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Design and evaluation of a rural intersection conflict warning system and alternative designs among various driver age groups

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ABSTRACT

Advanced Rural Intersection Conflict Warning Systems (RICWS) were deployed as countermeasures to reduce severe right-angle crashes at rural thru-STOP controlled intersections across the United States (U.S.). The simulator study designed and evaluated alternative RICWS designs to existing RICWS interventions, in varying rural driving scenarios, across age groups ($N = 40$ novice teenage, 40 middle-aged, and 40 older drivers). Each participant was randomly assigned to a RICWS design, either the original or an alternative, and drove through sequences of 17 thru-STOP controlled rural intersections (nine RICWS intervention and eight control intersections). Drivers' gap acceptance performance, intersection driving performance, traffic violation behaviors and self-reported workload were evaluated between intervention and control intersections. Regression models, applying the Generalized Estimating Equation (GEE), enabled efficacy determination of each RICWS design and an aggregated RICWS intervention effect, averaged across all simulated RICWS designs, among different levels of moderating factors. The safety performance and possible risks associated with the use of different RICWS designs were identified. Specifically, the original RICWS design had a significantly greater risk of STOP-sign violations at clear-view intersections with low traffic volumes, compared with control intersections (Risk Ratio = 2.18, 95% CI = 1.03 to 4.64). Except for Alternative RICWS Design 1, the alternative RICWS designs did not appear to outperform the Original RICWS Design. The moderating effects of drivers' ages and intersection types on aggregated RICWS intervention effects were also examined. This study provides important safety implications for development and evaluation of intelligent intersection warning systems, targeted to vulnerable driver populations at high-risk rural intersections.

1. Introduction

Intelligent transportation systems have been increasingly adopted and relied upon as safety infrastructure to help reduce motor vehicle crashes on United States (U.S.) roadways. For instance, the Rural Intersection Conflict Warning System (RICWS) has been deployed at the most hazardous rural thru-STOP controlled intersections (i.e., traffic on the main road of an intersection does not stop) in the state of Minnesota, in response to high occurrences of severe and fatal right-angle crashes reported at these intersections over the years (Preston et al., 2004). Previous research suggested that drivers' failure to identify safe vehicle gaps was associated with these types of serious crashes (Chovan et al., 1994; Laberge et al., 2006; Retting et al., 2003). To assist drivers with safe and timely intersection crossings, or when turning into the intersection, the RICWS intervention system was designed and developed to allow for early detection of vehicles approaching the intersections, as well as to communicate real-time gap information to drivers waiting at the STOP signs. However, there has been limited research conducted to examine whether and to what extent such a system may modify improper gap acceptance as well as other unsafe driving behaviors.

Drivers' age is also recognized as a substantial factor pertinent to crash and injury risks at rural intersections; in particular, older drivers

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have generally been observed to experience more challenges with intersection maneuvering (Lombardi et al., 2017; Preusser et al., 1998; Sifrit et al., 2010), as a result of possible deterioration in cognitive and physical conditions that limit judging the gap size correctly and responding as promptly as their younger counterparts (Braitman et al., 2007; Caird et al., 2005; Cicchino and McCartt, 2015). Older drivers have also been more likely to report higher mental workload in more complex driving environments (Cantin et al., 2009), as well as relying on assistance systems when performing extraneous tasks irrelevant to the primary driving activity (Becic et al., 2013). However, a recent national analysis revealed that U.S. teenage drivers were exposed to higher risks of death in intersection crashes (Lombardi et al., 2017). Reportedly, due to immaturity and lack of driving experience (Williams, 2003), novice teenage drivers have typically been characterized as prone to risk-taking behaviors (Simons-Morton et al., 2011; Steinberg, 2008), more vulnerable to distractions (Neyens and Boyle, 2007; 2008), and less likely to comply with stop signs at intersections (Yagil, 2001). Nevertheless, while evaluation studies have generally encompassed a broad age range of young drivers' behaviors at rural intersections, they may have had limited ability to represent the actual risks of the novice teenage driver population. This includes systematically investigating whether these drivers could accurately interpret the warning messages, efficiently respond to the advanced systems, and properly interact with them, particularly at rural intersections with high crash risks.

In addition, drivers' perceived trust in and attitudes towards an automated system (e.g., RICWS), may significantly influence how they might interact with the system (Lee and See, 2004; Parasuraman et al., 2000). For example, highly complex rural intersections are more likely to increase the drivers' perceived risk of hazards in the driving environment, as well as impose greater mental workload for performing the driving tasks. These may, in turn, increase drivers' reliance on and use of the automated system (Biros et al., 2004; Cantin et al., 2009; Parasuraman and Riley, 1997). With varying levels of driving experience, it is also possible that some drivers may fail to correctly comprehend sign messages, thus, perceiving the system to be less accurate and reliable and result in improper system use (Parasuraman and Riley, 1997). In particular, results of earlier usability tests of the implemented RICWS intervention design (original RICWS design in the present study), identified considerable public concerns and confusion among the local road users and executive agencies (Tian et al., 2018). Comparable results were also observed by Inman & Jackson (Inman and Jackson, 2016) in a human factors evaluation of various similar rural conflict warning signs. Thus, further investigation on potential risks associated with utilization and deployment of such systems is warranted.

2. Materials and methods

Using a driving simulator, the primary objective of this study was to evaluate the effectiveness and potential risks of an existing RICWS intervention design, along with three alternative RICWS designs; this involved testing among three age groups at different types of rural thru-STOP controlled intersections. Moreover, the study also incorporated an investigation into how drivers' age, mainstream traffic volume, and intersection visibility moderated the aggregated RICWS intervention effect, when the results from all RICWS intervention intersections were combined and compared to the control intersections.

2.1. Study population

A total of $N = 120$ participants (59 females and 61 males) were recruited into the study, including 40 older drivers (65–77 years old), 40 middle-aged drivers (35–50 years old), and 40 novice teenage drivers (16–18 years old). Fifteen participants (12.5% of the total), including seven older drivers, seven middle-aged drivers and one novice teenage driver, were discontinued from the study because of occurrence of mild to moderate levels of simulation sickness symptoms, either self-reported or observed by the researchers. Eligibility criteria for all participants consisted of normal vision (or corrected-to-normal), no color blindness, no previous history of motion sickness or sea sickness, and no other cognitive dysfunction or physical disabilities that might prohibit them from driving independently. For teenage drivers (i.e., aged 16 to 17 years old) to participate, a signed consent form was required from one parent or legal guardian, as well as a signed assent form from the teenager. This study was conducted with the approval of the Institutional Review Board at the University of Minnesota (IRB study number 1607S91763).

2.2. Materials and apparatus

2.2.1. RICWS functionality and Design interfaces

Fig. 1 illustrates the original RICWS intervention design at a typical thru-STOP controlled intersection configuration in Minnesota. In this paper, only the warning system facing toward waiting drivers on minor roads was examined because the majority of road user complaints reported by Minnesota county and state engineers pertained to this specific system design (i.e., minor road RICWS system). The original RICWS design (Fig. 2, design a), consisted of three major components, including two flashing beacons, triggered by radar detection of approaching vehicles within 6.5 s headway to the intersection from either direction, a diamond-shaped dynamic blank-out sign with a constantly illuminated light-emitting diode (LED) display of "TRAFFIC APPROACHING," and a rectangular static placard located beneath the blank-out sign with the permanent message, "WHEN FLASHING."

This system also has three changeable sequence states: 1) State 1—"Not safe to cross/turn," in which the two beacons flash constantly and alternatively to alert drivers waiting on the minor road about approaching traffic on the main road; 2) State 2—"No detected traffic, but use caution when crossing/turning," in which case the beacons cease flashing if no traffic is detected within the safe distance (i.e., 6.5 s headway); 3) State 3—"Sign is off or malfunctioning," in which case the dynamic sign was blacked out and the beacons were not flashing, regardless of the main road traffic conditions.

2.2.2. Human factors issues for the Original RICWS Design and system redesign

The original RICWS was developed, over time, using national and local standards for sign designs. A more complete history of its development can be found at the Minnesota Department of Transportation (MnDOT) RICWS project website (http://www.dot.state.mn.us/its/projects/2011–2015/ricws.html) and Intersection Safety Technology Guidebook (Kuehl et al., 2016). Since its implementation, the RICWS sign in question has been repeatedly reported to be "distracting",

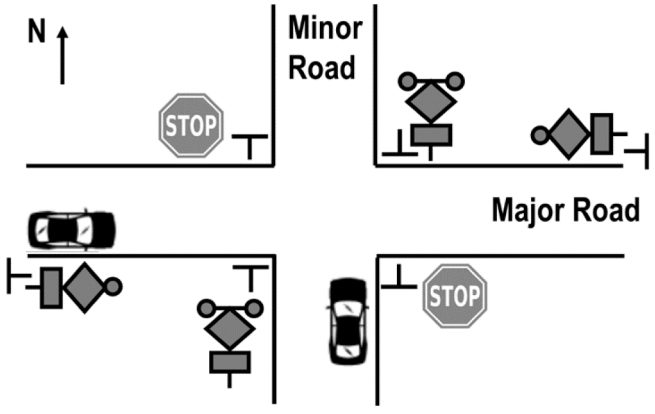

Fig. 1. Configuration of the RICWS Intervention (Adapted from the Minnesota Department of Transportation website at https://www.dot.state.mn.us/trafficeng/signals/conflictwarning.html).

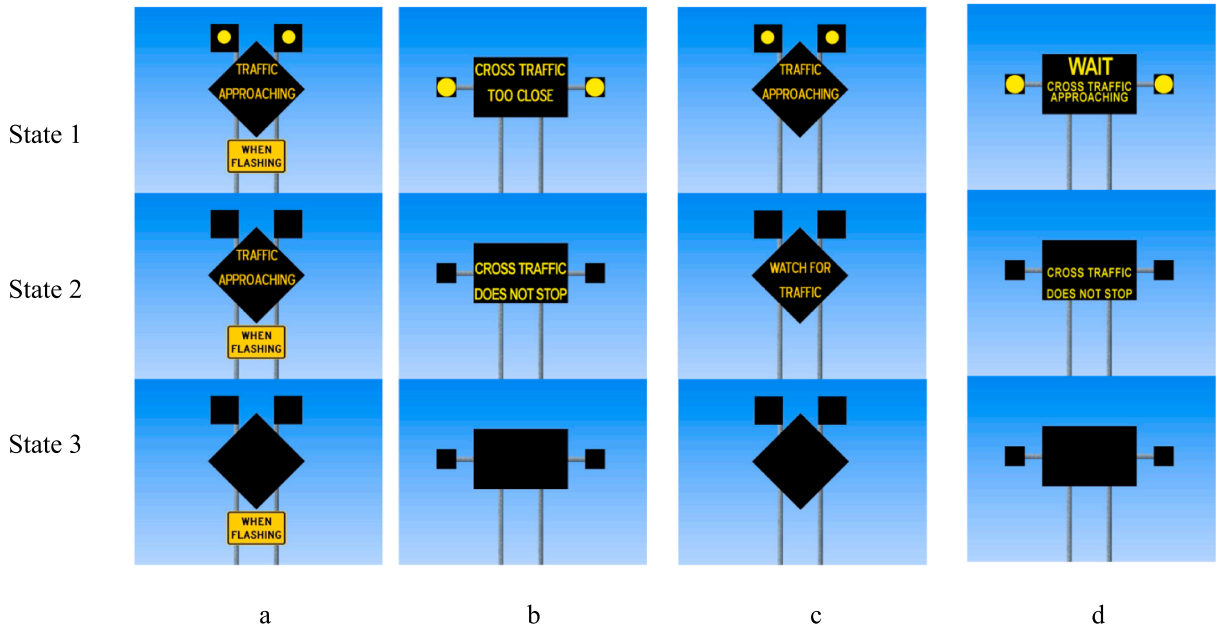

Fig. 2. Three sequence states of the original RICWS design and three alternative RICWS designs tested in the driving simulator (From left to right: a. Original RICWS Design; b. Alternative RICWS Design 1; c. Alternative RICWS Design 2; and d. Alternative RICWS Design 3).

'confusing", "overwhelming", and "always flashing/not functioning" (Tian et al., 2017). With these potential concerns, the MnDOT was unsure about the appropriateness of expanding the existing RICWS interventions (i.e., original design), given a relatively high cost for implementing and maintaining the system. This demonstrated an urgent need for obtaining a comprehensive and thorough understanding of the sign effectiveness, as well as establishing alternative, cost-effective RICWS designs that could better promote sign acceptance and comprehension among drivers. Other important human factor issues associated with the original RICWS design and a description of the development process for alternative RICWS designs can be found in an earlier publication from this study (Tian et al., 2017).

A series of usability studies were established to iteratively evaluate and modify a variety of alternative RICWS designs with the goal of improving upon the original RICWS design. Consequently, three designs with modified terminology and other design elements such as sign layout, shape and font size (See Fig. 2), that had previously received the highest user preferences, were ultimately identified and tested in the driving simulator, in addition to the original RICWS design. Fig. 2 shows all four RICWS designs for each of three sequence states.

2.2.3. Study apparatus

All of the experimental sessions took place in a driving simulator in a controlled laboratory environment, hosted in the HumanFIRST laboratory at the University of Minnesota, Minneapolis campus. Participants were recruited and tested on the simulator during the period from August 2016 to June 2017. Participants' driving performance outcomes were collected using a high-fidelity full-cab driving simulator provided by Realtime Technologies, Inc. (Ann Arbor, Michigan, USA). The driving simulator featured a custom-manufactured Saturn 2002 S-Series passenger vehicle chassis that enabled realistic driving experiences through multiple vehicle controls (e.g., power-assisted steering and resistance-based braking), mirroring systems, and various sensory feedback. (See Tian et al., 2018 for an image of the driving simulator). The SimCreator software (version 2.4), loaded with the simulator, allowed for the establishment of a simulated environment and collection of real-time vehicle information (Realtime Technologies Product Catalog, 2017). A five-channel, 210-degree screen, positioned in front of the vehicle, with peripheral screens around the driving simulator, allowed for projections of the simulated driving environment which shared common road features and surroundings with rural Minnesota. A trial driving session was conducted by six state and county engineers to ensure the simulated environment appropriately represented a rural intersection and realistic traffic conditions for the rural roadway. A modified NASA Task Load Index (NASA-TLX) questionnaire, based on a 1 to 5 Likert scale was administered to rate drivers' perceived workload during the experimental driving sessions (Hart and Staveland, 1988). Self-reported ratings on drivers' mental demand, physical demand, temporal demand, overall performance and overall effort were obtained and assessed.

2.3. Study procedure

The driving simulator study utilized a mixed factorial design that involved a balanced, randomized assignment of participants into four parallel groups upon recruitment. Fig. 3 provides a flowchart of the overall scheme of the study design. As shown in this figure, individuals in each group were exposed to only one of the RICWS designs (i.e., a between-subject factor) – either the Original RICWS Design, Alternative RICWS Design 1, Alternative RICWS Design 2 or Alternative RICWS Design 3. Equivalent numbers of males and females were recruited to each RICWS design group across all drivers' ages, except for the middle-aged (5 males and 6 females) and older (5 males and 4 females) drivers within the original RICWS design group. After participants arrived at the laboratory, they were introduced to the study goals, study procedure, and associated risks, including their right to discontinue at any time throughout the experiment should they feel any discomfort or motion sickness symptoms.

Each participant commenced with one practice drive, consisting of a one-mile road segment and multiple rural intersections to allow the participant to become comfortable with all simulator controls (including stopping/starting) and driving in the simulated rural environment. Additional practice drives were provided as needed. Following the practice drive, were four experimental drives; each drive required between five and seven minutes to complete and included negotiating a sequence of four intersections. The thru-STOP intersections in the first and the third drives were controlled by STOP signs only (i.e., served as Control intersections for the original or each of the alternative RICWS designs), whereas the second and fourth drives contained RICWS signs

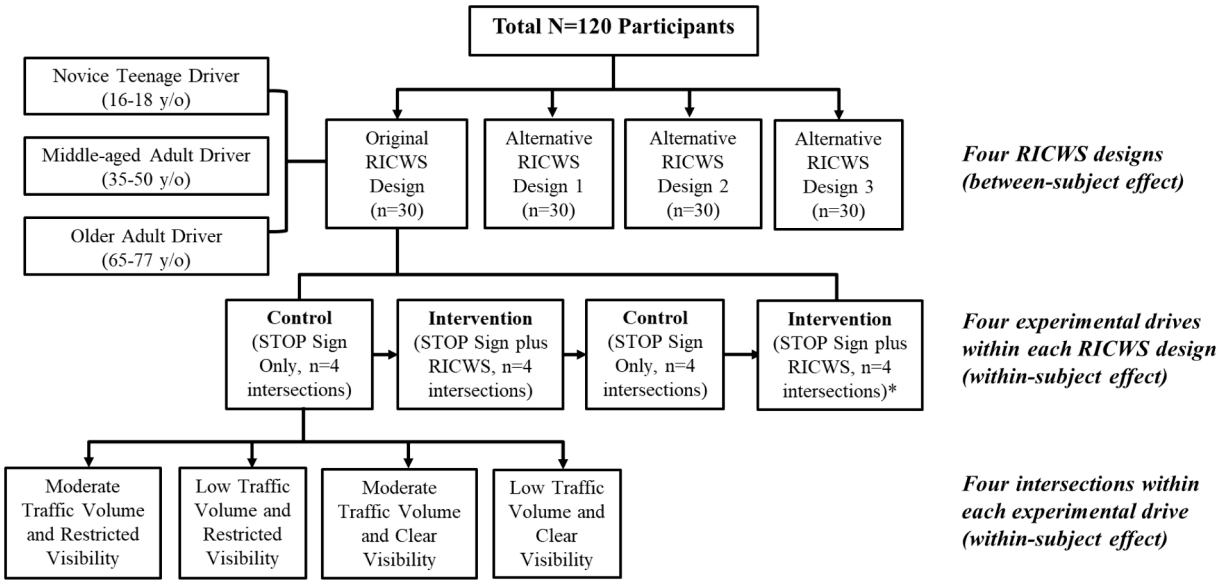

Fig. 3. A flowchart of the overall scheme of the study design.

plus STOP signs at each of the thru-STOP intersections (i.e., RICWS intervention intersections for the original or each of the alternative RICWS designs) (Fig. 3). A fifth thru-STOP intersection was included at the end of the fourth drive to display State 3 ("Sign is off") of the RICWS sign (Fig. 3). To reduce the training effect, in-between each simulated intersection, participants drove on a constructed one-mile minor rural road segment. Participants were instructed to come to a complete stop before travelling straight through all intersections they encountered, as well as to simultaneously avoid potential collisions with traffic on the main roads. For simplicity, no turning maneuvers were investigated in this study. Within each drive, four types of intersections were employed, varying by levels of the mainstream traffic volume and the intersection visibility (Fig. 3). The order of these types of intersections was randomly assigned within each drive.

To maximize the likelihood of observing behavioral adaptations to the system, all of the intersections with malfunctioning RICWS signs (i.e., State 3 or "Sign is off") featured a low level of mainstream traffic volume and clear visibility. Participants' perceived mental workloads were assessed after completing each drive, and their wellness levels against motion sickness were evaluated, as well (Kennedy et al., 1993). Following all testing, participants were presented with all four RICWS sign design options and explicitly informed of the functionalities for each sign state in order to determine their overall preferences of the intersection sign designs. Each participant received $50 compensation for completing this study.

2.4. Definitions of study exposures and outcomes

2.4.1. Study exposures

The primary exposures of interest in this study were the original RICWS sign design and three alternative RICWS sign designs. Driver behaviors obtained at the RICWS intervention intersections were compared with those obtained at the control intersections, respectively, within each group of the Original RICWS Design, Alternative RICWS Design 1, Alternative RICWS Design 2, and Alternative RICWS Design 3. The secondary exposures of interests—drivers' age, mainstream traffic volume, and intersection visibility, were used to investigate the moderating effects of these factors. Measurements were aggregated across all four RICWS sign designs, to compare between RICWS intervention and the control intersections, within each stratum of one moderating variable, while controlling for the other two moderating variables.

To define the moderating variables, the predetermined traffic volume levels were randomly sampled from two discrete gap distributions, ranging from three to nine seconds between-vehicle gaps for moderate traffic volume and from 10 to 16 s gaps for low traffic volume, respectively. The intersection visibility also consisted of two levels: *clear view*, defined as greater than 16-second sight distance to the intersection; and *restricted view*, defined as a 6.5-second sight distance to the intersection. At all restricted view intersections, simulated commercial truck and trees were located on the roadside to block drivers' visibility of the approaching vehicles, whereas no visual obstacles were presented for clear view intersections. Fig. 4 (a, b) provides graphical illustrations of the driving scenarios and the expected trajectories of a participant at two example intersections with varying levels of traffic volume and intersection visibility.

2.4.2. Study outcomes

The primary study outcomes incorporated participants' gap acceptance performance, their driving performance on entering into and crossing the intersection zones, any traffic violation behaviors (i.e., primarily stop sign violations), and the drivers' self-reported mental workloads. The gap acceptance performance at each intersection consisted of five measures, including: 1) the risk of accepting a critical gap at the STOP sign, measured when participants initiated acceleration after they completed a full stop at the STOP sign; 2) the risk of accepting a critical gap at the intersection boundary, which was measured when the participants' vehicles arrived at the inner boundary of the intersection; 3) the risk of a rejected safe gap, which represented the likelihood of participants missing a safe initial gap that should have been selected after they stopped at the STOP sign; 4) the time-to-collision (TTC) measured at the intersection boundary; and 5) the absolute TTC, measured at the center of the intersection. The purpose of evaluating gap acceptance performance at different locations was to help identify potential changes in drivers' decision-making processes and their crossing maneuvers at intervention and control intersections.

In this study, a gap was defined as space (measured in seconds) between two sequential vehicles on the main road; explicitly, the gap provided the maximum time allowed for crossing. TTC was then defined as the remaining time left for participants' vehicles to reach potential collision points with the nearest approaching car on the main road, whereas the absolute TTC represented the entire distance (measured in seconds) between the two vehicles when the middle line of the participants' vehicles passed across the center of the intersection lanes. For

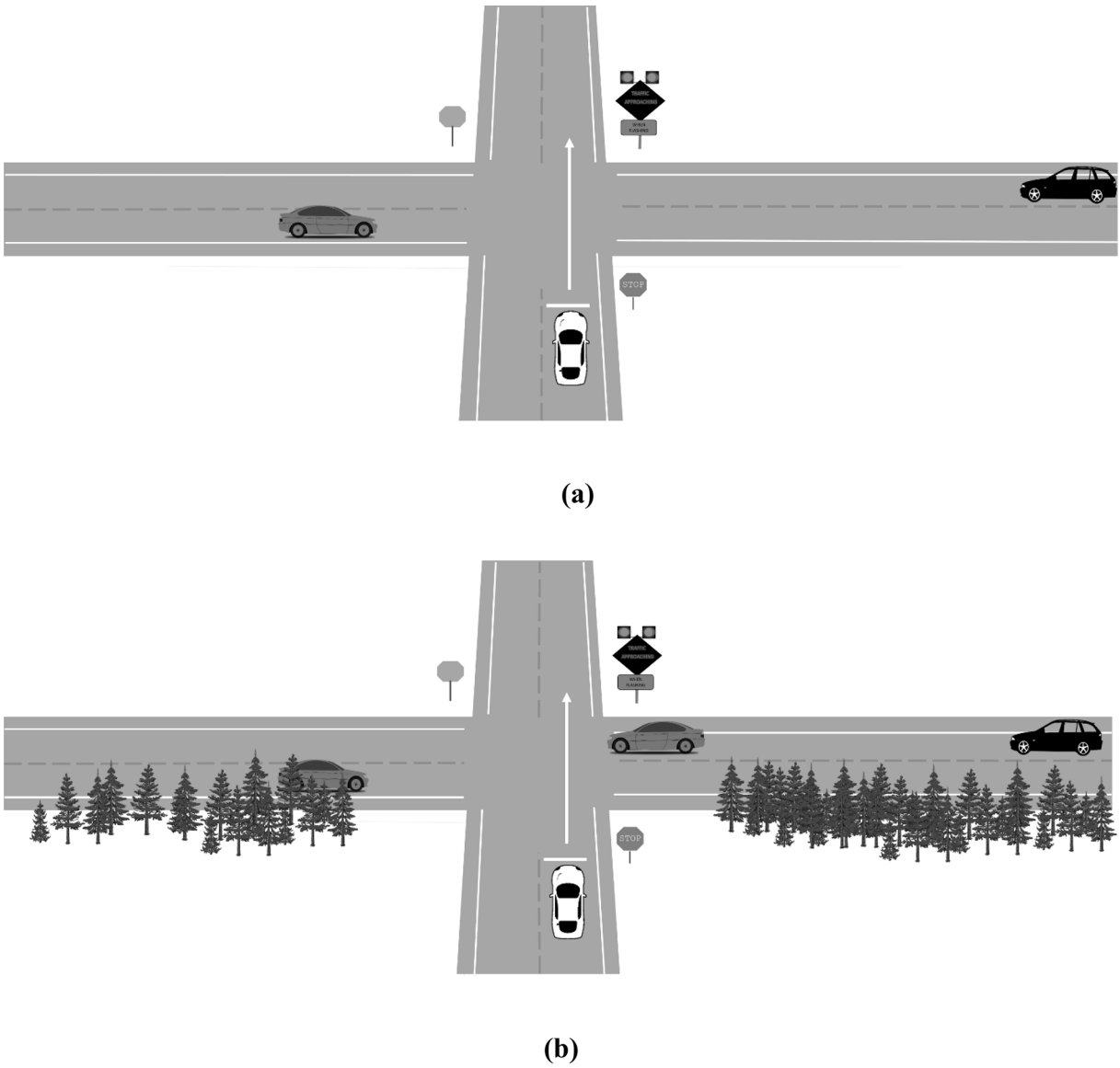

Fig. 4. Graphical illustrations of a driving scenario and the expected trajectory of a participant (a., upper figure) in low traffic volume and with clear visibility; (b., lower figure) in moderate traffic volume and with restricted visibility.

TTC and absolute TTC measures, the smaller value of time selected from the two directions of the mainstream traffic was applied. Furthermore, a vehicle gap, equal to or less than 6.5 s time headway, was considered "critical" by this definition ("gray vehicle" approaching from the right side of the road in Fig. 4.b); otherwise, it was treated as a "safe gap" ("black vehicle" in Fig. 4).

Three driving performance outcomes were also evaluated, including: 1) the participants' mean vehicle speeds (in kilometers per hour or km/h) as they passed through the entrances of the intersection zones; 2) the mean crossing acceleration rates of the participants' vehicles, averaged over the participants' intersection crossings (in meters per square second or m/s^2); and 3) the mean crossing speeds (in kilometers per hour or km/h). Additionally, if the participants failed to comply with the STOP sign (e.g., a rolling stop), then this was assigned as a "1″ for "yes" (versus "0" for "no") for assessing the risk of the stop-sign violation outcomes. The secondary study outcome involved ratings of drivers' self-reported mental workloads when driving through intervention and control intersections.

2.5. Statistical methods

For evaluations of all study outcomes, analyses were stratified by the two levels (i.e., moderate and low) of mainstream traffic volume. This stratification was considered because drivers' gap performances and other driving performances can predominately be determined by the sizes of vehicle gaps available to them (Beanland et al., 2013; Caird and Hancock, 1994; Cooper and Zheng, 2002), which in this study was determined by the levels of traffic volume, given that vehicles on the main roads held a constant traveling speed in the simulation. The moderating effects of drivers' age group (i.e., teenagers, middle-aged adults, and older adults) and intersection visibility (i.e., clear view and restricted view) on the efficacy of the signs were also examined for each traffic volume stratum. Moderation was indicated by statistically significant Type III effects associated with the interaction terms (i.e., Aggregated RICWS Intervention × Age and Aggregated RICWS Intervention × Visibility).

To account for correlations of outcome data within repeated measures on the same participant, the Generalized Estimating Equation (GEE) was applied for all statistical analyses in this study (Zeger et al.,

1988; Zorn, 2001). Log-binomial models were utilized to estimate risk ratios (RRs) and the associated confidence intervals (95% CIs) through comparisons of risks between RICWS intervention intersections and respective control intersections, for evaluating the binary outcomes of interest (accepted critical gaps at the STOP sign, accepted critical gaps at the intersection boundary, rejected safe gaps, and STOP sign violations). Linear models were applied to calculate the mean differences and 95% CIs for continuous outcomes, including the TTCs and driving performance measures. For analyses of drivers' self-reported workload, relative risk ratios (RRRs) were calculated using a series of ordinal logistic regression models to compare the likelihoods of rating a higher workload scale at the RICWS intervention intersections, compared to those at the control intersections. All of the statistical analyses in this study were conducted using SAS software, version 9.4 (SAS Institute Inc., Cary, NC).

3. Results

3.1. Gap acceptance performance

The risks of accepted critical gaps and rejected safe gaps were evaluated in the stratum of moderate traffic volume, only, since all simulated gaps were designed to be safe in the other traffic volume strata. When measured at the STOP sign, participants accepted a total of $n = 165$ (40.8%) and $n = 221$ (52.4%) critical gaps at the RICWS intervention intersections and control intersections, respectively. As shown in Table 1, for Alternative RICWS Design 1, participants' risk of accepting a critical gap was 0.7 times lower when driving through RICWS intervention intersections versus control intersections (RR = 0.70, 95% CI = 0.56 to 0.87). The results also appeared important, though not significant, for the Original RICWS Design and Alternative RICWS Design 3. The total aggregated intervention effect also resulted in a significant decreased risk, using combined data across all four RICWS sign designs (RR = 0.78, 95% CI = 0.68 to 0.90).

The results also revealed how drivers' age and intersection visibility would affect the aggregated RICWS intervention effect. Overall, the aggregated RICWS interventions reduced the risk of accepted critical gaps at STOP signs among the middle-aged (RR = 0.73, 95% CI = 0.60 to 0.90) and older drivers (RR = 0.69, 95% CI = 0.51 to 0.95), but not among teenage drivers. The aggregated effect was significant when intersection visibility was restricted (RR = 0.68, 95% CI = 0.53 to 0.88), and borderline significant when intersection visibility was clear (Table 1).

When measured at the inner boundary of the intersections, drivers had a significantly reduced risk of accepting a critical gap for the Original RICWS intervention Design, only (RR = 0.19; 95% CI = 0.05 to 0.76), compared with control intersections. The moderating effects of drivers' age or intersection visibility on the aggregated RICWS intervention effect was not significant for both accepted gap outcomes, regardless of the locations measured.

Regarding the rejected safe gap measure, drivers' age and intersection visibility were both found to have significantly moderated the aggregated RICWS intervention effect ($\chi^2 = 6.80$, $p = 0.03$ for the interaction term of Aggregated RICWS Intervention × Age; $\chi^2 = 5.09$, $p = 0.02$ for the interaction term of Aggregated RICWS Intervention × Visibility). Specifically, older drivers were 1.10 times more likely to reject versus accept a safe gap at aggregated RICWS intervention versus control intersections (RR = 1.10, 95% CI = 1.01 to 1.21). The aggregated RICWS intervention effects also appeared important, though not significant, among middle-aged drivers, and within both of the intersection visibility levels (Table 1).

Table 2 shows the results of TTC measured at the intersection boundary, as well as the absolute TTC measured at the middle line of the intersections. Minimal differences were detected between the TTC and absolute TTC values, because of the short travel distances between the two measurement locations. Significant moderating effects of age on the aggregated RICWS intervention effect were found for both TTC

Table 1
Results of gap acceptance performance at intervention versus control intersections, under moderate traffic volume conditions, only.

	Total Number=826 intersections		
	Control (STOP Sign Only, *N*=422)	Intervention (STOP Sign + RICWS, *N*=404)	Risk Ratios
	n (%)	n (%)	(95% CIs)
Accepted critical gap at the STOP sign			
Effects within Each RICWS Sign Design			
Original RICWS Design	53 (51.0)	37 (37.0)	0.72 (0.52, 1.01)
Alternative RICWS Design 1	**58 (59.2)**	**38 (41.3)**	**0.70 (0.56, 0.87)**
Alternative RICWS Design 2	50 (44.6)	41 (39.8)	0.89 (0.66, 1.20)
Alternative RICWS Design 3	60 (55.6)	49 (45.0)	0.81 (0.62, 1.06)
Aggregated RICWS Intervention Effects (across all sign designs)			
Total	**221(52.4)**	**165 (40.8)**	**0.78 (0.68, 0.90)**
Within Age Strata			
Teenage drivers	74 (50.7)	59 (42.8)	0.90 (0.71, 1.13)
Middle-aged adult drivers	**84 (61.3)**	**40 (35.7)**	**0.73 (0.60, 0.90)**
Older adult drivers	**63 (45.3)**	**66 (42.9)**	**0.69 (0.51, 0.95)**
Within Visibility Strata			
Clear view	126 (59.7)	103 (50.7)	0.85 (0.72, 1.01)
Restricted view	**95 (45.0)**	**62 (30.9)**	**0.68 (0.53, 0.88)**
Accepted critical gap at the intersection boundary			
Effects within Each RICWS Sign Design			
Original RICWS Design	**11 (10.6)**	**2 (2.0)**	**0.19 (0.05, 0.76)**
Alternative RICWS Design 1	12 (12.2)	7 (7.6)	0.62 (0.24, 1.62)
Alternative RICWS Design 2	6 (5.4)	8 (7.8)	1.45 (0.43, 4.85)
Alternative RICWS Design 3	4 (3.7)	5 (4.6)	1.24 (0.25, 6.17)
Aggregated RICWS Intervention Effects (across all sign designs)			
Total	33 (7.8)	22 (5.4)	0.70 (0.39, 1.24)
Within Age Strata			
Teenage drivers	14 (9.6)	9 (6.2)	0.65 (0.26, 1.60)
Middle-aged adult drivers	9 (6.6)	9 (6.9)	1.05 (0.40, 2.75)
Older adult drivers	10 (7.2)	4 (3.1)	0.44 (0.13, 1.46)
Within Visibility Strata			
Clear view	7 (3.3)	4 (2.0)	

(*continued on next page*)

Table 1 (*continued*)

	Total Number=826 intersections		
	Control (STOP Sign Only, *N*=422)	Intervention (STOP Sign + RICWS, *N*=404)	Risk Ratios
	n (%)	n (%)	(95% CIs)
			0.60 (0.18, 2.01)
Restricted view	26 (12.3)	18 (9.0)	0.73 (0.40, 1.35)
Rejected Safe Gap			
Effects within Each RICWS Sign Design			
Original RICWS Design	59 (53.6)	87 (58.0)	0.97 (0.76, 1.25)
Alternative RICWS Design 1	79 (66.4)	86 (61.4)	0.93 (0.77, 1.11)
Alternative RICWS Design 2	75 (54.7)	70 (53.0)	1.05 (0.82, 1.34)
Alternative RICWS Design 3	89 (65.0)	132 (68.8)	1.01 (0.85, 1.21)
Aggregated RICWS Intervention Effects (across all sign designs)			
Total	302 (60.0)	375 (61.1)	0.99 (0.89, 1.10)
Within Age Strata			
Teenage drivers	51 (41.5)	52 (39.7)	0.90 (0.65, 1.26)
Middle-aged adult drivers	77 (59.2)	73 (50.3)	0.81 (0.65, 1.01)
Older adult drivers	**174 (69.6)**	**250 (74.0)**	**1.10 (1.01, 1.21)**
Within Visibility Strata			
Clear view	265 (75.7)	308 (75.5)	0.95 (0.87, 1.04)
Restricted view	37 (24.2)	67 (32.5)	1.50 (0.97, 2.31)

measures under the low traffic volume condition ($\chi^2 = 13.89$, $p = 0.001$ for TTC and $\chi^2 = 13.98$, $p = 0.001$ for absolute TTC, respectively). Older drivers, when presented with low traffic volumes, tended to have significantly smaller TTC (Mean difference = -1.07, 95% CI = -1.97 to −0.17) and absolute TTC values (Mean difference = -1.11, 95% CI = -1.97, −0.17), at aggregated RICWS intervention versus control intersections. Significant moderating effects of intersection visibility on the aggregated RICWS intervention outcome was only identified for the absolute TTC measure and when the traffic volume was moderate ($\chi^2 = 5.16$, $p = 0.02$ for the interaction term of Aggregated RICWS Intervention × Visibility). However, none of the aggregated intervention outcomes was significant within either of the intersection visibility levels (Table 2).

3.2. Intersection driving performance

As shown in Table 2, under moderate traffic volume conditions, Alternative RICWS Design 3 was the only RICWS intervention design that was associated with a significant increase in drivers' average crossing speed, when comparing RICWS intervention to respective control intersections (Mean difference = 1.30, 95% CI = 0.23 to 2.37). Overall, middle-aged drivers were more likely to travel at greater approach and crossing speeds, as well as exhibit greater crossing accelerations, at the aggregated RICWS intervention versus control intersections (Table 2). No significant effects of the aggregated RICWS intervention outcomes were evident among teenage drivers or older drivers. The moderating effect of age group was only found to be significant for the average approach speed outcome ($\chi^2 = 8.69$, $p = 0.01$ for the interaction term of Aggregated RICWS Intervention × Age). Comparing the aggregated RICWS intervention to control intersections, the mean differences of average crossing speed and crossing acceleration were both found to be significant within each level of intersection visibility, with the differences slightly greater at restricted-view versus clear-view intersections (Table 2). No significant moderating effects of intersection visibility were evident for any intersection driving outcomes.

Under low traffic volume conditions, drivers were more likely to have significantly higher average approach speeds for the Original RICWS Design, the Alternative RICWS Design 1, and the aggregation of all four RICWS signs designs, compared with respective control intersections (Table 2). The aggregated RICWS intervention effect on approach speed was significant within the middle-aged group (Mean difference = 2.35, 95% CI = 0.69 to 3.99) and clear visibility intersection group (Mean difference = 2.40, 95% CI = 1.05 to 3.73) (Table 2). Among all intersection driving performances, none of the moderating effects of age was significant. The results revealed a significant moderating effect of the intersection visibility for the average crossing speed outcome ($\chi^2 = 7.39$, $p = 0.01$ for the interaction term of Aggregated RICWS Intervention × Visibility), yet neither of the strata-specific intervention effects was significant.

3.3. Traffic violation behaviors

Overall, participants demonstrated STOP sign violation behaviors at 4.5% of the intersections (37 of 826), under moderate traffic volume conditions, and 12.1% of intersections (93 of 771) under the low traffic volume conditions, respectively. As shown in Table 3, the risk of violating the STOP sign was significantly higher at the Original RICWS Design intervention compared with respective control intersections when the main road traffic volume was low (RR = 2.18, 95% CI = 1.03 to 4.64). This difference was not significant for any of the alternative RICWS designs, compared to respective controls. Participants were also found to have increased risks of STOP sign violations at clear-view intersections, when comparing aggregated RICWS intervention with control intersections, (RR = 1.62, 95% CI = 1.05 to 2.50). The result also appeared important, though not significant, among novice teenage drivers, and at restricted-view intersections (Table 3). Neither age nor intersection visibility had significant moderating effects on the aggregated RICWS intervention effect.

In addition, the effect of the systems' functionality on drivers' risks of violating STOP signs was also investigated among RICWS intervention intersections only, aggregated across all RICWS designs. The violation rate was 14.7% among intersections implemented with operable RICWS signs (i.e., Sign State 1 and Sign State 2 Combined), and 21.7% for those implemented with malfunctioning RICWS signs (i.e., Sign State 3 or "Sign is off"). Further analysis revealed that drivers' relative risk of failure to stop was 1.4 times higher when they attempted to cross RICWS intervention intersections with malfunctioning, compared with operating RICWS systems (RR = 1.4, 95% CI = 0.9 to 2.3; strata specific data not provided).

3.4. Self-reported workload

Table 4 illustrates the likelihood of having higher ratings on self-reported workload outcomes at RICWS intervention versus control intersections. Compared to respective controls, the reported scales of mental workload were more likely to be lower for Alternative RICWS Design 2, and with combined results from all RICWS designs; however, no difference was observed with the Original RICWS Design. The result

Table 2
Results of gap acceptance performance and intersection driving performance at intervention versus control intersections, stratified by the level of traffic volume.

	Moderate Traffic Volume (N=826 intersections)			Low Traffic Volume (N=771 intersections)		
	Control (STOP Sign Only, *N*=422)	Intervention (STOP Sign + RICWS, *N*=404)	Mean Differences	Control (STOP Sign Only, *N*=405)	Intervention (STOP Sign + RICWS, *N*=366)	Mean Differences
	Mean (SD)	Mean (SD)	(95% CIs)	Mean (SD)	Mean (SD)	(95% CIs)
Gap Acceptance Performance						
TTC at the intersection boundary (in seconds)						
Effects within Each RICWS Sign Design						
Original RICWS Design	5.7 (1.7)	5.6 (1.4)	−0.17 (-0.80, 0.46)	9.3 (3.4)	9.1 (3.0)	−0.24 (-1.35, 0.88)
Alternative RICWS Design 1	5.7 (1.8)	5.6 (1.7)	−0.10 (-0.79, 0.59)	9.3 (2.8)	8.9 (3.1)	−0.32 (-1.66, 1.02)
Alternative RICWS Design 2	5.7 (1.6)	5.7 (1.5)	0.01 (-0.50, 0.52)	9.2 (3.0)	9.0 (2.9)	−0.24 (-1.26, 0.77)
Alternative RICWS Design 3	5.8 (1.5)	5.6 (1.3)	−0.22 (-0.74, 0.30)	8.8 (3.0)	9.1 (2.8)	0.46 (-0.74, 1.66)
Aggregated RICWS Intervention Effects (across all sign designs)						
Total	5.7 (1.6)	5.6 (1.5)	−0.11 (-0.36, 0.14)	9.2 (3.1)	9.1 (2.9)	−0.07 (-0.57, 0.43)
Within Age Strata						
Teenage drivers	5.5 (1.5)	5.5 (1.4)	0.06 (-0.36, 0.48)	8.9 (2.9)	9.2 (3.0)	0.36 (-0.74, 1.29)
Middle-aged adult drivers	5.8 (1.8)	5.6 (1.5)	−0.21 (-0.77, 0.34)	8.8 (2.9)	9.4 (2.9)	0.59 (-0.14, 1.31)
Older adult drivers	5.9 (1.6)	5.7 (1.5)	−0.21 (-0.65, 0.22)	**9.8 (3.2)**	**8.7 (2.9)**	**−1.07 (-1.97, −0.17)**
Within Visibility Strata						
Clear view	6.6 (1.3)	6.3 (1.2)	−0.29 (-0.62, 0.04)	10.3 (2.5)	10.2 (2.4)	−0.14 (-0.74, 0.46)
Restricted view	4.9 (1.6)	5.0 (1.4)	0.04 (-0.32, 0.40)	8.0 (3.1)	8.0 (3.0)	0.01 (-0.73, 0.75)
Absolute TTC (in seconds)						
Effects within Each RICWS Sign Design						
Original RICWS Design	5.4 (1.6)	5.1 (1.4)	−0.25 (-0.77, 0.26)	8.9 (2.8)	8.7 (3.0)	−0.23 (-1.34, 0.88)
Alternative RICWS Design 1	5.3 (1.8)	5.3 (1.6)	−0.01 (-0.64, 0.61)	8.8 (3.4)	8.5 (3.1)	−0.32 (-1.66, 1.01)
Alternative RICWS Design 2	5.2 (1.6)	5.2 (1.5)	0.02 (-0.49, 0.53)	8.8 (3.1)	8.5 (2.9)	−0.25 (-1.26, 0.76)
Alternative RICWS Design 3	5.4 (1.5)	5.2 (1.3)	−0.20 (-0.71, 0.31)	8.4 (3.0)	8.8 (2.8)	0.46 (-0.73, 1.66)
Aggregated RICWS Intervention Effects (across all sign designs)						
Total	5.3 (1.6)	5.2 (1.4)	−0.11 (-0.34, 0.12)	8.7 (3.1)	8.7 (2.9)	−0.07 (-0.57, 0.43)
Within Age Strata						
Teenage drivers	5.0 (1.5)	5.1 (1.4)	0.07 (-0.35, 0.49)	8.5 (2.9)	8.7 (2.9)	0.27 (-0.75, 1.28)
Middle-aged adult drivers	5.5 (1.7)	5.2 (1.5)	−0.26 (-0.75, 0.23)	8.4 (2.9)	9.0 (2.9)	0.59 (-0.14, 1.32)
Older adult drivers	5.5 (1.6)	5.3 (1.4)	−0.14 (-0.53, 0.25)	**9.4 (3.2)**	**8.3 (2.9)**	**−1.11 (-1.97, −0.17)**
Within Visibility Strata						
Clear view	6.2 (1.2)	5.9 (1.2)	−0.32 (-0.62, 0.03)	9.9 (2.5)	9.7 (2.4)	−0.15 (-0.75, 0.45)
Restricted view	4.4 (1.6)	4.5 (1.3)	0.09 (-0.26, 0.44)	7.6 (3.1)	7.6 (3.0)	0.02 (-0.72, 0.76)
Intersection Driving Performance						
Average Approach Speed (kilometer per hour or km/h)						
Effects within Each RICWS Sign Design						
Original RICWS Design	22.5 (7.2)	24.8 (8.0)	1.59 (-0.56, 3.77)	**22.4 (7.7)**	**24 (6.8)**	**1.66 (0.13, 3.17)**
Alternative RICWS Design 1	24.8 (9.5)	25.9 (9.0)	0.84 (-1.80, 3.48)	**24.3 (9.8)**	**26.7 (9.8)**	**2.08 (0.05, 4.12)**
Alternative RICWS Design 2	23.2 (10.0)	24.1 (10.6)	0.68 (-1.56, 2.91)	23.0 (9.5)	25.3 (11.3)	2.56 (-1.06, 6.18)
Alternative RICWS Design 3	22.9 (7.9)	24.5 (9.0)	1.37 (-0.60, 3.33)	23.7 (9.5)	24.6 (8.4)	1.21 (-0.76, 3.17)
Aggregated RICWS Intervention Effects (across all sign designs)						
Total	**23.3 (8.7)**	**24.8 (9.2)**	**1.09 (0.16, 2.04)**	**23.3 (9.2)**	**25.1 (9.2)**	**1.83 (0.79, 2.90)**
Within Age Strata						
Teenage drivers	26.2 (8.5)	27.2 (8.7)	1.08 (-0.39, 2.53)	26.1 (8.7)	28.0 (9.3)	2.40 (-0.21, 5.02)
	25.1 (9.2)	**28.2 (9.5)**		**25.9 (10.3)**	**28.2 (9.0)**	

(*continued on next page*)

Table 2 (*continued*)

	Moderate Traffic Volume (N=826 intersections)			Low Traffic Volume (N=771 intersections)		
	Control (STOP Sign Only, *N*=422)	Intervention (STOP Sign + RICWS, *N*=404)	Mean Differences	Control (STOP Sign Only, *N*=405)	Intervention (STOP Sign + RICWS, *N*=366)	Mean Differences
	Mean (SD)	Mean (SD)	(95% CIs)	Mean (SD)	Mean (SD)	(95% CIs)
Middle-aged adult drivers			**2.64 (0.47, 4.81)**			**2.35 (0.69, 3.99)**
Older adult drivers	18.5 (6.3)	18.5 (5.8)	−0.31 (-1.95, 1.34)	18.0 (5.6)	19.2 (6.0)	0.84 (-0.61, 1.42)
Within Visibility Strata						
Clear view	23.3 (9.0)	24.6 (9.8)	1.08 (-0.34, 2.49)	**23.2 (9.3)**	**25.6 (9.3)**	**2.40 (1.05, 3.73)**
Restricted view	23.2 (8.5)	24.9 (8.5)	1.16 (-0.27, 2.61)	23.5 (9.0)	24.8 (9.2)	1.37 (-0.21, 2.95)
Average Crossing Acceleration (meters per square second or m/s^2)						
Effects for Each RICWS Sign Design						
Original RICWS Design	2.2 (0.5)	2.3 (0.6)	0.10 (-0.10, 0.3)	2.2 (0.5)	2.2 (0.6)	−0.02 (-0.17, 0.13)
Alternative RICWS Design 1	2.1 (0.6)	2.3 (0.6)	0.20 (-0.03, 0.43)	2.1 (0.5)	2.2 (0.5)	0.08 (-0.10, 0.25)
Alternative RICWS Design 2	2.2 (0.5)	2.3 (0.5)	0.08 (-0.08, 0.25)	2.2 (0.5)	2.3 (0.5)	0.08 (-0.08, 0.25)
Alternative RICWS Design 3	2.1 (0.6)	2.2 (0.5)	0.16 (-0.05, 0.37)	2.2 (0.5)	2.1 (0.5)	−0.06 (-0.20, 0.09)
Aggregated RICWS Intervention Effects (across all sign designs)						
Total	**2.1 (0.6)**	**2.3 (0.6)**	**0.13 (0.05, 0.22)**	2.2 (0.5)	2.2 (0.5)	0.02 (-0.04, 0.09)
Within Age Strata						
Teenage drivers	2.1 (0.5)	2.2 (0.6)	0.12 (-0.04, 0.26)	2.1 (0.5)	2.1 (0.5)	0.02 (-0.09, 0.14)
Middle-aged adult drivers	**2.0 (0.6)**	**2.2 (0.5)**	**0.20 (0.03, 0.38)**	2.1 (0.5)	2.2 (0.5)	0.08 (-0.04, 0.22)
Older adult drivers	2.3 (0.5)	2.4 (0.6)	0.09 (-0.08, 0.25)	2.4 (0.5)	2.4 (0.5)	−0.04 (-0.15, 0.08)
Within Visibility Strata						
Clear view	**2.1 (0.6)**	**2.2 (0.5)**	**0.13 (0.02, 0.23)**	2.2 (0.5)	2.2 (0.5)	−0.02 (-0.12, 0.07)
Restricted view	**2.2 (0.6)**	**2.4 (0.5)**	**0.15 (0.02, 0.27)**	2.2 (0.6)	2.3 (0.5)	0.06 (-0.04, 0.13)
Average Crossing Speed (kilometer per hour or km/h)						
Effects for Each RICWS Sign Design						
Original RICWS Design	15.3 (2.9)	16.1 (3.5)	0.85 (-0.16, 1.93)	15.9 (3.2)	16.3 (3.5)	0.19 (-0.64, 1.13)
Alternative RICWS Design 1	14.5 (3.1)	15.4 (2.9)	0.98 (-0.16, 2.09)	15.4 (3.2)	15.6 (2.9)	0.14 (-0.80, 1.13)
Alternative RICWS Design 2	15.3 (2.4)	15.6 (2.9)	0.42 (-0.60, 1.42)	16.1 (3.1)	16.3 (3.1)	0.27 (-0.61, 1.14)
Alternative RICWS Design 3	**14.3 (3.2)**	**15.6 (2.9)**	**1.30 (0.23, 2.37)**	15.8 (3.1)	15.6 (3.2)	−0.11 (-1.09, 0.87)
Aggregated RICWS Intervention Effects (across all sign designs)						
Total	**14.8 (2.9)**	**15.8 (3.1)**	**0.89 (0.42, 1.37)**	15.8 (3.2)	15.9 (3.1)	0.11 (-0.29, 0.51)
Within Age Strata						
Teenage drivers	15.0 (2.9)	15.6 (3.2)	0.66 (-0.18, 1.5)	15.4 (3.2)	15.8 (3.1)	0.14 (-0.66, 0.97)
Middle-aged adult drivers	**14.2 (3.1)**	**15.4 (2.7)**	**1.38 (0.45, 2.32)**	15.3 (3.1)	15.6 (3.1)	0.32 (-0.48, 1.13)
Older adult drivers	15.4 (2.7)	16.1 (3.2)	0.64 (-0.27, 0.96)	16.6 (2.9)	16.6 (3.2)	−0.11 (-0.8, 0.58)
Within Visibility Strata						
Clear view	**15.0 (3.1)**	**15.8 (3.2)**	**0.84 (0.23, 1.45)**	16.9 (2.9)	16.6 (3.2)	−0.32 (-0.92, 0.24)
Restricted view	**14.6 (2.7)**	**15.6 (2.9)**	**0.93 (0.31, 1.54)**	14.6 (2.9)	15.3 (3.1)	0.56 (-0.02, 1.14)

of physical workload appeared important, though not significant, for Alternative RICWS Design 3. The reported scales of visual workload tended to be lower for the Original RICWS Design, Alternative RICWS Designs (Design 1 not statistically significant), and with combined results from all RICWS designs. Drivers were more likely to report lower overall effort when driving with the Original RICWS Design, Alternative RICWS Design 2, and with combined results from all RICWS designs. The likelihood of reporting higher ratings of driving performance increased at intersections that were implemented with the Original RICWS Design (not statistically significant), Alternative RICWS Designs 2 and 3, compared to respective control intersections (Table 4).

Regarding age differences, middle-aged drivers were less likely to report increased ratings of mental workload, visual workload, and overall effort; but, they were more likely to report higher ratings of time pressure, when comparing aggregated RICWS intervention with control intersections (Table 4). Novice teenage drivers were more likely to

Table 3
Results of traffic violation outcomes at intervention versus control intersections, stratified by level of traffic volume.

	Moderate Traffic Volume (N=826 intersections)			Low Traffic Volume (N=771 intersections)		
	Control (STOP Sign Only,*N*=422)	Intervention (STOP Sign + RICW, *N*=404)	Risk Ratios	Control (STOP Sign Only, *N*=405)	Intervention (STOP Sign + RICWS, *N*=366)	Risk Ratios
	n (%)	n (%)	(95% CIs)	n (%)	n (%)	(95% CIs)
STOP Violation						
Effects for Each RICWS Sign Design						
Original RICWS Design	8 (7.1)	9 (8.2)	1.15 (0.43, 3.08)	**10 (8.8)**	**21 (19.3)**	**2.18 (1.03, 4.64)**
Alternative RICWS Design 1	6 (5.8)	6 (6.1)	1.05 (0.54, 2.04)	13 (12.6)	17 (17.3)	1.36 (0.69, 2.67)
Alternative RICWS Design 2	2 (1.8)	2 (1.9)	1.13 (0.17, 7.41)	6 (5.3)	9 (8.5)	1.70 (0.69, 4.22)
Alternative RICWS Design 3	3 (2.7)	1 (0.9)	0.33 (0.03, 3.30)	7 (6.3)	10 (9.1)	1.44 (0.62, 3.36)
Aggregated RICWS Intervention Effects (across all sign designs)						
Total	19 (4.3)	18 (4.3)	0.99 (0.55, 1.76)	**36 (8.2)**	**57 (13.5)**	**1.66 (1.11, 2.47)**
Within Age Strata						
Teenage drivers	8 (5.2)	6 (4.0)	0.78 (0.33, 1.84)	16 (10.4)	26 (17.1)	1.67 (0.92, 3.02)
Middle-aged adult drivers	8 (5.5)	6 (4.4)	0.78 (0.34, 1.80)	14 (9.7)	18 (13.1)	1.35 (0.78, 2.34)
Older adult drivers	3 (2.1)	6 (4.5)	2.10 (0.47, 9.37)	6 (4.2)	13 (9.7)	2.31 (0.87, 6.15)
Within Visibility Strata						
Clear view	9 (4.1)	7 (3.3)	0.80 (0.43, 1.51)	**20 (9.1)**	**31 (14.7)**	**1.62 (1.05, 2.50)**
Restricted view	10 (4.5)	11 (5.2)	1.14 (0.44, 2.97)	16 (7.2)	26 (12.3)	1.71 (0.99, 2.92)

report higher ratings of driving performance (Relative Risk Ratio = 1.65, 95% CI = 1.15 to 2.37), and lower ratings of overall effort (borderline significant) at aggregated RICWS intervention intersections, versus control intersections. Improvements in self-reported driving performance were borderline significant among middle-aged and older drivers (Table 4). The aggregated RICWS intervention effect was significantly moderated by drivers' age group among all self-reported workload measures (p less than 0.01 for all).

4. Discussion

The gap acceptance performance results of the current study may shed light on the complex decision-making process used by drivers to identify appropriate gap sizes, interact with warning signs, and execute crossing maneuvers at different locations. Compared to control intersections, the Original RICWS Design demonstrated its potential to increase driver safety by reducing drivers' likelihoods of accepting critical gaps at the intersection boundary. The alternative RICWS designs did not seem to outperform the Original RICWS Design, except for Alternative RICWS Design 1, which was associated with a significantly lower risk of accepted critical gaps at the STOP sign. In contrast to the Original RICWS design, several of the alternative RICWS designs were associated with reduced self-reported mental workload and improved self-reported overall performance ratings among drivers. Slightly smaller TTC and absolute TTC measures were observed within specific levels of driver's age and intersection visibility at RICWS intervention versus control intersections, and were not significant for any RICWS design. As designed, there were also no actual crash events among all of the driving experiments in the present study. Additional alternative RICWS designs that have received remarkably positive comments among users were described in an earlier effort from this study (Tian et al., 2017); while those designs were not tested in this study, due to the regulatory challenges and restraints, they might serve as potential solutions for further investigations. Future examinations of drivers' visual scanning behaviors may also add important knowledge regarding how drivers acquire and process traffic information from different RICWS designs, as well as how they may execute effective and efficient crossing decisions to further gauge the potential for crashes.

Importantly, a significant increased risk of STOP sign violations was identified among drivers of all ages only with the use of the Original RICWS Design, but not the alternative RICWS designs, when compared to respective controls. Drivers' inappropriate reliance on automated systems could be extremely hazardous, especially if unexpected system failures occur (Parasuraman and Riley, 1997). Nevertheless, this study also identified an elevated risk of stop sign violations when the RICWS signs malfunctioned (i.e., State 3 or "Sign is off" state), versus when they functioned properly (i.e., State 1 or State 2). In this study, participants' comprehension and preferences, regarding each sign state of the four different RICWS designs, were queried by researchers following completion of all simulated driving experiments. Some of the drivers were found to have misinterpreted the messages that the signs with blacked-out displays intended to convey; this included perceiving them as "safe to proceed" and "the other traffic (on the main road) was told to stop." In addition, the identified risk of STOP sign violations is also consistent with a previous simulator study that examined drivers' behavioral adaptation to an intersection crossing advisory system, over time (Dotzauer et al., 2014). In that study, the percentage of stops for the treatment groups decreased from 40% to 23% from the initial training period through the following four weeks (Dotzauer et al., 2014). Therefore, it is recommended that such behavioral risks be sufficiently recognized and assessed in future evaluations of similar conflict warning systems which, in turn, may serve as a basis for potential intervention efforts.

Also important are the moderating effects of drivers' age, mainstream traffic volume, and intersection visibility that may have influenced the intervention systems' efficacy upon combining all four RICWS design interfaces. Specifically, teenage drivers' gap judgments did not seem to be significantly enhanced by the RICWS signs, whereas older drivers tended to accept fewer critical gaps at intervention versus control intersections. Of particular interest, among older drivers, was also

Table 4
Results of drivers' self-reported mental workload, visual workload, time pressure, overall performance and overall effort (Modified NASA-TLX) at intervention versus control intersections.

Drivers' Self-Reported Measures	Control (STOP Sign Only)	Intervention (STOP Sign + RICWS)	Relative Risk Ratios(95% CIs)
	Mean (SD)	Mean (SD)	
Mental Workload			
Effects for Each RICWS Sign Design			
Original RICWS Design	3.0 (1.1)	2.8 (1.1)	0.71 (0.41, 1.23)
Alternative RICWS Design 1	3.1 (1.0)	2.9 (1.1)	0.82 (0.57, 1.18)
Alternative RICWS Design 2	**2.8 (1.1)**	**2.7 (1.2)**	**0.75 (0.57, 0.98)**
Alternative RICWS Design 3	2.6 (1.1)	2.5 (1.0)	0.91 (0.64, 1.29)
Aggregated RICWS Intervention Effects (across all sign designs)			
Total	**2.9 (1.1)**	**2.7 (1.1)**	**0.79 (0.65, 0.97)**
Within Age Strata			
Teenage drivers	2.9 (0.9)	2.8 (1.0)	0.83 (0.62, 1.12)
Middle-aged adult drivers	**2.7 (1.3)**	**2.3 (1.1)**	**0.59 (0.41, 0.84)**
Older adult drivers	3.1 (1.1)	3.1 (1.1)	1.01 (0.69, 1.49)
Physical Workload			
Effects for Each RICWS Sign Design			
Original RICWS Design	1.6 (0.8)	1.7 (0.8)	1.18 (0.79, 1.76)
Alternative RICWS Design 1	1.7 (1.0)	1.7 (0.8)	0.98 (0.70, 1.38)
Alternative RICWS Design 2	1.9 (1.0)	1.8 (1.1)	0.83 (0.59, 1.16)
Alternative RICWS Design 3	1.5 (1.0)	1.6 (0.8)	1.40 (0.95, 2.06)
Aggregated RICWS Intervention Effects (across all sign designs)			
Total	1.7 (0.9)	1.7 (0.8)	1.07 (0.89, 1.29)
Within Age Strata			
Teenage drivers	1.5 (0.7)	1.5 (0.8)	1.13 (0.82, 1.55)
Middle-aged adult drivers	1.4 (0.7)	1.3 (0.6)	0.98 (0.60, 1.59)
Older adult drivers	2.2 (1.1)	2.2 (0.9)	1.01 (0.72, 1.42)
Visual Workload			
Effects for Each RICWS Sign Design			
Original RICWS Design	**3.4 (1.0)**	**2.9 (1.0)**	**0.51 (0.32, 0.81)**
Alternative RICWS Design 1	3.6 (1.1)	3.4 (1.1)	0.74 (0.51, 1.06)
Alternative RICWS Design 2	**3.3 (1.1)**	**2.9 (1.2)**	**0.52 (0.34, 0.79)**
Alternative RICWS Design 3	**3.4 (1.3)**	**3.1 (1.2)**	**0.62 (0.40, 0.96)**
Aggregated RICWS Intervention Effects (across all sign designs)			
Total	**3.4 (1.1)**	**3.1 (1.1)**	**0.59 (0.48, 0.74)**
Within Age Strata			
Teenage drivers	**3.5 (1.0)**	**3.2 (1.0)**	**0.61 (0.41, 0.91)**
Middle-aged adult drivers	**3.2 (1.2)**	**2.8 (1.2)**	**0.55 (0.40, 0.76)**
Older adult drivers	**3.6 (1.1)**	**3.3 (1.1)**	**0.60 (0.41, 0.88)**
Time Pressure			
Effects for Each RICWS Sign Design			
Original RICWS Design	1.4 (0.7)	1.4 (0.7)	1.19 (0.80, 1.78)
	1.5 (0.8)	1.6 (1.0)	
Alternative RICWS Design 1			1.14 (0.79, 1.66)
Alternative RICWS Design 2	1.6 (0.8)	1.5 (0.7)	0.84 (0.54, 1.30)
Alternative RICWS Design 3	1.3 (0.6)	1.4 (0.6)	1.04 (0.58, 1.89)
Aggregated RICWS Intervention Effects (across all sign designs)			
Total	1.4 (0.7)	1.5 (0.8)	1.04 (0.83, 1.31)
Within Age Strata			
Teenage drivers	1.4 (0.7)	1.4 (0.8)	0.96 (0.71, 1.29)
Middle-aged adult drivers	**1.2 (0.6)**	**1.2 (0.5)**	**1.76 (1.07, 2.89)**
Older adult drivers	1.7 (0.8)	1.8 (1.0)	1.03 (0.65, 1.64)
Overall Performance			
Effects for Each RICWS Sign Design			
Original RICWS Design	3.9 (0.9)	4.0 (0.7)	1.49 (0.93, 2.40)
Alternative RICWS Design 1	4.1 (0.7)	4.1 (0.7)	0.99 (0.66, 1.49)
Alternative RICWS Design 2	**3.9 (0.9)**	**4.3 (0.7)**	**2.23 (1.42, 3.51)**
Alternative RICWS Design 3	**3.8 (1.1)**	**4.0 (1.1)**	**1.57 (1.15, 2.14)**
Aggregated RICWS Intervention Effects (across all sign designs)			
Total	**3.9 (0.9)**	**4.1 (0.8)**	**1.49 (1.21, 1.84)**
Within Age Strata			
Teenage drivers	**4.1 (0.7)**	**4.3 (0.6)**	**1.65 (1.15, 2.37)**
Middle-aged adult drivers	4.1 (0.9)	4.3 (0.8)	1.34 (0.99, 1.81)
Older adult drivers	3.6 (1.0)	3.7 (0.9)	1.46 (0.95, 2.26)
Overall Effort			
Effects for Each RICWS Sign Design			
Original RICWS Design	**2.2 (1.0)**	**2.0 (1.0)**	**0.69 (0.52, 0.91)**
Alternative RICWS Design 1	2.3 (1.1)	2.1 (1.1)	0.75 (0.47, 1.20)
Alternative RICWS Design 2	**2.2 (1.1)**	**2.0 (1.1)**	**0.64 (0.44, 0.92)**
Alternative RICWS Design 3	1.9 (1.0)	1.8 (0.9)	0.82 (0.54, 1.26)
Aggregated RICWS Intervention Effects (across all sign designs)			
Total	**2.1 (1.1)**	**2.0 (1.0)**	**0.72 (0.60, 0.88)**
Within Age Strata			
Teenage drivers	2.1 (1.1)	1.9 (1.0)	0.75 (0.53, 1.05)
Middle-aged adult drivers	**1.9 (1.1)**	**1.6 (1.0)**	**0.60 (0.43, 0.84)**
Older adult drivers	2.5 (1.0)	2.3 (1.0)	0.81 (0.59, 1.11)

an increased risk of rejecting more safe gaps, especially in the presence of higher mainstream traffic volumes. This finding further indicated a potentially inefficient use of the signs by these older drivers. One possible reason is that older drivers might become overwhelmed and require additional time to process or respond to the sign information, and, thus, adopt more conservative gap acceptance strategies at these intersections. In addition, a stronger protective effect of the intervention systems was also identified at restricted- versus clear-view intersections. While previous studies suggest that in-vehicle intersection warnings were typically associated with reduced driving speeds (Caird et al., 2008; Cooper and Zheng, 2002; Chen et al., 2011; Hsu and Chuang,

2016; Zhang et al., 2009), slight increases in the intersection approaching and crossing speeds were revealed in this study, particularly under moderate traffic volume conditions. This difference may be explained, in part, by the potential for different information processing mechanisms being applied; while drivers may receive and respond to an in-vehicle warning much earlier in their approach to the intersection, they may need to actively acquire information from an on-road infrastructure, such as the RICWS, after pulling to a complete stop. On one hand, because drivers in the current study reported significantly lower levels of mental and visual workloads, used less overall effort, had improved overall performance, and recorded faster intersection traveling speeds and acceleration at RICWS intervention versus control intersections, these findings suggest that less conservative crossing behaviors were adopted by drivers in the relevant scenarios. On the other hand, Dotzauer et al. (2013) argued that it was not yet conclusive whether such behavioral changes should be interpreted as safer and more efficient versus being characterized as riskier behavior, due to the implementation of a safety countermeasure. Furthermore, higher crossing speeds and accelerations consistently found among middle-aged drivers contributed greatly to the overall increase in both measures across all age groups. Combined with the self-reported findings, middle-aged drivers also perceived significantly higher levels of time pressure with the presence of the RICWS signs, which may, in turn, have resulted in greater driving speeds and accelerations—findings also supported by similar studies (Fitzpatrick et al., 2017; Peer, 2011).

4.1. Advantages and limitations

One advantage of this study is that it presented one of the initial efforts to identify the potential human factors issues associated with the RICWS system use among novice teenage drivers (i.e., minors and not simply young drivers aged 18 and older), at high-risk rural intersections. Specifically, in the current study, observations of the teens' visual performances during the driving experiments revealed a great propensity for obliviousness toward or disuse of the RICWS signs as they drove through the RICWS intervention intersections. These drivers also consistently reported "failing to notice" the RICWS signs or perceived them "to be less useful." Several possible reasons may explain this phenomenon. First, inexperienced teenage drivers may be less knowledgeable of traffic signs (de Waard et al., 1999) and, thus, did not fully recognize the usefulness of the signs. Second, the teens also tended to be cognitively distracted at the intersections and, therefore, may have failed to see the signs or possibly were reluctant to spend time or effort in processing information from them (Neyens and Boyle, 2007). Finally, teenage drivers have been found to underestimate driving risks (Cohn et al., 1995) and tend to place too much trust in their own driving abilities. To increase use, it is of great importance for the design of intersection countermeasures to be easily comprehended and complied with by novice teenage drivers. Such comprehension and compliance require novice teen drivers to be included in early human factors testing of novel road treatments and signage.

Another notable strength of this study is that it provided direct comparisons of drivers' gap selection measures between the STOP sign (i.e., acceleration points), and the inner boundaries of the intersections, which has rarely been analyzed in previous studies. The results indicated significant declines in the proportions of accepted critical gaps between those measured at the STOP sign and those measured at the inner boundary of the intersections (52.4% and 40.8% versus 7.8% and 5.4%, respectively), when the traffic volume was moderate. Combined with the system's functionalities, this finding suggests that drivers did not appear to utilize the same vehicle gap to complete the crossing maneuvers, even within relatively short traveling distances, prior to entering the intersections. A scrutinized inspection further showed that many participants may have been deliberately accelerating when a vehicle was close to the intersection on the main road, then quickly gained speed as the vehicle passed in front of them, and selected the next following gap to complete the crossing. Therefore, critical gap acceptance measurements at the inner intersection boundary may provide a more accurate understanding of the unique dynamic process of gap identification and decision-making for high-risk intersection crossing maneuvers, compared to measurements at the STOP signs. Further investigations are essential to more completely identify drivers' considerations to accept or reject a specific gap in a sequence, as well as the role that similar intervention systems might play in altering such decisions.

There are several possible limitations to this current study. First, the potential effects of drivers' familiarity with the signs used in the study analyses, were not considered (Kantowitz et al., 1997). Because the original RICWS signs had already been implemented in Minnesota, some drivers may have had previous experience with them which could have biased the study results towards an overestimation of the efficacy of the Original RICWS Design, compared to the Alternative RICWS Designs 1–3. Second, according to the theory of human-automation interaction, various levels of system trust can be employed when using an intelligent system, within a wide span, ranging from none to all (Lee and See, 2004). However, the data collected in the current study could not enable identification of individual differences concerning reliance on, and use of the system. The impact of a specific intervention or control drive was not examined, due to modest differences within each group and small cell sizes for certain response variables. Third, selection bias may have occurred in the study, because those who were recruited for the study may not have demonstrated the same driving behaviors as those who were not recruited, and may not have been representative of the general population. In addition, prior familiarity with the original RICWS sign design may have varied among participants. Furthermore, since the study only explored drivers' performances on straight crossings through intersections, the results may have limited generalizability regarding the extent to which the signs might modify turning maneuvers at these intersections.

Several common limitations associated with applications on the driving simulator, versus the real environment, should also be considered. These may include limited perceptual and motor capabilities, the influences of motion sickness, as well as possible limitations of the study reproducibility due to relatively small sample sizes (Kaptein et al., 1996; De Winter et al., 2012; Open Science Collaboration, 2015; Wynne et al., 2019). While there has been some evidence to support the validity of similar simulation technologies against actual vehicle performance under certain driving scenarios (Romano and Schultz, 2004; Parker et al., 2009; Winston et al., 2014), it should also be noted that drivers' behaviors could potentially be influenced by the geometric design in the simulated road settings (Bobermin et al., 2021). For example, Staplin (Staplin, 1995) reported that older drivers might have less accurate speed perceptions and gap judgments for maneuvering intersections in simulated environments. Specifically in the current study, it is also unclear whether drivers, particularly novice teenagers, would process and respond to the warning messages provided by the simulated signs similarly to their real-world performance on the road. Future investigations that compare drivers' behaviors in the simulator to those in field operations may be considered, to improve understanding of the actual effectiveness of the signs. Finally, other factors such as the size and speed of approaching vehicles (Caird and Hancock, 1994; Yan et al., 2007), as well as drivers' intended negotiation maneuvers (Beanland et al., 2013), could also have affected gap acceptance performances and the safety implications of the signs under investigation in this study.

5. Conclusions

The study, using a driving simulator, identified potential benefits and possible risks associated with the use of the original and alternative RICWS designs, from several aspects. Overall, the original RICWS design demonstrated a protective effect of enhancing drivers' gap acceptance performance, as well as reducing their perceived workload. However, it

also appeared to incur an increased risk of STOP sign violation behaviors at clear-view intersections with low traffic volumes, particularly when the signs malfunctioned. With one exception, no apparent improvements in gap acceptance performance were found for Alternative RICWS designs over the original design. The exception was Alternative RICWS Design 1, which was associated with a significantly lower risk of accepted critical gaps at the STOP sign. Drivers also reported reduced mental workload and improved overall performance ratings when using several of the alternative RICWS designs, but not the original design. Combining data across all four RICWS designs, the aggregated RICWS intervention effects on certain driving outcomes were also found to be modified by the levels of mainstream traffic volume, intersection visibility, and drivers' age groups. This study demonstrated methods that can be used to test future design modifications and evaluate similar countermeasures that might be implemented. The study also provides important safety implications related to the development and evaluation of intelligent intersection warning systems that are targeted to the most vulnerable driver populations at high-risk rural intersections.

CRediT authorship contribution statement

Disi Tian: Conceptualization, Investigation, Data curation, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Susan G. Gerberich:** Conceptualization, Supervision, Methodology, Resources, Writing – original draft, Writing – review & editing. **Nichole L. Morris:** Conceptualization, Funding acquisition, Methodology, Supervision, Project administration, Resources, Writing – original draft, Writing – review & editing. **Hyun Kim:** Methodology, Writing – review & editing. **Andrew D. Ryan:** Methodology, Writing – review & editing. **Darin J. Erickson:** Methodology, Writing – review & editing. **Peter A. Easterlund:** Data curation, Software.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest. The contents of this effort are solely the responsibility of the authors and do not necessarily represent the official view of MnDOT, the HumanFIRST Laboratory, NIOSH, CDC, DHHS, or associated entities.

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