Transportation Research Part F 15 (2012) 544–555

Contents lists available at SciVerse ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

Intersection crossing assist system: Transition from a road-side to an in-vehicle system

Ensar Becic [a,*], Michael P. Manser [a], Janet I. Creaser [a], Max Donath [b]

[a] *Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN 55455, United States*
[b] *ITS Institute, University of Minnesota, United States*

ARTICLE INFO

Article history:
Received 25 January 2012
Received in revised form 30 March 2012
Accepted 30 May 2012

Keywords:
Intersection
Driving
Design
Assist system
Aging

ABSTRACT

Due to high vehicle velocities rural intersections have a disproportionately high rate of fatalities. The current study examines the transition from an infrastructure-based rural intersection crossing assist system to one located inside a vehicle. Moreover, we investigate the efficacy of the in-vehicle system. Three different designs of the assist system were examined regarding their impact on driving performance and applicability to varying age groups and visibility conditions. These designs differed in terms of their complexity based on the amount of information that drivers received about the intersection traffic. Seventy-two older and younger participants divided into the three design groups crossed a busy rural intersection in a simulated environment. Drivers completed four blocks of trials in which the presence of the assist system and visibility conditions (limited, clear) were counterbalanced. When presented with the assist system drivers were less likely to accept a smaller gap, especially under low-visibility conditions. The design of the assist system that resulted in the best overall intersection crossing performance was also the most informative about the traffic. Older drivers exhibited some benefits from the presence of the assist system, although not to the same extent as the younger drivers. The results suggest that some infrastructure-based assist or information display systems could successfully be transitioned to inside a vehicle.

1. Introduction

Collision avoidance systems (CASs), such as blind spot monitoring, are rapidly becoming a standard feature in vehicles. The development and design of the CASs has received considerable attention from researchers in both industry and academia. On the other hand, the research on in-vehicle systems which do not warn but instead present driving-related information to drivers has not been as extensive. The design and development of such systems has largely been limited to navigational devices (Dingus et al., 1997) and systems that extend drivers' view of their surroundings (e.g., backing up cameras—Hurtwitz et al., 2009). As the development of advanced communications protocols continues to support the deployment of in-vehicle information systems, such as the Connected Vehicles program the United States, it is increasingly important to investigate the utility of these systems. In the present study, we describe the development and evaluation of an in-vehicle information display system that assists drivers when crossing stop-controlled rural intersections (see Fig. 1). An infrastructure-based (located on a roadside) version of this system already exists (Rakauskas, Creaser, Manser, Graving, & Donath, 2010); the Cooperative Intersection Collision Avoidance System–Stop Sign Assist (CICAS–SSA) monitors gap sizes

---

* Corresponding author. Tel.: +1 6126242877.
E-mail address: ebecic@umn.edu (E. Becic).

1369-8478/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.trf.2012.05.010

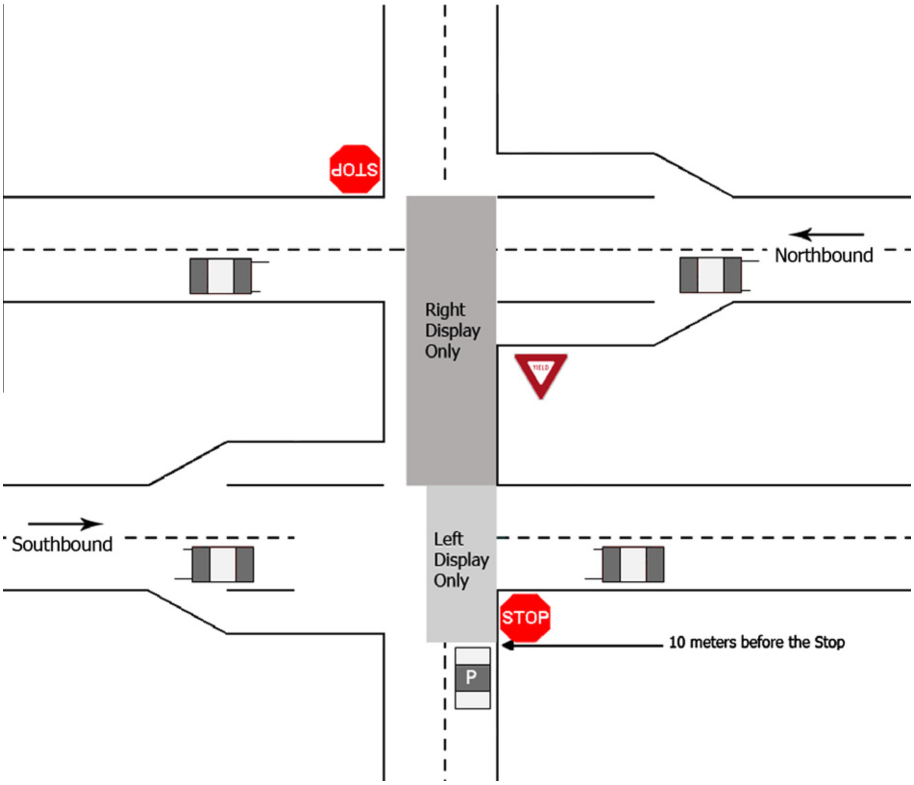

Fig. 1. Representation of the tested intersection with zones of activation for the left and right display of the assist system. *P* indicates the participant's vehicle.

in traffic on a major road and presents that information to a driver located on a minor road. The primary goal of this system is to aid drivers in rejecting small gaps at rural intersections. An existing road sign (i.e., divided highway) served as a basic platform on which the interface for the CICAS–SSA was designed (Laberge, Creaser, Rakauskas, & Ward, 2006). However, the interface of the CICAS–SSA sign located on a roadside may not be the optimal interface to use inside a vehicle.

The existing literature on design and efficacy of in-vehicle collision avoidance systems represents a logical starting point when designing any in-vehicle driver assist system. A multitude of studies examined various warning systems which alert drivers to a variety of potentially dangerous situations (e.g., frontal collision, blind spot detection, lane departure). The methods by which the drivers were alerted to a potential danger also differed. Some warning systems utilized auditory cues to alert the driver (Chang, Lin, Hsu, Fung, & Hwang, 2009; Cummings, Kilgore, Wang, Tijerina, & Kochhar, 2007) while other systems used visual (Mulder, Mulder, van Paassen, & Abbink, 2008; Scott & Gray, 2008), tactile (Kiefer & Hankey, 2008; Mohebbi, Gray, & Tan, 2009), or some combination of the stimuli, creating a bi-modal warning (Ho, Reed, & Spence, 2007; Kramer, Cassavaugh, Horrey, Becic, & Mayhugh, 2007). Spatially relevant cues have also been shown to be effective (Ferris, Penfold, Hameed, & Sarter, 2006), such that a spatially relevant auditory cue (e.g., a tone sounding from the left when departing a lane to the left) was more effective in capturing a driver's attention than a spatially irrelevant auditory cue (e.g., a tone sounding from the location in front of the driver). Another consistent finding reported in the literature relates to the benefit of a bi-modal warning cue compared to a uni-modal cue. Researchers commonly reported faster response times to sudden events when drivers were alerted by a bi-modal signal (e.g., auditory/visual, auditory/haptic) compared to a uni-modal cue (Ho et al., 2007; Kramer et al., 2007), an advantage from which older and younger drivers benefited equally.

1.1. Information display systems

The literature on the CASs could provide natural guidance when designing an in-vehicle assist system, however the findings that apply to the CASs may not necessarily pertain to an in-vehicle system that only presents driving-related information to the driver. The purpose of the CICAS–SSA (roadside or in-vehicle) is somewhat different to that of a typical warning system. The goal of a typical warning system, such as forward collision, is to immediately direct a driver's attention to a potential crash. This high-priority situation also requires a driver's immediate response in order to avoid a crash. Other warning systems may monitor a driver's behavior and provide alerts in the early stages of potentially dangerous situations (e.g., deviating within one's lane). These descriptions of a typical warning system differ from the rural intersection crossing scenario for which the CICAS–SSA was created in one important aspect. The CICAS–SSA displays information regarding the gap of vehicles on a major road and as such does not require a driver to make a quick maneuver in order to avoid a potential collision. That is, the CICAS–SSA is not a warning system, but is instead an information display system. The sign provides a driver with information about gap sizes of vehicles on a major road, however, it is up to the driver to determine if they should act, and when to act (i.e., cross the intersection). The negative consequence of not acting (i.e., not crossing) is nearly non-existent, the driver remains at the stop sign. However, the negative consequence of not acting upon a warning system alert could potentially be fatal.

Some findings from the research conducted on CASs have been successfully applied to information display systems such as a navigational device. Although navigational systems are primarily devices of convenience designed to aid drivers when traversing unknown roads, they can be viewed as information display systems. Most navigational devices use both visual and auditory cues to guide a driver to his destination. The bi-modal navigation has been shown to be more effective when compared to visual only guidance (Bayly, Young, & Regan, 2009; Dingus et al., 1997). Therefore, the general benefit of bi-modal cues is not limited to warning systems only, but also applies to some information display systems such as a navigational device.

1.2. Designing an in-vehicle CICAS–SSA

The benefit of a redundant alert is apparent in the CASs and even in some in-vehicle information display systems; however, should we expect the same benefits in a system like the CICAS–SSA (in-vehicle or infrastructure)? Although effective in the context of a warning system, auditory and/or haptic cues as part of the in-vehicle CICAS–SSA may render the system ineffective or even distracting. The tones or vibrations that may be used to signal a risky/inappropriate gap in the in-vehicle CICAS–SSA would need to be presented for the duration of that gap which, during a rush hour, may last several minutes. Constant or even frequent beeping/vibrations to a situation of which the driver is already cognizant, due to signal saturation, may result in signal inhibition; the driver may learn to ignore those signals (Lahrmann, Madsen, & Boroch, 2001). Also, in this situation the “go signal” for the driver would be the lack of signal, which is harder to detect than the presence of a signal. If tones or vibrations are used to signal only an appropriate gap, at least one potentially confounding situation may occur. In that situation the “go signal” is represented by a tone/vibration, which would conflict with the meaning of tones/vibrations in a typical warning system, where it usually indicates a potential danger. Alternatively, an audio stimulus may be used to signal changes in the state of the system interface. In heavy traffic, the changes occur frequently and in a direction that is not always consistent (they depend on gap size of the next cross-traffic vehicle). Inclusion of three distinct audio stimuli to signal the changes would increase driver’s working memory load while the use of a single audio cue would not be sufficient to determine the direction of the change.

We created three different versions of the in-vehicle CICAS–SSA interface (see Fig. 2), each of which addressed a potential concern. One of the designs represented a direct transition of the infrastructure-based system while the remaining two designs were significantly modified. All three in-vehicle CICAS–SSA designs used two displays to present information about the state of traffic on the major road. The use of a single display to present the in-vehicle CICAS–SSA interface was likely to be ineffective due to diminishing visual field. When the driver turns to the side (e.g., left) to examine the gap size of traffic coming from that direction, the display located centrally would appear in the distant part of driver’s peripheral vision, decreasing their chances of accurately identifying the status of the assist system. For this reason, the in-vehicle CICAS–SSA interfaces were presented on two displays located on the left and right A pillars. This configuration of displays negated the need for eye and/or head movements that would be required when monitoring the interface presented on a centrally located display only. In light of the considerations we presented earlier, the three versions of the in-vehicle CICAS–SSA sign all used visual interfaces and did not rely on any auditory or haptic cues to inform the driver about gap sizes on the major road.

Each of the three designs was developed to address a specific concern associated with crossing a rural stop-controlled intersection, while maintaining the primary goal of providing gap information to the driver. One-stage maneuvers are the most common type associated with crashes at the TH 52 and CSAH 9 test intersection in Minnesota (Preston, Storm, Donath, & Shankwitz, 2004). In a one-stage maneuver, drivers cross the intersection in a single crossing, without making a stop in the median (see Fig. 1). In two-stage maneuvers drivers make a stop at the median before crossing the second set of lanes of traffic. Therefore, the first of the three interfaces of the in-vehicle CICAS–SSA was designed with the intent of promoting two-stage maneuvers. This was accomplished by segmenting the gap-related information presented to the drivers. Presenting a driver with information about the gap sizes for the entire intersection at driver’s initial approach may, in fact, encourage rather than dissuade a one-stage crossing maneuver. We hypothesize that drivers presented with gap information only about the immediate lanes they are about to cross may be more inclined to stop at the median before completing the crossing (i.e., make a two-stage maneuver). The design of the second interface was driven by the consideration that factors such as comprehension and speed of processing may affect the efficacy of the assist system. This was accomplished by presenting a driver with, arguably, the only relevant information when a cross vehicle is too close to the intersection. The final interface represented a direct transition of the infrastructure-based system. Self-reports from the participants in a pilot, on-road study investigating the impact of an infrastructure-based CICAS–SSA suggested that drivers may be more likely to utilize the assist system under low visibility conditions (Becic & Manser, 2011).

An assist system, even one that has shown to be highly effective, may not be utilized in situations when drivers feel highly confident in their own perceptual abilities and motor skills. However, in situations when users’ perceptual faculties are

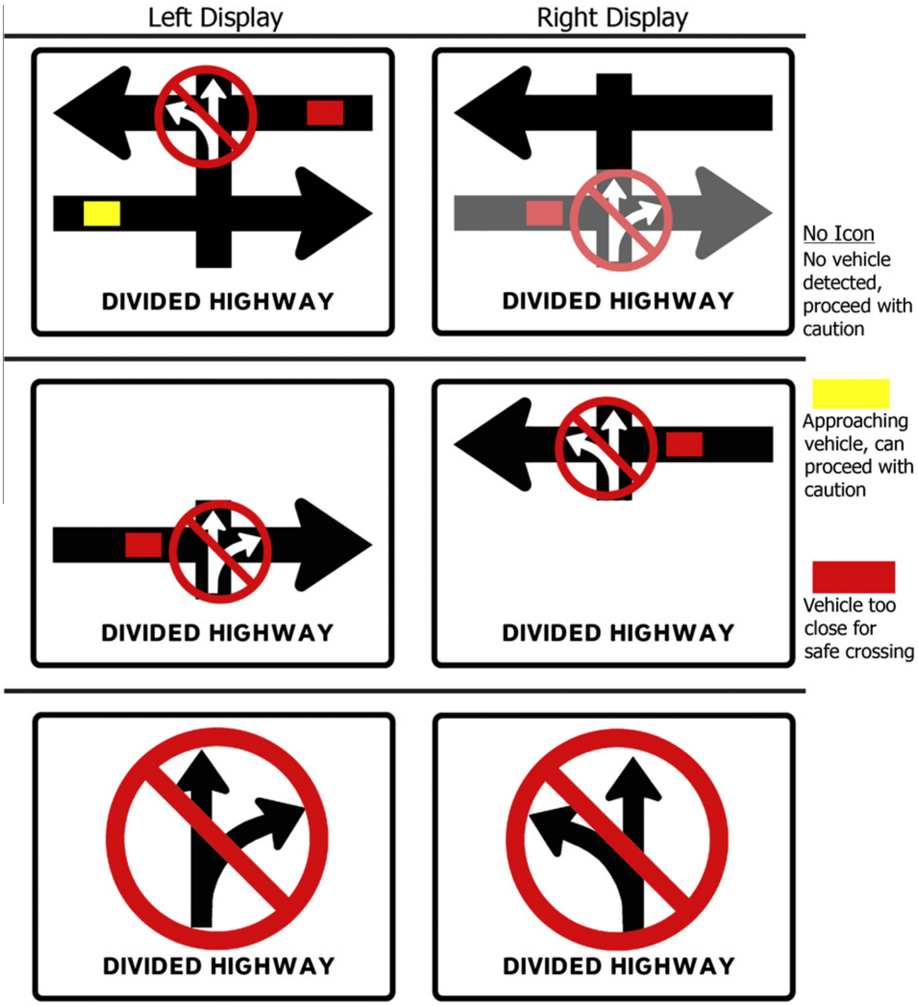

Fig. 2. The three designs of the in-vehicle CICAS–SSA as presented on the left and right displays. The top panel depicts the Complete design showing an approaching vehicle (left display) and no vehicle (right display) on the major road. The lower portion of the right display is greyed out as it represents the lanes of traffic a driver has already crossed. The Divided (middle panel) and the Prohibitive (bottom panel) designs show an inappropriate crossing gap.

limited, such as under high-workload conditions, they may be more inclined to use the system (Wickens & Dixon, 2007), a hypothesis examined through driving under different visibility conditions. Additionally, a successful assist system is one that is beneficial to drivers across age groups, an important factor considering the general cognitive slowing exhibited by older adults (Salthouse, 1996). Therefore, the current study also examines the age-related differences in the use of the in-vehicle CICAS–SSA.

Finally, the need to design and test an in-vehicle support system such as this is important for several reasons. First, the ever increasing presence of the in vehicle warning and information display systems in today's vehicles indicates a trend towards the integration of multiple systems in vehicles. Arguably, the primary benefit of the in-vehicle systems relates to their dynamic nature; such systems can receive and present continually updated traffic-related information. On a larger scale, vehicles with multiple assist, warning or information display systems could create a network of *connected vehicles* with open and constant communication, providing a driver with dynamic and relevant traffic-related information. Second, the infrastructure-based systems can be costly to install and maintain at multiple intersections, especially if we consider that multiple in-vehicle systems can be presented on a single display. Finally, an in-vehicle based intersection crossing system (or other in-vehicle systems) could also be individualized. The critical gap, in the case of the in-vehicle CICAS–SSA, could be adjusted based on driver preferences (older drivers may require longer gaps), weather conditions (icy roads may elicit slower starts, thus requiring longer gaps) or even vehicle type (vehicles with trailers may require different critical gap compared to a sports car).

The current study is part of a larger research project involving the development and evaluation of the CICAS–SSA technology and concept. While earlier research efforts explored the design and implementation of the system located within the infrastructure (Creaser, Manser, Rakauskas, & Donath, 2010; Gorjestani, Menon, Cheng, Shankwitz, & Donath, 2010;

Rakauskas et al., 2010), the current study represents the first step in transitioning the CICAS–SSA to an in-vehicle system. The primary goal of the current study is to examine the effectiveness of three different interfaces of the in-vehicle CICAS–SSA on rural intersection crossing performance in a simulated environment. The three designs differ in their complexity, determined by the amount of information presented to the driver. Additionally, we examine the impact of visibility conditions on drivers' use of the in-vehicle CICAS–SSA, as well as explore any age-related effects that may arise.

2. Methods

2.1. Participants

Seventy-two adults participated in this study, dichotomized into two age groups: 36 older participants between the ages of 60 and 86 (18 women, 18 men; with a mean age of 66 and sd = 6.2 years) and 36 younger participants between the ages of 18 and 29 (17 women, 19 men; with a mean age of 22.8 and sd = 2.7 years). The younger and older drivers had an average of 13.7 and 15.3 years of education, respectively. All the participants possessed a valid driver's license, normal or corrected-to-normal vision (visual acuity of at least 20/40, normal color vision) and no previous history of disorders predisposing them for motion sickness (e.g., epilepsy). Participants were compensated $40 for their 2-h long participation.

2.2. Materials and apparatus

2.2.1. Driving simulator

This study was conducted in a partial motion-base driving simulator manufactured by Realtime Technologies, Inc. The simulator consisted of a 2002 Saturn SC2 full vehicle cab featuring realistic control operation and instrumentation including power assist for the brakes and force feedback for the steering. Haptic feedback was provided by car body vibration and a three-axis electric motion system producing roll, pitch and yaw motion within a limited range of movement. The auditory feedback was provided by a 3D surround sound system. The driving environment was projected to a five-channel, 210° forward visual field screen (2.5 arc-minutes per pixel) with rear and side mirror views provided by a rear screen and vehicle-mounted LCD panels, respectively. The simulator software generated a replica of Trunk Highway 52 and County State Aid Highway (CSAH) 9 intersection, near Cannon Falls, Minnesota. The cross traffic vehicles drove at the posted speed limit of 65 m/h and consisted of heavy trucks (∼10%) and passenger vehicles (∼90%). The traffic density on the major road resembled the actual traffic flow at the intersection of TH 52 and CSAH 9. Within the constraints of the current study, the appropriate traffic flow was achieved by predetermined distribution of gaps of the approaching cross-traffic vehicles. This gap was derived from time-to-contact (TTC) which was determined by the velocity of the cross-traffic vehicle and its distance from the center of the intersection. The cross-traffic vehicles in the current study had the following distribution of gaps: 35% of gaps had TTC of 3 s or less, 20% of gaps had TTC greater than 3, but less than 6 s, 15% of gaps had TTC between 6 and 8 s, and 30% of gaps had TTC between 8 and 11 s. The gaps of the cross-traffic vehicles were randomly selected based on this distribution.

2.2.2. Displays

The three in-vehicle CICAS designs were presented on two displays located on the bottom half of the left and right A pillars of the simulator vehicle and were oriented towards the driver. The displays were Samsung i9000 Galaxy S mobile-phones using an Android platform with the diagonal screen size of four inches. When drivers turned to the right/left to examine the traffic coming from that direction, they were able to also observe the information presented by the assist system located on the right/left display. The information that was presented on the displays depended on the current gap sizes of the vehicles on the major road, while the activation of the displays depended on the location of the driver (see Fig. 1). When crossing the intersection, only one of the displays was active at any one time. When the participant's vehicle approached the stop sign, the left display turned on and started presenting information regarding the gap sizes of vehicles on the major road. The left display continued presenting information until the participant's vehicle entered the median at which time the left display turned off and the right display became active and started presenting gap size information.

2.2.3. Critical crossing gap

The three different designs of the in-vehicle intersection crossing assist system were derived from the infrastructure-based CICAS–SSA sign (Creaser et al., 2010; Rakauskas et al., 2010) with varying levels of modification. The critical gap presented on all three interfaces was defined as any gap below the threshold of 7.5 s, the same gap that was used in previous studies examining the intersection crossing at the TH 52 and CSAH 9 (Creaser et al., 2010; Rakauskas et al., 2010). This value was derived from the observations of traffic at this intersection where it was concluded that a vast majority of drivers reject gaps below a certain threshold, determined to be 7.5 s (Gorjestani et al., 2010).

2.2.4. Designs of the in-vehicle CICAS–SSA Sign

2.2.4.1. Complete CICAS–SSA. The Complete CICAS–SSA interface represented a direct transition from the infrastructure-based CICAS–SSA design. Like the infrastructure-based system, the Complete CICAS–SSA sign used icons to illustrate the presence of a vehicle on the major road. The top panel of Fig. 2 shows an approaching vehicle state (i.e., with the yellow icon) of the

Complete CICAS–SSA, as presented on the left display. Red and yellow icons were used to signal the presence of vehicles on the major road. The yellow icon indicated that a cross-traffic vehicle was approaching the intersection (i.e., gap between 7.5 and 11 s) and the driver should exercise caution when crossing. As the cross-traffic continued to get closer, the yellow icon was replaced by a red icon (i.e., gap less than 7.5 s) indicating to the driver that they should not proceed because a cross-traffic vehicle was too close to the intersection. The lack of an icon indicated that the system did not detect a cross-traffic vehicle within its sensor rage (i.e., gap greater than 11 s).

2.2.4.2. Divided CICAS–SSA. Since one-stage maneuvers are the predominant type associated with crashes at TH 52 and CSAH 9 intersection (Preston et al., 2004), the Divided CICAS–SSA sign was designed to reduce the rate of one-stage maneuvers. It is possible that presenting a driver with information about both the near and far lanes of traffic at the stop sign (e.g., Complete design) could do very little to dissuade a single-stage maneuver. The Divided version of the sign split the upper and lower portions of the Complete CICAS–SSA sign and presented them separately on the left and right display (see middle panel of Fig. 2). In the Divided CICAS–SSA interface, participants were presented with information about gap sizes only for the lanes of traffic they were about to cross, not for the upcoming lanes.

2.2.4.3. Prohibitive CICAS–SSA. Although the CICAS–SSA has been shown to be easily and readily comprehended (Creaser et al., 2010), it is possible that the interpretation of the original CICAS–SSA sign was not instantaneous. The ease and speed of comprehension are important factors for any assist system and it may be possible to improve the speed of comprehension of the in-vehicle CICAS–SSA. The Complete and Divided versions of the system inform the driver not only when a vehicle on the major road is close to the intersection, but also when the system detects any approaching vehicles. It could be argued that the only information of high priority relates to the presence of vehicles on the major road that are close to the intersection. Presenting the driver with less information may reduce information processing time, resulting in faster decision making about intersection crossing. To accomplish this, the design of the in-vehicle Prohibitive CICAS–SSA sign presents only the "inappropriate crossing gap condition" (see bottom panel of Fig. 2) separately for the two directions of traffic. The "do not cross/turn" images are elements of the other two in-vehicle CICAS–SSA interfaces and since they are acknowledged icons in transportation, they should be familiar to drivers.

2.3. Procedure

Participants completed a practice drive before proceeding to the experimental portion of the study. In the practice drive participants crossed the tested intersection without the assist system and continued driving on a county road until they felt comfortable with the dynamics of the vehicle. Older and younger participants were randomly assigned into one of the three interface groups (i.e., designs of the assist system), such that each interface group consisted of 12 older and 12 younger participants. Driving performance was examined through a trial-based driving task in which participants were asked to approach the intersection, stop at the stop sign and then cross the intersection in a safe and timely manner. Since the vast majority of crashes at this intersection occur during an attempt to make a complete crossing (Preston et al., 2004), the current study does not examine right- and left-turn maneuvers. Participants were provided with a detailed explanation of the purpose and the function of the system and were instructed to use the system or not, according to their preference. Each trial ended after the participant crossed the intersection. Participants completed 16 intersection crossings, half with the assist system turned on and the rest with the system turned off. In half of the trials, the participants crossed the intersection under limited visibility conditions (i.e., fog partially obscured the visibility of the cross traffic) while in the rest of the trials the visibility was clear, day-time like. The 16 trials were divided evenly between the four blocks and counterbalanced using a Latin square design.

3. Results

Intersection crossing driving performance was examined separately for the crossing of the southbound (i.e., stop sign as the starting position) and the northbound (i.e., the median as the starting position) lanes, as the same performance measures may differ across the two sets of lanes. Although we may observe an impact of crossing different lanes of traffic (e.g., longer wait time when crossing the southbound lanes), such findings would not be of sufficient interest to justify the inclusion of another factor in the analyses. Driving performance was assessed through four measures. *Weighted accepted critical gap* represented the weighted proportion of trials in which a participant crossed the intersection when time-to-contact (TTC) was less than the critical gap threshold of 7.5 s. The calculations for the accepted critical gap were performed for seven different bins in which TTC of the accepted gap ranged, in one second intervals, from less than 1.5 s to less than 7.5 s. Accepting a critical gap smaller than 7.5 s was assigned a weight of 1 (i.e., 7.5/7.5), while accepting a critical gap smaller than 1.5 s was assigned a weight of 5 (7.5/1.5). *Likelihood of stopping* indicated the proportion of trials in which a participant made a complete stop at the stop sign or while passing through the median. *Wait Time* was defined as the time between a complete stop at the stop sign or median and the start of the intersection crossing. Trials in which a participant failed to make a complete stop were not included in the analysis. *Rejected non-critical gap* represented the proportion of times that a driver failed to cross the intersection when the gap was greater than the critical gap threshold of 7.5 s. Each measure was submitted to a

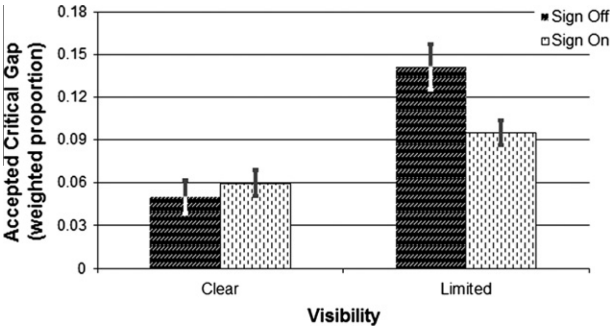

Fig. 3. Proportion of accepted critical gap when crossing the southbound lanes as a function of Visibility and Sign State with standard error bars.

four-way mixed-mode ANOVA with Age (Older, Younger) and Design of the in-vehicle CICAS–SSA (Complete, Divided, Prohibitive) as between-subject factors and Visibility (Clear, Limited) and Sign State (Sign On, Sign Off) as within-subject factors comprising a $2 \times 3 \times 2 \times 2$ design. Prior to conducting the analyses, data were examined for outliers (more than two standard deviations from a mean), however none were present.

3.1. Accepted critical gap

3.1.1. Southbound

The results of this analysis revealed a significant main effect of Visibility ($F(1,66) = 41.16$, $p < .001$, $\eta\rho^2 = .384$). When crossing the southbound lanes drivers were more likely to accept a critical gap under limited visibility conditions (.118 weighted proportion of trials) compared to good visibility (.055 weighted proportion of trials). Furthermore, this analysis also showed a significant Sign State × Visibility interaction ($F(1,66) = 6.7$, $p = .012$, $\eta\rho^2 = .092$). As illustrated in Fig. 3, under limited visibility conditions the drivers were less likely to accept a critical gap when the in-vehicle CICAS–SSA sign was turned on compared to the Sign Off condition ($F(1,66) = 6.12$, $p = .015$; M = .14 and .09 weighted proportion of trials for Sign Off and Sign On conditions, respectively). The impact of Sign State was not significant in the clear visibility condition ($p > .4$).

3.1.2. Northbound

The analysis of the accepted critical gap measure for crossing of the northbound lanes uncovered significant main effects of Sign State ($F(1,66) = 12.53$, $p = .001$, $\eta\rho^2 = .16$) and Visibility conditions ($F(1,66) = 48.44$, $p < .001$, $\eta\rho^2 = .423$). The drivers were less likely to accept a critical gap when crossing the northbound lanes when the in-vehicle CICAS–SSA sign was turned on compared to the Sign Off condition ($M = .06$ and .08 weighted proportion of trials, respectively). Following the pattern found when crossing the southbound lanes, drivers were more likely to accept a critical gap under limited visibility conditions (.1 weighted proportion of trials) compared to good visibility conditions (.05 weighted proportion of trials). This analysis revealed another significant main effect, that of Design of the sign ($F(2,66) = 3.65$, $p = .031$, $\eta\rho^2 = .1$). Drivers in the Prohibitive design group were more likely to accept a critical gap (.089 weighted proportion of trials) compared to those drivers in the Divided (.068 weighted proportion) and in the Complete design (.064 weighted proportion) groups. The pairwise comparisons revealed a significant difference between the Complete and the Prohibitive design groups ($p = .014$) as well as between the Divided and the Prohibitive design groups ($p = .039$). The accepted critical gap was comparable between the Complete and Divided design groups ($p > .6$).

The analysis of the accepted critical gap for crossing of the northbound lanes revealed several interactions involving the Sign State factor. State of the sign interacted with Age ($F(1,66) = 9.09$, $p = .004$, $\eta\rho^2 = .121$). As illustrated in Fig. 4, younger

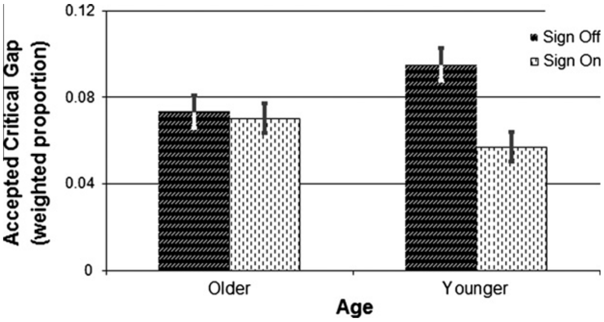

Fig. 4. Proportion of accepted critical gap when crossing the northbound lanes as a function of Age and Sign State with standard error bars.

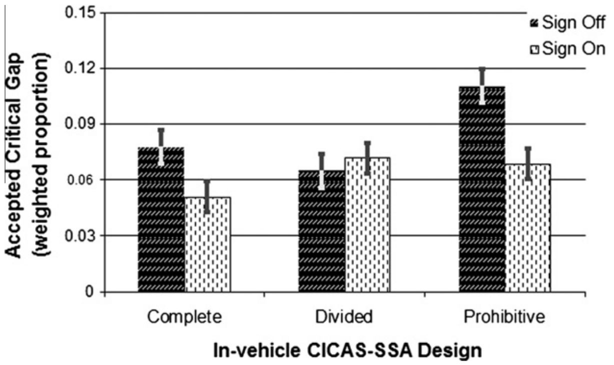

Fig. 5. Proportion of accepted critical gap when crossing the northbound lanes as a function of Design of the in-vehicle CICAS–SSA and Sign State with standard error bars.

drivers were less likely to accept a critical gap when the system was turned on compared to the Sign Off condition ($F(1,33) = 25.55$, $p < .001$; M = .057 and .095 weighted proportion for Sign On and Sign Off conditions, respectively). However, for older drivers, the accepted critical gap measure was not affected by the state of the sign ($p > .7$).

Sign State also interacted with the Design of the sign ($F(2,66) = 6.15$, $p = .004$, $\eta\rho^2 = .157$). Fig. 5 shows that the drivers in the Complete design group were less likely to accept a critical gap when crossing the northbound lanes when the in-vehicle CICAS–SSA was turned on compared to the Sign Off condition ($F(1,22) = 8.21$, $p = .009$; M = .05 and .077 weighted proportion of trials, respectively). The state of the sign did not impact the accepted critical gap for the participants in the Divided design group ($p > .3$) However, for the participants in the Prohibitive design group the accepted critical gap was affected by the Sign State factor ($F(1,22) = 10.7$, $p = .003$). When presented with the Prohibitive design participants were less likely to accept a critical gap (.068 weighted proportion of trials) compared to the Sign Off condition (.11 weighted proportion of trials).

The accepted critical gap measure revealed a significant Sign State × Visibility interaction ($F(1,66) = 6.96$, $p = .01$, $\eta\rho^2 = .095$). Under the conditions of limited visibility, the drivers were less likely to accept a critical gap when the in-vehicle CICAS–SSA sign was turned on compared to the Sign Off condition ($F(1,66) = 16.33$, $p < .001$; $M = .083$ and .118 weighted proportion of trials for Sign On and Sign Off conditions, respectively). The impact of the Sign State factor, similar to the findings when crossing the southbound lanes, was not significant under clear visibility conditions ($p > .3$).

Finally, this analysis revealed a significant three-way interaction between Sign State, Visibility, and Design of the sign ($F(2,66) = 5.7$, $p = .005$, $\eta\rho^2 = .147$). As Fig. 6 shows, the Design × Sign State interaction was significant under the conditions of limited visibility ($F(2,66) = 8.91$, $p < .001$), but not under clear visibility conditions ($p > .19$). This 3-way interaction provides further insight into the Design × State Sign interaction as examined in Fig. 5. The Design × Sign State interaction is present only in the low visibility conditions, just as the overall effect of Sign State exists only when visibility is limited.

3.2. Likelihood of stopping

3.2.1. Southbound

The results of the likelihood of stopping analysis revealed a significant effect of Sign State ($F(1,66) = 5.53$, $p = .022$, $\eta\rho^2 = .077$). Drivers were more likely to make a complete stop at the stop sign when the sign was turned on (.91 proportion of trials) compared to the Sign Off condition (.87 proportion of trials). This analysis also showed an age-related main effect

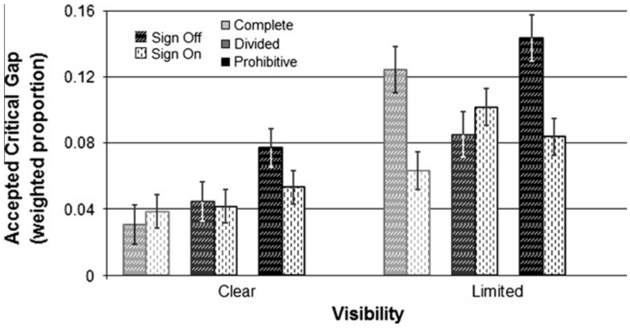

Fig. 6. Proportion of accepted critical gap when crossing the northbound lanes as a function of Visibility, Design of the in-vehicle CICAS–SSA and Sign State with standard error bars.

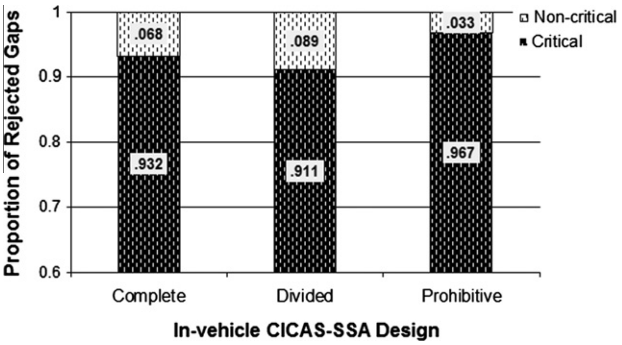

Fig. 7. Proportion of rejected critical and non-critical gaps when crossing the northbound lanes as a function of Design of the in-vehicle CICAS–SSA.

($F(1,66) = 4.31$, $p = .042$, $\eta\rho^2 = .061$). Older drivers were more likely to make a complete stop at the stop sign compared to their younger counterparts (.93 and .86 proportion of trials for older and younger drivers, respectively).

3.2.2. Northbound

The likelihood of stopping before crossing the northbound lanes of traffic indicates the type of the crossing maneuver drivers made (i.e., one- or two-stage). This analysis failed to uncover any significant main effects or interactions, indicating that drivers in the three design groups did not differ in their adoption of two-stage maneuver, but also that none of the designs were effective in promoting the two-stage crossing, as evidenced in the lack of Sign State effect.

3.3. Rejected non-critical gap

3.3.1. Southbound

This analysis showed a significant main effect of Age ($F(1,65) = 8.14$, $p = .006$, $\eta\rho^2 = .111$) exemplifying older drivers' tendency towards a more conservative driving style. Older drivers rejected more non-critical gaps (i.e., greater than 7.5 s) compared to younger drivers (.12 and .08 proportion of rejected gaps were non-critical for older and younger drivers, respectively). The larger proportion of rejected non-critical gaps can be an indication of more conservative driving; older drivers waited for a gap that was greater than the one considered minimally acceptable by the assist system.

3.3.2. Northbound

This analysis revealed a significant main effect of Visibility ($F(1,62) = 28.79$, $p < .001$, $\eta\rho^2 = .317$). When driving in the low visibility conditions, only .04 of all the gaps that drivers rejected were non-critical (i.e., greater than 7.5 s) compared to .09 when driving under clear visibility conditions. The limited visibility made it difficult for the drivers to detect the cross traffic vehicles located more than 7.5 s from the intersection. This failure to detect a cross-traffic vehicle at a distance just beyond the critical gap threshold could be the likely source of the Visibility main effect. Additionally, this analysis also revealed a significant main effect of Design of the sign ($F(2,62) = 5.12$, $p = .009$, $\eta\rho^2 = .142$). As illustrated in Fig. 7, of all the gaps that the participants in the Complete design group rejected, .07 of them were non-critical gaps (i.e., gaps greater than 7.5 s) compared to .09 for the participants in the Divided group and .03 for the participants in the Prohibitive group. The pairwise analyses showed that the differences between the participants in the Prohibitive and Complete groups ($p = .046$), as well as between the Prohibitive and Divided groups ($p = .002$) were significant. The participants in the Complete and Divided design groups exhibited a more conservative driving behavior by rejecting more non-critical gaps.

3.4. Wait time

3.4.1. Southbound

The wait time analysis revealed a significant effect of Visibility ($F(1,65) = 4.58$, $p = .036$, $\eta\rho^2 = .066$). The drivers waited longer to cross the southbound lanes under clear visibility conditions (17.5 s) compared to driving under limited visibility conditions (14.7 s). This analysis also showed a significant effect of Sign State ($F(1,65) = 11.28$, $p = .001$, $\eta\rho^2 = .148$). When any of the in-vehicle CICAS–SSA designs was turned on drivers waited longer to cross the intersection compared to the Sign Off condition ($M = 12.6$ and 19.6 s, respectively). As expected, this analysis revealed that older drivers waited longer when crossing the southbound lanes (21.4 s) compared to their younger counterparts (10.8 s) as exhibited by a significant main effect of Age ($F(1,65) = 9.27$, $p = .003$, $\eta\rho^2 = .125$). The analysis of the wait time measure revealed a couple of significant interactions involving Sign State. One of those interactions included the Age factor ($F(1,65) = 5.69$, $p = .02$, $\eta\rho^2 = .081$). As depicted in Fig. 8, although both older and younger drivers waited longer to cross the southbound lanes when the system was turned on, the effect of the sign was less substantial for younger drivers ($F(1,35) = 5.94$, $p = .02$; difference of 2 s) compared to their older counterparts ($F(1,34) = 7.86$, $p = .008$; difference of 12 s).

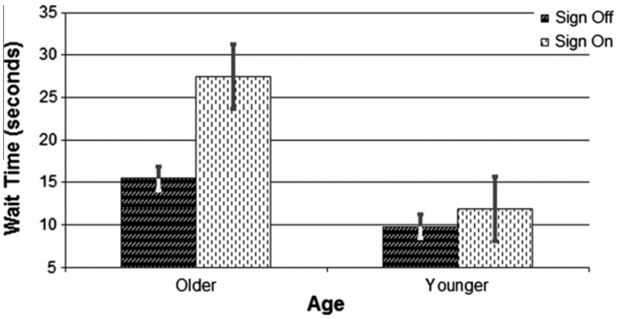

Fig. 8. Wait time before crossing the southbound lanes as a function of Age and Sign State with standard error bars.

Additionally, this analysis showed a significant interaction involving Sign State and Visibility conditions ($F(1,65) = 11.39$, $p = .001$, $\eta\rho^2 = .149$). This interaction followed a similar pattern as the Visibility × Sign State interaction for other measures in that the impact of the sign was greater under limited visibility condition. In the low visibility conditions drivers waited longer to cross the southbound lanes when the sign was turned on compared to the Sign off condition ($F(1,65) = 13.91$, $p < .001$; $M = 20.1$ and 9.3 s, respectively). The state of the sign did not have an impact on wait time in clear visibility conditions ($p > .07$).

3.4.2. Northbound

This analysis revealed nearly identical findings as the wait time measure for crossing of the southbound lanes. This analysis uncovered significant main effects of Sign State ($F(1,62) = 22.97$, $p < .001$, $\eta\rho^2 = .27$), as well as the Visibility factor ($F(1,62) = 6$, $p = .017$, $\eta\rho^2 = .088$). The participants waited longer to cross the northbound lanes when the CICAS–SSA sign was turned on compared to the Sign Off condition (11.1 and 7.9 s, respectively). Also, participants waited longer to cross the northbound lanes under clear visibility conditions (10.5 s) compared to times when visibility was limited due to fog (8.5 s). The impact of sign state on wait time differed across visibility conditions as shown in the presence of a significant Sign State × Visibility interaction ($F(1,62) = 11.7$, $p < .001$, $\eta\rho^2 = .159$). Following the identical pattern found when crossing the southbound lanes, the state of the sign played a role only when the visibility was limited ($F(1,64) = 37.06$, $p < .001$, $M = 11.5$ and 5.6 s for Sign On and Sign Off conditions, respectively). The impact of the sign under clear visibility conditions was not significant ($p > .7$).

4. Discussion

The design of an effective infrastructure-based information display system may not be the most optimal design of the same type of a system inside a vehicle. We created and compared three different interfaces of an in-vehicle CICAS–SSA sign in an effort to successfully transition the infrastructure-based CICAS–SSA to a display inside a vehicle. The three designs differed in terms of their complexity, which was based on the amount of information presented to the driver about the traffic on the major road. One of the designs, which provided the most extensive level of information to the driver (i.e., the Complete design), represented the direct transition from the infrastructure-based CICAS–SSA.

The results showed a consistent overall effect of the in-vehicle CICAS–SSA on driving performance. When the assist system was activated (across all three in-vehicle designs) drivers were more likely to stop at the stop sign, waited longer to cross and were less likely to accept a critical gap. Furthermore, the results showed that the intersection crossing performance differed among drivers in the three design groups. Participants in the Prohibitive design group were more likely to accept a critical gap (i.e., gap smaller than 7.5 s) when crossing the northbound lanes compared to the drivers in the Complete and Divided groups. Some of these driving performance measures allow us to more directly infer the risk level of crossing, while the interpretation of other measures may not be as straightforward. We can argue that the increased probability of accepting a critical gap represents riskier driving behavior while measures such as wait time and rejected non-critical gap (i.e., gap greater than 7.5 s) characterize a driving style (e.g., conservative/aggressive). We can reasonably ascertain that the increased proportion of rejected non-critical gaps is a strong indicator of more conservative driving. The results showed that participants in the Complete and Divided design groups exhibited that facet of conservative driving compared to the participants in the Prohibitive design group. However, rejecting a gap that is accepted by the majority of other drivers, or waiting longer to cross an intersection, does not imply either worse of better driving behavior, but rather a more conservative/defensive driving style.

The findings of the significant effects of the Design of the sign, although interesting, would be of limited insight without further exploration of the possible interaction of different designs with the state of the sign (i.e., Sign On, Sign Off). Drivers in the Complete and Prohibitive design groups exhibited improvement (i.e., reduced probability of accepting a critical gap) when the system was turned on compared to the Sign Off condition, while the presence of the Divided design of the in-vehicle CICAS–SSA provided no such benefit. This finding suggests that the participants in the Divided design group may have ignored the assist system and relied on their own perceptual faculties to complete the crossing. The intended function of the Divided design of the assist system was to facilitate drivers' ability to separate the intersection crossing into two distinct segments. This finding would suggest that the drivers did not favor the compartmentalization of the intersection crossing. Instead, they may prefer to have access to traffic information beyond their immediate location which would allow them to plan their driving path or maneuver in advance. As an example, even when driving on an open road drivers focus their gaze at a location approximately 2 s ahead of their current position (Land & Land, 1994; Wilkie & Wann, 2003). Drivers' preference of the design was inferred from driving performance measures. The participants also completed usability questionnaires assessing their impression of usefulness, understanding and trust, however, responses to questions exploring those issues did not differ between the participants in the three design conditions.

The overall differences between the Complete and Prohibitive groups, to some degree, appear to be due to baseline differences (see Fig. 5), although participants in the Complete design group also exhibited better driving performance in the Treatment (i.e., Sign On) condition as well. The Complete and Divided designs provided graded information about the gap size. Before the red icon appeared drivers were presented with a yellow icon indicating the presence of a cross-traffic vehicle. The yellow icon acted as a cue to the drivers about the imminence of the critical gap threshold. The presence of this pre-cue may explain the differences in the Treatment condition between the participants in the Complete and Prohibitive design groups. However, that does not explain the Baseline differences; a relatively low number of participants (12) and especially the limited number of trials may partially account for that.

The results uncovered a consistent and substantial beneficial impact of the assist system; however, all instances of the Sign State effects were also accompanied by the interaction with the Visibility factor. The beneficial impact of the presence of the in-vehicle CICAS–SSA was found only when crossing the intersection under low visibility conditions. It appears that the drivers' reliance on the in-vehicle CICAS–SSA is reduced when weather and traffic conditions allow them an unrestricted and clear view of the cross-traffic. It is possible that in situations when drivers feel confident in their perceptual judgment and motor abilities, the need to rely on an assistive technology is greatly reduced. However, when the perceptual task becomes overly demanding, the extent to which the drivers rely on and adhere to the assistive technology (i.e., in-vehicle CICAS–SSA) may increase. While it appears that the drivers may be able to utilize the in-vehicle CICAS–SSA only when they consider it necessary, it is important to observe that the in-vehicle CICAS–SSA does not act as a distractor in situations when drivers' reliance on the system is limited (i.e., clear visibility condition in the current study).

The impact of the in-vehicle CICAS–SSA under varied visibility conditions, in general, does not differ greatly between older and younger drivers. Although older drivers exhibited some evidence of more conservative driving when presented with a version of the in-vehicle CICAS–SSA, such as longer wait time, the analyses uncovered only two Age × Sign State interactions. The benefits of the assist system were exhibited by younger drivers when crossing the northbound lanes of traffic, but not by older drivers. No such age-related differences were found when crossing the southbound lanes of traffic. The results suggest that the beneficial impact of the in-vehicle CICAS–SSA is somewhat reduced for older drivers compared to their younger counterparts, with a previously established caveat: the beneficial effects were found only under limited visibility conditions.

A likely limitation of the current study includes the manner in which the driving task was administered. Crossing the same intersection multiple times in succession may not provide good representation of a real-world driving behavior, thereby reducing the face validity of the current results. Furthermore, a relatively low number of intersection crossing trials can potentially produce higher variability of the results. Further research, with increased number of trials, would be needed to confirm the robustness of the current findings. Considering the benefits of bi-modal cues in warning systems we discussed earlier, the uni-modal design of the in-vehicle CICAS–SSA could potentially be regarded as a limiting factor. Although we were not able to successfully address the concerns raised earlier regarding the bi-modal interface of the in-vehicle CICAS–SSA, we acknowledge that the general benefits of dual cues validate further exploration of the bi-modal design implementation in systems such as ours. None of the three designs of the in-vehicle CICAS–SSA were effective in promoting a two-stage maneuver, which is the maneuver type associated with crashes at this particular intersection (TH 52 and CASH 9). Although the primary function of the in-vehicle CICAS–SSA is to assist drivers in rejecting small gaps, future research may seek to address the issue of one-stage crossings, at least for intersections where a maneuver type is a factor of concern.

5. Conclusions

To summarize, the design of the in-vehicle CICAS–SSA that resulted in the best overall intersection crossing performance was also the most informative about the traffic. Of course, displaying a large amount of traffic-related information to drivers may not always be the best idea as potentially negative consequences can arise. The additional traffic-related information can be useful to the drivers only until a certain point, a point at which it becomes distracting. The benefits of the assist system were somewhat reduced for older drivers suggesting a need for age-related examination of similar systems. The current findings show that in-vehicle based assist systems do have a capacity to provide effective assistance to drivers, potentially negating the need for infrastructure-based systems. One of the major benefits of the in-vehicle CICAS–SSA includes its broad adaptability. With certain changes in interface and timing of critical gap, the system could be adapted to various situations (e.g., weather, driver preference, vehicle type), as well as other intersections (e.g., without median, urban), thereby expanding its application and efficiency.

Acknowledgements

This research was conducted as part of the CICAS Gap Assessment Processing System, co-sponsored by Federal Project DTFH61-07-H-00003 and MnDOT 89031. We would like to acknowledge the help of Peter Easterlund for his substantial programming contributions and Christopher Drucker for help collecting data.

References

Bayly, M., Young, K. L., & Regan, M. A. (2009). Sources of distraction inside the vehicle and their effects on driving performance. In M. A. Regan, J. D. Lee, & K. L. Young (Eds.), *Driver distraction: Theory, effects and mitigation* (pp. 191–214). Boca Raton, FL: CRC Press.

Becic, E., & Manser, M. P. (2011). Long-term evaluation of the impact of the CICAS–SSA. Unpublished raw data.

Chang, S., Lin, C., Hsu, C., Fung, C., & Hwang, J. (2009). The effect of a collision warning system on the driving performance of young drivers at intersections. *Transportation Research, Part F, 12*, 371–380. http://dx.doi.org/10.1016/j.trf.2009.05.001.

Creaser, J. I., Manser, M. P., Rakauskas, M. E., & Donath, M. (2010). *Sign comprehension, considering rotation and location, using random gap simulation for a Cooperative Intersection Collision Avoidance System – Stop Sign Assist: CICAS–SSA Report #4* (Report No. CTS 10-34). Minneapolis, MN: Center for Transportation Studies.

Cummings, M. L., Kilgore, R. M., Wang, E., Tijerina, L., & Kochhar, D. S. (2007). Effects of single versus multiple warnings on driver performance. *Human Factors, 49*, 1097–1106. http://dx.doi.org/10.1518/001872007X249956.

Dingus, T. A., Hulse, M. C., Mollenhauer, M. A., Fleischman, R. N., McGehee, D. V., & Manakkal, N. (1997). Effects of age, system experience, and navigation technique on driving with an advanced traveler information system. *Human Factors, 39*, 177–199.

Ferris, T., Penfold, R., Hameed, S., Sarter, N. (2006). The implications of crossmodal links in attention for the design of multimodal interfaces: A driving simulator study. In *Proceedings of the human factors and ergonomics society 50th annual meeting* (pp. 406–409), San Francisco.

Gorjestani, A., Menon, A., Cheng, P., Shankwitz, C., & Donath, M., (2010). *Determination of the alert and warning timing for the cooperative intersection collision avoidance system – stop sign assist using macroscopic and microscopic data: CICAS–SSA report #1* (Report No. CTS 10-31). Minneapolis, MN: Center for Transportation Studies.

Ho, C., Reed, N., & Spence, C. (2007). Multisensory in-car warning signals for collision avoidance. *Human Factors, 49*, 1107–1114. http://dx.doi.org/10.1518/001872007X249965.

Hurtwitz, D. S., Pradhan, A., Fisher, D. L., Knodler, M. A., Muttart, J. W., Menon, R., et al (2009). Backing collisions: A study of drivers' eye and backing behaviour using combined rear-view camera and sensor systems. *Injury Prevention, 16*, 79–84. http://dx.doi.org/10.1136/ip. 2009.021535.

Kramer, A. F., Cassavaugh, N., Horrey, W., Becic, E., & Mayhugh, J. (2007). Influence of age and proximity warning devices on collision avoidance in simulated driving. *Human Factors, 49*, 935–949. http://dx.doi.org/10.1518/001872007X230271.

Kiefer, R. J., & Hankey, J. M. (2008). Lane change behavior with a side blind zone alert system. *Accident Analysis and Prevention, 40*, 683–690.

Lahrmann, H. S., Madsen, J. R., & Boroch, T. (2001). Intelligent speed adaptation: Development of a GPS based ISA-system and field trail of the system with 24 test drivers. In *Proceedings from 8th world congress on intelligent transport systems*, Sydney, Australia.

Laberge, J. C., Creaser, J. I., Rakauskas, M. E., & Ward, N. J. (2006). Design of an intersection decision support (IDS) interface to reduce crashes at rural stop-controlled intersections. *Transportation Research Part C: Emerging Technologies, 14*, 39–56. http://dx.doi.org/10.1016/j.trc.2006.03.001.

Land, M. F., & Land, D. N. (1994). Where we look when we steer. *Nature, 369*, 742–744.

Mohebbi, R., Gray, R., & Tan, H. (2009). Driver reaction time to tactile and auditory rear-end collision warnings while talking on a cell phone. *Human Factors, 51*, 102–110. http://dx.doi.org/10.1177/0018720809333517.

Mulder, M., Mulder, M., van Paassen, M. M., & Abbink, D. A. (2008). Haptic gas pedal feedback. *Ergonomics, 51*, 1710–1720. http://dx.doi.org/10.1080/00140130802331583.

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/DOT 2004-31). St. Paul, MN: Minnesota Department of Transportation.

Rakauskas, M., Creaser, J., Manser, M., Graving, J., & Donath, M. (2010). *Validation study – On-road evaluation of the cooperative intersection collision avoidance system – Stop sign assist sign: CICAS–SSA Report #5* (Report No. CTS 10–35). Minneapolis, MN: Center for Transportation Studies.

Salthouse, T. A. (1996). Processing-speed theory of adult age differences in cognition. *Psychological Review, 103*, 403–428.

Scott, J., & Gray, R. (2008). A comparison of tactile, visual and auditory warnings for rear-end collision prevention in simulated driving. *Human Factors, 50*, 264–275. http://dx.doi.org/10.1518/001872008X250674.

Wickens, C. D., & Dixon, S. R. (2007). The benefits of imperfect diagnostic automation: A synthesis of the literature. *Theoretical Issues in Ergonomics Science, 8*, 201–212.

Wilkie, R. M., & Wann, J. P. (2003). Eye-movements aid the control of locomotion. *Journal of Vision, 3*, 677–684. http://dx.doi.org/10:1167/3.1.1.