indicated that older drivers were less likely to fully scan toward both directions of the intersection, especially when maneuvering turns. In addition, Romoser & Fisher (2009) further enabled development of effective trainings to proactively modify older drivers' behaviors through improving their visual scanning performance at the onset of turning into intersections.

Moreover, there are also considerable discrepancies between experienced drivers and novice drivers with respect to their visual searching patterns. Compared to experienced drivers, novice drivers were typically found to be less competent in anticipating hazards. They also tended to focus their view within a narrow window and looked less frequently at their mirrors (Bao & Boyle, 2009). All these research findings represent significant aspects of novice drivers' visual searching behaviors, which will help to rectify the need for an in-depth understanding of how well novice teenage drivers will attend to critical visual cues and search for meaningful information under complex intersection driving conditions.

Interestingly, perpendicular intersections with clear views may not always be the most favorable types of intersections for motorists, especially in very rural areas. Despite of a great sight distance between two vehicles as they both approach an intersection, there may be certain circumstances under which one driver might fail to perceive the other vehicle as moving and have a delayed response, if the two vehicles are on a collision course with each other (Uchida, De Waard, & Brookhuis, 2011). Such a view is also supported by other studies that revealed drivers appeared to use more caution, approached the intersection at a reduced speed, and better detected vehicles on the roads if the intersection visibility was naturally obstructed in an un-abrupt manner (Charlton, 2003). With few studies available, however, it may also be difficult to reliably predict to what extent drivers will be effectively assisted by such traffic controls, as well as whether possible risks exist as a consequence of restricting the visibility of the intersections in the long run.

1.2.4 Driver Perception, Attitude, and Use of ITS

Advancements in technologies provide a great opportunity for an increasing tendency toward adopting Intelligent Transportation Systems (ITSs) as a safety infrastructure to enhance intersection safety in the U.S. To better understand how drivers would interact with automated systems, a comprehensive review of the fundamental theories and implications in this field is a necessity. Individual's attitudes toward and trust in a system may vary significantly (Lee & See, 2004; Wang, Jamieson, & Hollands, 2009). Subsequently, an individual reliance on the system may also be subject to change over time, as well as by other factors such as perceived risks and mental workload, system reliability, user familiarity, etc. (Parasuraman & Riley, 1997; Kantowitz, Hanowski, & Kantowitz, 1997; Parasuraman, Sheridan, & Wickens, 2000; Biros, Daly, & Gunsch, 2004).

Moreover, an overreliance of the RICWS sign is likely to cause detrimental consequences to road users, particularly when they do not function properly; however, in contrast, frequent false alarms or system collapses may also prevent drivers from using the system (Parasuraman & Riley, 1997; Lee & See, 2004). With respect to the impact of age on drivers' attitudes toward ITSs, older drivers tended to have more positive feedback, whereas younger drivers, particularly teens, were more likely to misjudge their own driving risks and interpret the system as an enforcement (De Waard, Van der Hulst, & Brookhuis, 1999). Moreover, rural residence was also found to be associated with almost double the risk of running stop signs at intersections compared with urban residence among older drivers (Keay et al., 2009). As a result, in addition to the safety effectiveness of using ITSs as intersection safety countermeasures, additional questions may need to be discussed in the future, in terms of how to effectively improve rural public acceptance of the system, as well as how to clearly identify crash liabilities resulting from drivers' misuses of the system or any possible system collapses.

1.3 SAFETY COUNTERMEASURES AT INTERSECTIONS

Most literature on assessing prevention strategies at intersections has been focused on evaluations of in-vehicle support or warning systems. Chang et al. (2009) suggests that providing drivers with real-time intersection audio warnings was effective to significantly reduce driver speed, and decrease critical incidents, as well as promote prompt reactions to crash avoidance. In another driving simulator study, Werneke, & Vollrath (2012) further demonstrated that presence of an earlier warning appeared to have the most pronounced safety potentials of altering drivers with an abrupt critical event during its course of turning into a three-legged intersection. In particular, while the short-term safety effectiveness regarding a similar in-vehicle intersection assistance system among both older drivers and young drivers was supported by Dotzauer et al. (2015), in its longitudinal analysis it also indicated that the safety benefits of the system to reduce time-to-collisions was less likely to be sustained among older drivers over time.

Consistently, the safety impacts of on-road intersection conflict warning systems (i.e., ICWS) were also identified in a recent Federal Highway Administration (FHWA) report, through analyzing crash data from Minnesota, Missouri, and North Carolina. These similar types of interventions (e.g., including the RICWS signs in this project) were designed and implemented to communicate real-time gap information to drivers at four-legged rural intersections. It was found that ICWSs significantly reduce crash rates of all types (i.e., except for rear-end and nighttime crash rates at specific types of intersections), using an Empirical Bayesian analysis of crash outcomes prior to and after the implementation periods of these systems (Himes, Gross, Eccles, & Persaud, 2016). This report also provided an additional cost-benefit analysis of the ICWSs and further revealed significant economic savings associated with the deployments of the systems to reduce crash frequencies and relevant injuries (Himes et al., 2016). However, due to a limited number of intervention sites and because of the probable randomness of the crash outcomes at these intersections, it is important that future research efforts be undertaken with a larger sample size and over a longer post-implementation period.

1.4 OTHER RELEVANT FACTORS

In addition to driver behavior risks, intersection characteristics and other relevant environmental factors may account for elevated crash and injury risks at intersections. Some common significant influencing factors have been identified as major and minor road traffic volumes, number of legs, highway curvature, intersection size and skew, type of traffic control, surrounding development, and other crash-related factors (Huang, Chin, & Haque, 2008; Haleem, & Abdel-Aty, 2010). Multiple advanced statistical modeling methods have been developed by researchers in attempts to capture the nature of intersection-related crash frequencies and severity of crash injuries; however, sometimes the results appear inconsistent relevant to the significance of certain risk factors (Yan, Radwan, & Abdel-Aty, 2005; Huang et al., 2006; Kim, Lee, Washington, & Choi, 2007; Malyshkina & Mannering, 2010). This inconsistency may be explained in part by the differences of the modeling assumptions, data sources and inclusion criteria, completeness of the datasets, etc. (Lord & Mannering, 2010).

1.5 SUMMARY

To summarize, this thorough review of literature pertinent to driver behaviors and intersection risks provides a theoretical basis for designing experiments to evaluate drivers' gap acceptance performance, visual attention, and perceptions of RICWS signs in Minnesota. The literature points to many important factors to consider during the evaluation of RICWS; however, those specifically related to age and certain intersection features are critical for this study. In addition, this review also provides significant insights into the following iterative usability tests that aim to identify the critical human factors issues associated with the current RICWS sign, as well as to develop innovative strategies that incorporate feedback from county engineers and the professional assessments by human factors experts.

CHAPTER 2: USABILITY TESTS AND RESULTS

2.1 INTRODUCTION

Chapter 2 starts with a brief review of the layout, functionality, and design of the current RICWS system. Subsequently, the study procedure and results are presented for a survey of the RICWS signs administered to MnDOT county engineers, that queried their experiences and perceptions of RICWS signs with regard to comments or complaints from drivers and any additional information to guide the design of the project. An additional human factors assessment of the current RICWS sign was conducted to instruct the design modifications.

To develop cost-effective alternative solutions, an iterative design process was conducted that allowed signs to be tested and re-designed periodically throughout the study. Specifically, the usability study initially consisted of six different smart sign designs, one of which was the original RICWS design, which aimed to measure driver's cognitive processes, first impressions, and decision making regarding each sign. The primary goal of the study was to evaluate the effectiveness of each signs' ability to convey information regarding each of its three states: 1) traffic is too close to safely cross/turn, 2) sign is on/operating, and 3) sign is non-operational. A secondary goal was to understand the level of aid the sign provides for safe decision making at intersections (e.g., wait for cars to pass). Signs were designed to comply with best usability practices and to address specific issues identified with the original RICWS sign. The sample used for the study included 30 participants, equal males and females, with a diverse age range (Mean age = 43.4, *SD* = 16.5).

To better comply with the Minnesota Manual of Uniform Traffic Control Devices (MMUTCD), a follow-up online survey of an additional 51 participants (Mean age = 40.9, *SD* = 11.6) was conducted. The purpose of the follow-up study was to evaluate drivers' opinions and decision making towards alternatives to building an action message (i.e., stop) into the RICWS design, as well as modify the design elements to meet the MMUTCD standards for traffic sign design and implementation. The final alternative designs that received the best user preferences and sign acceptances from the initial rounds of usability tests and the follow-up study, along with the original RICWS sign, were identified as candidate sign options to be tested in the driving simulator.

2.1.1 RICWS System Review

A typical RICWS system adapted in Minnesota consists of a major warning system and/or a minor warning system deployed at either the minor (i.e., STOP-sign controlled route) or the major road (i.e., through route) of a rural thru-STOP intersection. As depicted in Figure 2.1, the major warning system is positioned on the roadside of both directions to alert drivers about the presence of vehicles stopped at the intersection. Similarly, the minor road system is designed to detect oncoming traffic on the major road when vehicles from either direction approaches within a critical gap range (i.e., less than 6.5 seconds time-to-collision away from the intersection at an approximate travel speed of 65 mph). The minor road system is positioned across the traffic lanes on the opposite side of the intersection and is made legible for minor road drivers waiting at the stopping line.

In this study, only the minor road warning sign was investigated (i.e., referred as RICWS system in all the following discussions) because it was found to be the most problematic with local road users and received numerous complaints regarding its design. Moreover, because the sole implementation of the minor road warning system serves as the most common practice at the majority of the Minnesota RICWS intervention sites, identification of the existing human factors issues with the current system is expected to have a broader generalizability to help promote better decision making about safer gaps at all rural thru-STOP intersections in the state.

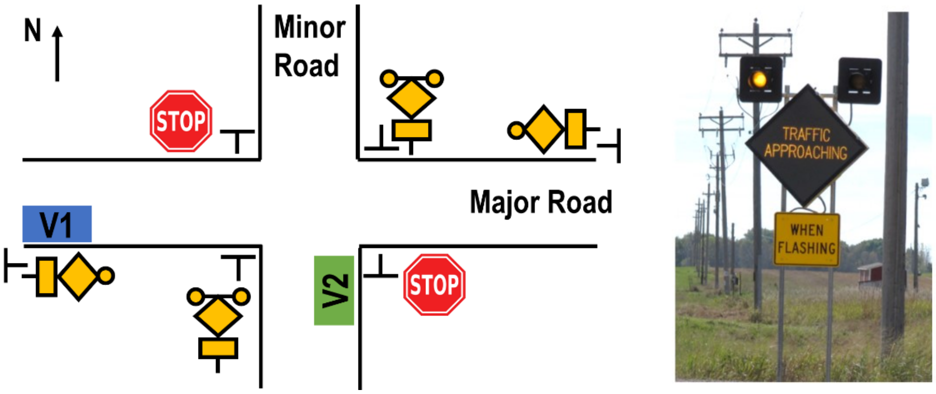


Figure 2.1 Layout of the Rural Intersection Conflict Warning System (RICWS) (Left) and Design of the Minor Road Warning System (Right)

Specifically, the design of the RICWS system is composed of three major components (See Figure 2.1 on right, adapted from MnDOT document at http://www.dot.state.mn.us/its/projects/2011-2015/rural-intersect-conflict-warn-system/documents/ricwsIIconops.pdf), including two flashing beacons, a dynamic sign with consistently illuminated LED message of "TRAFFIC APPROACHING," and a static placard positioned underneath of them with the message of "WHEN FLASHING." The system consists of three different sign states including: 1) "Traffic is approaching, and it is unsafe to cross" when the beacons are consistently flashing; 2) "Sign is on/operating and no traffic is detected" when the beacons are off; and 3) "Sign is off/inoperable" when the beacons are off and when the dynamic sign's LED message is blacked out.

2.2 IDENTIFICATION OF PRIMARY HUMAN FACTORS CONCERNS

2.2.1 Human Factors Concerns for Executive Agencies and Road Users

To date, there are 52 RICWS intersections implemented in 30 counties across Minnesota. It is important to understand the perceptions of both citizens and engineers with regard to the design of the current RICWS sign; therefore, the research team conducted a survey of the county engineers where RICWS signs are located. All 30 county engineers were contacted by email and asked to provide feedback by participating in a survey (See Appendix C) to assist the research team in understanding the effectiveness of the current RICWS design. Engineers were asked to provide their personal feedback as well as any positive or negative remarks they have heard from residents of their county. The survey included questions that asked about the nature of feedback (positive/negative) received from residents, any specific issues raised by residents, and the approximate number of residents who have reported any feedback about the RICWS sign. Additionally, engineers were asked whether they personally felt they had an understanding of functions of the signs and the failsafe mode of the sign. Comments from the engineer were welcomed at the end of the survey.

Twenty responses resulted from the online survey. Among all respondents, 12 (60%) engineers reported having heard any kind of feedback since the RICWS sign was installed in their county. While the vast majority of the feedback consisted of negative remarks, Clay County, however, reported that the feedback they have received has been strictly positive. Notably, Wright County reported that its two different RICWS signs have generated two different opinions. The Wright County report explains that the sign located at an intersection with a high average daily traffic volume (ADT) has little impact since the heavy traffic pattern rarely provides large gaps and the sign constantly flashes. Consistently, this idea was also supported by other counties, where the sign appeared to be ineffective with the presence of high traffic volume. Overall, frequent beacon flashing was a common concern and distraction was mentioned by four engineers as a concern raised by citizens. One engineer reported a complaint received regarding poor sign visibility at night, particularly with regard to the small “when flashing” plaque under the large blank-out diamond.

When asked to estimate the total number of comments and concerns raised by residents, each of the twelve counties who received feedback claimed to have received a range of 4 to 20 comments. Approximately 60 to 70 people across all twelve counties were reported to have commented on the sign since its installation.

Thirteen out of sixteen county engineers, who provided opinions on their knowledge of the system, reported to be fairly confident that they understood and could explain how the system works. However, among those thirteen engineers, only two were able to correctly describe the functionality of the sign’s three states using technical terms such as loop detectors. Seven engineers simply answered “yes” or “somewhat” to this question but did not provide any further explanations. Concerning, a number of engineers were not sure how the fail-safe/inoperable mode works, claiming that they did not know this existed at all or that they thought that the light might flash regardless of traffic presence. One county engineer who failed to understand the functionality of the system reported that he/she did not attend any training on operation and maintenance of the sign.

When prompted for additional feedback, sixteen county engineers provided personal anecdotes about their opinion of the signs, with the responses being mostly negative. The following list provides many of the quotes provided in the anecdotes.

- [I] *love it… Hope that I can keep it after the contract is up for it...*
- *I have had a few residents comment that **the lights flash when there is no traffic approaching**. A couple comments about the lights are **confusing** and **distracting**.*
- *So far since they have been installed we have not had any crashes at that location. I also haven't received any negative feedback.*
- *In my opinion the system is an effective warning system that acts as a backup to most motorists. **I wonder if it effectively communicates the warning to people who would otherwise have cognitive difficulties evaluating the intersection geometrics and speed of oncoming traffic (i.e. elderly).***

- *The only thing I would like to see is if there are NO approaching cars then the lights should all be dark, once a car enters the radar cone and is approaching from the side then the backlight and the flashing yellow lights should all come on*.
- *Like anything that seems to work when you install it, once people see that it works they want them at all intersections that have even minor problems. I think part of the reason they work so well is that they are not everywhere, so* ***drivers really take notice of the intersection when they see the flashing beacons.***
- *I don't believe the "When Approaching" portion of the sign needs to be electronic. It can be static, similar to the "When Flashing" sign. Although I answered no to the previous questions of receiving feedback,* ***I have heard people state they believed traffic was approaching without the flashers going off as they only paid attention to the electronic part of the sign and missed the "when flashing" sign.***
- *I feel they've been a good solution to busy rural intersections and seemed to have eliminated accidents so far. Limit their use so they remain effective. Would like to look for the next level down solution (lower cost) for* ***intersections that traffic seems to not see STOP signs****.*
- *A yellow flashing light that is ALWAYS flashing becomes background noise after a bit and the* ***locals don't notice it after a while****. Based this* ***'background noise'*** *concept, I think the signs would be more effective if there was no message at all when the coast is clear. Having both the yellow lights flashing and a message appear would more a change from the norm; and I think this would help grab the attention of the driver.*
- *We feel that the jury is still out on these systems, as to what are the recommended criteria for installation (based on approaching traffic volumes, geometry of the intersection, other factors, etc.). It seems like the* ***high ADT highways, where the perception is that they are always flashing, they may not be a benefit for safety****?*
- *A traditional flashing yellow beacon eventually blends in vs.* ***edge lit LED signs or maybe a faster flashing LED*** *that could be a different color (I have seen driver feedback speed limit signs that flash a strobe at you, similar to the Opticon system on emergency vehicle preemption). I think that would* ***draw more attention than a traditional flashing yellow beacon.***
- ***I would estimate that 5 or 6 people have mentioned to me that they missed the "when flashing" portion of this system.***
- *Negative comments have mostly been along the lines of "****the signs are distracting****", "****they're always flashing****", or "****they block sight lines****."*
- *There have been a few positive comments that the RICWS "****draws attention to oncoming traffic****" and that the system is much better than the dynamic warning billboard signs that previously existed at this location.*
- *One of the systems is located on a very* ***high-volume intersection*** *and was the first one installed in this area. Feedback on this system was mostly negative, complaints being some variation of the sign being* ***distracting****,* ***overwhelming****, and being yet* ***another thing for the motorist to watch at an intersection where it can be difficult to find a safe gap*** *to enter due to the volume on thru and turning vehicles at the intersection.*

- *…public, especially at first, did not understand how the sign worked and* ***assumed that the sign message being lit meant that this message was being conveyed even though the lights were not flashing.***

2.2.2 Additional Human Factors Assessments

Built upon the above-mentioned comments, it was also noteworthy that the consistently illuminated message of "TRAFFIC APPROACHING" appears to cause issues for drivers to clearly distinguish between the "Do not cross/turn" and "sign-on" states. This may be in part due to the saliency of this message, which is likely to instantly capture drivers' attention at the first glance of the sign and in turn lead to confusions among drivers with "TRAFFIC APPROACHING" to be always presented, despite of whether it is coming or not. Similarly, the "WHEN FLASHING" placard may be unnoticed due to its less salient design, particularly during night driving. This idea was also supported by a FHWA sponsored study, in which drivers' comprehension of the signs did not appear to be significantly affected with or without the presence of the static placard (Inman & Jackson, 2016). Additionally, the sign may lack clarity in terms of what component of the sign should be flashing, since both the LED message and beacons can flash.

Most importantly, the ordering of the three components of the sign might also require extra visual search effort to gather useful information and understand how the sign works. Sustaining all of this knowledge while simultaneously performing the driving task at intersections may be very challenging, particularly for older drivers. A strategy of repeated scanning between different components of the sign might be potentially adopted by older drivers, since information is not laid out in a natural order that will geographically match with drivers' perceptions.

2.3 ITERATIVE DESIGN MODIFICATIONS AND USABILITY TESTS

2.3.1 Study Method and Procedure

The usability study undertaken in this Chapter employed a researcher-moderated approach that introduced participants to a scenario intended to elicit decision-based responses for each sign. Researchers began the study by introducing participants to the layout of the thru-STOP intersection and provided context for the placement of the "smart" (RICWS) sign (See Figure 2.2). In order to simplify the decision-making process and clarify the scenario, participants were asked to only consider going straight across the major road, rather than turning left or right.

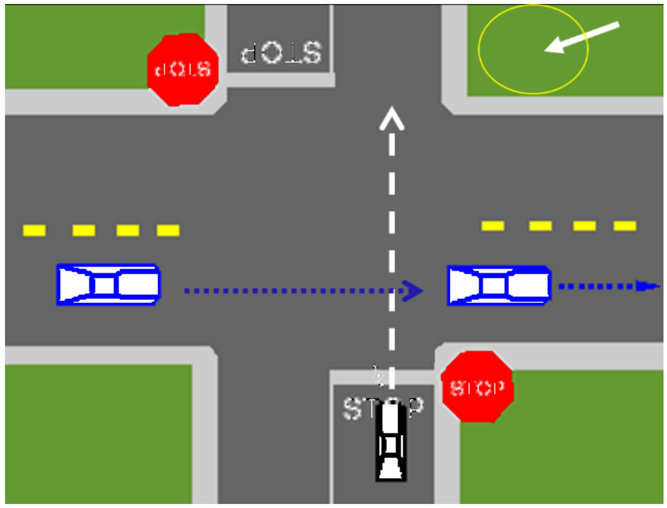


Figure 2.2 Intersection layout provided to usability participants

Participants were read the following scenario prior to encountering each sign:

> *"You are in a hurry! You arrive at the stop sign and make a complete stop. A car from the left and right are approaching the intersection, but you can't judge their speed from where you are sitting. The sign is "smart" and will assist your decision whether or not to cross before the cars reach the intersection. Based on what the sign says, please decide if you will: cross through the intersection, wait for the cars to pass, or feel that you don't have enough information."*

Prior to evaluating signs, participants were given an example of each state of sign using police officers as a proxy for conveying various messages (See Table 2.1). This comparison allowed researchers to convey each of the three states of the sign without priming participants by using actual signs, which may have biased their perceptions upon later exposure.

Table 2.1 Comparison examples of 'sign states' using a police officer

Sign States	Traffic is too close to safely cross/turn	Sign is on/operating, and	Sign is non-operational
Police Examples			
Message Conveyed	*There is not enough time to cross.*	*There is enough time to cross.*	*This officer is not operational, like signs can sometimes be.*

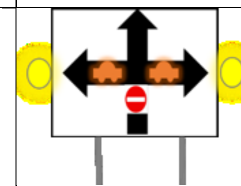
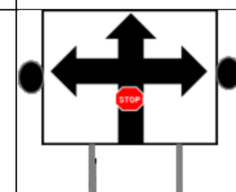
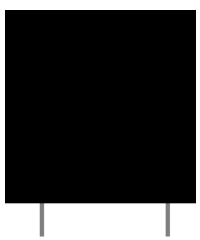
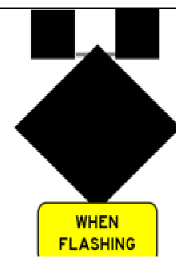
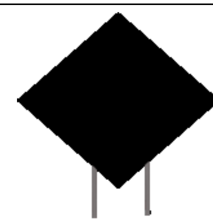
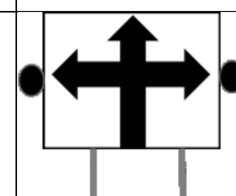
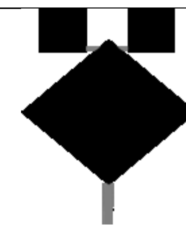
Upon confirming that each participant understood the intersection layout and the various messages for each state of the sign, participants began the evaluation portion of the study. The order in which signs were displayed was counterbalanced for each participant in order to eliminate any order or practice effects on the results.

2.3.2 Version 1.0 Design Process and Results

2.3.2.1 Version 1.0 Designs

The first iteration of signs included six designs, one of which was an identical mock-up of the original RICWS sign (i.e. Sign C; Table 2.1). The signs were designed by research staff, using human factors best practices along with existing designs from other states and a number of novel approaches that were developed in the HumanFIRST lab.

Table 2.2 Sign mockups for Version 1.0 designs

	A	B	C	D	E	F
Do not cross/turn (SIGNS FLASH)						
Sign is on						
Sign is off						

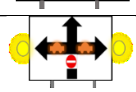
2.3.2.2 Version 1.0 Results

Five participants took part in evaluating the first version of sign designs by engaging the usability scenario for each sign set. The primary goal of the initial designs was to understand the overall preferences of road users in order to eliminate any sign designs with low comprehension and acceptance.

After seeing all sign designs, participants were asked to rank their top three sign sets, based on comprehension, design, safety, and overall preference. The scoring mechanism that researchers used to synthesize the results involved assigning scores for each sign set that participants ranked in their top 3. The top ranked sign set received a score of 3, second place received a score of 2, and third place received a score of 1. Signs which were selected as the participant's least favorite received a score of -1. All points were summed in order to determine the comprehensive preference of Version 1.0 signs. Individual highest and lowest rankings can be found in Appendix D.

The results of the comprehensive ranking are displayed in Table 2.3; showing that Sign F and C ranked the highest in preference and Signs A and D received the poorest rankings.

Table 2.3 Version 1.0 highest ranked sign sets

1.0 Signs	Example	Comprehensive Score
F		11
C		9
B		5
E		1
D		-1
A		-2

Other relevant findings include the responses to inquiries about appropriate terminology to be displayed on the sign for the various states. Similar terminologies were also tested in the FHWA study in their examination of minor road signs (Inman & Jackson, 2016). For example, participants were asked to choose the top three that convey the message "traffic on major road is too close to safely cross." The same scoring mechanism from the overall sign preferences was used. The top ranked sign received a score of 3, while the third place received a score of 1. The results of this item are displayed in Table 2.4, showing that the preferred terminologies are: TRAFFIC APPROACHING, EXPECT CROSS TRAFFIC, CROSSING TRAFFIC, and TRAFFIC TOO CLOSE. Further, there was high agreement that the *presence of flashing lights* helped to indicate a driver should not cross or turn.

Table 2.4 "Traffic on major road is too close to safely cross" 1.0 terminology preferences

Terminology	Score
TRAFFIC APPROACHING	10
EXPECT CROSS TRAFFIC	7
CROSSING TRAFFIC	5
TRAFFIC TOO CLOSE	4
TRAFFIC AHEAD	2
ENTERING TRAFFIC	0

In terms of terminology preferences for the 'Sign is on' message, participants were given another list of phrases and were told to choose the top three phrases that they felt conveyed the message "traffic may not be coming, but you should still use caution." Several candidates were selected as preferred terminology for this sign state with no overwhelming agreement for a single message (Table 2.5). Although not surprisingly, TRAFFIC APPROACHING received no points indicating that drivers would not expect to see this message in the 'Sign is on' state.

Table 2.5 "Traffic may not be coming, but still use caution" 1.0 terminology preferences

Terminology	Score
CROSS TRAFFIC DOES NOT STOP	8
WATCH FOR TRAFFIC	7
LOOK FOR TRAFFIC	6
ON-COMING TRAFFIC DOES NOT STOP	6
THRU TRAFFIC	2
TRAFFIC AHEAD	0
TRAFFIC APPROACHING	0

The final item that provided relevant feedback for the next design iteration involved asking participants what they thought the term THRU TRAFFIC conveys in order to determine any confusion with this terminology. Based on the responses of the first five participants, it was discovered that THRU TRAFFIC does not provide a high level of clarity (see Table 2.6).

Table 2.6 Participant explanations for THRU TRAFFIC

Participant	Quotes
1	*"Drive Thru? Like at a drive thru restaurant. No clue really."*
2	*"Means that traffic does not stop."*
3	*"Traffic is constantly moving back and forth."*
4	*"Means to look for traffic all around, but honestly it isn't clear."*
5	*"Total guess, but I think I have seen it before. I just can't remember what it means."*

2.3.2.2 Version 1.0 Discussion

The aim of this exercise was to identify and remove any sign designs and terminology that had low user acceptance and comprehension. The insight provided by the five participants yielded important information regarding the six sign sets.

- Sign set E was identified as a sign design which should be removed from consideration given its low user preference and its costly and complex design.
- Sign D was rescaled to match the standard diamond blank out dimensions given it received no positive feedback to indicate a justifiable cost-benefit relationship to warrant the larger size.
- The Do Not Enter icon (i.e., red circle with white bar) presented on Sign A yielded negative feedback, with many drivers reporting they would believe they would permanently, rather than temporarily, be unable to cross the road and should turn around. A Stop sign icon was proposed to replace the icon to further examine how an icon may assist in driver decision making.
- The terminology THRU TRAFFIC was determined to be confusing to most drivers. Its removal from a majority of signs was determined to be critical to improve the comprehension of the overall sign message. The alternative term selected in its place was selected to be CROSS TRAFFIC; however, since the sample size was small, it was decided that it should remain on a single sign design to further examine its usefulness. Further, CROSS TRAFFIC DOES NOT STOP was selected as a preferred combination for the 'Sign is on' terminology which would be incorporated into a sign design.
- Visibility was an important aspect discussed by multiple participants. Nearly all participants suggested ways in which they felt the sign would be brighter or capture a driver's attention. There was little agreement among all participants, however, regarding whether the flashing beacons or flashing boarder was a superior method to increase the urgency and conspicuity of the sign's message.
- Results were mixed with regard to the efficacy of the WHEN FLASHING placard. While one participant perceived the placard to be "overkill" or "unnecessary", the 'Do not cross/turn' state received few reported issues regarding the placard. The placard, however, received negative comments (e.g., it is confusing) or was unnoticed in the 'Sign is on' state (e.g., "sign is telling me traffic is coming" or "I'll wait for the cars"). It was determined that the placement of the placard (i.e., bottom of the sign) and limited inclusion (i.e., only on Sign C) should be manipulated in subsequent investigations. To understand the efficacy of the WHEN FLASHING placard in an experimental manner, a new sign with an alternative message (i.e., EXPECT CROSS TRAFFIC) and rearrangement of the placard location was introduced in Version 2.0.

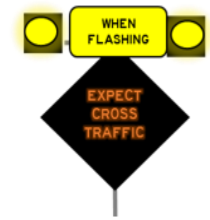
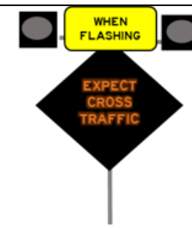
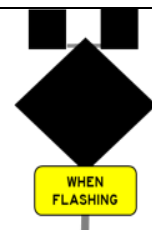
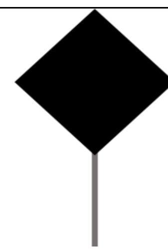
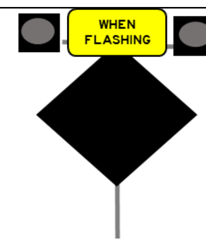
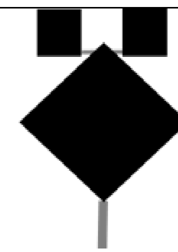
2.3.3 Version 2.0 Design Process and Results

2.3.3.1 Version 2.0 Designs

The results of Version 1.0 were leveraged to inform the designs of Version 2.0. The results led to the substitution of Sign E with an updated option, as well as major changes in A and D (Table 2.7).

Terminology changes were made on many of the signs in order to eliminate problematic issues with the term THRU TRAFFIC; however, one design left the term THRU TRAFFIC in order to validate the original finding. Sign E was adapted to display the WHEN FLASHING placard on top of the sign design in order to provide an ideal comparison between E and C. The rationale behind these changes was based on a full evaluation of the quantitative and qualitative results observed in Version 1.0.

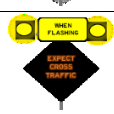
Table 2.7 Sign mockups for Version 2.0 designs

	A	B	C	D	E	F
Do not cross/turn (SIGNS FLASH)						
Sign is on						
Sign is off						

2.3.3.2 Version 2.0 Results

Five participants took part in evaluating the second version of the rural intersection warning collisions signs by engaging in the usability scenario for each sign set. The primary goal of the second iteration was to better understand participants' comprehension and user preference of the signs. The scoring mechanism used in Version 1.0 was applied to this ranking. Individual highest and lowest ranking of Version 2.0 signs can be found in Appendix E. The results of the comprehensive rankings for overall sign preference are displayed in Table 2.8; showing that Sign A and C ranked the highest in preference and Signs D and E received the poorest ranking.

Table 2.8 Version 2.0 highest ranked sign sets

2.0 Signs	Example	Comprehensive Score
A		8
C		8
B		3
F		1
D		1
E		0

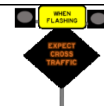
In addition to ranking their overall preference, participants were asked to rank their top three and least preferred choices of signs in separate individual states (i.e., 'Do not cross/turn', 'Sign is on'). Collecting ranking and feedback in the signs' 'off' or 'fail-safe' mode yielded little information and was not further investigated. Sign A ranked consistently high is both individual states of the sign. Sign C was also highly preferred in the 'Do not cross/turn' state (Table 2.9), however, it was devalued in the 'Sign is on' state (

Table **2.10**). Signs F and E increased in preference in the 'Sign is on' state. Notably, the signs individually ranked for least preferred for the 'Sign is on' state were those which contain the yellow WHEN FLASHING placard. The hypothesized reason for this outcome is due to the difficulty in comprehending the logic of a sign that has a conditional statement. Individual most preferred and least preferred preference scores can be found in Appendix E.

Table 2.9 ‘Do not cross/turn’ 2.0 results

2.0 Signs	Example	Comprehensive Score
A		13
C		6
D		4
E		1
B		1
F		-1

Table 2.10 ‘Sign is on’ 2.0 results

2.0 Signs	Example	Comprehensive Score
A		11
F		8
E		2
C		0
B		0
D		-1

When the results of terminology preferences for the ‘Do not cross/turn’ state were evaluated, it was revealed that the highest ranked terminology was consistent for Version 1.0 and Version 2.0 (i.e., TRAFFIC APPROACHING). Those ranked second and third (i.e., TRAFFIC TOO CLOSE and CROSSING TRAFFIC) were not included in the Version 1.0 signs and suggest they be incorporated (Table 2.11). The terminology of EXPECT CROSS TRAFFIC garnered some encouraging results, combined with the results of the ‘Sign is on’ ranking (see Table 2.10) and suggest further examination into its use.

Table 2.11 “Traffic on major road is too close to safely cross” 2.0 terminology preferences

Version 2.0 Terminology	Score
TRAFFIC APPROACHING	10
TRAFFIC TOO CLOSE	6
CROSSING TRAFFIC	4
EXPECT CROSS TRAFFIC	3
TRAFFIC AHEAD	1
ENTERING TRAFFIC	0

The results for the ‘Sign is on’ state in Version 2.0 (Table 2.12) reveal that participants prefer the same top three terminology preferences as those reported in Version 1.0 (see Table 2.5). Participants were given the same scenario for this item as they were in Version 1.0, being told that the phrase should both comply with the standard that the ‘Sign is on’, but also convey “traffic may not be coming, but you should still use caution.”

Table 2.12 "Traffic may not be coming, but still use caution" 2.0 terminology preferences

Version 2.0 Terminology	Score
WATCH FOR TRAFFIC	6
CROSS TRAFFIC DOES NOT STOP	5
ON-COMING TRAFFIC DOES NOT STOP	5
LOOK FOR TRAFFIC	4
TRAFFIC APPROACHING	3
THRU TRAFFIC	0
TRAFFIC AHEAD	0

2.3.3.3 Version 2.0 Discussion

The results of the version 2.0 exercise helped to further refine the sign designs and terminology to enhance user acceptance and comprehension. The information gathered based on participant feedback proved useful in drawing important conclusions about necessary sign modifications.

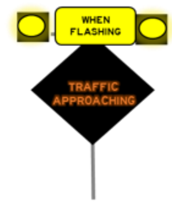
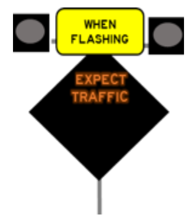
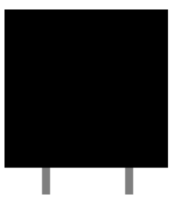
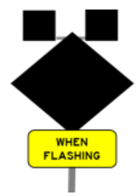
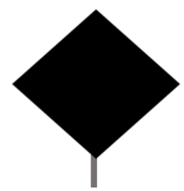
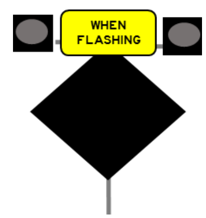
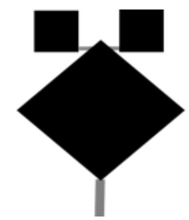
- The term CROSS TRAFFIC resulted in more confusion than expected. Specifically, participants indicated that the term listed by itself (i.e., Sign B 'Sign is on') does not convey enough information for drivers to make a decision about a prescribed action. The design was recommended to receive a change from CROSS TRAFFIC APPROACHING to CROSS TRAFFIC TOO CLOSE (which yielded positive feedback) in the 'Do not cross/turn' state and from CROSS TRAFFIC to CROSS TRAFFIC DOES NOT STOP in the 'Sign is on' state. Further, CROSS TRAFFIC in Sign A was replaced with VEHICLE to determine if the change in terminology improved driver comprehension and acceptance.
- THRU TRAFFIC (Sign D) continued to evoke negative feedback from participants. A recommendation for its removal was made and WATCH FOR TRAFFIC to be used instead.
- EXPECT CROSS TRAFFIC on Sign E was reported to present language that was not direct enough and did not definitively indicate the current presence of traffic in the 'Do not cross/turn' sign state. It was recommended that the terminology be changed from EXPECT CROSS TRAFFIC to TRAFFIC APPROACHING in the 'Do not cross/turn' state and from EXPECT CROSS TRAFFIC to EXPECT TRAFFIC in the 'Sign is on' state. This change was also recommended because it was more consistent with the use of a WHEN FLASHING placard to indicate the logic statement more clearly and directly.
- The WHEN FLASHING placard continued to generate mixed responses from participants. Some participants responded positively to its placement at the top of Sign E, while others saw it as "tacky". The information went unnoticed by participants who perceived the sign as indicating the presence of imminent traffic in the 'Sign is on' state.

2.3.4 Version 3.0 Design Process and Results

2.3.4.1 Version 3.0 Designs

The results from Version 2.0 illustrated a necessity for updates to the sign terminology rather than to the structure (e.g., shape, lights) in order to capture the overall comprehension of road users. Feedback from the Technical Advisory Board was solicited prior to launching Version 3.0. All results of Version 2.0, along with TAP feedback, were leveraged to create new designs for Version 3.0. The primary change came in the form of terminology experimentation with no changes made to the structure of the sign designs. Table 2.13 displays each sign set that was used for the third, and final, iteration.

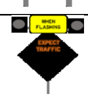
Table 2.13 Version 1.0 highest ranked sign sets

	A	B	C	D	E	F
Do not cross/turn (SIGNS FLASH)						
Sign is on						
Sign if off						

2.3.4.2 Version 3.0 Results

A total of 19 participants took part in evaluating the third set of sign designs. All participants experienced the same scenario that was presented in Version 1.0 and Version 2.0 for each set of signs. As presented in previous versions, users were asked to rate their overall preference at the end of the usability test based on comprehension, design, and safety of the sign designs. Results for highest, least preferred, and comprehensive scoring were completed as they were in Versions 1.0 and 2.0. The results of the individually tallied highest and lowest ranked signs can be found in Appendix F. The comprehensive results reveal sign set C and B as the highest ranked, however, it should be noted that the distribution of scores is small, with the remaining five signs being within 7 points of the top ranked sign (Table 2.14). The small range in point allocation makes it difficult to identify true user preference, therefore, deconstructing the sign sets and evaluating each state individually will provide more insightful results.

Table 2.14 Version 3.0 highest ranked sign sets

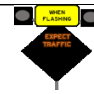
3.0 Signs	Example	Comprehensive Score
C		18
B		18
D		15
A		12
E		12
F		11

There was little consistency for the sign rankings across the three breakdowns (i.e., Overall, 'Do not turn/cross', and 'Sign is on'); however, Sign B held the first or second preference in all three rankings. Sign A appeared to have polarizing effects in achieving the most and least preferred ranking for the 'Do not cross/turn' and 'Sign is on' states, respectively (see

Table 2.15 and Table 2.16 Results for 'Sign is on' design

3.0 Signs	Example	Comprehensive Score
B		40
D		23

F		13
C		9

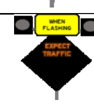
E		9
A		-10

). Based on drivers' comments, the discrepancy in rankings appear to stem from the use of the term VEHICLE which is acceptable in the 'Do not cross/turn' state (i.e., VEHICLE APPROACHING), but not in the 'Sign is on' state (i.e., "vehicle does not stop"). While their comprehensive score fared better overall in the 'Sign is on' state, signs C and E received the most frequent ranking of least preferred sign (see Appendix F), both of which contain the WHEN FLASHING-placard and both contain the same terminology in both sign states which appears to have negative perceptions among road users in this context. These findings are interesting because they capture part of the user experience story that is not described in the overall preference results. Based on the feedback for the 'Do not cross/turn' state, users tend to favor clarity, discreteness, and iconography in order to help with decision-making. In synthesizing the results for the 'Sign is on" state, Sign D came in second place and the remaining designs ranked significantly below the top two.

Table 2.15 Results for 'Do not cross/turn' sign

3.0 Signs	Example	Comprehensive Score
A		29
B		20
C		15
E		11
D		11
F		7

Table 2.16 Results for 'Sign is on' design

3.0 Signs	Example	Comprehensive Score
B		40
D		23
F		13
C		9
E		9
A		-10

The terminology results for the 'Do not cross/turn' state maintained a similar pattern as Version 2.0. The terms TRAFFIC APPROACHING and TRAFFIC TOO CLOSE were two highly ranked signs, extending 20+ points above the remaining four options (Table 2.17).

Table 2.17 "Traffic on major road is too close to safely cross" terminology 3.0 preferences

Terminology	Score
TRAFFIC APPROACHING	40
TRAFFIC TOO CLOSE	36
CROSSING TRAFFIC	10
EXPECT CROSS TRAFFIC	4
TRAFFIC AHEAD	1
ENTERING TRAFFIC	1

In Version 3.0, there were 19 users surveyed providing a more robust sample by which to measure language preference regarding the 'Sign is on' messaging. In the end, CROSS TRAFFIC DOES NOT STOP emerged as the most helpful terminology to communicate, "traffic may not be coming, but you should still use caution" while also indicating the 'Sign is on' and functioning properly. WATCH FOR TRAFFIC and LOOK FOR TRAFFIC, however, also receive favorable ratings (Table 2.18).

Table 2.18 "Traffic may not be coming, but still use caution" terminology 3.0 preferences

Terminology	Score
CROSS TRAFFIC DOES NOT STOP	36
WATCH FOR TRAFFIC	23
LOOK FOR TRAFFIC	17
TRAFFIC APPROACHING	10
TRAFFIC AHEAD	0

2.3.4.3 Version 3.0 Discussion

The larger sample size in this examination of the six signs provided a greater opportunity to find trends in perceptions and opinions of the signs and their attributes across multiple participants. Each sign was closely scrutinized by the participant pool.

- **Sign A:** The sign received a fair amount of praise and received high preference scores for its 'Do not cross/turn' state with participants stating it "*has a punch to it*" and "*is clear why I should not go*". The stop sign icon with red frame largely received positive feedback for being "*clear*" and "*universal*". While some liked the redundancy of the icon, others felt it was "*too redundant*" or was unnecessary. The 'Sign is on' state, however, received harsh criticism, largely for its use of the word VEHICLE. Comments received ranged from "*It's confusing*", "*Does VEHICLE mean me?*", and even "*VEHICLE DOES NOT STOP would cause fatalities*". Most recommended that CROSS TRAFFIC replace VEHICLE.
- **Sign B:** The sign received mostly positive feedback for both of its sign states. Participants reported that CROSS TRAFFIC TOO CLOSE in the 'Do Not Cross/Turn' state was "*explicit*", "*direct*" and "*very clear*". The message conveyed for the 'Sign is on' state (i.e., CROSS TRAFFIC DOES NOT STOP) received overwhelmingly positive feedback as a "*good/great/helpful reminder*". The novel square shape, orange, side positioned beacons received positive feedback. Some were

critical, however, stating the sign had "*too many words*", the wording "*lacks flow*", or that TOO CLOSE was "*too subjective*".

- **Sign C:** This original RICWS sign had a mediocre ranking overall; however, some of the positive feedback tended to come from participants who reported that they had already seen the sign, felt that it was "*familiar*", and "*clearly identifies a threat*". Largely, participants reported that the sign was "*too cluttered*", "*too much stuff*", or required "*too many head movements to process*". The terminology was called "*weird*" and "*disconnected*" between the two sign states. Repeatedly, participants expressed confusion about when the lights were not flashing, reporting "*when the lights are not flashing and makes me think traffic could still be approaching*" and that the sign is "*not helpful*", "*passive*", and "*vague*".
- **Sign D:** Participants appeared to be divided regarding this sign in relation to whether or not its streamlined design was useful. Some reported that the "limited information" on the sign was preferred because it is *"not confusing*", "*simple*", and "*helpful*". Moreover, the absence of beacons and flashing border were rated as "*bold and nice*", "*minimal and modern*". Others were more critical in stating that the overall terminology was "unappealing" and that the sign appeared to "*look like a business sign*" and not a traffic safety sign. Some recommendations related to changing the border to yellow and should not blink, however, this was not a universally shared recommendation.
- **Sign E:** This sign received scrutiny and praise relating to the top placement of the WHEN FLASHING placard. Some participants preferred the sign on top, while others strongly recommended it be placed at the bottom. One participant recommended that the sign and beacons be moved to the bottom. Largely, EXPECT TRAFFIC received a poor reception among participants who felt it was "*too vague*", "*would be troublesome for ESL speakers*", and "*sounds like an upcoming traffic jam*".
- **Sign F:** Similar to Sign D, this sign received mixed reviews regarding whether it contained enough information. Some participants requested a WHEN FLASHING placard, while others felt it was not necessary. Those who favored the sign described it as "*concise*", "*simple/minimal design*", and "*really clear*". WATCH FOR TRAFFIC in the 'Sign is on' state was called a "*nice reminder*" and conveys that drivers should "*be responsible*" or "*be attentive*". Conversely, some reported that the message "*doesn't convey that it is a good time to cross*".
- **WHEN FLASHING Placard:** Participants continued the exploration of how this sign is perceived by motorists. A pattern emerged relating to the placard and the sign in the 'Sign is on' state with participants failing to follow the logic statement when the beacons are not flashing, reporting that it "*makes it confusing and I am unsure of where the cars are*". Moreover, the expectation of the sign's flashing behavior was uncertain with participants saying it is "*unclear how it [the proposed flashing] relates to the sign*" and that it is "*unclear if it is supposed to be for the beacons or for the sign*".

2.4 FOLLOW-UP TEST ON SIGN A AND ALTERNATIVE DESIGNS

2.4.1 Study Method and Procedure

Although Sign A received high driver preferences for its “Don’t cross/turn” state, it faced many regulatory challenges and restricts, primarily the MMUTCD guidelines that have prevented it from being selected for test in the driving simulator. Based on the feedback from the TAP members of this project, the RICWS sign was initially developed as a warning system rather than a regulatory traffic sign (e.g., STOP sign), therefore by regulation its design cannot allow for incorporating elements such as the red flashing frame, and the message of “stop”, either represented in text or icon. Two alternative sign options (i.e., Sign A.1 and Sign A.2) were developed and drivers’ perceptions of them, especially with respect to the “Don’t cross/turn” state, were evaluated along with Sign A in a follow-up online survey. As depicted in Figure 2.3, two alternative representations of the action component to Sign A were illustrated at the onset of system’s detection of oncoming traffic (i.e., “WAIT” message in Sign A.1 and a hand icon in Sign A.2).

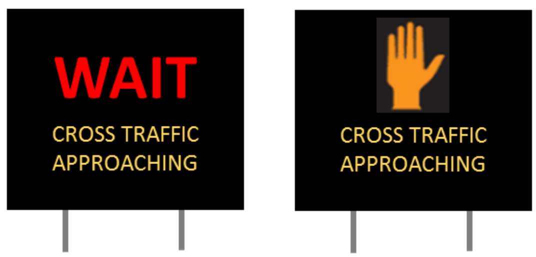


Figure 2.3 Alternative designs for Sign A (Left to Right: Sign A.1 and Sign A.2)

A total of 51 participants (Mean age = 40.9, *SD* = 11.6), including 35 females and 15 males (i.e., one participant did not wish to disclose gender), completed this follow-up online survey (See Appendix G). Like the previous settings of the initial usability tests, participants were first randomly presented with either one of the three Sign A options in an imaginary driving condition of a rural thru-STOP intersection (See Appendix G Q3-Q5) Following a brief introduction to the design of the corresponding sign, participants were then inquired about their interpretations on the sign messages as well as their decision making based on this information. Upon evaluating each sign option, participants were explicitly informed of the intention of the sign for its “Don’t cross/turn” state and they were asked to rank all sign options based on how they perceive each sign was able to accurately communicate the message of an “unsafe gap”. Finally, drivers’ preferences of the terminology for the “Sign is on/operational” state was also evaluated, with a special emphasis on comparing between “WATCH FOR TRAFFIC” and “CROSS TRAFFIC DOES NOT STOP”, given that participants were presented with all three sign states and how they functioned. The follow-up survey provided additional guidance into designing and developing alternative solutions that would best promote sign acceptance and correct perceptions of the sign messages.

2.4.2 Results of the Follow-up Usability Test

A total of N=43 respondents were resulted from Q3 to Q5 for the follow-up usability questionnaire. Overall, with the combinations of the action component and contextual information, all participants were observed to develop a higher level of situation awareness, have a higher rate of correct perceptions for all Sign A options, and that they were more likely to anticipate approaching traffic in advance. A comparably high rate of correct perceptions of Sign A was obtained; while 86.3% of participants were able to interpret the message correctly, some drivers have also reported redundancy of the stop icon and considered the system to serve as an additional reinforcement for avoiding stop sign violations at the intersection. One participant also reported confusion on the sign messages and stated that "*…the fact that it would be on the other side of the street as a normal stop sign would* ***throw me***…" However, on the other hand, many drivers may also perceive the stop icon to be *"…**universal signage** for stop",* "…***gets the most attention***" and *"…**it is the most recognizable**."* Examples of the anecdotal quotes from participants regarding Sign A were cited as the following:

- *"The **stop sign is indicating for me to stop**. The LED sign is indicating that I need to stop because the traffic on the major road is not stopping. Based on the information, I will **stop at the intersection and proceed when the sign changes**."*
- *"The sign above is 1) telling me to stop, and 2) there are vehicles on the major road headed toward the intersection. I would assume I must **remain stopped until the sign ceases flashing**."*
- *"There is a car approaching on the major road and I should **wait longer than a usual stop for it to pass by**."*
- *"…**wait for cross traffic to clear**... one might think this would **change to a go signal**."*
- *"I would probably pause at a complete stop for a longer period of time assuming the sign is **warning me of cross traffic that I may not be able to see yet**"*
- *"The sign is **an extra precaution** to tell drivers this is a major road/possibly rural highway where traffic does not stop. It is probably there because the intersection has had a lot of accidents. I would **stop and look more than once in both directions before continuing**".*

Participants demonstrated the most accurate perception or action towards Sign A.1, with 90.2% of participants reported that they would stop/wait at the stop sign. With the "WAIT" message, it was also indicated that participants were more likely to naturally expect changes in the action commands when the traffic is clear. While the majority of participants were able to develop correct mental model towards Sign A.1, the common confusion reported by participants was that they were unsure whether the sign was directed for drivers or pedestrians and that they would "…***ignore the sign across the street and focus on my own stop sign***…" Similar to Sign A, some drivers may view Sign A.1 to reinforce the stop sign too but they also indicated that they would use caution and wait extra time for checking traffic at the intersection. Examples of participants' anecdotal comments on Sign A.1 were cited as the following:

- *"Traffic is coming from left or right. I would look both ways and **wait until traffic passed…**"*
- *"Cross traffic is approaching and **it's not safe to cross**. **Wait till cross traffic clears** and then proceed through the intersection."*
- *"The sign conveys traffic is coming that does not stop and wait to cross. I will wait until thru traffic clears the intersection, **wait for the sign to change to "proceed" or another word that implies crossing is safe to do**."*

- *“This is a warning that you need to stop and wait at my stop sign. I would **stop and wait until the "Wait" goes away**, double check each direction by looking, then proceed to cross the major road.”*
- *“The sign says to wait. Assuming there is vehicle approaching I would **wait to see if the sign changed** and also look both ways.”*
- *“I would **stop and wait for traffic that I cannot see**”*
- *“…I would stop at the intersection and look both ways, **waiting for traffic to clear enough for me to safely cross**.”*
- *“I believe this sign is alerting me to live traffic that is coming on the main road. I would **wait until it stopped flashing wait and then go and cross** the street.”*

With respect to Sign A.2, most of the participants associated the hand icon with pedestrians and may not perceive the sign message to be directed at drivers, therefore it was eliminated from further consideration. However, the rate of correct perception was expected to increase in the more realistic or at real-world rural highway intersections where pedestrians were less likely to be presented.

After surveying participants about their perceptions of Sign A and the two alternative Sign A designs, they were explicitly provided with the intention of the signs regarding the “Don’t cross/turn” state (See Appendix G: Q6). Participants were later asked to rank their preferences of the sign designs based on how they think the signs were able to accurately convey the intended messages of an unsafe gap. Out of N=41 respondents, participants overall ranked Sign A as their most preferred sign option to convey the most accurate messages, followed by Sign A.1 and Sign A.2. Additional comments regarding the each sign option were summarized in Table 2.19. It was also interesting to point out that many participants perceived “stop” icon to convey more of a regulatory message, whereas “wait” and “hand” icon were more likely to act as suggestions to drivers.

Table 2.19 Results of participants’ references on the accuracy of the signs

Sign Option	Overall Ratings (Total N=41)	Additional Comments
Sign A (i.e., STOP icon and the red flashing boarder)	1st: n=22 2nd: n=12 3rd: n=7	**Positive:** *“stop means the most”, “stop seems more severe, so I’d pay more attention”, “…cohesive with normal road signs and… is universal and means do not to go”, “most recognizable”, “…most likely to catch my attention”, “the stop sign seems more matter of fact”,* etc. **Negative:** *“additional reminder to stop at the stop sign”, “while it gets the message across, could be mistaken for another reminder of traffic and not the alter it is meant to be”, “…odd as you’re already stopped at the intersection”, “repetition of the stop sign”,* etc.
Sign A.1 (i.e., flashing “WAIT” message)	1st: n=12 2nd: n=20 3rd: n=9	**Positive:** *“…indicate more than just a reminder to temporarily stop, but to stop and stay”, “most succinct message”, “ …tells me to wait before crossing…different than the usual stop sign many ignore”, “most accurate because it signals to wait for traffic”, “wait is effective”,* etc. **Negative:** *“…more like suggestions- not rules”, “…the most vague”, “…could be an issue for non-English speaking drivers”, “not as “severe” as stop”, “more of a suggestion”,* etc.

Sign A.2 (i.e., steady "hand" icon)	1st: n=7 2nd: n=9 3rd: n=25	**<u>Positive:</u>** *"hand indicates more caution up to driver to check then proceed", "…a steady icon conveys stop better than a flashing one", "probably a little less recognizable, but seems pretty obvious",* etc. **<u>Negative:</u>** *"less important", "…reminds me of walk signals which people ignore all the time", "used more for pedestrians and less for driving", "…a signal for walkers, so I'd probably disregard it as a driver", "because it's not blinking, so it doesn't seem as dire/important", "doesn't mean much",* etc.

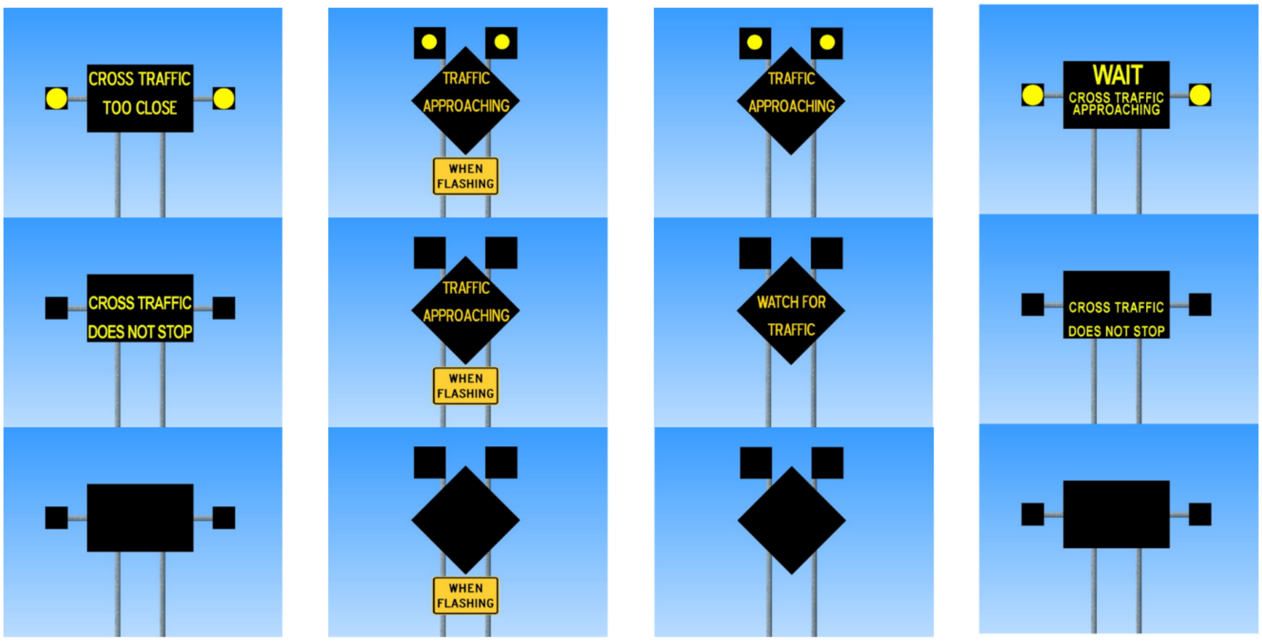
**Note: 1st means the most accurate; 2nd means less accurate and 3rd means the least accurate*

The last question of the follow-up survey further inquired participants' preferences on the terminology of the "Sign is On/Operational" state. The majority of participants preferred "CROSS TRAFFIC DOES NOT STOP" to "WATCH FOR TRAFFIC". Among all forty participants who responded to this question, only seven of them (i.e., 17.5%) thought "WATCH FOR TRAFFIC" would more accurately convey the information that the "sign is on/operating, proceed with caution". The majority of participants (i.e., 31 out of 40) favored "CROSS TRAFFIC DOES NOT STOP" because it conveyed more meaningful information of the traffic and altered drivers to use caution. The remaining two participants, however, perceived the two terminologies to be "***equally poorly thought out***".

In particular, to comply with the restraints of MMUTCD, further discussions were brought up in terms of how Sign A should be modified and refined to obtain a better design acceptance by MnDOT planners and engineers. The integration of STOP icon was thereby not allowed to be used in the dynamic signs and nor was the flashing dashed border. Although the word of "STOP" has not been tested in the follow-up usability test, it might be considered as an alternative option that could be further assessed, to communicate the action commands to drivers. Additionally, red letter color was deemed to inappropriately convey prohibited information, instead an orange "WAIT" was prescribed by engineers to represent the warning messages within MMUTCD standards. However, the prescribed adaptations of the message display, color and layout executed upon the signs raised concerns of a potential reduction in contrast and saliency of the messages, as well as mitigate the power to enforce action information. Furthermore, the ability of Sign A.1 to promote better sign acquisition may be further suppressed by fitting all the message lines within a limited size of LED sign. A modified design option, Sign G, was submitted to the driving simulator test, as a substitute of Sign A.

2.5 SUMMARY

The design of the five alternative signs underwent two major rounds of iterative design modifications and three rounds of user testing. One design was eliminated completely (i.e., Version 1.0 Sign E) while the remaining signs received a series of modifications of terminology and other design elements (e.g., icons, size, and color). Rejected terminology by participants was: THRU TRAFFIC/THRU TRAFFIC APPROACHING, EXPECT TRAFFIC/EXPECT CROSS TRAFFIC and VEHICLE DOES NOT STOP. The top-rated terminology recommendations for the 'Do not cross/turn' sign state were: TRAFFIC APPROACHING, CROSS TRAFFIC APPROACHING and CROSS TRAFFIC TOO CLOSE. The top-rated terminology recommendations for the 'Sign is on' sign state were: CROSS TRAFFIC DOES NOT STOP and WATCH FOR TRAFFIC. The use of the terminology TRAFFIC APPROACHING (with WHEN FLASHING placard) in the original RICWS sign was familiar to a number of participants (see Sign C in Figure 2.4) but received substantial criticism and reported confusion in the 'Sign is on' (i.e., beacons not flashing) sign state. Three alternative sign designs (see Signs B, F and G in Figure 2.4) along with the original RICWS were chosen for subjective and behavioral analyses in the driving simulator.



Sign B Sign C Sign F Sign G

Figure 2.4 Recommended sign designs for simulation study

There are several candidate signs that were recommended for further consideration as an alternative solution to the existing RICWS design. The candidate signs were reduced to the three most feasible options, along with the existing RICWS design (i.e., Sign C), to limit the costs of their further examination in the driving simulator. The final signs are displayed in Figure 2.4 and their justifications and final modifications are listed below.

The signs recommended to be eliminated from further consideration were Signs D and E. While Sign D received some positive feedback from participants, others were critical of the design. Moreover, while there was positive feedback about the flashing border, when asked directly, participants consistently reported the need for flashing beacons in the 'Do not cross/turn' sign state. Sign F was chosen in its place since the two signs contained the same message terminology, were similarly ranked, and it is less expected that the flashing border will meet MUTCD standards or even driver expectations of a hazardous state compared to the use of the flashing beacons. Sign E also had some positive reviews; however, the top mounted WHEN FLASHING placard received polarizing responses and the terminology EXPECT TRAFFIC was widely criticized.

The terminology of Sign A was reverted back to the design featured in Version 2.0 which would eliminate the use of VEHICLE and instead feature CROSSING TRAFFIC APPROACHING in the 'Do not cross/turn' state and CROSS TRAFFIC DOES NOT STOP in the 'Sign is on' state. Through a follow-up usability tests of Sign A and its alternatives, a modified design option (i.e., Sign G) was developed which incorporated a larger font of “wait” word as the action command as well as the terminology of “CROSS TRAFFIC DOES NOT STOP” as the contextual information in its “Don’t cross/turn” state, to best comply with the MMUTCD guidelines. Sign G was later submitted to the driving simulator test.

The terminology used for Sign B received highly positive feedback and is recommended for continued use. The combination of the flashing beacons and flashing border, however, is deemed to be too cluttered and distracting to meet human factors design standards. The rectangular shape and side mounted beacons are recommended to be maintained; however, the flashing border is recommended to be removed from the design.

Finally, Sign C, the original RICWS, received some strong criticisms for its cluttered elements and confusing message in the ‘Sign is on’ state. Its inclusion in its existing design state is important, however, to properly benchmark participants’ perceptions and driving behavior using it as a decision aid compared to the three alternative designs.

CHAPTER 3: DRIVING SIMULATOR STUDY

3.1 INTRODUCTION

The alternative RICWS design options, along with the original RICWS sign, were tested in the driving simulator. The primary research objective was to evaluate the effectiveness of different RICWS signs on promoting safe driving behaviors for motorists at high-risk rural thru-STOP controlled intersections. By study design, the research findings also enabled a broader understanding of how the overall intervention effect was moderated by various levels of driver's age group, mainstream traffic volume, and visibility of the intersection. Several important aspects of driver behaviors were investigated in this study, including drivers' driving performance, visual attention, and other subjective measures regarding each of the RICWS signs.

Furthermore, this study also sought to identify the potential inefficiency and risks associated with the current deployments of the RICWS intervention, which can later be translated into practical implications for design, implementation, and use of similar intersection intelligent warning systems in the real world. A stratified statistical analysis approach was utilized to compare the above-mentioned driver behaviors between the intervention (i.e., at rural intersections with both thru-STOP and RICWS controls) and the baseline conditions (i.e., at rural intersections with thru-STOP control only). More detailed results will be presented in the following subsections.

3.2 METHODS

3.2.1 Participants

A total of 120 participants were enrolled into this driving simulator study, including 40 novice teenage drivers (age of 16-18 years old), forty experienced middle-aged drivers (age of 35-50 years old) and forty older drivers (age of 65-77 years old). Table 3.1 summarizes the basic demographics of the recruited participants in this study. Balanced numbers of males and females were recruited for each sign option across each age group.

Prior to conducting the experiment, a pre-screening questionnaire (See Appendix H) was applied to all individuals who indicated their interests in participation via telephone interview or online survey. Those who were color blinded or did not have a normal or corrected normal vision, had experienced any motion sickness or sea sickness symptoms, and had a history of physical, cognitive and neurological problems that may have prevented them from everyday driving, etc. were excluded from this study. Specifically, novice teenage drivers should have obtained a valid provisional driver's license (i.e., being able to drive independently) within less than two years. For teenage drivers to participate in the study, signature consent was obtained from at least one legal custodian of the teen and teenagers signed a minor assent form to agree to participate.

Fifteen (12.5%) of these participants, including one teenage driver, seven middle-aged drivers, and seven older drivers, experienced a mild to moderate level of motion sickness symptoms that prevented them from completing the whole experimental session. This risk was acceptable since a drop-off rate of 30% to 40% was observed from previous driving simulator studies that involved older drivers and/or driving tasks that were more prone to motion sickness such as exhibiting frequent stops at intersections. Throughout the entire driving experiment, participants were monitored closely through the eye tracking videos by researchers to allow early detection of any motion sickness symptom, as well as protect participants from getting sick in a timely manner. Due to the limitations of the eye tracking system, only partial data were obtained on drivers' visual attention behaviors and were thereby analyzed in this study.

Table 3.1 The basic demographics of the recruited participants

	Sign B	**Sign C**	**Sign F**	**Sign G**
Teenage Drivers (16-18 years old) *M*= 17.3, *SD*= 0.7	*N*= 10 (5 Males; 5 Females) *M* = 17.4, *SD*= 0.7	*N*= 10 (5 Males; 5 Females) *M* = 17.4, *SD*= 0.7	*N*= 10 (5 Males; 5 Females) *M* = 17.3, *SD*= 0.8	*N*= 10 (5 Males; 5 Females) *M* = 17.3, *SD*= 0.8
Middle-Aged Drivers (35-50 years old) *M*= 41.6, *SD*= 5.0	*N*= 10 (5 Males; 5 Females) *M* = 42.0, *SD*= 4.6	*N*= 11 (5 Males; 6 Females) *M* = 40.5, *SD*= 4.0	*N*= 10 (5 Males; 5 Females) *M* = 41.5, *SD*= 4.4	*N*= 10 (5 Males; 5 Females) *M* = 42.6, *SD*= 7.1
Older Drivers (65-77 years old) *M* = 68.5, *SD* = 3.1	*N*= 10 (5 Males; 5 Females) *M* = 68.0, *SD*= 2.3	*N*= 9 (5 Males; 4 Females) *M* = 68.7, *SD*= 4.4	*N*= 10 (5 Males; 5 Females) *M* = 68.5, *SD*= 3.2	*N*= 10 (5 Males; 5 Females) *M* = 68.7, *SD*= 2.9
Total *N* = 120 (including 59 Males and 61 Females)				

3.2.2 Equipment and Apparatus

3.2.2.1 Driving Simulator

The driving experiment was conducted using a full-cab driving simulator (See Table 3.1) that features realistic driving experiences as well as sensory feedback for drivers to best capture their natural driving performance in the vehicle(i.e., the current model is 2002 Saturn S-Series SC2 passenger car, by Realtime Technologies, Inc.). Multiple electrical systems connecting to the computing consoles were also wired into the simulator to measure and collect real-time vehicle information throughout the driving session, including vehicle speed, acceleration, yaw rate, etc. Participants were able to obtain power assisted steering and resistance-based braking control of the vehicle, as well as receive motion feedback based on corresponding vehicle movements.

To assess participants' driving performance at high-risk rural thru-STOP controlled intersections, the simulated world was established to include a sequence of rural intersections that represented similar characteristics (e.g., geometric design, visibility, level of traffic volume, surrounding environment, etc.) of the candidate intersections where RICWS signs have been implemented in Minnesota. Specifically, a one-mile roadway segment that delineated Minnesota rural driving environment was constructed in-between each mock-up rural intersections to reduce the effect of training. The posted speed limit on the minor road on which the subject vehicle was travelling was 55 mph. Operational signs would begin presenting the "Do Not Cross/Turn" sign state when the approaching vehicle within 6.5s TTC to the intersection. The selection and construction of rural intersections in the simulator were based on the MUTCD standards and feedback from the TAP committee members.

The simulated driving environment was projected to a five-channel, 210-degree (2.5 arc-minutes per pixel) screen that allowed drivers to encompass a broad range of frontal and peripheral view like the real-world driving conditions. From inside the vehicle, participants were also able to keep track of traffic and other surrounding environment through the side mirrors and the rear-view mirror, provided by two vehicle-instrumented LCD displays and a backward-faced projecting screen, respectively.

Figure 3.1 HumanFIRST full-cab driving simulator set up

3.2.2.2 Eye Tracking System

The Smart Eye Pro eye tracking system (i.e., Smart Eye AB, Gothenburg, Sweden) was utilized for collecting data on participants' visual attention performance in this study. The system consists of four in-vehicle instrumented digital cameras and a forward-facing scene camera (See Figure 3.2) that enables tracking of where participants navigated on as well as for how long they have looked. In this project, the in-vehicle cameras were mounted on the dashboard and facing backward to ensure the system would reliably capture drivers' head and eye movements during the experiment session. Once drivers' gaze direction was determined and calibrated to the front view screen, their gazes can be superimposed onto the where they are viewing through the scene camera. In this study, the EyesDx MAPPS (Cedar Rapids, IA) software was utilized to help researchers to track the location and frequency of participants' gazes on the simulated driving scenario.

Figure 3.2 Smart Eye Pro Eye Tracking Camera

3.2.3 Procedure and Experimental Design

The study design used a between-subject design approach, with each participant being randomly assigned to only one sign option. After participants signed the informed consent form and completed a driving history questionnaire (See Appendix I), they were instructed to have their eye position calibrated so that their eye movements could be captured while they were performing the driving tasks. Participants were then asked to complete one practice drive and four experimental drives, each lasting approximately 5-7 minutes. The order of the experimental drives followed an A-B-A-B reversal design, with A's being the baseline drives where participants experienced only STOP sign controlled intersections and B's being the treatment drives where RICWS signs were presented in addition to the STOP signs at intersections. For each of the first three experimental drives, participants drove through four intersections in a sequence, with varying levels of intersection visibility (i.e., obstructed view versus clear view) and mainstream traffic volume (i.e., low versus moderate). To evaluate drivers' behavior adaptation towards the sign, a fifth intersection was included in the final drive where the sign was intentionally displayed in its "off-state." All of the fifth intersections were characterized with the same driving conditions as having a low level of mainstream traffic volume and a clear visibility. The reason for this set up is to expose drivers to a considerably low level of driving risks and maximize their likelihood of demonstrating adaptation to the sign. Several questionnaires were administered, respectively, to measure participants' mental workload for each drive (See Appendix J for a modified NASA RTLX Mental Workload Questionnaire) and perceived trust in the system (See Appendix K) after each drive, as well as their overall sign preferences (See Appendix L) at the end of the study. The framework of the experimental design for this study is depicted in Figure 3.3.

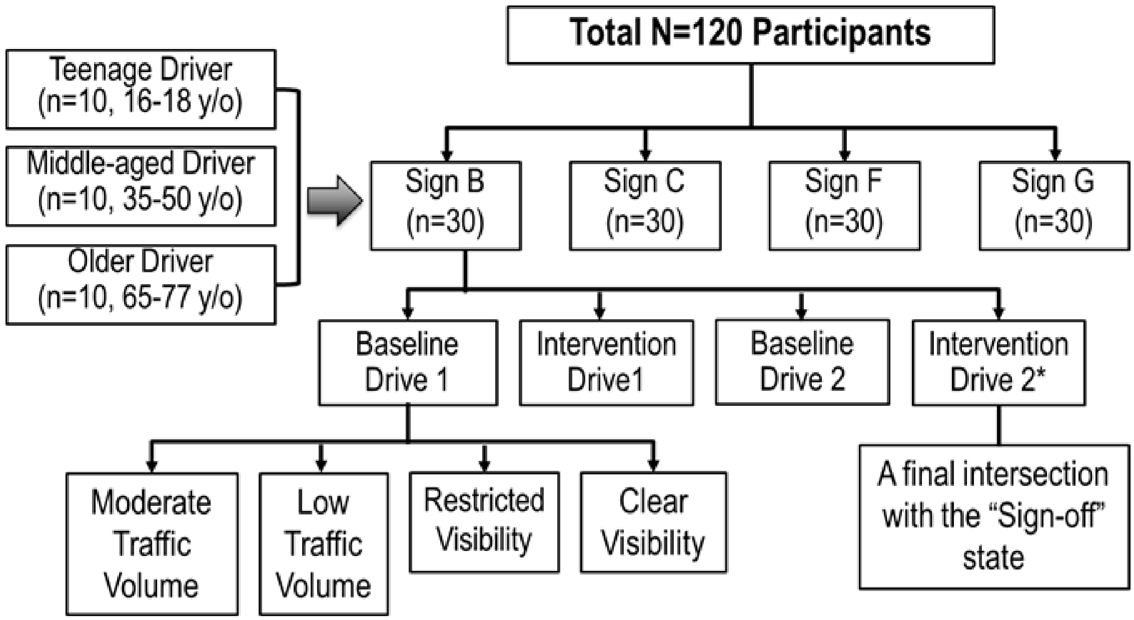


Figure 3.3 Experimental design for the simulator study

3.2.4 Study Exposures and Outcomes

The primary exposure of interest for this study was identified as the RICWS sign options (i.e., the variable of Sign, with four levels of Sign B, Sign C, Sign F, and Sign G). By study design, drivers' age group, mainstream traffic volume and visibility of the intersection were balanced randomized in a controlled study setting and remained constant across each group of the sign options. The moderation effects of these factors on the primary intervention effect were also investigated, through comparing the study outcomes across all sign options within each stratum of the following exposures:

- Age, which involved three levels of Teenage drivers (age 16-18), Middle-aged drivers (age 35-50) and Older drivers (age 65-77).
- Visibility, which contained two levels of Clear view (i.e., >16 sec sight distance) and Restricted view (i.e., 6.5 sec sight distance).
- Traffic Volume, which consisted of two levels of Low Traffic Volume (10s-16s TH between vehicles with 4.5s-9.5s for sign in "On" state) and Moderate Traffic Volume (3s-9s time headways (TH) between vehicles with 0s-2.5s for sign in "On" state).

The study outcomes contained three different aspects of driver behaviors that provide both qualitative and quantitative measures to evaluate the safety performance of the intervention and potential risks associated with its use, including driving performance outcomes, drivers' subjective measures, and visual attention outcomes. The driving performance outcomes consisted of drivers' gap acceptance performance, stop sign violation, wait time at the intersection, and other attributes such as the speed and acceleration of the participant's vehicle. Drivers' subjective measures included self-reported trust in the system, self-reported mental workload, and drivers' overall preferences on the signs. Finally, the outcomes of visual attention focused on examining how drivers' visual gaze allocation patterns might have been changed when driving with the presence of the RICWS intervention.

3.2.5 Analytical Methods

This study utilized a variety of statistical models to investigate the effectiveness of different RICWS sign options on promoting safe gap acceptance behaviors at rural thru-STOP intersections. The Generalized Estimating Equation (GEE) modeling technique was deployed to compare various outcomes between the intervention drives and the baseline drives, while simultaneously accounting for the inter-correlations within each individual participant. To ensure the statistical power of this study, the study outcomes were further collapsed into two groups, by merging data within the two baseline drives (i.e., Baseline) and within the two intervention drives (i.e., Intervention). The learning effect of the intervention was thereby not investigated in the current analyses, due to an observed large variation in individual driving behaviors for each drive.

A stratified modeling structure by mainstream traffic volume was also utilized for analyzing the driving performance and visual attention performance outcomes. This is because drivers' decision making of whether to accept or reject a gap, as well as their visual search behaviors, can be largely determined by the distributions of vehicle gap sizes (i.e., measured in seconds between two nearest approaching vehicles on the main road) available to them. Specifically, in this study vehicles on the main road are constructed to travel at a constant speed for all driving conditions. As a result, the level of mainstream traffic volume served as a most predominant influencing factor that directly restricted drivers' accessibility to certain gap sizes, which in turn affected the potential safety effectiveness of the RICWS intervention. By study design, half of the rural intersections were presented to participants with a moderate level of mainstream traffic volume, under which circumstances the vehicles on the main road were randomly sampled from a discrete distribution of gap sizes ranging from 3s to 9s. In contrast, at the other half of rural intersections, participants also experienced a lower level of traffic volume where vehicles were aligned at a distance of 10s- to 16s- gaps away from each other. All analyses in this study, except for the subjective measures, were conducted separately within each of the low and moderate traffic volume conditions. The stratified analyses are beneficial to transportation agencies in determining a more appropriate threshold of traffic volume for effective and efficient use of the RICWS systems in real-world practices.

3.3 DRIVING PERFORMANCE RESULTS

3.3.1 Definitions and Methods

A total of 10 study outcomes were evaluated for drivers' driving performance, which consisted of drivers' 1) risk of accepted critical gap, 2) absolute time-to-collision, 3) risk of rejected critical gap, 4) number of rejected critical gaps, 5) risk of rejected non-critical gap, 6) total wait time, 7) stop sign violation, 8) average approaching speed, 9) average crossing speed and, 10) average crossing acceleration.

- *Accepted critical gap*, represented the size of gap selected by the participant immediately upon when he or she decided to accelerate into the intersection, which was measured in seconds between the nearest approaching vehicle on the mainstream road (i.e., approaching to the intersection from either the right or the left direction) and the participant's own vehicle. For analysis purposes and for safety considerations, the outcome of accepted gaps was further categorized into two levels of critical gaps and non-critical gaps. Critical gaps were identified in this study as those insufficient gaps that were smaller than 6.5s, given vehicles on the main road were travelling at a constant speed of 65mph or at approximately 29 meters per second. For analyzing this binary outcome, the log-binomial regression models were used to estimate the risk of drivers accepting a critical gap among all accepted gaps for both baseline and intervention conditions. The intervention exhibited a protective effect on shifting driver behaviors to accept less critical gaps if the stratum specific relative risk (i.e., RR) yielded a value of less than 1.

- *Absolute time-to-collision,* represented the absolute distance measured in second from the nearest vehicle on the main road to the participant's own vehicle in the collision course, at the point when participant's own vehicle travelled through the middle line of the intersection. This measurement was treated as a continuous outcome, which served as a direct indicator of the crash risks and possible near misses observed in this study. Linear regression models with repeated measurements were utilized for analyzing this outcome and the other vehicle performance, such as average speed and acceleration, etc.
- *Rejected critical gap,* similarly, examined the probability of drivers rejecting a critical gap among all rejected critical gaps. This measurement reflected the overall distributions of all gaps rejected by drivers; however, by itself it might not be sufficient to directly quantify the capabilities of the RICWS intervention to prevent drivers from inappropriate selections of critical gaps, since some drivers could have made their decisions to proceed into the intersection without ever having been exposed to a non-critical gap. Therefore, the number of rejected critical gaps was also included as a more direct measure for this purpose. Similar approaches for analyzing the binary outcome were also applicable here.
- *Number of rejected critical gaps,* represented the frequency of only critical gaps rejected by drivers. This measurement calculated the incidence prevalence or rate of the rejected critical gaps for both baseline and intervention conditions. Because the variances of this study outcome were much higher than its mean values for each stratum of the primary exposure and other effect modifiers, negative binomial distribution was thereby used to account for the presence of over dispersion of data.
- *Rejected non-critical gap,* described the risk for drivers to reject a non-critical gap versus accept it given the condition that they were actually presented with at least one non-critical gap. Non-critical gaps were identified in this study as those sufficient gaps that were larger than 6.5s, given vehicles on the main road were travelling at a constant speed of 65mph or at approximately 29 meters per second. A greater value of the relative measurement might imply less efficient use of the intervention or adoption of more conservative attitudes, because in this case drivers were more prone to reject non-critical gaps that should have been accepted in the first place.
- *Total wait time,* measured the time in seconds starting from participants came to a complete stop to when they decided to accelerate into the intersection. However, a longer wait time at the intersection may not essentially imply inefficiency under certain driving circumstances, since drivers might remain stopped at the intersection to allow multiple critical gaps to pass or use more time for safety purposes, such as looking for traffic or checking signs.
- *Stop sign violation*, represented a binary outcome of whether participants managed to make a complete stop at the stopping line on the minor road. If participants failed to comply with the stop sign (i.e., roll through the intersection), then a value of "Yes" would be assigned indicating a stop sign violation at that specific intersection, otherwise a value of "No" would be assigned. Since there was a noticeable increase in the frequency of stop sign violations at "sign-off"

intersections, which was likely caused by malfunctions of the sign, these intersections were assessed in a separate follow-up analysis. Likewise, log-binomial regression models with the GEE adjustments for individual participant were deployed.

- *Average approaching speed,* measured the average speed (mph) of the participant's own vehicle when it entered the starting point of the intersection zone throughout approaching to the stopping line. The intersection zone was determined by examining the speed and deceleration profiles for all drivers to identify a proper approaching range prior to the intersection. The intersection zone began 35 meters from the center of the intersection as the driver approached.
- *Average crossing speed,* identified the average speed of the participant's own vehicle from the starting point of the crossing maneuver until the vehicle passed through the middle line of the intersection.
- *Average crossing acceleration,* identified the average acceleration rate, measured in miles per hour per second (mi/(h*s)), of the participant's own vehicle when crossing the intersection. The above-mentioned speed and acceleration outcomes were used to demonstrate drivers' perceived risks and urgency prior to and when crossing the intersection with and without the presence of the intervention, and how this effect was moderated by other factors. Linear regression models with repeated measurements were adopted to calculate the differences of the overall means within each stratum of the exposures of interest.

These gap pertinent outcomes aimed to evaluate the safety potentials of the RICWS intervention to promote recognition of inadequate gaps as well as reduce risks for accepting these gaps. The efficiency of the system was also examined through probing into the proportion of the rejected non-critical gaps by drivers and the total wait time at the stopping line. Furthermore, the study results also allowed identification of the potential risks associated with the RICWS deployments through analyses of other driving performance. Due to an observed remarkably high frequency of running stop sign behaviors at those intersections with the "sign-off" state (i.e., the last intersection of the driving experiment), a separate analysis was also performed to compare the risks of stop sign violations between intersections at which RICWS signs failed to function properly and those intersections with the same characteristics at baseline.

3.3.2 Definitions and Methods

3.3.2.1 Accepted critical gap

Under the driving condition of moderate traffic volume, drivers accepted a total of 826 gaps which consisted of n = 442 for baseline drives (i.e., including 221 critical gaps and 201 non-critical gaps) and n = 404 for intervention drives (i.e., including 165 critical gaps and 239 non-critical gaps). The analysis result presented an overall estimated risk of 0.41 (95% CI=0.36-0.47) for drivers to accept a critical gap with the presence of the RICWS intervention, compared to an increased risk of 0.53 (95% CI=0.48-0.57) at baseline. The RICWS intervention was found to have an overall significant impact on reducing the likelihood of accepting a critical gap across all levels of sign options, age groups and visibilities (Relative Risk or RR=0.78, 95% CI=0.68-0.90, p=0.0005). In particular, although all four sign options exhibited protective effects on reducing the risks of accepted critical gaps with all RRs being less than 1, the results were only tested significant for Sign B (RR=0.70, 95% CI=0.56-0.87, p=0.0016) and Sign C (borderline significant, RR=0.72, 95% CI=0.52-1.01, p=0.0544). Figure 3.4 illustrated the frequency and proportion of drivers' accepted gaps by sign option under the moderate traffic volume condition. As was noticed in this figure, Sign F appeared to be much less effective compared to other sign options, with the occurrences of the accepted critical gaps being slightly less frequent and the non-critical gaps remained identical in the intervention condition. Drivers' risks of accepting a critical gap were compared between baseline and intervention under the moderate traffic volume condition across different sign options (See Figure 3.5).

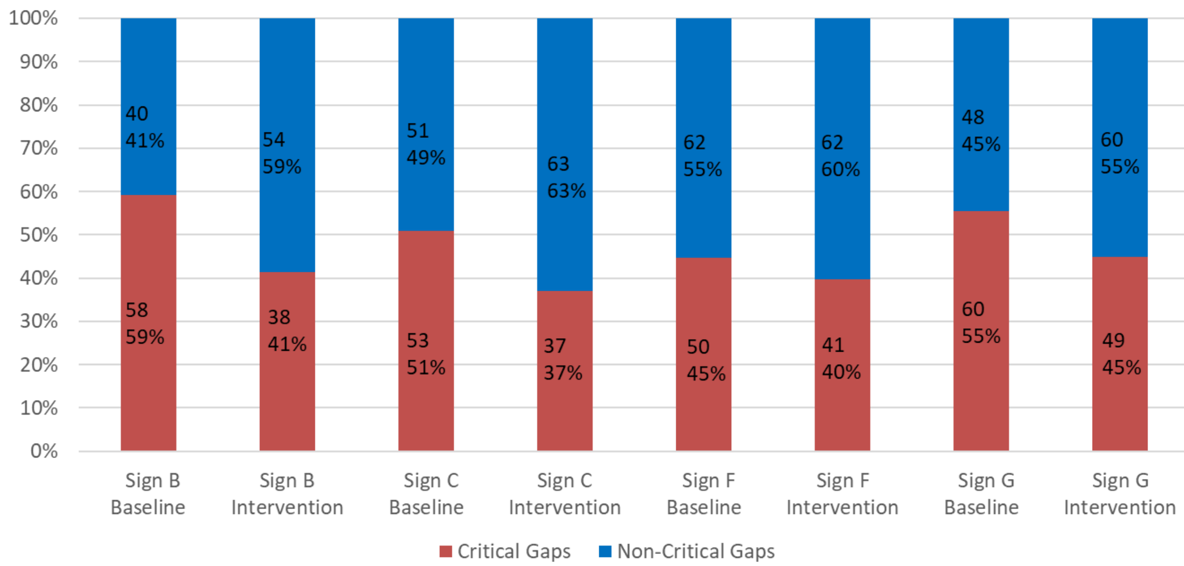


Figure 3.4 The frequency and proportion of drivers' accepted gaps under the moderate traffic volume condition by sign option

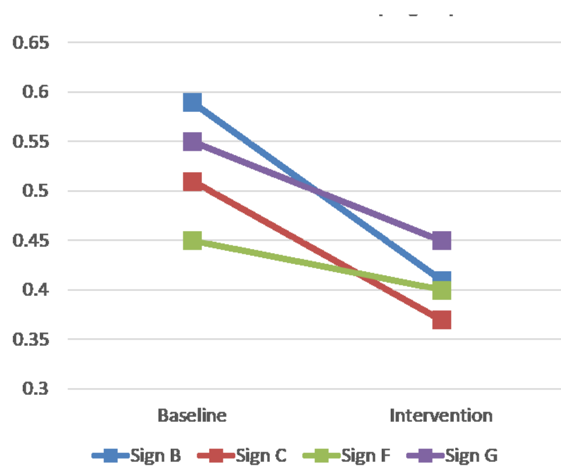


Figure 3.5 Risk of accepting a critical gap under the moderate traffic volume condition by sign option

Similarly, the intervention effect was also observed to be moderated by different levels of visibility and age group. As illustrated in the Figure 3.6, drivers were less likely to accept critical gaps and more likely to accept non-critical gaps when comparing intervention to baseline. A moderation effect of visibility was also suggested in that the RICWS intervention was in general more effective when used at restricted view intersections compared to clear view intersections (RR=0.68, 95% CI=0.53-0.88, p=0.0028 and RR=0.85, 95% CI=0.72-1.00, p=0.0537, respectively) (See Figure 3.7). One possible explanation could be that, with restricted visibility, drivers might rely more on the traffic information provided by the sign and use the sign more frequently to facilitate their decision-making.

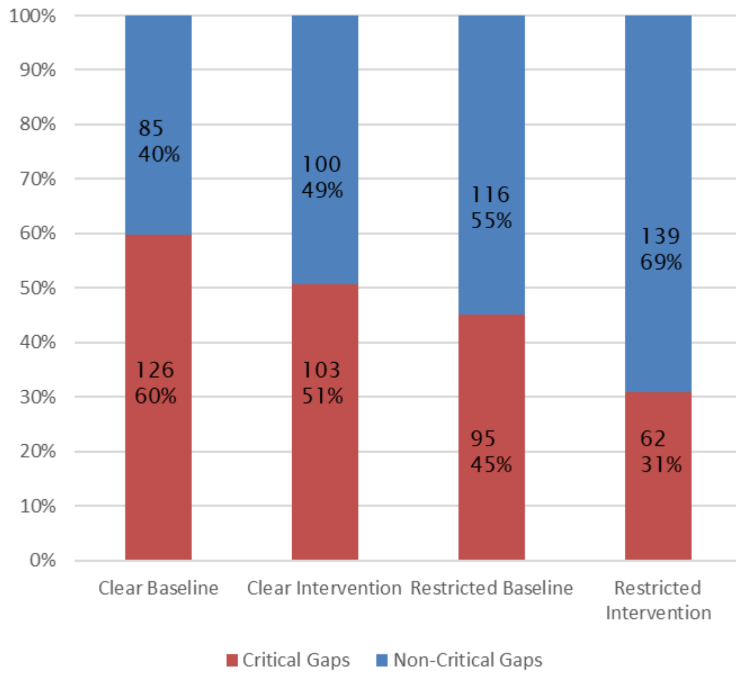


Figure 3.6 The frequency and proportion of drivers' accepted gaps under the moderate traffic volume condition by visibility

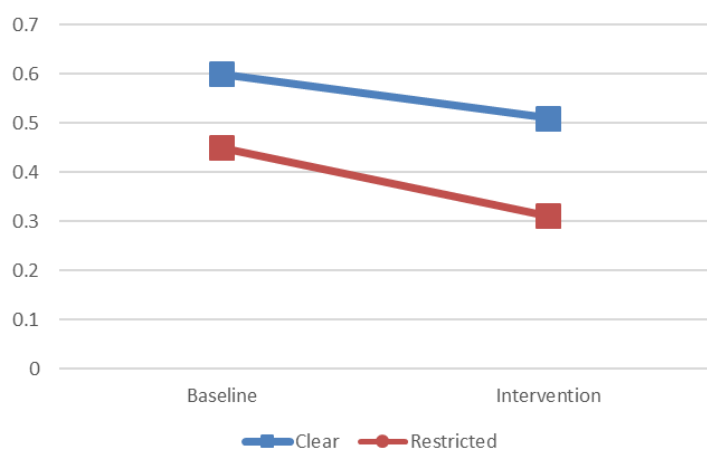


Figure 3.7 Risk of accepting a critical gap under the moderate traffic volume condition by visibility

Likewise, Figure 3.8 illustrates the frequency and proportion of drivers' accepted gaps under the moderate traffic volume condition by driver age group. Notably, while novice teenage drivers did not seem to be assisted by the signs, significant protective effects of the intervention were detected among middle-aged drivers (RR=0.73, 95% CI=0.60-0.90, p=0.0025) and older drivers (RR=0.69, 95% CI=0.51-0.95, p=0.0228) (See Figure 3.9). Compared to their older counterparts, teenage drivers were in general found to be more distracted and unaware of the signs while driving. Some teenage drivers also perceived the sign to be less useful due to an incorrect mental model of the sign messages, had greater perceived effort in engaging with the sign, failed to notice its presence, etc.

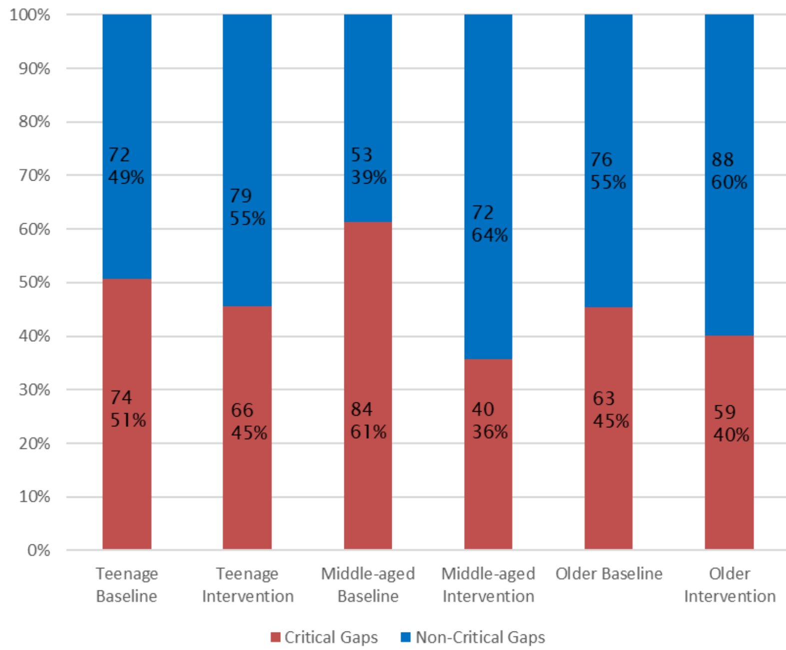


Figure 3.8 The frequency and proportion of drivers' accepted gaps under the moderate traffic volume condition by driver age group

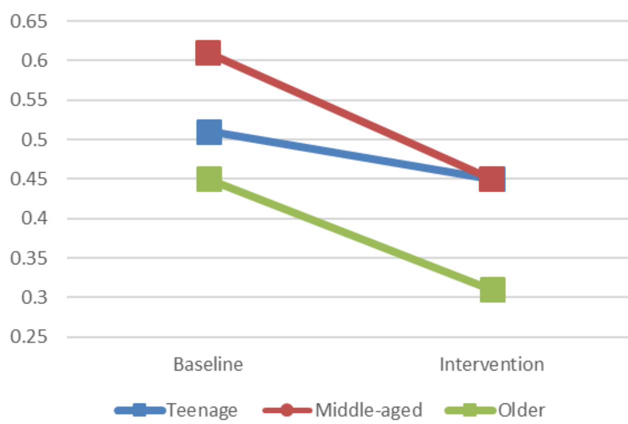


Figure 3.9 Risk of accepting a critical gap under the moderate traffic volume condition by driver age group

3.3.2.2 Absolute Time-to-collision (TTC)

There was no significant overall effect of the intervention observed on the absolute TTC under the moderate traffic volume condition (*M*=5.31, *SE*=0.08 for Baseline, and *M*=5.20, *SE*=0.07 for Intervention, respectively, *p*=0.2096). Nevertheless, neither of the moderation effects was significant for sign option and age group. In general, the absolute TTC was slightly decreased in the intervention condition for all sign options, except for Sign F. However, these reductions were very minimal (i.e., the greatest amount equals to 0.25s for Sign C) and none of them yield significant results. With regard to the effect of age group, teenage drivers demonstrated slightly greater absolute TTC in the intervention condition (*M*=5.09, *SE*=0.10) compared to baseline (*M*=5.02, *SE*=0.11), however this trend was reversed among middle-aged drivers (*M*=5.19, *SE* =0.15 for Intervention, and *M* =5.45, *SE* =0.14) and older drivers (*M*=5.46, *SE*=0.12 for Intervention, and *M*=5.32, *SE*=0.11 for Baseline). None of the pairwise comparisons were significant for age group with Tukey-Kramer adjustments.

Nevertheless, a clear moderation effect by visibility was observed under the moderate traffic volume condition for the intervention (See Figure 3.10). At clear view intersections, the presence of RICWS intervention significantly reduced the absolute TTC (*M*=5.84, *SE*=0.09 for Intervention, and *M*=6.17, *SE*=0.08 for Baseline), Mean difference=0.32, *SE*=0.11, p=0.0246. As opposed to this, the difference of the absolute TTC was not significant between baseline (*M*=4.45, *SE*=0.11) and intervention (*M*=4.53, *SE*=0.09) at restricted view intersections (*Mean difference*=-0.09, *SE*=0.13, and *p*=0.9158). This finding is noteworthy as drivers' risk of crash or near-crash may increase as the TTC decreases, particularly, pertaining to the use of RICWS signs at clear view intersections with a higher level of traffic volume.

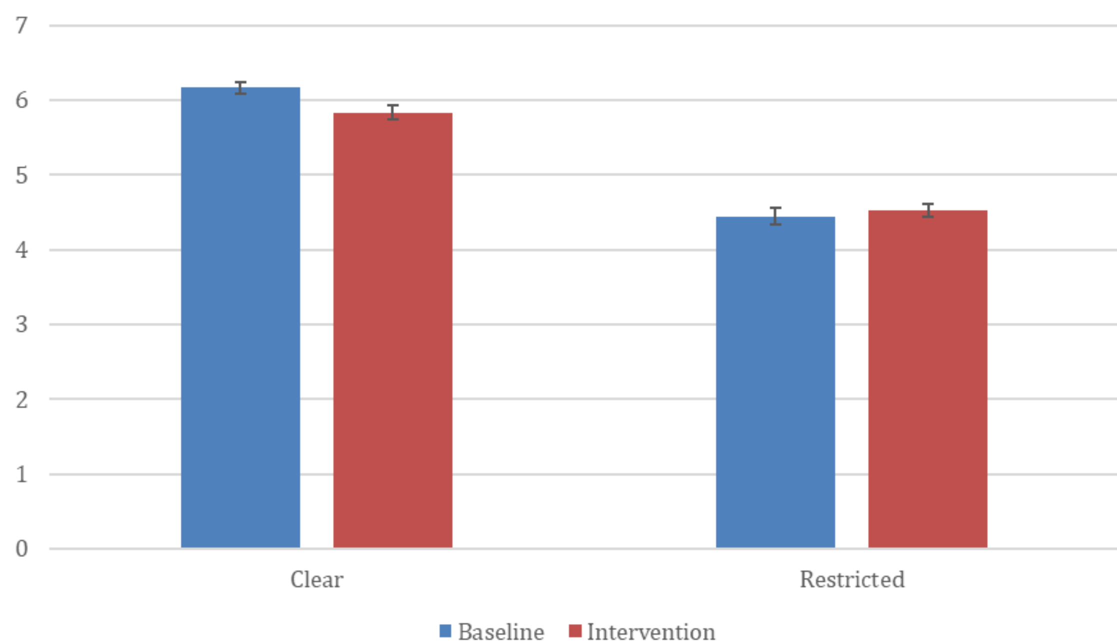


Figure 3.10 The effect of RICWS intervention on the absolute TTC by visibility under moderate traffic volume

Neither the overall intervention effect nor the sign specific effect was significant on the absolute TTC under the low traffic volume condition (*Overall Mean*=8.73, *SE*=0.15 for Baseline, and *Overall Mean*=8.65, *SE*=0.16 for Intervention, respectively). Except for Sign G, drivers experienced a slightly lower absolute TTC in the intervention condition compared to baseline. With respect to the age differences, whereas a greater absolute TTC was detected among both teenage drivers and middle-aged drivers, older drivers exhibited a significantly lower absolute TTC when driving with the RICWS intervention (M=8.28, SE=0.26) than driving without it (M=9.35, SE=0.27; Mean difference=1.07, SE=0.31, and p=0.0087). Within either the teenage driver group or the middle-aged driver group, the comparison between baseline and intervention was nonexistent. As illustrated in Figure 3.11, for middle-aged drivers, M=8.37, SE=0.23 at baseline and M =8.97, SE=0.26 in the intervention condition. For teenage drivers, M=8.47, SE =0.25 at baseline and M =8.73, SE=0.27 in the intervention condition. Because the average absolute TTC was well above the threshold of the critical gap of 6.5s under all driving conditions, the measurement of average absolute TTC might act as a less reliable predicator of drivers' actual risks under the low traffic condition. A scrutinized examination of the most critical events deemed further consideration.

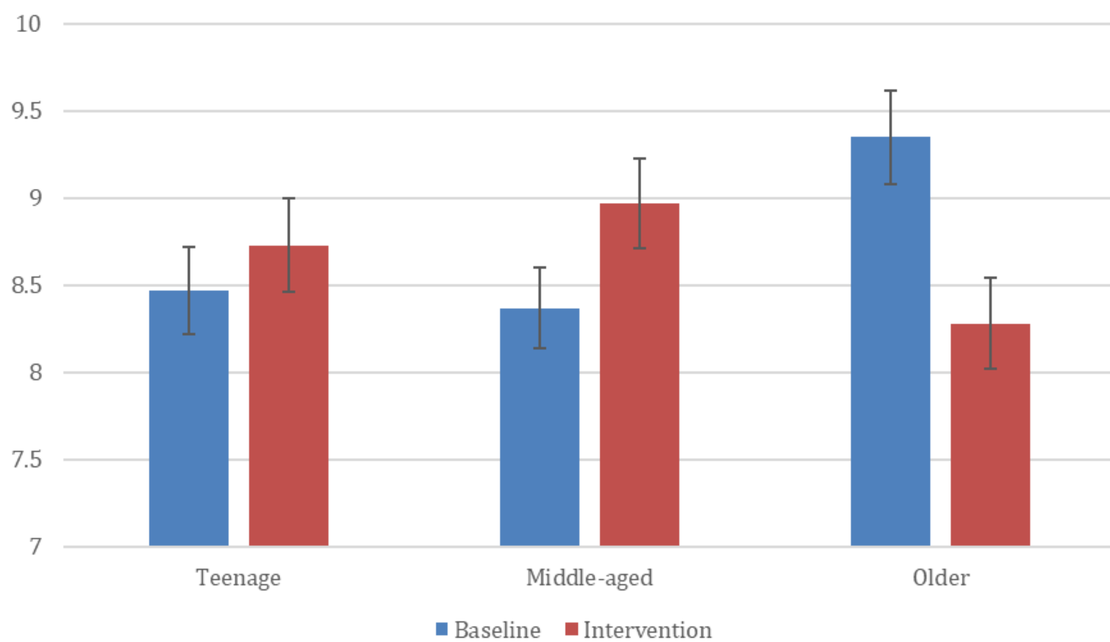


Figure 3.11 The effect of RICWS intervention on the absolute TTC by age group under low traffic volume

Unlike the moderate traffic volume condition, the intervention was not found to significantly affect the absolute TTC outcome under the low traffic volume condition, regardless of any visibility level. However, the overall trend was consistent with the moderate traffic volume condition, where drivers in general experienced an overall greater absolute TTC at clear view intersections (M=9.84, SE=0.15) than at restricted view intersections (M=7.59, SE=0.18*; Mean difference*=2.25, SE=0.23, p<0.001) under the low traffic volume condition.

3.3.2.3 Rejected Critical Gap

Using a similar approach, all rejected gaps by drivers were submitted to a series of log binomial regression models to estimate the risk of rejecting a critical gap versus a non-critical gap. The result of the overall comparison between intervention and baseline was not significant (RR=1.03, 95% CI=0.95-1.12, p=0.4527, Risk=0.54 for baseline and Risk=0.56 for intervention, respectively). However, it is noteworthy that Sign C and Sign G not only increased the proportions of rejected critical gaps, but also simultaneously increased the proportions of rejected non-critical gaps (See Figure 3.12). This trend was reversed for Sign B and Sign F, though. Likewise, although the estimated risk of having rejected critical gaps slighted increased, there were no observed significant main effects or moderation effects by any of the sign options, driver age group or visibility of the intersection (See Figure 3.13).

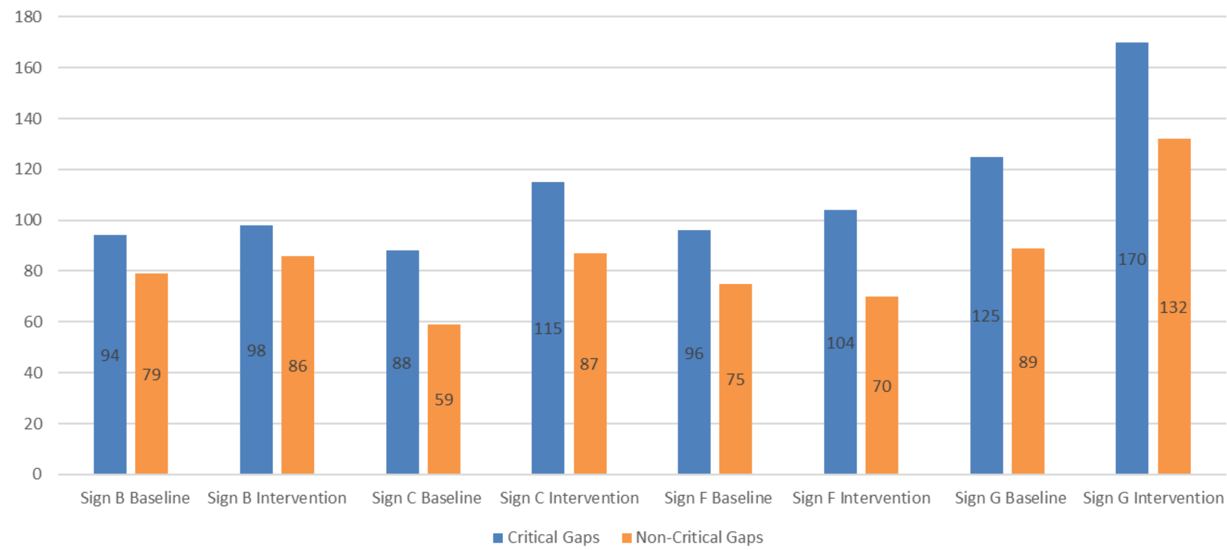


Figure 3.12 The frequency of drivers' rejected gaps under the moderate traffic volume condition by sign option

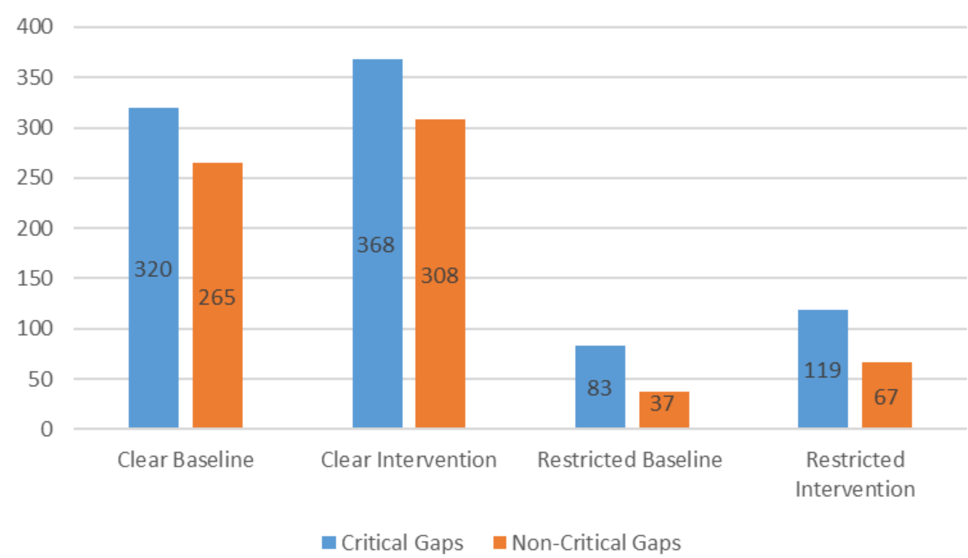


Figure 3.13 The frequency of drivers' rejected gaps under the moderate traffic volume condition by visibility

Similarly, when presented with restricted view intersections, drivers were more likely to exhibit more conservative decision-making in terms of rejecting more non-critical gaps. Moreover, although the relative risks were not significant among all age groups, older drivers appeared to more frequently reject non-critical gaps (i.e., 250 (66.7%) for intervention compared to 174 (57.6%) for baseline), which may indicate less efficient use of the signs at intersections with restricted visibility (See Figure 3.14). To provide a more comprehensive understanding of how the RICWS intervention separately influenced drivers' rejection of critical and non-critical gaps, the number of rejected critical gaps as well as drivers' actual responses towards non-critical gaps were included in the following analyses.

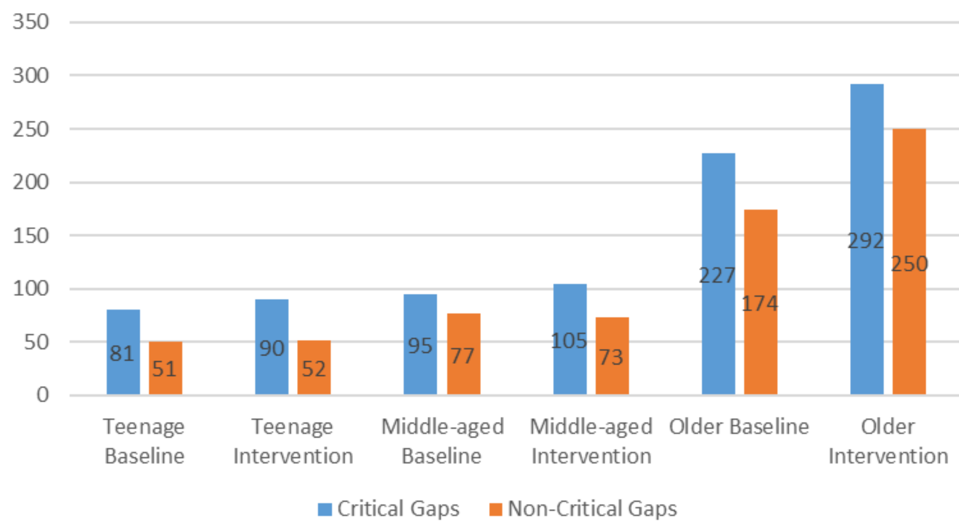


Figure 3.14 The frequency of drivers' rejected gaps under the moderate traffic volume condition by age group

3.3.2.4 Number of rejected critical gaps

Because no significant effects were detected for reducing drivers' risks of rejecting critical gaps, researchers further examined how the number of rejected critical gaps would have been changed as a result of the RICWS intervention. As shown in Figure 3.15, drivers were overall found to reject more critical gaps when the intervention was presented. Specifically, there was a significant effect of the intervention on increasing the number of rejected critical gaps within the Sign G group (exp(β)=1.36, 95% CI=1.05-1.77, *p*=0.0210).

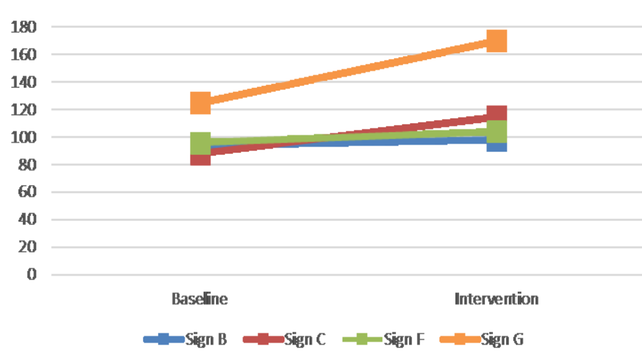


Figure 3.15 Number of rejected critical gaps under the moderate traffic volume by sign option

With respect to the moderation effect of visibility, a significant difference was only found at restricted view intersections (exp(β)=1.56, 95% CI=1.02-2.39, *p*=0.0419), but not at clear view intersections (See Figure 3.16).

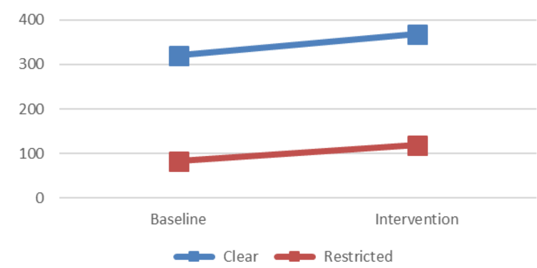


Figure 3.16 Number of rejected critical gaps under the moderate traffic volume by sign option by visibility

As illustrated in Figure 3.17, although drivers of all age groups tended to reject more critical gaps when driving with the intervention, a significant difference was measured only for older drivers (exp(β)=1.40, 95% CI=1.03-1.90, *p*=0.0265). Negative binomial regressions were used for obtaining all point estimates and 95% CIs in a log scale with no offsets.

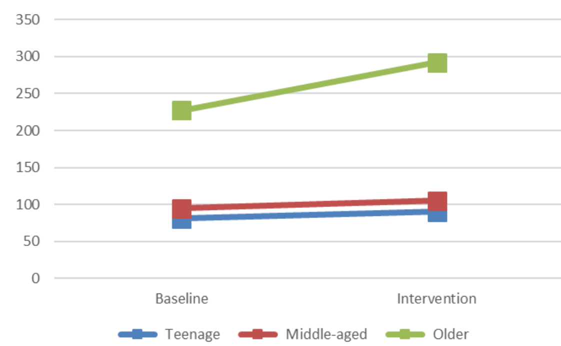


Figure 3.17 Number of rejected critical gaps under the moderate traffic volume by age group

3.3.2.5 Rejected non-critical gaps

This outcome measures drivers' decision of whether to reject or accept a non-critical gap when they were presented with one. Overall, significant effect of the intervention on the risk of rejected non-critical gaps was non-existent (RR=0.99, 95% CI=0.89-1.10, *p*=0.8436).

Notably, however, older drivers exhibited a 1.1 times greater risk of rejecting non-critical gaps than accepting them when driving under the intervention condition compared to the baseline condition (95% CI=1.01-1.21, *p*=0.0369). A similar trend was also presented for the stratum of restricted visibility, yet the result was not significant. Figure 3.18 summarizes the results of drivers' risk of rejecting a non-critical gap under moderate traffic volume by age group.

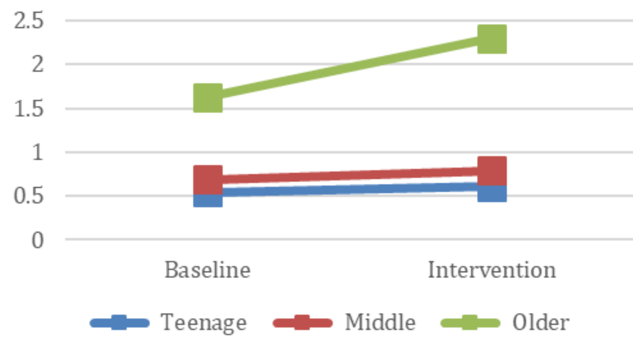


Figure 3.18 Risk of rejecting a non-critical gap under moderate traffic volume by age group

3.3.2.6 Total Wait Time

Because drivers waited for a very short time at intersections with low traffic volume and the effect of the intervention was not significant, only the moderate traffic volume condition was considered for this outcome. There was an overall significant main effect of the intervention on keeping drivers waiting for a slightly longer time at the stopping line (rate ratio=1.25, 95% CI=1.02-1.52, *p*=0.0313, with an estimate of 3.36s in the intervention condition compared to 2.69s at baseline) when a moderate level of traffic was presented on the main road. Among all four sign options, Sign F had the smallest difference of wait time between the intervention and baseline. Not surprisingly, the rate ratios were greater for Sign C and Sign G options, which were consistent with the results of gap acceptance performance that drivers were prone to reject more gaps prior to making their final decisions to cross. The only significant result regarding the variable of sign option was Sign G, with a rate ratio being equal to 1.43, 95% CI=1.12-1.80, *p*=0.0036. The results of wait time using negative binomial regressions to control for over dispersion of data by sign option, visibility, and age group are shown in corresponding figures (see Figure 3.19) as follows.

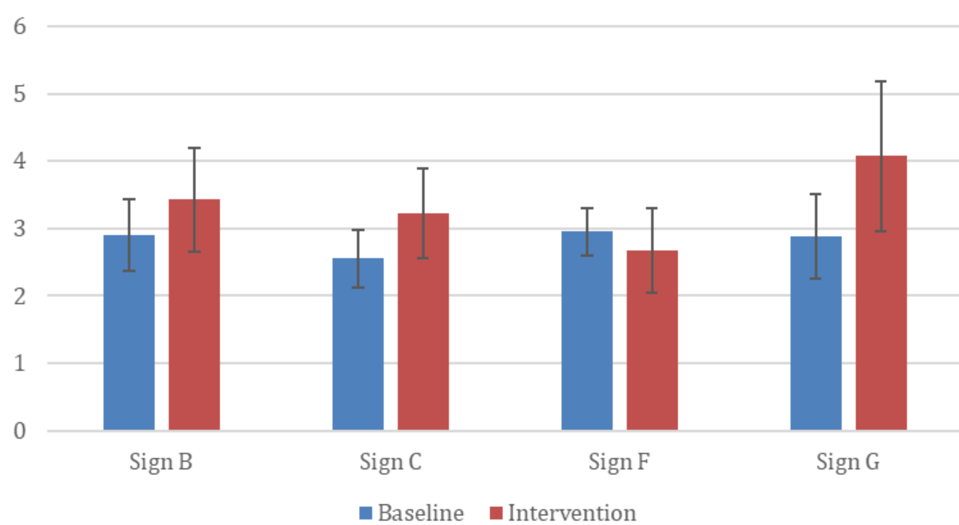


Figure 3.19 Total wait time (in second) with standard errors under moderate traffic volume by sign option

Unexpectedly, drivers in general experienced much longer wait times at clear view intersections than restricted view intersections especially at baseline. This was likely due to their limited capabilities of developing accurate perceptions of the gap size and therefore were more inclined to proceed into the intersection earlier when sufficient gaps were not yet visible (see Figure 3.20). However, by providing more meaningful traffic information, the presence of RICWS signs appeared to have a greater potential in encouraging drivers to be more cautious and patient in crossing restricted view intersections (rate ratio=1.92 in reference to the baseline condition, 95% CI=1.35-2.72, p=0.0003).

Furthermore, older drivers, on average, spent the longest time waiting at the rural thru-STOP intersections, followed by middle-aged drivers and novice teenage drivers, regardless if the intervention was present or not (see Figure 3.21). The results also revealed a significant increase in the wait time for older drivers, potentially indicating that they might have experienced more difficulty driving with the signs due to various reasons, such as longer response time, longer processing time of sign messages, failure to make the crossing maneuver in time for a sufficient gap, etc.

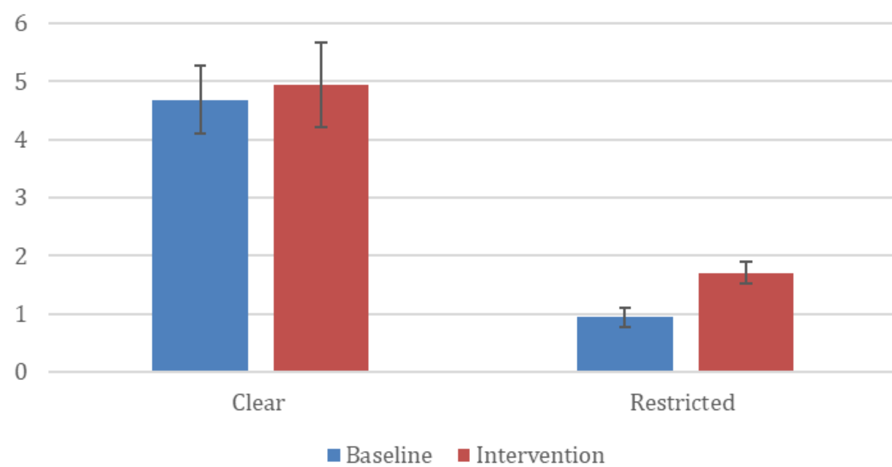


Figure 3.20 Total wait time (in second) with standard errors under moderate traffic volume by visibility

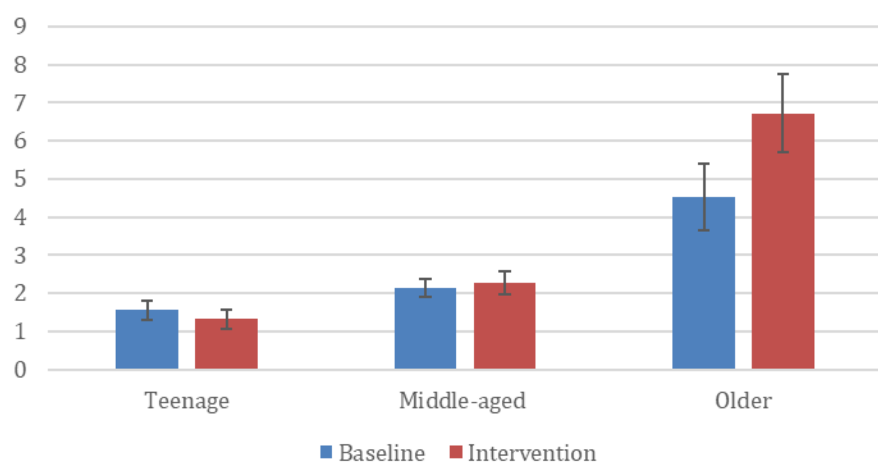


Figure 3.21 Total wait time (in second) with standard errors under moderate traffic volume by age group

3.3.2.7 Stop Sign Violation

Due to the limited occurrences of stop sign violations (i.e., less than 5 observations for each of the sign options) under the condition of moderate traffic volume, this measurement was only evaluated for the level of low traffic volume. A higher frequency of stop sign violation behaviors was detected for all sign options in the intervention condition (See Figure 3.22). It was also revealed that the RICWS intervention had an overall significant effect on increasing the risks of stop sign violations. Among all sign options, the most remarkable impact was found to be Sign C, in which this group's drivers were 2.18 times more likely to be involved in a stop sign violation when driving with the intervention compared to the baseline (RR=2.18, 95% CI=1.03-4.65, p=0.0424), see Figure 3.23.

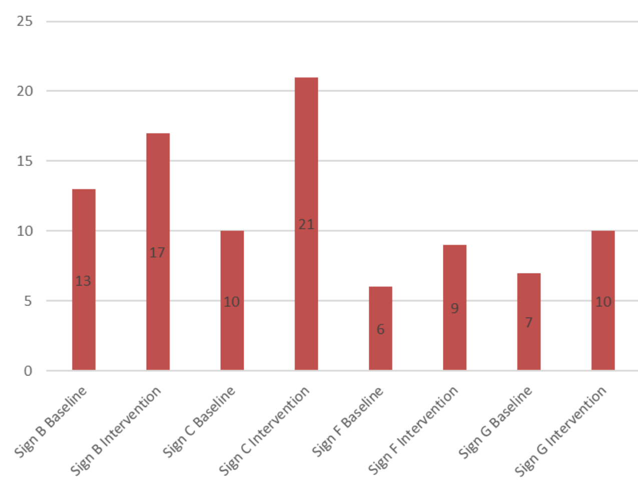


Figure 3.22 Frequency of stop sign violation behaviors under the low traffic volume by sign option

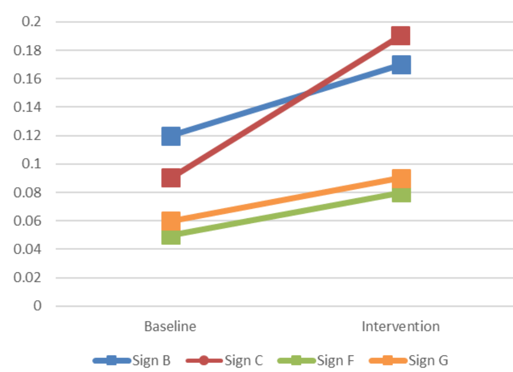


Figure 3.23 Risk of stop sign violation behaviors under the low traffic volume by sign option

The results also indicated elevated risks with the presence of the intervention within each stratum of visibility (See Figure 3.24 and Figure 3.25). In particular, clear visibility intersections had a significantly higher probability to incur stop sign violations (RR=1.62, 95% CI=1.05-2.50, p=0.0297), whereas the result was at borderline significant for restricted view intersections (RR=1.71, 95% CI=1.00-2.92, p=0.0506).

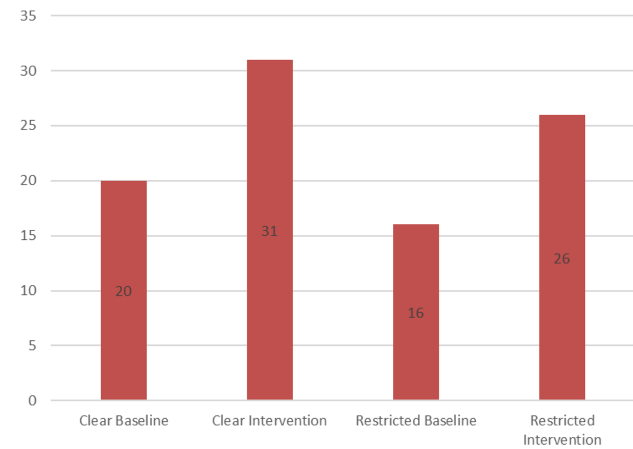


Figure 3.24 Frequency of stop sign violation behaviors under the low traffic volume by visibility

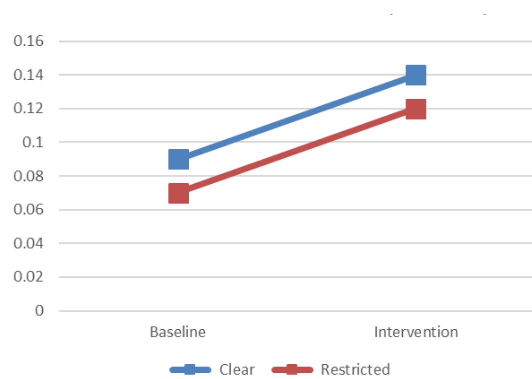


Figure 3.25 Risk of stop sign violation behaviors under the low traffic volume by visibility

Although age group appeared to effect the risk of violating stop signs differently, with teenage drivers demonstrating more frequent stop sign violations compared to their older counterparts, none of these stratum specific effects were significant due to wide CIs (see Figure 3.26 and Figure 3.27).

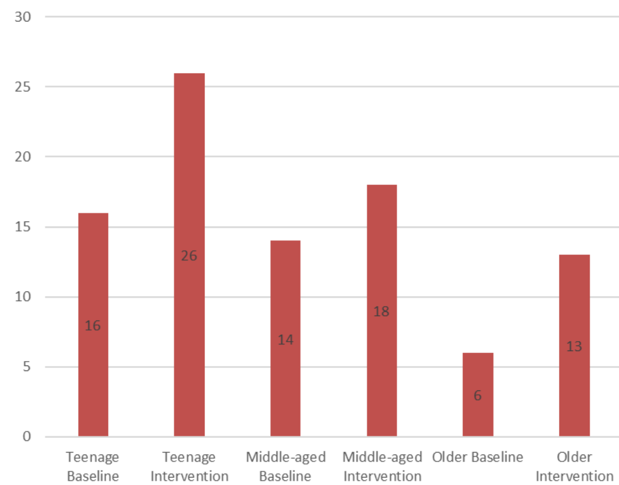


Figure 3.26 Frequency of stop sign violation behaviors under the low traffic volume by age group

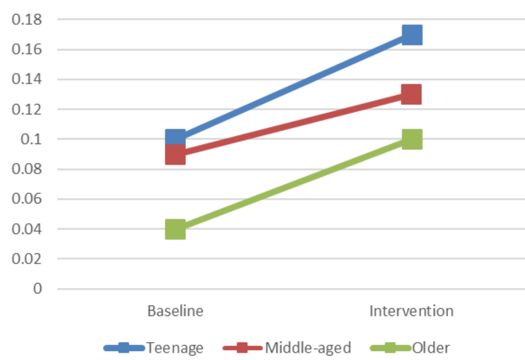


Figure 3.27 Risk of stop sign violation behaviors under the low traffic volume by age group

Furthermore, a separate analysis of the stop sign violation outcome was performed to involve intersections at which the signs failed to function properly (i.e., with the "sign-off" state). Each of the "sign-off" intersection was matched with two baseline intersections (i.e., no sign presented) and two intervention intersections (i.e., sign functioning) with identical characteristics of low traffic volume and clear visibility. As illustrated in Figure 3.28, the effect of sign functionality on stop sign violations was examined by aggregating data across all levels of other exposures.

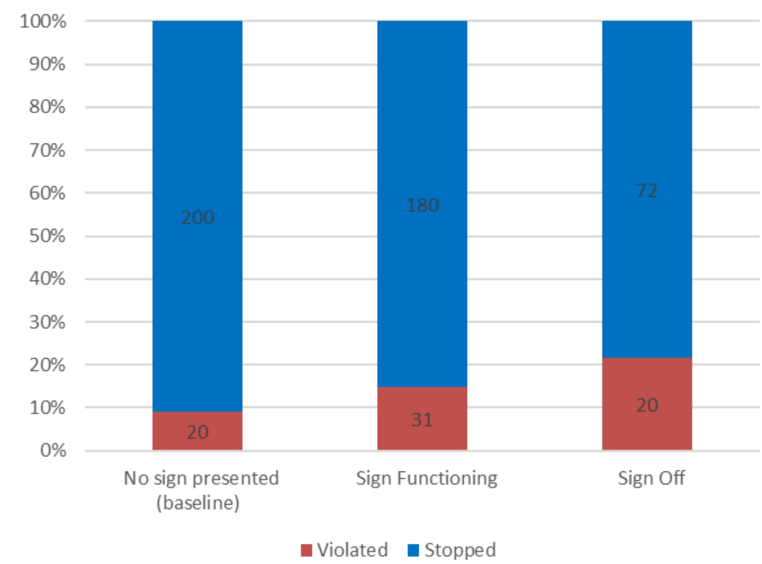


Figure 3.28 The frequency and proportion of stop sign violation behaviors by sign functionality

Compared to the baseline condition, it was consistent with previous analysis that drivers were more prone to violate stop signs with the presence of a functioning sign (RR=1.62, 95% CI=1.05-2.51, *p*=0.0283), however, this effect was more predominant if the intervention malfunctioned (RR=2.34, 95% CI=1.09-3.94, *p*=0.0014) (See Figure 2.1Figure 3.29 for estimated risks within the three groups, respectively). The result further implied that some drivers might have a problem in interpreting the blank-out state of the system, such as perceiving it as “safe to cross”, and therefore increased the risk of violating a stop sign (see Figure 3.29). The effects of Sign Option and Age were not investigated due to limited prevalence of violated behaviors for each stratum.

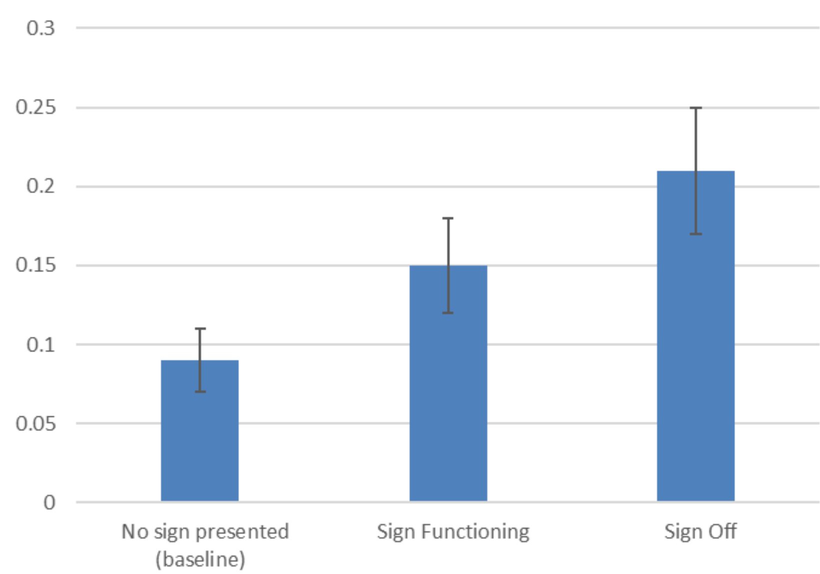


Figure 3.29 Risk of stop sign violation behaviors by sign functionality (with standard errors)

3.3.2.8 Average approaching speed

The effects of the intervention on participants' average approaching speed (i.e., speed in miles per hour (mph)) were investigated under both conditions of moderate traffic volume and low traffic volume. For moderate traffic volume, there was either no significant overall or individual effect of the intervention for any of the sign option, neither the visibility of the intersection would affect average approaching speed. In contrast, under the condition of low traffic volume, Sign B and Sign C significantly elevated the average speed of the participant's vehicle when approaching to the intersection (*Mean difference*=1.29, *SE*=0.54, *p*=0.0401 for Sign B and *Mean difference*=1.03, *SE*=0.44, *p*=0.0217 for Sign C) (See Figure 3.30).

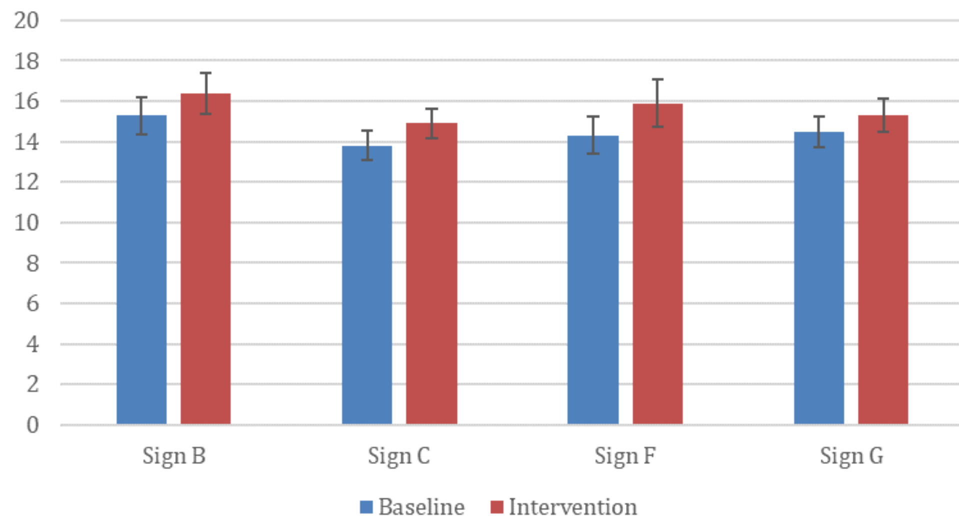


Figure 3.30 Average approaching speed under the low traffic volume by sign option

As illustrated in Figure 3.31, drivers in general were more inclined to travel at a significantly greater approaching speed with low mainstream traffic volume, regardless if the visibility was clear or restricted. The average approaching speed was 15.8 mph (*SE*=0.50) in the intervention condition compared to *M*=14.3 (*SE*=0.46) at baseline for clear view intersections. Consistently, a significantly greater average approaching speed was found when the visibility was restricted when comparing intervention (*M*=15.4, *SE*=0.53) to baseline (*M*=14.5, *SE*=0.46).

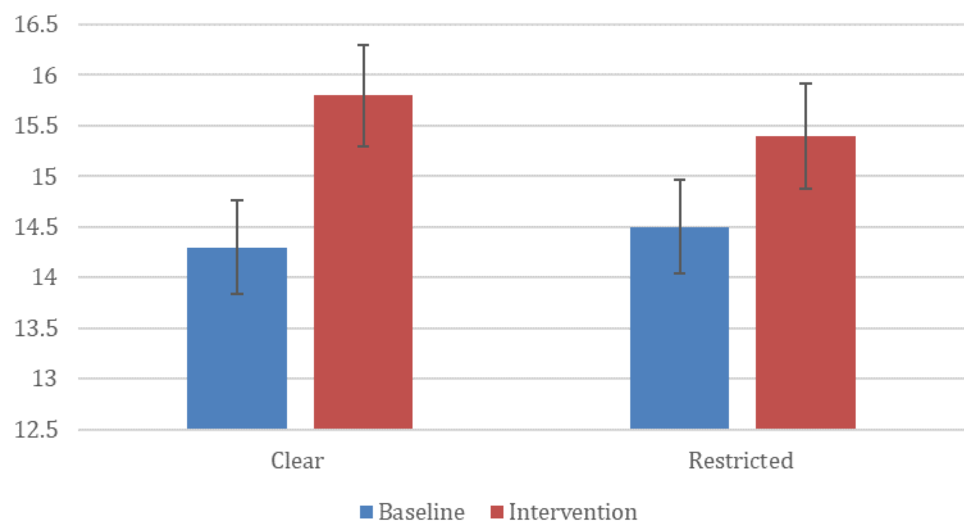


Figure 3.31 Average approaching speed under the low traffic volume by visibility

Consistent results were found for both levels of traffic volume that the average approaching speed was significantly elevated with the middle-aged drivers (See Figure 3.32: *Mean difference*=1.54, *SE*=0.47, *p*=0.0071 for moderate traffic volume condition; See Figure 3.33: *Mean difference*=1.46, *SE* =0.36, *p*=0.0007 for low traffic volume condition, respectively). Not surprisingly, older drivers in general exhibited more conservative driving habits when approaching to the intersections, reflected by much slower average approaching speeds compared to those for teenage and middle-aged drivers, at either baseline or intervention, for both traffic volume conditions. Tukey adjustments were adopted for all pairwise comparisons.

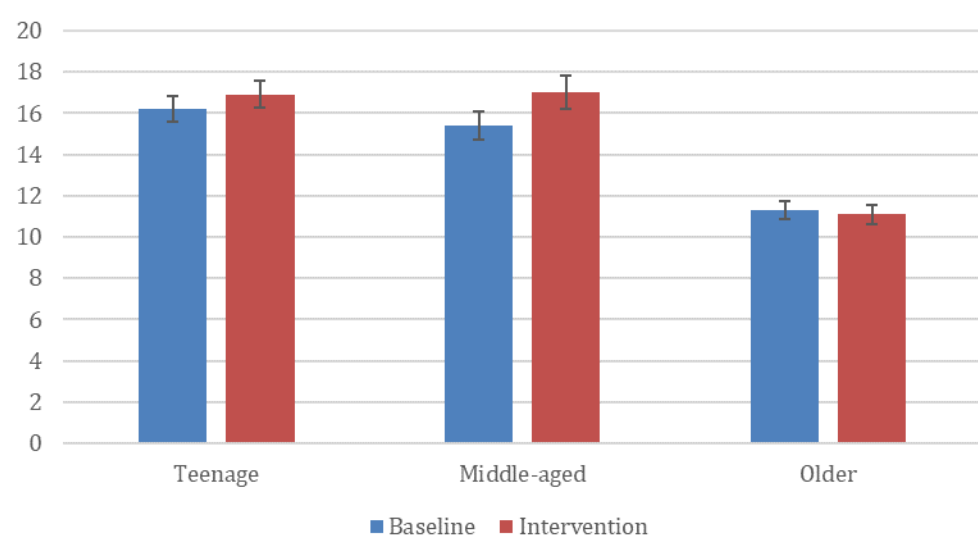


Figure 3.32 Average approaching speed under the moderate traffic volume by age group

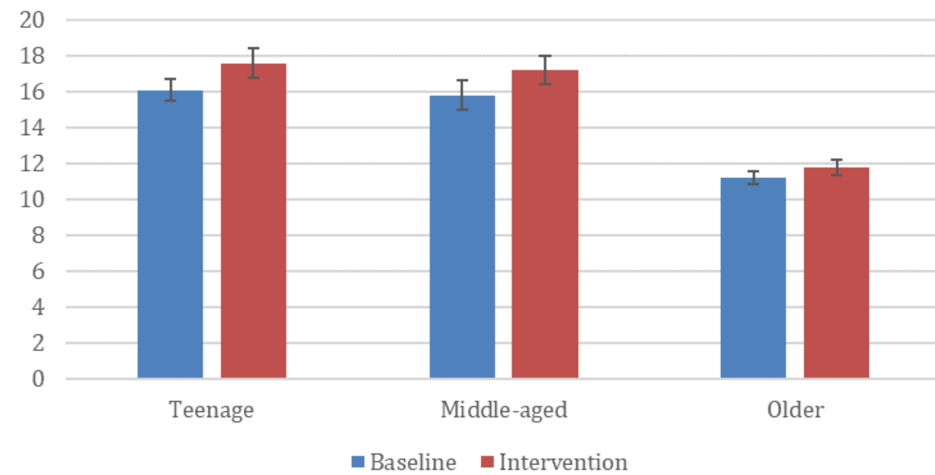


Figure 3.33 Average approaching speed under the low traffic volume by age

3.3.2.9 Average crossing speed

Drivers' average crossing speed was also significantly affected by the RICWS intervention, yet the effect was not significant regarding any specific sign option. Unlike the overall trend of the average crossing speed, older drivers exhibited slightly faster speeds upon travelling through the rural intersections for both baseline and intervention conditions, compared to the other two age groups. However, the results only indicated significant difference of the average crossing speed between the intervention and baseline for middle-aged drivers (*Mean difference*=0.45, *p*=0.0135), but not for teenage drivers and older drivers (See Figure 3.34). Moreover, an elevated average crossing speed was exhibited in either the stratum of clear visibility (*Mean difference*=0.28, *p*=0.0133) or restricted visibility (*Mean difference*=0.33, *p*=0.0111) (See Figure 3.35). There were no significant intervention or moderation effects under the driving condition of low traffic volume.

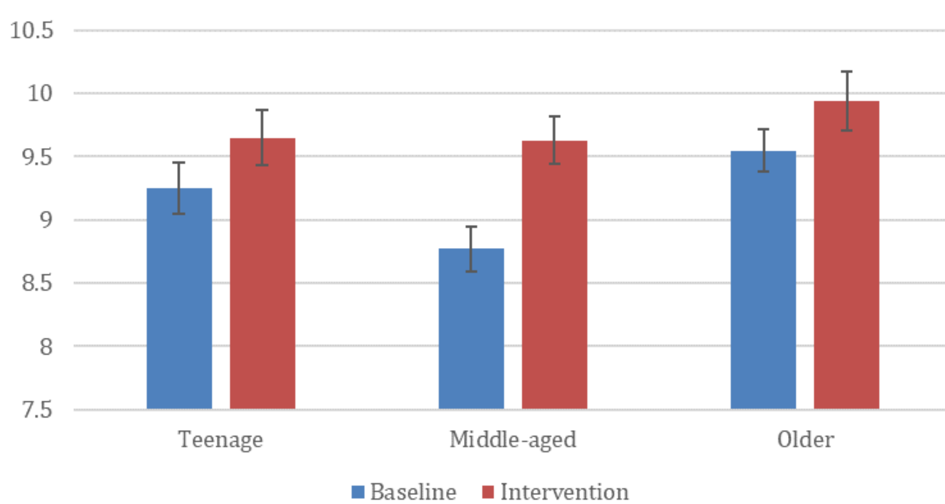


Figure 3.34 Average crossing speed under the moderate traffic volume by age group

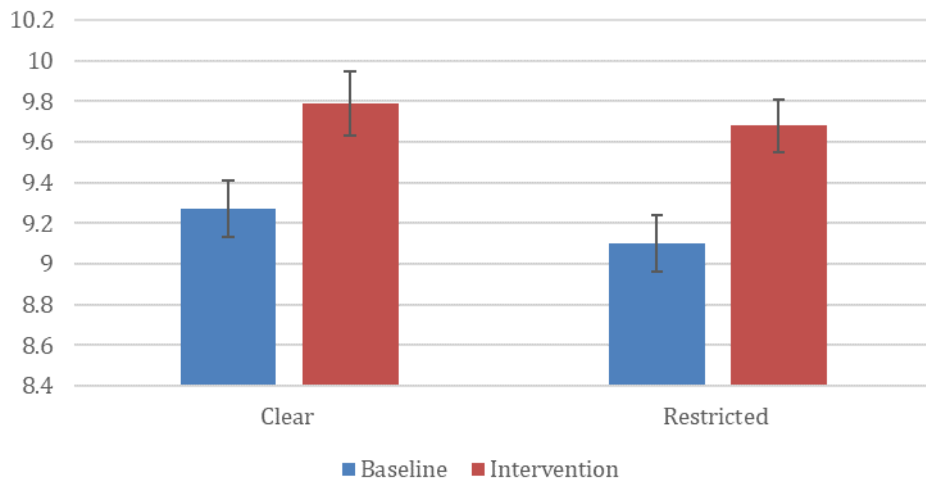


Figure 3.35 Average crossing speed under the moderate traffic volume by visibility

3.3.2.10 Average crossing acceleration

Consistent with the previous driving performance results, the presence of the intervention also slightly increased the average acceleration rate (i.e., mi/(h*s)) of the participant's own vehicle when crossing the intersection. In particular, this intervention effect was found to be the most apparent for Sign G, compared to other sign options (*Mean difference*=0.81, *p*=0.0061). The moderation effect of visibility on the average crossing acceleration was in accordance with that of the average crossing speed, with the mean difference being slightly greater in restricted view (*Mean difference*=0.58) than in clear view (*Mean difference*=0.52). For each stratum of visibility, the comparison between intervention and baseline was significant (*p*=0.0026 and *p*=0.0006, respectively). Likewise, older drivers in general established a greater acceleration rate than teenage drivers and middle-aged drivers, and the trend was consistent for both baseline and intervention conditions. However, the effect of the intervention was only found to be significant among middle-aged drivers (*Mean difference*=0.86, *p*=0.0003). Figure 3.36 to Figure 3.38 summarize the results of the average crossing accelerate rate under moderate traffic volume by sign option, visibility and age group, respectively.

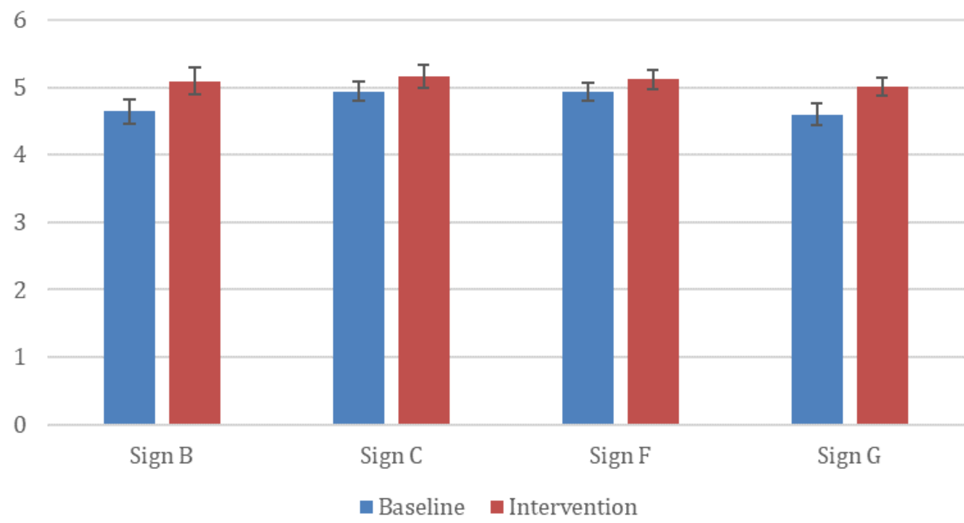


Figure 3.36 Average crossing acceleration under the moderate traffic volume by sign option

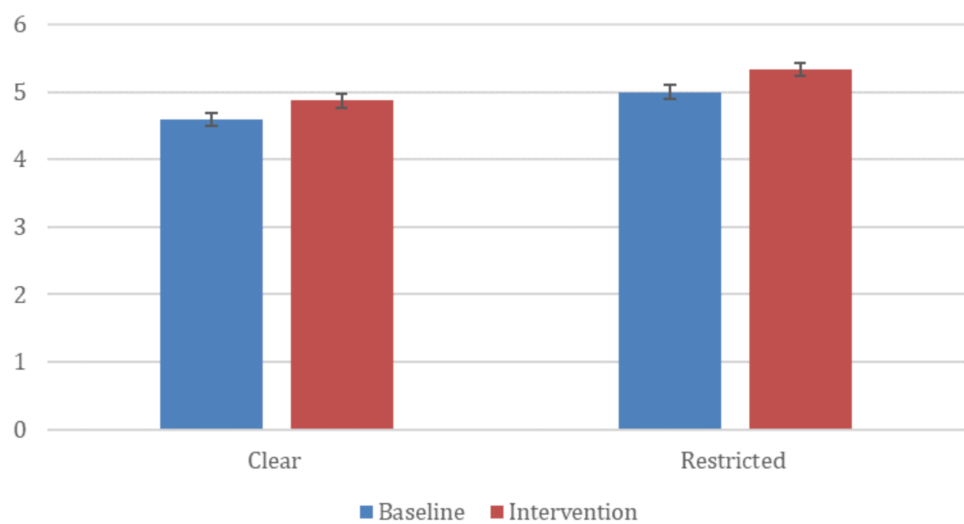


Figure 3.37 Average crossing acceleration under the moderate traffic volume by visibility

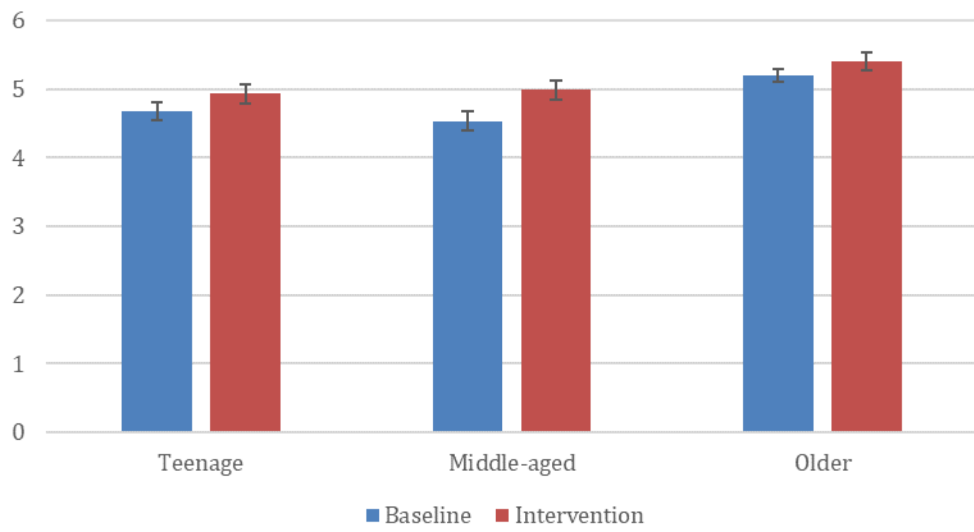


Figure 3.38 Average crossing acceleration under the moderate traffic volume by age group

3.3.3 Driving Performance Results Discussion

The analyses of driving performance results revealed the potential benefits of deploying RICWS interventions at rural thru-STOP intersections, as well as identified the associated risks with the use of the systems in the following:

Potential benefits:

- Sign B and Sign C (at borderline) significantly reduced the risks of drivers' acceptance of critical gaps and shifting their decision making towards accepting more non-critical gaps under the moderate traffic volume condition.
- Sign G significantly increased the rate of rejected critical gaps, while this was not observed for other signs. Drivers perceived Sign G to have a significant positive effect on reducing their visual demand and improving their overall driving performance.
- Drivers' gap acceptance performance tended to be significantly enhanced by the intervention (i.e., any sign type) at restricted viewed intersections.
- The sign intervention demonstrated the most safety potentials to improve their gap acceptance performance for experienced, middle-aged drivers.

Associated risks:

- Drivers were in general more prone to experience a significantly reduced absolute TTC with the intervention at clear view under the moderate traffic volume condition.
- Drivers were less likely to comply with stop signs when driving with the intervention at clear view intersections and this adverse consequence was the most salient for the original RICWS sign (i.e., Sign C) under the low traffic volume condition.

- The risk of stop sign violations was found to be the greatest when the system malfunctioned (i.e., “sign-off” state).
- Drivers, particularly within the middle-aged group, were more prone to approach the stop bar/line at a greater speed (e.g., Sign B and Sign C under low traffic volume), drive through the line much faster and accelerate more harshly through the intersection with the presence of the intervention. Consistently, middle-aged drivers also reported significantly higher levels of temporal (time) pressure at the intersections.
- Teenage drivers did not appear to be significantly assisted by the intervention in objective driving performance; however, they reported that the intervention had significantly improved their overall driving performance.
- Older drivers demonstrated less efficiency in using the system, in terms of more frequent rejections to non-critical gaps that they should have accepted them at the first place.

3.4 SUBJECTIVE MEASURES RESULTS AND DISCUSSION

3.4.1 Subjective Measures Results

Drivers’ subjective measures consisted of self-reported mental workload on performing the driving tasks, trust in the system, as well as their overall sign preferences. For mental workload, the effect of the intervention was obtained within each sign group as well as each stratum of driver’s age groups. For assessments of drivers’ perceived trust and overall sign preferences, only the main effects of Sign and Age were available.

3.4.1.1 Mental Workload

Mental workload was assessed with the NASA RTLX Mental Workload Questionnaire (see Appendix J). It contains seven main constructs of mental workload including: Mental Demand, Physical Demand, Visual Demand, Time Pressure, Performance, Overall Effort, and Frustration. Each construct was analyzed separately.

MENTAL DEMAND

Drivers on average perceived lower mental demands when driving under the intervention condition across all sign options (OR=0.79, 95% CI=0.65-0.97, *p*=0.0209). The stratum specific comparisons between the intervention and baseline was only significant for Sign F (OR=0.75, 95% CI=0.57-0.96, *p*=0.0368). With respect to the effect of age, it generally demanded slightly more mental effort for older drivers (*M*=3.08, *SD*=1.11) to perform the driving tasks than teenage drivers (*M* =2.81, *SD*=0.96) and middle-aged drivers (*M* =2.51, *SD*=1.18), averaging across the baseline and intervention conditions. Specifically, the odds of having a high rating scale for mental demand with the presence of the intervention was 0.59 times lower than that under the baseline driving condition (OR=0.59, 95% CI=0.41-0.84, *p*=0.0035).

PHYSICAL DEMAND

Drivers' subjective ratings on their physical demand were not significantly affected by any of the sign options. The overall difference of the rating scale was very minimal between baseline (*M*=1.69, *SD*=0.93) and intervention (*M*=1.68, *SD* =0.86). Similarly, middle-aged drivers (*M*=1.34, *SD* =0.63) perceived the least overall physical effort compared to teenage drivers (*M*=1.49, *SD*=0.75) and older drivers (*M*=2.23, *SD* =1.02) in general. The odds were 7.29 times greater for an older driver to have a higher physical demand rating compared to a middle-aged driver (OR=3.19-16.67, p<0.0001). However, the intervention did not seem to significantly influence the ratings of physical demand within any stratum of the three age groups.

VISUAL DEMAND

A significant overall effect was revealed for intervention on reducing drivers' perceived visual demand for performing all driving tasks (OR=0.59, 95% CI=0.48-0.74, p<0.0001). All comparisons of ratings between intervention and baseline were significant for all sign options, except for Sign B. Likewise, older drivers appeared to have the highest visual demand rating, followed by teenage drivers and middle-aged drivers. The trend was consistent for both conditions of baseline and intervention. For all age groups, drivers' self-reported visual demand was significantly reduced by the intervention.

TEMPORAL PRESSURE

Overall drivers experienced relatively low levels of temporal (time) pressure throughout the experimental drives. There were no significant results detected for any of the four sign options. In general, older drivers (*M*=1.73, *SD*=0.87) were more likely to perceive a higher level of temporal pressure compared to teenage drivers (Mean=1.40, *SD*=0.73) and middle-aged drivers (*M* =1.21, *SD* =0.56). Noticeably, the ratings of drivers' temporal pressure only seemed to be significantly elevated by the intervention for middle-aged drivers (OR=1.76, 95% CI=1.07-2.89, p=0.0259).

PERFORMANCE

Drivers were more likely to report an improved overall performance with the presence of the RICWS intervention (OR=1.44, 95% CI=1.19-1.75, p=0.0002). Specifically, drivers within the Sign F group (OR=2.26, 95% CI=1.43-3.58, p=0.005) and the Sign G group (OR=1.58, 95% CI=1.16-2.16, p=0.0041) had significantly higher odds of perceiving better performance under the intervention condition. It was also noteworthy that, unlike other self-reported mental workload measures, teenage drivers and middle-aged drivers on average self-reported better performance than did older drivers. Although teenage drivers perceived that their driving performance had been significantly enhanced in the intervention drives (OR=1.67, 95% CI=1.15-2.41, p=0.0067), their perception did not match the results of their actual driving performance, as were observed in previous analyses.

OVERALL EFFORT

Drivers' perceived level of overall effort was negatively affected by the intervention, with an average rating scale of 2.14 (*SD*=1.07) at baseline and 1.97 (*SD*=1.03) under the intervention condition (OR=0.72, 95% CI=0.60-0.88, *p*=0.0011). Specifically, drivers were more likely to report less overall effort with the assistance of the Sign C (OR=0.69, 95% CI=0.52-0.91, *p* =0.0087) and Sign F (OR=0.64, 95% CI=0.44-0.92, *p*=0.0164). Although drivers of all age groups tended to report lower overall effort when comparing the intervention and baseline conditions, the result was only significant among middle-aged drivers (OR=0.60, 95% CI=0.43-0.84, *p*=0.0033). Consistently, middle-aged drivers, on average, had the lowest ratings of perceived overall effort throughout all drives.

FRUSTRATION

Drivers generally reported relatively low levels of frustration in performing the driving tasks. Although the rating scales slightly decreased across all sign options and age groups, no significant overall or stratum specific effect existed.

3.4.1.2 Perceived Trust

To evaluate drivers' trust in the system, all responses were further categorized into four ordered ranks, with the cut-off values being the 25th, 50th and 75th quantiles of the score for each individual survey question. For all survey questions (See Appendix B), none of the results were significant when comparing across levels of quantiles between either two sign options. Specifically, detailed results of the effects of age group were presented as below:

Question 1: The performance of the system enhanced my driving safety

Drivers in general agreed that their driving performance was enhanced by the system, with an average rating score of 63.0% (*SD*=25.3%), based on a scale of 0-100 percent. Regarding the effect of age, older drivers overall reported a higher level of trust in the safety effectiveness of the system (*M*=2.44, *SD* =1.17), compared to teenage drivers (*M*=2.20, *SD* =1.07) and middle-aged drivers (*M*=1.93, *SD* =1.15). In particular, the odds of reporting a higher level of agreement that the system enhanced safety performance among older drivers was 2.42 times greater than that of middle-aged drivers (OR=2.42, 95% CI=1.04-5.60, *p*=0.0397). Teenage drivers did not significantly differ from middle-aged drivers or older drivers, in their perceived trust in the safety aspect of the system.

Question 2: I am familiar with the operation of the system

Overall, drivers reported a relatively high level of trust in their familiarity with the operation of the system after the experiment (*M*=81.4%, *SD*=24.9). The only borderline significant effect was in the comparison between older drivers (*M*=2.23, *SD*=0.84) and teenage drivers (*M*=1.85, *SD*=0.86), where older drivers were 2.23 times more likely to rank a higher quantile of agreement for Question 2 than teenage drivers (OR=2.23, 95% CI=0.99-5.06, *p*=0.0541). Middle-aged drivers (*M*=2.12, *SD*=0.90) also indicated greater familiarity with the system's operation than teenage drivers, yet the result was not significant. Three categories were generated for this analysis since the 75th quantile was equivalent to the 100th quantile (i.e., 100% strongly agree).

Question 3: I trust the system

The average rating of drivers' trust in the system was 70.8% with a SD of 26.1%. Based on the categorized data, it was not surprising that teenage drivers (*M*=2.63, *SD*=1.17) tended to perceive a significantly higher level of overall trust in the system compared to middle-aged drivers (*M*=2.12, *SD*=1.12) and older drivers (*M*=2.05, *SD*=1.00). The odds of having a higher agreement of reported trust among teenage drivers was 2.50 times greater than that of older drivers (OR=2.50, 95% CI=1.13-5.53, *p*=0.0233), and was 2.34 times greater than that of middle-aged drivers (OR=2.34, 95% CI=1.02-5.32, *p*=0.0436).

Question 4: The system is reliable

Overall, drivers reported a moderate level of trust in the reliability of the system (*M*=69.6%, *SD*=25.4). Similarly, teenage drivers (*M*=2.45, *SD*=1.15) generally perceived the system to be more reliable than middle-aged drivers (*M*=2.05, *SD*=1.07) and older drivers (*M*=1.97, *SD*=0.99. The comparison for having higher odds of being in a greater rank was only borderline significant between teenage drivers and older drivers (OR=2.16, 95% CI=0.97-4.80, *p*=0.0585).

Question 5: The system is dependable

Likewise, the effect of age group on drivers' trust in the system's dependability was consistent with that in the previous analysis, with teenage drivers having the highest rank (*M*=2.50, *SD*=1.11), followed by middle-aged drivers (*M*=2.10, *SD*=1.18) and older drivers (*M*=1.90, *SD*=0.94). Teenage drivers were more prone to report a significantly higher dependence on the system, compared to older drivers (OR=2.60, 95% CI=1.20-5.61, *p*=0.0151). The overall average score was 69.0% (*SD*=25.6%) for Question 5 without categorization.

Question 6: The system has integrity

Although teenage drivers demonstrated the highest level of trust in the system's integrity among all three age groups, none of the results were significant (*M*=2.28 and *SD*=1.06 for teenage drivers; *M*=2.22 and SD=1.24 for middle-aged drivers; as well as *M*=2.18 and *SD*=1.12 for older drivers, respectively). Upon averaging across all groups, the mean score for this question was equivalent to 72.3% (*SD*=25.2%).

Question 7: I am comfortable with the intent of the system

Drivers were positive overall regarding the intent of the system, with an average score of 85.5% (*SD*=21.1%). Since the cut-off score for the 50th quantile yielded a high value of 90%, two rather than four categories were generated around the median. The relative risk of having a score within the upper category was calculated in reference to the lower category. Teenage drivers were more likely to feel comfortable with system's intention, followed by middle-aged drivers, and older drivers. However, none of the results were significant.

Question 8: I am confident in my ability to drive the car safely without the system

Not surprisingly, all drivers appeared to exhibit overconfidence in their own abilities to drive the car safely without the assistance of the system (*M*=91.0%, *SD*=15.7). For simplicity, a binary outcome was established with the score being either 100% or not (i.e., 100% was also the 50th quantile of Question 8). No significant results were revealed, except for the comparison between middle-aged drivers and older drivers (OR=1.59, 95% CI=0.99-2.53, *p*=0.0528, borderline significant). Middle-aged drivers were most likely to trust in themselves over the system, compared to teenage drivers, followed by older drivers.

3.4.1.3 Sign Preference

Table 3.2 illustrated the numbers and proportions of participants' rankings on each of the sign options. A weighted score, ranging from one to four, was assigned to each level of the ranks, with the 1st rank representing the highest score. On average, Sign C (M=3.16, SD=1.00) had the highest score, followed by Sign G (M=2.85, SD=1.00), Sign F (M=2.20, SD=1.00) and Sign B (M=1.81, SD=0.96).The results of multinomial logistic regression models indicated that drivers were 1.88 times more likely to rate a higher score on Sign C compared to Sign G (OR=1.88, 95% CI=1.01-3.52, p=0.0478), controlling for the correlations within individual participants. All comparisons between each pair of two adjacent signs were also significant, with an odds ratio equaled to 3.01when comparing Sign G to Sign F (95% CI=1.67-5.44, p=0.0003), as well as an odds ratio of 2.10 when comparing Sign F to Sign B (95% CI=1.14-3.87, p=0.0173). There was no evidence of significant moderation effect of age group on the assessments of drivers' overall sign preferences.

Table 3.2 Descriptive results of overall sign preferences

Signs	1st Rank (Score 4)	2nd Rank (Score 3)	3rd Rank (Score 2)	4th Rank (Score 1)
B	9 (8.3%)	14 (13.1%)	33 (30.8%)	52 (48.6%)
C	52 (48.2%)	29 (27.1%)	15 (14.0%)	10 (9.35%)
F	12 (11.1%)	31 (29.0%)	31 (29.0%)	33 (30.8%)
G	35 (32.4%)	33 (30.8%)	28 (26.2%)	12 (11.2%)

3.4.2 Subjective Measures Results Discussion

Some of the key findings of the participants' subjective measures results were highlighted in the following:

- Sign C and Sign G were perceived by drivers to significantly reduce their mental workload in one way or another.
- There was a mismatch between drivers' perceptions and their actual driving performance regarding Sign F: drivers were more likely to perceive lower levels of mental demand, visual demand and overall effort, as well as having better performance with Sign F; however, these were not supported by the driving performance results.
- In general, older drivers exhibited the greatest levels of mental workload on all surveyed items except for overall performance, followed by teenage drivers and middle-aged drivers. Simultaneously, they also had a greater level of confidence in the system to enhance their safety performance, that is, the safety effectiveness of the system.
- Teenage drivers were less familiar with the operation of the system after completing the driving experiment; however, compared to their older counterparts, teenage drivers were more likely to be overconfident in the system, report higher levels of trust in the system's reliability, dependability, and integrity.

- Middle-aged drivers tended to feel "…more confident in their own ability to drive the car safely without the system" and that they were less likely to agree that the sign enhanced their driving performance, as compared to drivers of other age groups.
- Middle-aged drivers also reported a significantly higher level of temporal (time) pressure at the intersections with the intervention. This finding is consistent with their actual driving performance such that they tended to demonstrate more risky driving behaviors (e.g., greater approaching and crossing speeds, greater acceleration rate) when maneuvering the intersections with the assistance of the signs.

3.5 VISUAL ATTENTION RESULTS AND DISCUSSION

3.5.1 Visual Attention Results

3.5.1.1 Frequency of Visual Searching for Traffic

Drivers looked left-to-right to inspect vehicles approaching from both directions on the mainstream road. The influence of the intersection on the frequency of drivers' visual searching was examined. There was a significant overall effect of the intervention under low traffic volume, but not under moderate traffic volume. Compared to baseline, drivers were found to less frequently check on traffic left-to-right when driving under the conditions of all sign options except for Sign B under low traffic volume (exp(β)=0.90, 95% CI=0.80-1.02, *p*=0.0912 for Sign B; exp(β)=0.78, 95% CI=0.70-0.86, *p*<0.0001 for Sign C; exp(β)=0.89, 95% CI=0.81-0.96, p=0.0049 for Sign F; exp(β)=0.90, 95% CI=0.81-0.99, *p*=0.0384 for Sign G). Figure 3.39 illustrates the effect of the intervention on the frequency of drivers' visual search for traffic by sign option (i.e., left-to-right) under low traffic volume condition.

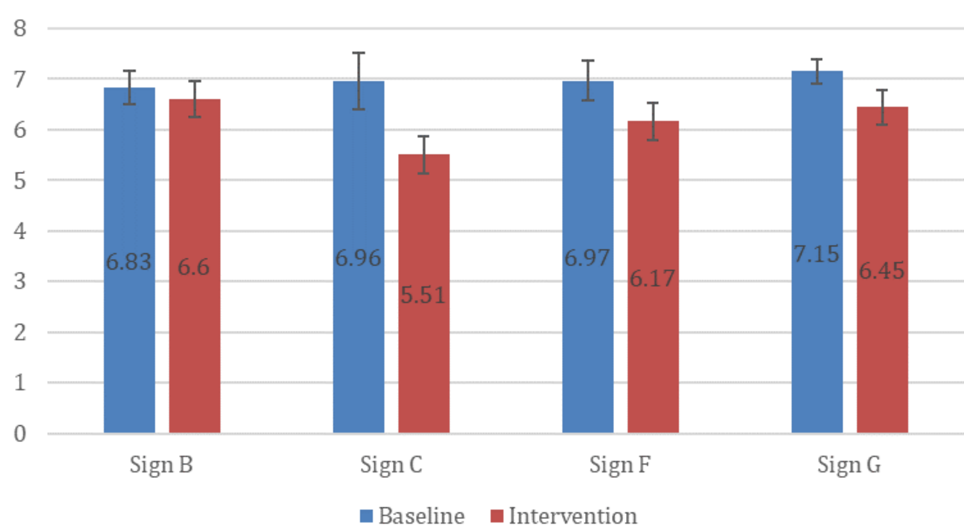


Figure 3.39 Frequency of drivers' visual search for traffic by sign option under low traffic volume

Although all stratum specific comparisons between baseline and intervention yielded significant results, the strengths of the intervention effects did not seem to significantly differ between clear view intersections and restricted view intersections (exp(β)=0.89, 95% CI=0.83-0.96, p=0.0022 for clear visibility; exp(β)=0.86, 95% CI=0.80-0.92, p<0.0001 for restricted visibility). Drivers in general were more likely to look left-to-right more frequently with restricted view (See Figure 3.40).

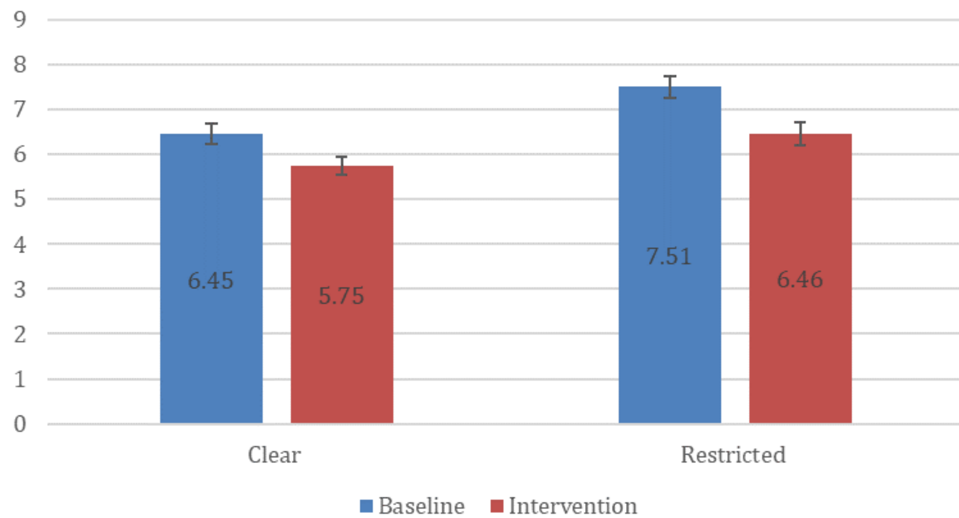


Figure 3.40 Frequency of drivers' visual search for traffic by visibility under low traffic volume

Consistent results were revealed for all age groups. Specifically, participants were significantly less frequent in searching for traffic from left-to-right with the assistance of the intervention (See Figure 3.41), with the exp(β)=0.83, 95% CI=0.75-0.92 and p=0.0004 for teenage drivers; exp(β)=0.91, 95% CI=0.85-0.98, and p=0.0119 for middle-aged drivers; and exp(β)=0.86, 95% CI=0.78-0.94, and p=0.0017 for older drivers. In general, older drivers appeared to employ more searching than middle-aged drivers and teenage drivers regardless of whether the intervention was presented or not under the low traffic volume condition. However, as opposed to the results of low traffic volume, more frequent visual searching behaviors were detected for older drivers in the intervention drives compared to baseline under the moderate traffic volume condition (borderline significant result). This result might indicate less efficiency, as well as a possible higher level of mental workload, associated with the use of RICWS signs among older drivers.

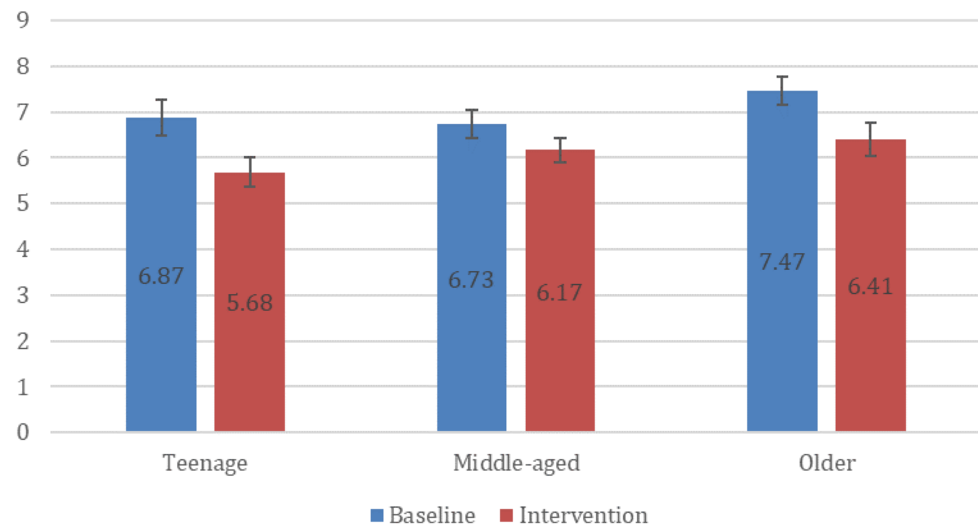


Figure 3.41 Frequency of drivers' visual search for traffic by age group under low traffic volume

3.5.1.2 Frequency of Visual Gaze Allocation to Signs

The frequency of drivers' visual gaze allocation to signs was investigated within the intervention condition and was compared across each of the exposures of interest. As shown in Figure 3.42, under moderate traffic volume, drivers were more prone to look more frequently at Sign G (exp(β)=4.70, SE=0.79), followed by Sign C (exp(β)=4.17, *SE*=0.55), Sign B (exp(β)=3.65, *SE*=0.65) and Sign F (exp(β)=2.70, *SE*=0.61). Specifically, Sign G was 1.74 times more likely than Sign B to draw drivers' visual attention (exp(β)=1.74, 95% CI=1.00-3.01, *p*=0.0487).

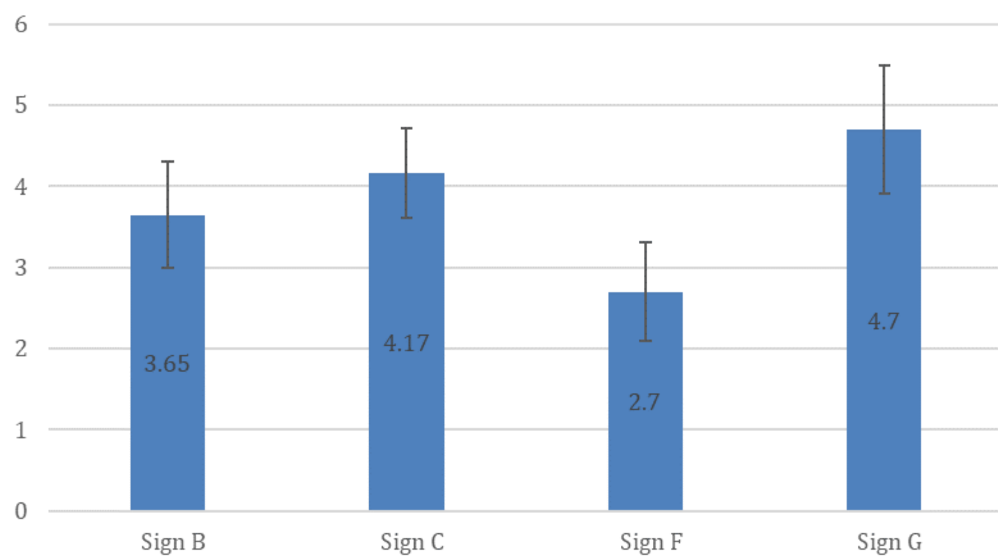


Figure 3.42 Frequency of drivers' visual gaze allocation to signs by sign option under moderate traffic volume

In addition, the frequency of visual gaze allocation to signs was 0.81 times lower at restricted view intersections than clear view intersections (exp(β)=0.81, 95% CI=0.66-0.99, and *p*=0.0391), which might be partially explained by less response and decision-making time at restricted view intersections. Not surprisingly, compared to their younger counterparts, older drivers appeared to pay more attention to the signs, rely on them more, and demand more visual resources to process the information. However, the comparison was only significant between older drivers and teenage drivers (exp(β)=1.80, 95% CI=1.17-2.76, and *p*=0.0076). The frequency of drivers' visual gaze allocation to signs under the moderate traffic volume condition was shown in Figure 3.43 by visibility and in Figure 3.44 by age group, respectively.

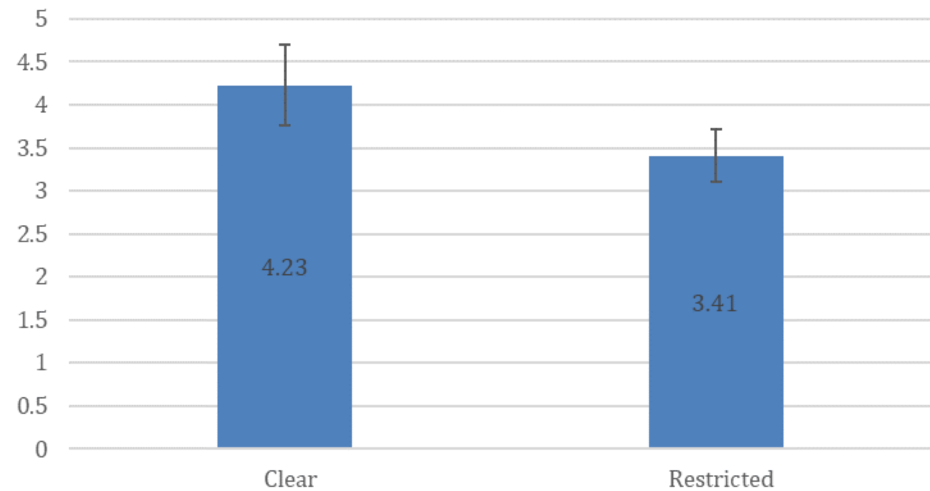


Figure 3.43 Frequency of drivers' visual gaze allocation to signs by sign option under moderate traffic volume

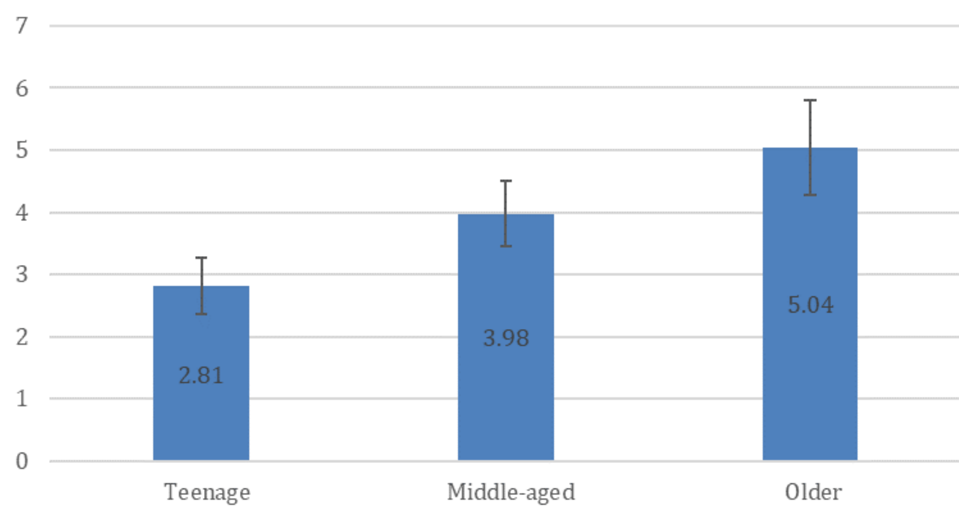


Figure 3.44 Frequency of drivers' visual gaze allocation to signs by sign option under moderate traffic volume

Alternatively, under low traffic volume, driver's frequency of drivers' visual attention on signs did not seem to be significantly affected by which sign option they had experienced (See Figure 3.45). Similarly, there was no evident difference of the frequency of drivers' visual gaze allocation to signs between restricted view and clear view intersections (See Figure 3.46). Unlike what was observed under moderate traffic volume, as shown in Figure 3.47, middle-aged drivers (exp(β)=3.01, *SE*=0.35) were more inclined to more frequently check on the signs compared to older drivers (exp(β)=2.29, *SE*=0.30) and teenage drivers (exp(β)=1.70, *SE*=0.22). The frequency of middle-aged drivers to visually check the signs were 1.77 times greater than that of teenage drivers (exp(β)=1.77, 95% CI=1.26-2.50, *p*=0.0011).

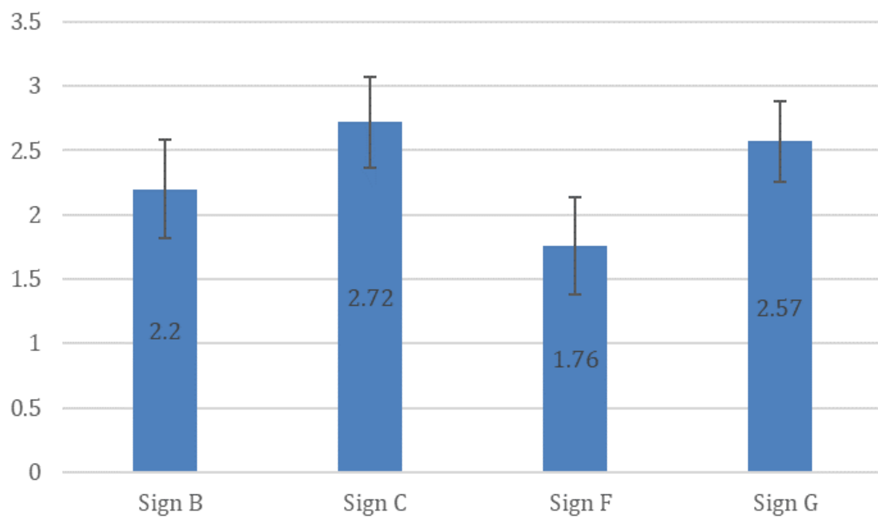


Figure 3.45 Frequency of drivers' visual gaze allocation to signs by sign option under low traffic volume

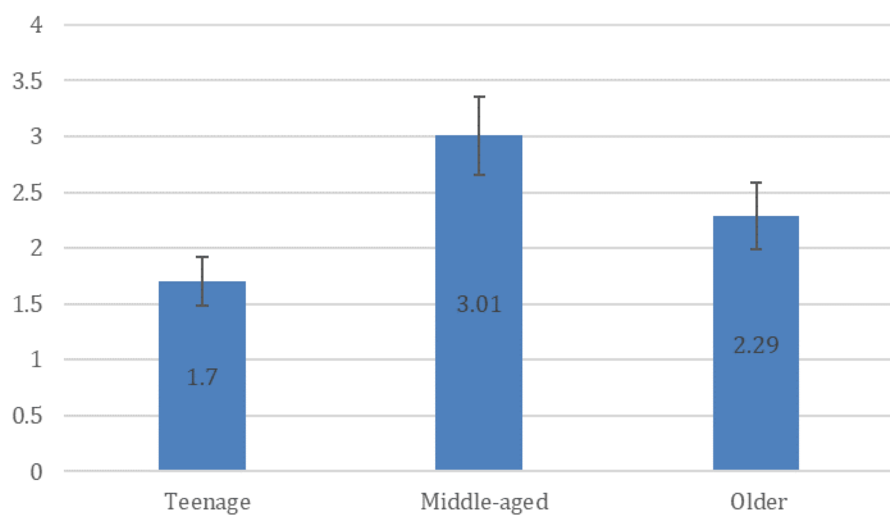


Figure 3.46 Frequency of drivers' visual gaze allocation to signs by sign option under low traffic volume

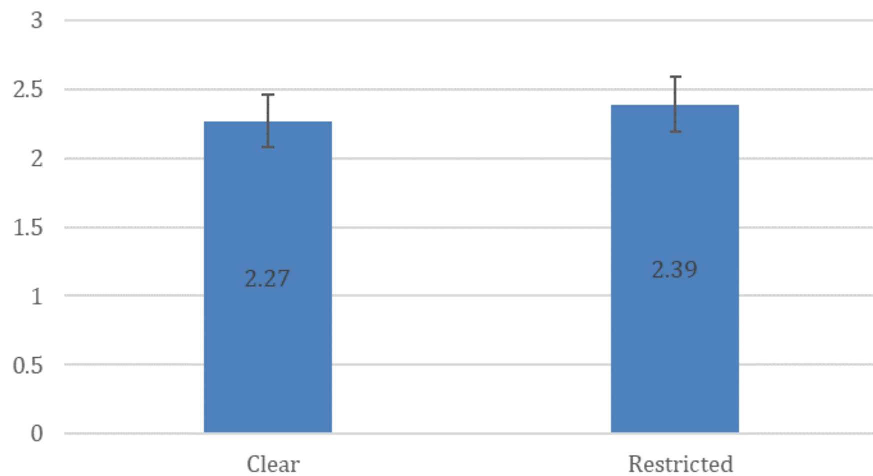


Figure 3.47 Frequency of drivers' visual gaze allocation to signs by sign option under low traffic volume

3.5.2 Visual Attention Results discussion

Overall, participants' visual attention results are summarized in the following:

- Drivers were generally less likely to look left-to-right to observe vehicles approaching from both directions on the mainstream road with the presence of all signs under the low traffic volume.
- Sign C and Sign G were more likely to capture drivers' visual attention compared to Sign F and Sign B, under both levels of traffic conditions on the main road.
- With respect to the effect of visibility, the frequency of visual gaze allocation to signs was significantly lower at restricted view intersections than clear view intersections under the moderate traffic volume condition. However, under the low traffic volume condition, there was no evident difference of the frequency of drivers' visual gaze allocation to signs between restricted view and clear view intersections.
- Under the moderate traffic volume, older drivers had a significantly higher frequency of visual gaze allocation to signs compared to teenage drivers, whereas under the low traffic volume, middle-aged drivers looked most frequently at signs.

Notably, the current analyses of participants' visual attention performance in this study were conducted based on real-time coding of participants' gaze counts and positions observed through the eye tracking systems four camera-based system during each driving session. Average measurements were obtained and used in the study, upon validation of data between two researchers who kept track of participants' visual searching for traffic and gaze allocation to signs and individually made recordings in a timely manner. However, these measurements may not be sufficient to provide an accurate and reliable estimation on the drivers' visual search gaze numbers, particularly on signs, since it was difficult to discern between gazes without knowing how long each one took.

There were several limitations associated with the use of eye trackers to collect gaze data. For example, in this study, half of the thru-STOP intersections were built with low visibility by having a large truck parked on the roadside to block participant's view of the approaching traffic. Under these driving circumstances, a common strategy used by participants to obtain a better view was to lean forward slightly and look over the end of the dashboard at the road. When drivers' eyes were brought very close to the in-vehicle cameras, it was particularly difficult for the system to reliably recognize the locations of drivers' heads and eyes, and to accurately calculate the gaze direction and duration. Furthermore, the quality of eye tracking data was negatively affected when participants wore reflective glasses, donned smaller glasses frames, and after equipment malfunction. Additionally, the older driver population used in this study also tended to yield unreliable eye tracking data due to a number of factors, including eye glasses, drooping eyelids, and other calibration issues. Future actions should be considered to minimize biases and obtain valid eye tracking data to provide more objective measurements of participants' visual attention performance.

3.6 SUMMARY

To summarize, this study reviewed using conflict warning signs in rural intersections to increase safety. The results of the study show that all of the conflict warning signs (except for Sign F described above) improved safety for drivers. In fact, the study showed significant increases in safety when placed at intersections with moderate traffic volumes.

It is important to note that these signs may also create risk for drivers, such as drivers being less likely to obey stop signs when driving through intersections clear of traffic or when the signs malfunction. While middle-aged drivers demonstrated the greatest safety potential to improve their gap acceptance performance through the RICWS intervention, they were also observed to have higher average approaching speed, average crossing speed and average crossing acceleration rate. Novice teenage drivers did not appear to be significantly assisted by the intervention despite that they reported the intervention had significantly improved their overall driving performance. Older drivers, however, demonstrated less efficiency in crossing using the system, which may compromise the safety performance of the intervention. Efficiency declines are important to consider because failure to accept a non-critical gap (i.e., one that they should accept) may impose extra mental workload and time pressure for safe decision making among older drivers.

Importantly, under the moderate traffic volume condition, drivers' gap acceptance performance tended to be significantly enhanced by the intervention at restricted view intersections, however, the frequency of their visual gaze allocation to signs was significantly lower compared to clear view intersections. Similarly, with the presence of the intervention, drivers of all sign groups (except for Sign B) tended to significantly less frequently check traffic from the left to right on the main roadway.

Finally, the results of the subjective measures provided considerable mismatches between drivers' perceptions and their actual driving behaviors were observed in this study.

CHAPTER 4: FINAL DISCUSSION AND CONCLUSIONS

4.1 DISCUSSION

4.1.1 Study Limitations

There were several limitations of this study, possibly including:

- First, the study did not take into account participants' familiarity with the original RICWS sign. The safety effectiveness of the overall intervention, particularly the original Sign C, might have been overestimated if there were a significant number of drivers who had previous knowledge with this sign in the study.
- Second, a learning effect may have occurred as participants' exposure to the signs increased throughout the study. The effect of continued sign exposure was not investigated.
- Third, this study observed that drivers exhibited various levels of trust in an automated system. In this analysis, individual differences in automation trust were not considered because various factors such as driver personality and history might have influenced an individual's ability to correctly interpret the sign messages, how fast they were able to build trust with the system during the experiment, and how efficiently they were able to understand the system under various driving conditions. Further examinations of this issue are needed for a more in-depth understanding of actual use of the system.

4.1.2 Lessons Learned

First, older drivers demonstrated less capability of handling his or her vehicle and very often lost vehicle control immediately upon passing through the rural intersections. This situation often occurred under moderate traffic volume conditions, where older drivers typically remained waiting at the stop line for a significantly longer amount of time than they would in the low volume condition before making their decision to cross.. This was worsened with the presence of the sign intervention, which might have imposed additional mental demand and time pressure on older drivers.

Second, many drivers thought that the system was sometimes not functioning correctly or asked if the researchers had intentionally changed the reliability of the system. This occurred often when participants had decided to proceed into the intersection, based on the activation of the sign on its "Sign is On/Operational" state, followed by the beacons beginning to flash when they were already in the course of the crossing maneuver. If drivers did not know they could still safely cross the intersections even when the beacons has begun to flash, they would become more cautious in driving which might be harmful in certain circumstances.

Third, although teenage drivers consistently reported higher levels of trust in the system, they appeared less likely to use it, making the system less effective. Furthermore, based on the observations and interviews of novice teenage drivers and interviews with them following the experiment, there are several explanations for our findings:

1) an inaccurate understanding by novice teenage drivers so that sign messages were misunderstood;
2) they were less familiar with the system than experienced middle-aged drivers and the usefulness of the sign was not understood;
3) some reported that it was easier to use their own judgement instead of the signs; and
4) most frequently, novice teenage drivers often noted that they did not even notice or pay attention to the signs while they were waiting at the intersections.

One teenager was unable to remember that signs were present at the intersections, even when researchers presented the sign design right after the final drive, which contained five of the signs. However, another teenage driver highly relied on the system after appearing to understand its intention and did not even bother to check for traffic before proceeding through the intersection. Finally, novice teenage drivers were also generally found to be more likely to misinterpret whether the system was malfunctioning, which may have serious safety implications if the system were to fail.

4.2 CONCLUSIONS

4.2.1 Practical Implications and Recommendations

This project attempted to identify the major human factors issues with the current RICWS design and develop alternative sign options through an iterative process of usability tests. The safety efficacy and efficiency of RICWS signs were investigated under different types of rural thru-STOP intersections, with various levels of mainstream traffic volume and intersection visibility.

Vulnerable driver populations were of special interest, namely older drivers and novice teenage drivers compared to experienced middle-aged drivers. Through the project, the researchers were able to identify the risks associated with the current signs, as well as help recognize the mismatches between drivers' perceptions and actual driving.

The design of Sign G might have similar safety benefits but fewer risks compared to the original RICWS sign (i.e., Sign C). Specifically, certain design elements such as the action word or icon, which were highly preferred by drivers, may be recommended for follow-up field evaluations and future implementation. However, the safety and efficiency of Sign G might have been diminished due to the layout of the current design, which may have made the messages less readable in the simulated world. This readability issue might have introduced added difficulty, particularly for older drivers, for understanding the information on Sign G. An enlarged version of Sign G, with enough spacing, might be considered in future tests.

4.2.2 Future Steps

This project highlighted the importance of a human-oriented approach in identifying potential cognitive processing problems, driver acceptance issues, and driver trust (i.e., both through overreliance and under-reliance on the signs) associated with the RICWS system design and evaluation. The importance of iterative, human-centered design should influence future projects to consider implementing these steps early and throughout the design and implementation processes.

For future practices:

- There should be increased involvement of multiple stakeholders, such as executive agencies, roadway planners, and local road users, at the early phase of the intelligent transportation system (ITS) development.
- This project provided future insight into risk assessments of new safety infrastructure deployment in simulated and real-world field tests, and provides a model for future testing for high-risk safety projects.
- The research findings could have a broad practical implication for design, development, and implementation of effective intersection countermeasures targeted to local rural drivers, as well as non-local rural, suburban, and urban drivers in Minnesota. Future research should specifically consider both urban and rural driving environments.
- The results contribute to significant knowledge building of the visual and cognitive considerations of the most vulnerable driver populations, specifically teenage and older drivers. These populations should be emphasized in future designs and testing.

REFERENCES

Alexander, J., Barham, P., & Black, I. (2002). Factors influencing the probability of an incident at a junction: results from an interactive driving simulator. *Accident Analysis & Prevention*, *34*(6), 779-792.

Arnett, J. J. (1996). Sensation seeking, aggressiveness, and adolescent reckless behavior. *Personality and Individual Differences*, *20*(6), 693-702.

Bao, S. N., & Boyle, L. (2008). Driver performance at two-way stop-controlled intersections on divided highways. *Transportation Research Record, 2069*(2069), 26-32.

Becic, E., Manser, M., Drucker, C., & Donath, M. (2013). Aging and the impact of distraction on an intersection crossing assist system. *Accident Analysis and Prevention, 50*, 968-974.

Biros, D. P., Daly, M., & Gunsch, G. (2004). The influence of task load and automation trust on deception detection. *Group Decision and Negotiation*, *13*, 173-189.

Braitman, K. A., Kirley, B. B., Ferguson, S., & Chaudhary, N. K. (2007). Factors leading to older drivers' intersection crashes. *Traffic Injury Prevention*, *8*(3), 267-274.

Caird, J.K., Chisholm, S.L., & Lockhart, J. (2008). Do in-vehicle advanced signs enhance older and younger drivers' intersection performance? Driving simulation and eye movement results. *International Journal of Human - Computer Studies, 66*(3), 132-144.

Caird, J. K., & Hancock, P. A. (1994). The perception of arrival time for different oncoming vehicles at an intersection. *Ecological Psychology*, 6(2), 83–109.

Caird, J. K., & Hancock, P. A. (2002). Left turn and gap acceptance crashes. In R. Dewar, & P. Olson (Eds.), *Human Factors in Traffic Safety* (pp. 613–652).

Caird, J. K., Chisholm, S. L., & Lockhart, J. (2008). Do in-vehicle advanced signs enhance older and younger drivers' intersection performance? Driving simulation and eye movement results. *International Journal of Human-Computer Studies, 66*(3), 132-144.

Caird, J. K., Edwards, C. J., Creaser, J. I., & Horrey, W. J. (2005). Older driver failures of attention at intersections: using change blindness methods to assess turn decision accuracy. *Human Factors*, *47*(2), 235-249.

Cantin, V., Lavallière, M., Simoneau, M., & Teasdale, N. (2009). Mental workload when driving in a simulator: Effects of age and driving complexity. *Accident Analysis & Prevention*, *41*(4), 763-771.

Chang, S. H., Lin, C. Y., Hsu, C. C., Fung, C. P., & Hwang, J. R. (2009). The effect of a collision warning system on the driving performance of young drivers at intersections. *Transportation Research Part F: Traffic Psychology and Behaviour*, *12*(5), 371-380.

Charlton, S. G. (2003). Restricting intersection visibility to reduce approach speeds. *Accident Analysis & Prevention*, *35*(5), 817-823.

Cicchino, J. B., & Mccartt, A. (2015). Critical older driver errors in a national sample of serious U.S. crashes. *Accident Analysis and Prevention, 80*, 211-219.

Cicchino, J. B., & McCartt, A. T. (2014) Trends in older driver involvement rates and survivability in the United States: An update. *Accident Analysis and Prevention, 72*, 44-52.

Cooper, P. J., & Zheng, Y. (2002). Turning gap acceptance decision-making: The impact of driver distraction. *Journal of Safety Research*, *33*(3), 321-335.

Dahl, R. E. (2008). Biological, developmental, and neurobehavioral factors relevant to adolescent driving risks. *American Journal of Preventive Medicine*, *35*(3), S278-S284.

De Waard, D., Van der Hulst, M., & Brookhuis, K. A. (1999). Elderly and young drivers' reaction to an in-car enforcement and tutoring system. *Applied Ergonomics*, *30*(2), 147-157.

DeLucia, P. R., Bleckley, M. K., Meyer, L. E., & Bush, J. M. (2003). Judgments about collision in younger and older drivers. *Transportation Research Part F: Traffic Psychology and Behaviour*, *6*(1), 63-80.

Dotzauer, M., De Waard, D., Caljouw, S. R., Pöhler, G., & Brouwer, W. H. (2015). Behavioral adaptation of young and older drivers to an intersection crossing advisory system. *Accident Analysis and Prevention, 74*, 24-32.

Haleem, K., & Abdel-Aty, M. (2010). Examining traffic crash injury severity at unsignalized intersections. *Journal of Safety Research*, *41*(4), 347-357.

Himes, S., Gross, F., Eccles, K., & Persaud, B. (2016). *Safety Evaluation of Intersection Conflict Warning Systems* (No. FHWA-HRT-16-035). *Transportation Research Board*, *2583,* 8-16.

Ho, G., Scialfa, C., Caird, J., & Graw, T. (2001). Visual search for traffic signs: The effects of clutter, luminance, and aging. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *43*(2), 194-207.

Huang, H., Chin, H. C., & Haque, M. M. (2008). Severity of driver injury and vehicle damage in traffic crashes at intersections: a Bayesian hierarchical analysis. *Accident Analysis & Prevention*, *40*(1), 45-54.

Inman, V. W., & Jackson, S. (2016). *Intersection Conflict Warning System Human Factors: Final Report* (No. FHWA-HRT-16-061). Retrieved from http://www.pooledfund.org/Browse/report

Kantowitz, B. H., Hanowski, R. J., & Kantowitz, S. C. (1997). Driver acceptance of unreliable traffic information in familiar and unfamiliar settings. *Human Factors*, *39*, 164-176.

Keay, L., Jasti, S., Munoz, B., Turano, K. A., Munro, C. A., Duncan, D. D., . . . West, S. K. (2009). Urban and rural differences in older drivers' failure to stop at stop signs. *Accident Analysis and Prevention, 41*(5), 995-1000.

Kim, D. G., Lee, Y., Washington, S., & Choi, K. (2007). Modeling crash outcome probabilities at rural intersections: Application of hierarchical binomial logistic models. *Accident Analysis & Prevention*, *39*(1), 125-134.

Lee, J., & See, J. (2004). Trust in automation: Designing for appropriate reliance. *Human Factors*, *46*, 50-80.

Lee, S. E., Simons-Morton, B. G., Klauer, S. E., Ouimet, M. C., & Dingus, T. A. (2011). Naturalistic assessment of novice teenage crash experience. *Accident Analysis & Prevention*, *43*(4), 1472-1479.

Lombardi, D.A., Horrey, W. J., & Courtney, T. K. (2017). Age-related differences in fatal intersection crashes in the United States. *Accident Analysis and Prevention, 99*, 20-29.

Lord, D., & Mannering, F. (2010). The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives. *Transportation Research Part A: Policy and Practice*, *44*(5), 291-305.

Louveton, N., Bootsma, R. J., Guerin, P., Berthelon, C., & Montagne, G. (2012). Intersection crossing considered as intercepting a moving traffic gap: Effects of task and environmental constraints. *Acta Psychologica, 141*(3), 287-294.

Malyshkina, N. V., & Mannering, F. L. (2010). Zero-state Markov switching count-data models: An empirical assessment. *Accident Analysis & Prevention*, *42*(1), 122-130.

McDowd, J., & Shaw, R. (2000). Attention and aging: A functional perspective. In: Craik, F., Salthouse, T. (Eds.), The Handbook of Aging and Cognition, Mahwah: Erlbaum, NJ, 221-292.

Neyens, D. M., & Boyle, L. N. (2008). The influence of driver distraction on the severity of injuries sustained by teenage drivers and their passengers. *Accident Analysis & Prevention*, *40*(1), 254-259.

Ouimet, M. C., Simons-Morton, B. G., Zador, P. L., Lerner, N. D., Freedman, M., Duncan, G. D., & Wang, J. (2010). Using the US National Household Travel Survey to estimate the impact of passenger characteristics on young drivers' relative risk of fatal crash involvement. *Accident Analysis & Prevention*, *42*(2), 689-694.

Owsley, C., Stalvey, B., Wells, J., & Sloane, M. E. (1999). Older drivers and cataract: driving habits and crash risk. *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences*, *54*(4), M203-M211.

Parasuraman, R., & Riley, V. (1997). Humans and automation: Use, misuse, disuse, abuse. *Human Factors*, *39*(2), 230-253.

Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A model for types and levels of human interaction with automation*. IEEE Transactions on Systems, Man & Cybernetics: Part A: Systems and Humans*, *30*, 286-297.

Preston, H., & Storm, R. (2003, August). Reducing Crashes at Rural Thru-STOP Controlled Intersections. In *Mid-Continent Transportation Research Symposium* (pp. 21-22).

Preston, H., Storm, R., Donath, M., & Shankwitz, C. (2004). *Review of Minnesota's Rural Crash Data: Methodology for Identifying Intersections for Intersection Decision Support (IDS).* (Report No. MN/RC-2004-31). Saint Paul, MN: MnDOT.

Preusser, D. F., Williams, A. F., Ferguson, S. A., Ulmer, R. G., & Weinstein, H. B. (1998). Fatal crash risk for older drivers at intersections. *Accident Analysis & Prevention*, *30*(2), 151-159.

Romoser, M. R., & Fisher, D. L. (2009). The effect of active versus passive training strategies on improving older drivers' scanning in intersections. *Human Factors*, *51*(5), 652-668.

Romoser, M. R., Pollatsek, A., Fisher, D. L., & Williams, C. C. (2013). Comparing the glance patterns of older versus younger experienced drivers: Scanning for hazards while approaching and entering the intersection. *Transportation Research Part F: Traffic Psychology and Behaviour*, *16*, 104-116.

Rusch, M. L., Schall, M. C., Lee, J. D., Dawson, J. D., Edwards, S. V., & Rizzo, M. (2016). Time-to-contact estimation errors among older drivers with useful field of view impairments. *Accident Analysis and Prevention,95*, 284-291.

Scialfa, C., Guzy, L., Leibowitz, H., Garvey, P., & Tyrrell, R. (1991). Age differences in estimating vehicle velocity. *Psychology and Aging*, *6*(1), 60.

Simons-Morton, B. G., Cheon, K., Guo, F., & Albert, P. (2013). Trajectories of kinematic risky driving among novice teenagers. *Accident Analysis & Prevention*, *51*, 27-32.

Simons-Morton, B. G., Zhang, Z., Jackson, J. C., & Albert, P. S. (2012). Do elevated gravitational-force events while driving predict crashes and near crashes? *American Journal of Epidemiology*, *175*(10), 1075-1079.

Simons-Morton, B. G., Lerner, N., & Singer, J. (2005). The observed effects of teenage passengers on the risky driving behavior of teenage drivers. *Accident Analysis & Prevention*, *37*(6), 973-982.

Steinberg, L. (2008). A social neuroscience perspective on adolescent risk-taking. *Developmental Review*, *28*(1), 78-106.

Uchida, N., De Waard, D., & Brookhuis, K.A. (2011). Countermeasures to prevent detection failure of a vehicle approaching on collision course. *Applied Ergonomics* 42.4: 540-547.

Wang, L., Jamieson, G. A., & Hollands, J. G. (2009). Trust and reliance on an automated combat identification system. *Human Factors*, *51*, 281-291.

Werneke, & Vollrath. (2012). What does the driver look at? The influence of intersection characteristics on attention allocation and driving behavior. *Accident Analysis and Prevention*, *45*, 610-619.

Williams, A. F. (2003). Teenage drivers: Patterns of risk. *Journal of Safety Research*, *34*(1), 5-15.

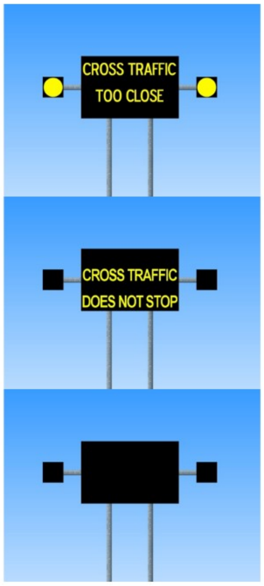
Yagil, D. (2001). Reasoned Action and Irrational Motives: A Prediction of Drivers' Intention to Violate Traffic Laws 1. *Journal of Applied Social Psychology, 31*(4), 720-739.

Yan, X., Radwan, E., & Abdel-Aty, M. (2005). Characteristics of rear-end accidents at signalized intersections using multiple logistic regression model. *Accident Analysis & Prevention*, *37*(6), 983-995.

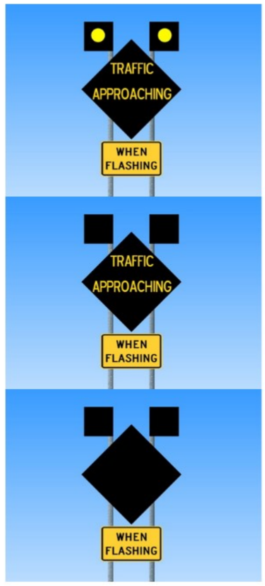
Yan, X., Radwan, E., & Guo, D. (2007). Effects of major-road vehicle speed and driver age and gender on left-turn gap acceptance. *Accident Analysis & Prevention*, *39*(4), 843-852.

APPENDIX A

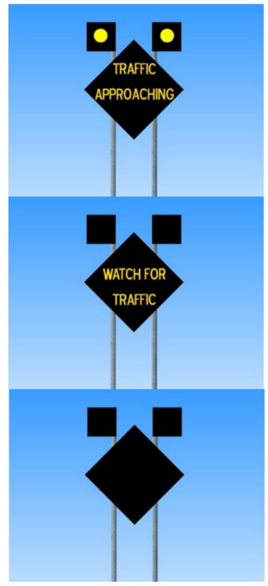
FINAL SIGN DESIGNS FOR THE SIMULATOR STUDY



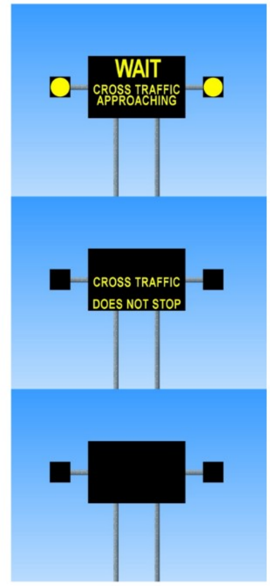
Sign B



Sign C (Original RICWS)



Sign F



Sign G

APPENDIX B

ALTERNATIVE SIGN A DESIGNS FOR THE FOLLOW-UP USABILITY TEST

Sign A.1

Sign A.2

APPENDIX C

SURVEY QUESTIONS TO COUNTY ENGINEERS

Greetings,

The University of Minnesota is partnering with MnDOT to examine perceptions of the RICWS implementations across the state. We are seeking input from Minnesota county engineers about reported experiences or feedback from residents in each county. Additionally, we are interested in each county engineer's own perspective and understanding of the RICWS signs.

Thank you for your time and consideration.

Q1. Please state your name

[Text Box]

Q2. Please state the county you represent

[Text Box]

Q3. Have you received any feedback (e.g., comments, complaints, praise, etc.) from residents regarding the RICWS signs in your county?

[Text Box]

Q4. Please describe what specifically about the RICWS (e.g., message, flashing beacons, placement, etc.) has been raised by residents along with the nature of the feedback (e.g., positive, negative, confusion, etc.).

[Text Box]

Q5. Can you estimate the number of instances that residents have reached out to you or someone connected to you about the RICWS signs dating back to when they were first installed? If so, please enter your estimate.

[Text Box]

Q6. Do you feel you have a good understanding of the modes and functions of the RICWS sign? Can you explain how it works; in particular, explain how the fail safe works (e.g., sign inoperable vs. no traffic detected)?

[Text Box]

Q7. Please provide any additional feedback you would like to give about the RICWS signs in your county?

[Text Box]

APPENDIX D
Version 1.0 Results

Table D1. Results for Version 1.0 highest preferences

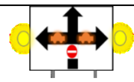
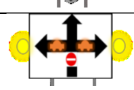
Sign	Example	Score
F		11
C		9
B		5
D		2
E		2
A		1

Table D2. Results for Version 1.0 lowest ranked design

Sign	Example	Score
A		-3
D		-3
E		-1
B		0
C		0
F		0

APPENDIX E
Version 2.0 Results

Version 2.0 Rankings for Most and Least Preferred Overall Sign Sets

Table E1. Results for Version 2.0 overall preference for sign design

Sign	Example	Score
A		10
C		8
B		4
F		3
D		2
E		2

Table E2. Results for Version 2.0 overall lowest ranked sign design

Sign	Example	Score
A		-2
E		-2
F		-2
D		-1
B		-1
C		0

Version 2.0 Rankings for Most and Least Preferred 'Do Not Cross/Turn' Signs

Table E3. Highly ranked results for Version 2.0 sign design 'Do not cross/turn'

Sign	Example	Score
A		13
C		6
D		4
E		4
B		3
F		0

Table E4. Lowest ranked results for Version 2.0 sign design 'Do not cross/turn'

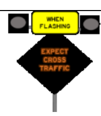
Sign	Example	Score
E		-3
B		-2
F		-1
A		0
C		0
D		0

Version 2.0 Rankings for Most and Least Preferred ‘Sign is on’ Signs

Table E5. Highly ranked results for Version 2.0 sign design ‘Sign is on’

Sign	Example	Score
A		12
F		8
E		4
C		2
B		1
D		0

Table E6. Lowest ranked results for Version 2.0 sign design ‘Sign is on’

Sign	Example	Score
E		-2
C		-2
B		-1
A		-1
D		-1
F		0

APPENDIX F
Version 3.0 Results

Version 3.0 Rankings for Most and Least Preferred Overall Sign Sets

Table F1. Results for Version 3.0 highest ranked sign designs

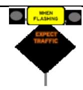
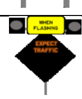
Sign	Example	Score
C		22
B		20
D		19
A		18
E		17
F		15

Table F2. Results for Version 3.0 lowest ranked sign designs

Sign	Example	Score
A		6
E		5
F		4
D		4
C		4
B		2

Version 3.0 Rankings for Most and Least Preferred 'Do Not Cross/Turn' Signs

Table F3. Highly ranked results for Version 3.0 sign design 'Do not cross/turn'

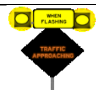
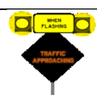
Sign	Example	Score
A		31
B		23
C		20
E		16
D		15
F		11

Table F4. Lowest ranked results for Version 3.0 sign design 'Do not cross/turn'

Sign	Example	Score
E		-5
C		-5
F		-4
D		-4
B		-3
A		-2

Version 3.0 Rankings for Most and Least Preferred 'Sign is on' Signs

Table F5. Highly ranked results for Version 3.0 sign design 'Sign is on'

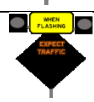
Sign	Example	Score
B		40
D		25
F		13
C		12
E		11
A		2

Table F6. Lowest ranked results for Version 3.0 sign design 'Sign is on'

Sign	Example	Score
A		-12
C		-3
E		-2
D		-2
B		0
F		0

APPENDIX G

FOLLOW-UP ONLINE SURVEY FOR SIGN A OPTION

Thank you for your participation in this brief survey. We are investigating the effectiveness of a "smart" sign to aid drivers to safely cross thru-STOP intersections.

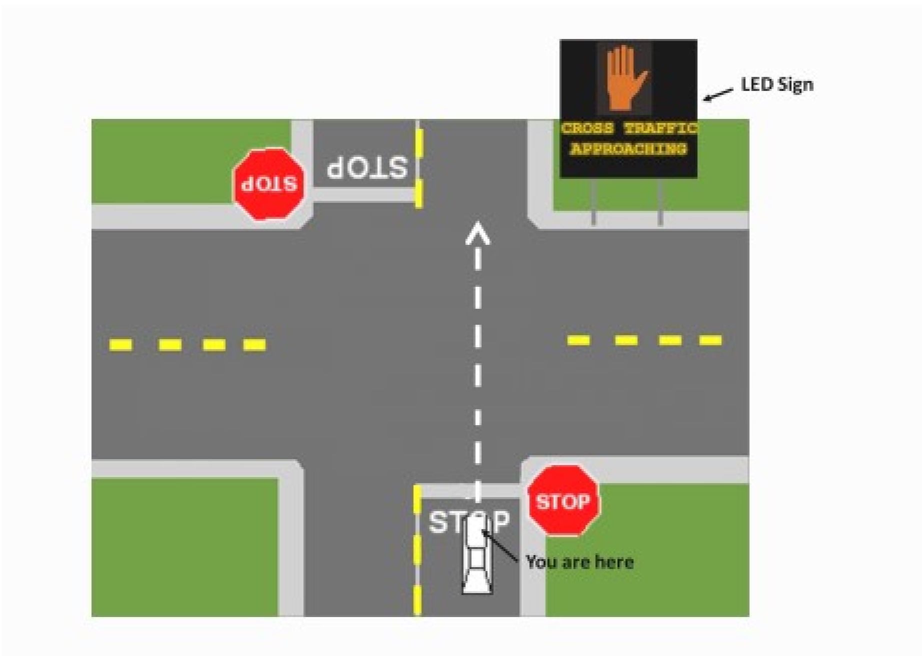
Q1. Please enter your age:

[Text Box]

Q2. Please select your gender:

- ❑ Male
- ❑ Female
- ❑ I do not wish to disclose my gender

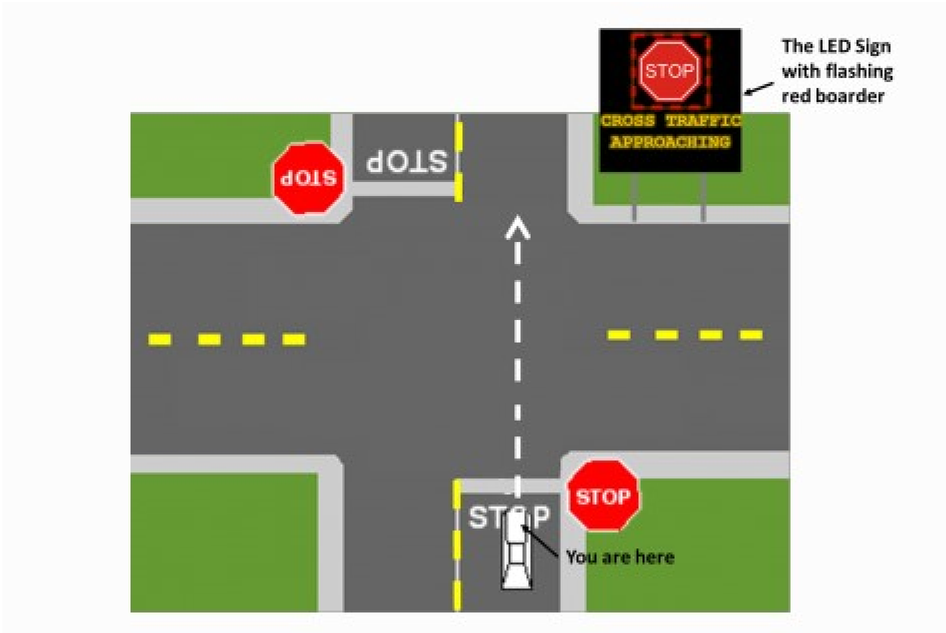
Q3. Imagine you arrive at the stop sign on a minor road and you want to go straight across the major road, which does not have a stop sign (this is known as a thru-STOP intersection, see the below figure). You are able to see a changeable, LED sign placed on the other side of the road. Note that the "hand" icon is steady on the LED sign.



Based on what the sign says, what information do you think the sign conveys? What will you do based on this information? Please enter your answer in the box below:

[Text Box]

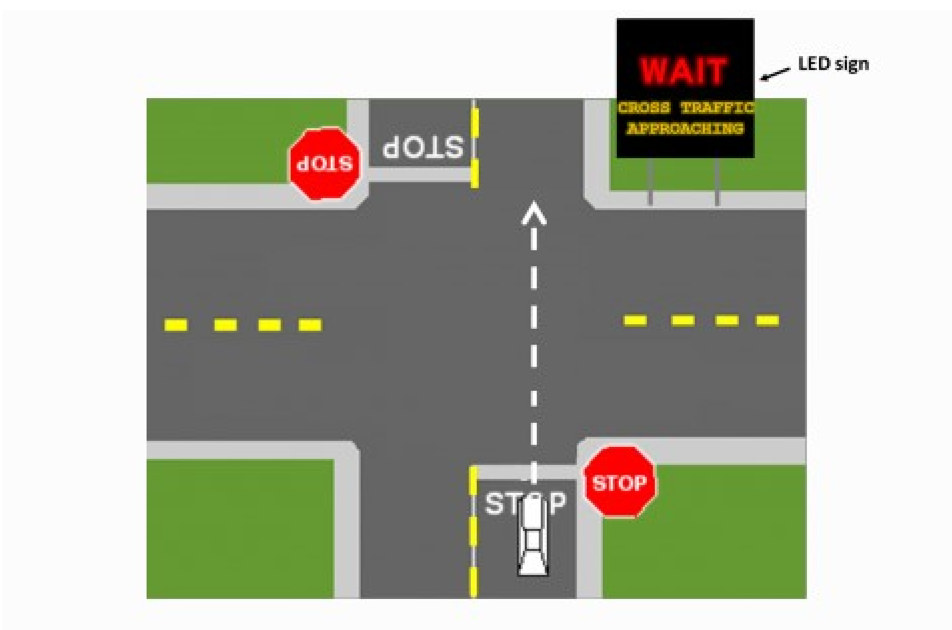
Q4. Imagine you arrive at the stop sign on a minor road and you want to go straight across the major road, which does not have a stop sign (this is known as a thru-STOP intersection, see the below figure). You are able to see a changeable, LED sign placed on the other side of the road. Note that both the STOP icon and the boarder are flashing on the LED sign.



Based on what the sign says, what information do you think the sign conveys? What will you do based on this information? Please enter your answer in the box below:

[Text Box]

Q5. Imagine you arrive at the stop sign on a minor road and you want to go straight across the major road, which does not have a stop sign (this is known as a thru-STOP intersection, see the below figure). You are able to see a changeable, LED sign placed on the other side of the road. Note that the "WAIT" message is flashing on the LED sign.



Based on what the sign says, what information do you think the sign conveys? What will you do based on this information? Please enter your answer in the box below:

[Text Box]

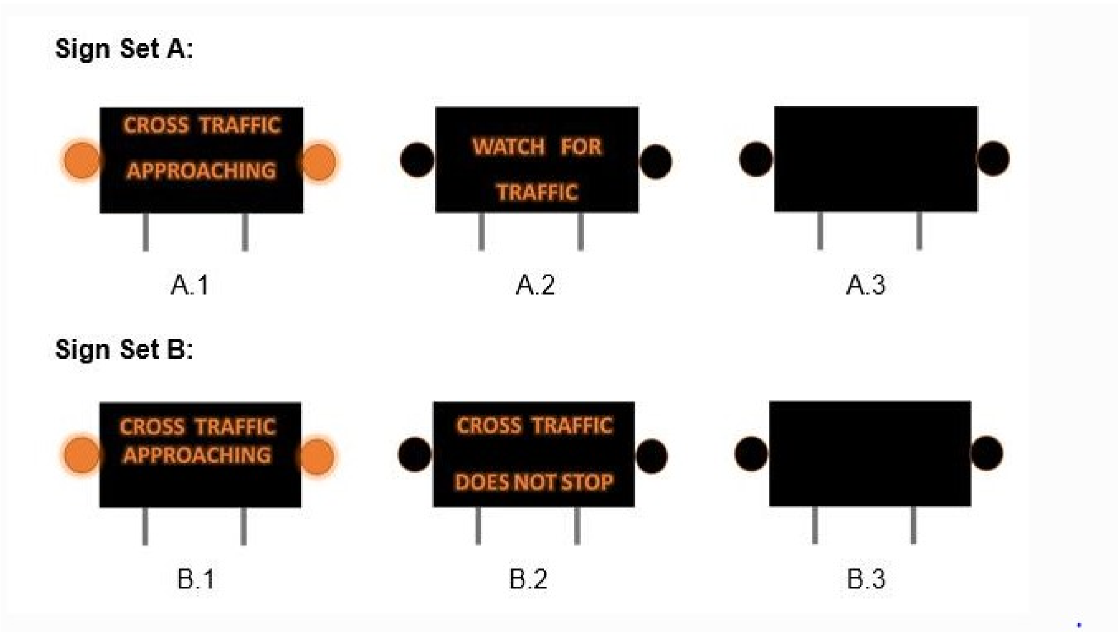
Q6. If all "smart" signs are intended to prohibit you from entering the intersection due to an unsafe gap between you and an oncoming car, i.e., you should wait until the car passes and it is safe to cross, which of the below signs you think would most accurately convey this message? Please rank your preferences by placing numbers in the box on the upper right of each figure (1 means the most accurate; 2 means less accurate; 3 means the least accurate).

- ❑ Sign A: Both the "STOP" icon and the red boarder are flashing on the LED sign.
- ❑ Sign B: The "WAIT" message is flashing on the LED sign.
- ❑ Sign C: The "hand" icon is steady on the LED sign.

Please briefly explain your preference rankings for the three signs in the below box:

[Text Box]

Q7. Please review the below two sign sets. In each set, there are three changeable sign states: 1) traffic is too close to safely cross; 2) sign is on/operating, proceed with caution; 3) sign is non-operational.



You are stopped at a thru-STOP intersection and you want to go straight through the intersection, which sign (either A.2 or B.2) do you think would more accurately convey the intended information that the "sign is on/operating, proceed with caution"?

[Text Box]

Please provide you answer in the box below (your answer should be either A.2 or B.2):

[Text Box]

Thank you very much for your participation. Your feedback and time are highly appreciated by our research team!

APPENDIX H
PRESCREENING QUESTIONNAIRE

RICWS Sign Project Screening Questionnaire

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

1. What is your age?
    - EXCLUDE IF NOT IN THE THREE AGE GROUPS OF INTEREST

2. For teenage drivers, have you had a Provisional Driver's License (i.e., license to drive independently)?
    - EXCLUDE IF NO

   Alternatively, for middle-aged drivers and older drivers, have you had a U.S. driver's license for at least two years?
    - EXCLUDE IF NO

3. For teenage drivers, if you have a Provisional Driver's License, when did you obtain it?
    - EXCLUDE IF NO

   Alternatively, for middle-aged drivers and older drivers, 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 contact 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 I

DRIVING HISTORY QUESTIONNAIRE

DRIVING HISTORY (16-18 YEARS OLD)

This questionnaire will collect information such as your age, gender and how often you expect to drive. Your answers are confidential. If you feel uncomfortable answering a particular question, you may leave it blank. Please tick one box for each question.

1. Your date of birth: MM: _______ / DD: _______ / YYYY _______

2. Your current age: _____ years

3. Your sex:

☐ Male
☐ Female

4. What is your cumulative GPA this academic year? __________________________

5. Please state the month, day and year when you obtained your provisional driving license.

MM: _______ / DD: _______ / YYYY _______

6. Are you sharing vehicle(s) with a family member or others?

☐ Yes ☐ No

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

☐ Motorcycle
☐ Passenger Car
☐ Pick-Up Truck
☐ Sport utility vehicle
☐ Van or Minivan
☐ Other, briefly describe: ________________________________

8. Please indicate, on average, how many days per week you drive:

☐ Less than one day per week
☐ 1 or 2 days per week
☐ 3 or 4 days per week
☐ 5 or 6 days per week
☐ Every Day

9. Estimate roughly how many miles do you driver every week: ____________________

10. Do you drive frequently on…?

	Yes	No
Highways	☐	☐
Main Roads other than Highways	☐	☐
Urban Roads	☐	☐
Country Roads	☐	☐

11. Since you received your license, how many <u>minor</u> road accidents have you been involved in?

    (A minor accident 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)

12. Since you received your license, how many <u>major</u> road accidents have you been involved in?

    (A major accident 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)

13. Since you received your license, have you ever been cited for:
    a. Speeding
        ☐ Yes
        ☐ No
    b. Stop sign violation
        ☐ Yes
        ☐ No
    c. Careless or dangerous driving
        ☐ Yes
        ☐ No
    d. Driving under the influence of alcohol/drugs
        ☐ Yes
        ☐ No

DRIVING HISTORY (35-50 YEARS OLD OR 65-77 YEARS OLD)

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. Please state your occupation:____

5. Please state the year when you obtained your full driving licence: __________

6. What type of vehicle do you drive most often?
   - ☐ Motorcycle
   - ☐ Passenger Car
   - ☐ Pick-Up Truck
   - ☐ Sport utility vehicle
   - ☐ Van or Minivan
   - ☐ Other, briefly describe: ____________________________

7. Please indicate, on average, how many days per week you drive: often (days per week)
   - ☐ Less than one day per week
   - ☐ 1 or 2 days per week
   - ☐ 3 or 4 days per week
   - ☐ 5 or 6 days per week
   - ☐ Every Day

8. Estimate roughly how many miles do you driver every week: __________________

9. Do you drive frequently on…?

	Yes	No
Highways	☐	☐
Main Roads other than Highways	☐	☐
Urban Roads	☐	☐
Country Roads	☐	☐

10. During the last three years, how many <u>minor</u> road accidents have you been involved in?

    (A minor accident 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)

11. During the last three years, how many <u>major</u> road accidents have you been involved in?

    (A major accident 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)

12. During the last three years, have you ever been cited for:
    e. Speeding
        - ☐ Yes
        - ☐ No
    f. Stop sign violation
        - ☐ Yes
        - ☐ No
    g. Careless or dangerous driving
        - ☐ Yes
        - ☐ No
    h. Driving under the influence of alcohol/drugs
        - ☐ Yes
        - ☐ No

APPENDIX J

NASA RTLX MENTAL WORKLOAD QUESTIONNAIRE

MENTAL WORKLOAD RATINGS

Think about how you felt during the session you just completed. Please rate for the six characteristic summarized below based on a 1-5 scoring scale:

Mental Demand — **Your rating: ___________**
How much thinking, deciding, calculating, remembering, looking, searching, did you need to do?
(1 means the lowest, 5 means the highest)

Physical Demand — **Your rating: ___________**
How much physical activity was required?
(1 means the lowest, 5 means the highest)

Visual Demand — **Your rating: ___________**
How much looking, searching, visual activity was required?
(1 means the lowest, 5 means the highest)

Time Pressure — **Your rating: ___________**
Did you feel under pressure to complete the driving task in the time available?
(1 means the lowest, 5 means the highest)

Performance — **Your rating: ___________**
How satisfied were you

Effort — **Your rating: ___________**
Did you feel under pressure
How hard did you have to work?
(1 means the lowest, 5 means the highest)

Frustration Level — **Your rating: ___________**
How insecure, discouraged, irritated, stressed and annoyed during the drive?
(1 means the lowest, 5 means the highest)

APPENDIX K

SYSTEM TRUST QUESTIONNAIRE

SYSTEM TRUST QUESTIONNAIRE

(Please provide your score based on a 0-100 scale)

The performance of the system enhanced my driving safety.

0 Strongly Disagree — 50 — 100 Strongly Agree

I am familiar with the operation of the system.

0 Strongly Disagree — 50 — 100 Strongly Agree

I trust the system.

0 Strongly Disagree — 50 — 100 Strongly Agree

The system is reliable.

0 Strongly Disagree — 50 — 100 Strongly Agree

The system is dependable.

0 Strongly Disagree — 50 — 100 Strongly Agree

The system has integrity.

0 Strongly Disagree — 50 — 100 Strongly Agree

I am comfortable with the intent of the system.

0 Strongly Disagree — 50 — 100 Strongly Agree

I am confident in my ability to drive the car safely without the system.

0 Strongly Disagree — 50 — 100 Strongly Agree

APPENDIX L

SIGN USABILITY QUESTIONNAIRE

SIGN USABILITY QUESTIONNAIRE

The following questions ask about your opinions on the warning sign you experienced during the drive, as well as some other alternative designs that will also be deployed at the rural thru-STOP intersections.

Question 1.

What message do you think the sign was conveying to you while you were stopped at the intersection?

1) Answer: ____

2) Answer: ____

3) Answer: ____

What action did you take when you saw the message?

1) Answer: ____

2) Answer: ____

3) Answer: ____

Question 2.

The first row of traffic signs are intended to convey that "it is unsafe to cross the intersection because of the approaching traffic"; the second row of traffic signs are intended to convey that "the sign is on/operable; traffic is not approaching; and you may cross with caution"; and the last row of traffic signs are intended to convey "the sign is inoperable".

Please rank your overall preferences on the sign sets, considering how helpful they are in providing traffic information to aid you to safely cross intersections (1 means most helpful; 4 means least helpful).

1.__________ 2.__________ 3.__________ 4.__________