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Effectiveness and acceptance of the intelligent speeding prediction system (ISPS)

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ABSTRACT

Background: The intelligent speeding prediction system (ISPS) is an in-vehicle speed assistance system developed to provide quantitative predictions of speeding. Although the ISPS's prediction of speeding has been validated, whether the ISPS can regulate a driver's speed behavior or whether a driver accepts the ISPS needs further investigation. Additionally, compared to the existing intelligent speed adaptation (ISA) system, whether the ISPS performs better in terms of reducing excessive speeds and improving driving safety needs more direct evidence.
Objectives: An experiment was conducted to assess and compare the effectiveness and acceptance of the ISPS and the ISA.
Method: We conducted a driving simulator study with 40 participants. System type served as a between-subjects variable with four levels: no speed assistance system, pre-warning system developed based on the ISPS, post-warning system ISA, and combined pre-warning and ISA system. Speeding criterion served as a within-subjects variable with two levels: lower (posted speed limit plus 1 mph) and higher (posted speed limit plus 5 mph) speed threshold. Several aspects of the participants' driving speed, speeding measures, lead vehicle response, and subjective measures were collected.
Results: Both pre-warning and combined systems led to greater minimum time-to-collision. The combined system resulted in slower driving speed, fewer speeding exceedances, shorter speeding duration, and smaller speeding magnitude.
Conclusions: The results indicate that both pre-warning and combined systems have the potential to improve driving safety and performance.

1. Introduction

Speeding (exceeding the posted speed limit, racing or driving too fast for conditions) is one of the most prevalent contributing factors in traffic crashes. In 2009, speeding contributed to 31% of all fatal crashes in the United States, which resulted in the loss of 10,591 lives (NHTSA, 2009). More importantly, speeding is common and even universal. The National Highway Traffic Safety Administration (NHTSA) conducted a survey in 2002 and reported that 80% of all drivers exceeded the posted speed limit during the month before the survey was taken. These drivers believe that they can drive about 7–8 mph over the posted speed limit before they will be ticketed (Royal, 2003).

Many strategies consisting of infrastructural (i.e., speed bumps, roundabouts) or legislative interventions (i.e., reduced speed limit, higher fines for speeding violation) are adopted to improve speed limit compliance and reduce excessive speeds; in-vehicle speed assistance systems are one of these strategies. Intelligent speed adaptation/assistant (ISA) is a typical speed assistance system that compares the vehicle's current speed with the posted speed limit and manages excessive speed with a few levels of intervention. For example, informative/open ISA provides the driver with visual and/or auditory warnings if he/she exceeds the speed limit beyond a specific speed threshold (e.g., 5 mph). Actively supporting ISA provides the driver with a tactile warning, usually in the form of increased upward pressure through the accelerator pedal. Intervening/closed ISA make it impossible for the driver to exceed the speed limit by automatically limiting a vehicle's speed using speed governors or retarders (Young et al., 2010).

Much research has examined the safety benefits of several ISA technologies and their influence on driving performance in various countries, generally with positive effects on average speed (Brookhuis and De Waard, 1999; Comte and Jamson, 2000; Hjälmdahl and Várhelyi, 2004; Várhelyi et al., 2004; Carsten and Tate, 2005; Regan et al., 2000; Vlassenroot et al., 2007; Adell and Várhelyi, 2008; Arhin et al., 2008; Van Nes et al., 2008; Warner and Aerg, 2008; Marchau et al., 2010; Young et al., 2010). However, intervening ISA induces behavior change by enforcing it externally, which may limit its acceptance and hinder its widespread

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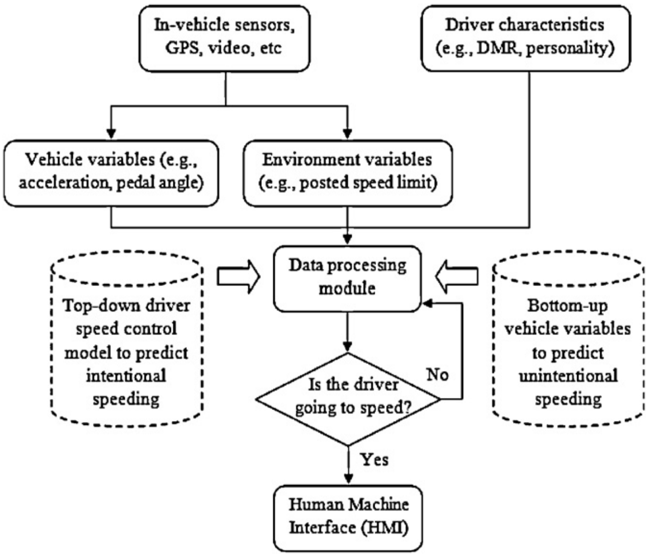

Fig. 1. System architecture of ISPS.

implementation on the real road (Kassner, 2008; Van Der Pas et al., 2000). Moreover, informative or actively supported ISAs are post-feedback systems that provide a warning message (visual, auditory or tactile) after the driver exceeds the pre-defined speed limit. These post-feedback systems may be too late to warn a driver when he/she is already speeding, particularly in some emergent situations. For example, a driver is speeding and, at this moment, a lead vehicle suddenly stops or a pedestrian suddenly crosses the street. Although ISA warns the driver about his/her travelling speed, it may be too late for the driver to stop or avoid a collision.

As the braking distance and kinetic energy are positively proportional to the square of the driving speed, the possibility of a collision, as well as collision severity, always becomes larger as speed increases (Elvik et al., 2004, 2009; Nilsson, 2004). The previous study with real traffic data estimated that a 1% increase in speed resulted in a 3.7% increase in fatal accidents and 2% increase in accidents with injuries (Elvik et al., 2009). Additionally, as speed increases, the distance travelled during the time taken to respond a hazard increases linearly, giving a driver less time to identify and react to the hazard. Therefore, a driver may benefit more from a new speed assistance system that can predict the occurrence of speeding violations (i.e., a proactive speeding warning system) than the previous ISA systems.

Recently, Zhao and Wu have developed an intelligent speeding prediction system (ISPS; Zhao and Wu, 2012, Tech Report 03-2012-A). As illustrated in Fig. 1, mechanical sensors, in-vehicle GPS, video, and other technologies record vehicle motion signals (e.g., pedal angle, vehicle acceleration) and environmental dynamics (e.g., the location of speed limit signs and traffic signals). These data as well as self-reported driver characteristics, including individual decision making reference (DMR) and personal impulsiveness are filtered and transmitted into an in-vehicle computer as model inputs. The data processing module consists of a top-down driver speed control model and a bottom-up model. If the data processing module predicts that a driver is going to speed, a visual and auditory warning message is scheduled and presented via a human machine interface (HMI).

More specifically, driver speed control model is built upon the mechanism of human information processing and control theory (Zhao et al., 2011; Zhao and Wu, in press). It integrates speed perception, speed choice, foot movement required for pedal operation, vehicle mechanics, and individual differences to provide quantitative predictions of intentional speeding. Here, intentional speeding refers to the intention or motivation to speed (e.g., the driver has his/her desired target speed that is above the posted speed limit), while unintentional speeding may result from a lack of awareness of the current speed limit and/or travelling speed, or an inaccurate foot movement required for pedal operation. The bottom-up model predicts unintentional speeding based on the deviation of the throttle pedal input. As a result, the ISPS is able to predict both intentional and unintentional speeding, and predictions consist of the time at which the driver exceeds the speed limit and the magnitude of speeding.

The authors also conducted an experimental study involving a driving simulator to evaluate the ISPS. They found no statistically significant differences between modeled predictions of intentional speeding and experimental data, in terms of the time and magnitude of speeding. The ISPS was sensitive (average d' is 2.1)[1] and accurate (average testing accuracy is over 86%) in predicting the majority of unintentional speeding with a relatively small portion of unnecessary speeding warnings. The ISPS is able to predict speeding more than 4 s prior to its occurrence (Zhao and Wu, 2012, Tech Report 03-2012-A). This amount of time is enough to play a warning message and respond for a normal driver (Mohebbi et al., 2009). Compared to existing ISA technologies, the ISPS can warn the driver about the current speed limit before his/her speed exceeds the pre-defined threshold and may help the driver avoid potential speeding-related hazards (e.g., when it is too late to stop or to avoid a rear-end collision).

Although the ISPS's prediction of speeding has been validated with experimental data, whether the ISPS can regulate a driver's speed behavior or whether a driver is willing to accept the ISPS needs further investigation. The ISSP cannot always predict speeding with 100% accuracy. It may fail to predict a true speeding instance (i.e., miss) or predict a false speeding and send unnecessary warning messages (i.e., false alarm). The previous study of in-vehicle warning systems (e.g., adverse condition warning systems, ACWS) found a consistent reduction in trust, compliance, and acceptance when the alerting system was less sensitive and reliable, or was unnecessarily activated more often (Gupta et al., 2002; Bliss and Acton, 2003; Clark et al., 2009). Additionally, compared to existing ISA systems, whether the ISPS performs better in terms of reducing excessive speeds and improving driving safety needs more direct evidence. To address these problems, we conducted an experiment involving a driving simulator to evaluate and compare the effectiveness and acceptance of the ISPS and ISA. Since intervening ISA makes speeding impossible (which may lead to the ceiling effect, Van Nes et al., 2008), this experiment only tests informative ISA that allows for all manipulations to have an effect on speeding behavior.

In this study, three speed assistance systems were evaluated: ISA (post-warning system), ISPS (pre-warning system), and combined system that integrates the ISPS with ISA. These three systems were compared to each other as well as the condition where there is no speed assistance system (baseline). Because the ISPS and combined system warn a driver before he/she is going to speed, if the driver listens to the warning message and regulates his/her travelling speed, these two systems will lead to slower driving speed and fewer speeding violations than the baseline condition (H1a) and ISA system (H1b) (hypotheses related to driving speed and speeding measures). Also, it was hypothesized that both ISPS and combined system could provide the driver more spare time to begin responding in emergent situations (e.g., to avoid a rear-end collision) compared to the baseline condition (H2a) and ISA system

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[1] d' represents the ability of the ISPS to detect the occurrence of speeding. The larger the value of d' is, the more sensitive the ISPS is (d' for chance selection/performance is zero).

(H2b) (hypotheses related to breaking response in emergency). Additionally, each driver has his/her own desired speed or acceptable speed range (e.g., drive 7–8 mph over the posted speed limit; Royal, 2003). It was hypothesized that the speed assistance system with a higher level of speeding criterion (e.g., the posted speed limit plus 5 mph) resulted in lower system acceptance compared to a lower level of speeding criterion (e.g., the posted speed limit plus 1 mph) (hypothesis related to speeding criterion, H3).

2. Methods

2.1. Participants

We recruited 40 participants (20 males and 20 females), whose average age was 31.8 years (range = 23–43, SD = 5.04). Participants were screened to ensure that they had good visual acuity and hearing. Additionally, all participants were right-handed, had valid driver licenses and had driven within the last six months.

2.2. Experimental design

A 4 × 2 mixed design was used to examine differences related to the types of systems and speeding criterion. System type served as a between-subjects variable with four levels: BAS (no speed assistance system; baseline), ISA (post-warning system; informative ISA), PRE (pre-warning system; ISPS), and COM (combined system that integrates the ISPS with ISA). Speeding criterion served as a within-subjects variable with two levels: lower level (the posted speed limit plus 1 mph) and higher level (the posted speed limit plus 5 mph).

The BAS system continuously provided visual information about the current speed limit in force, but never warned the driver when he/she exceeded the speed threshold. The ISA system displayed the same speed limit information but warned the driver visually (the speed limit indicator on the screen increased in size and started flashing) and verbally (by default, a female voice stated: “You are speeding. Speed limit is xx mph”). This message was repeated every 10 s until the speed was reduced to below the speed threshold (Van Nes et al., 2008). The data processing module in the PRE system continuously monitored the driver’s speed behavior. Once the ongoing speeding was detected and predicted, the warning message was scheduled and presented immediately. The PRE system provided the same visual and verbal information as the ISA system (e.g., increase in size, flashing, the frequency of playing) except the verbal message. The warning message for the PRE system was designed as follows: “Be careful. Speed limit is xx mph”. Note that the PRE system did not warn the driver after he/she exceeded the specific speed threshold. Finally, The COM system combined the features of both ISA and PRE systems: it was used as the PRE system *before* the driver exceeded the speed threshold, while performing as the ISA system *after* the driver was speeding.

The driving scenario was a 9-mile, two-lane (in each direction) local environment. Two types of lead vehicles were designed: a target and a non-target. Six target lead vehicles were designed to brake at a certain rate of acceleration[2] if and only if the driver (i.e., follower) was within the randomly pre-defined areas (500 ft in length) *and* he/she exceeded the posted speed limit by 5 mph. Before a lead vehicle braked, it travelled at the same speed as the driver no matter what the driver’s speed was. Hence, the headway spacing between a lead vehicle and the driver remained constant (200 ft). To reduce learning effects, non-target lead vehicles were displayed with an exact ratio of 1:3 (target: non-target). These non-target lead vehicles travelled at the same speed as the driver but did not slow down when the driver exceeded the speed limit by 5 mph. We also designed two types of pedestrians to cross the road: a target and a non-target. Initially, pedestrians were displayed 2 ft from either the left or right roadway edge line. When the driver was within 200 ft of the target pedestrian (6 in total) *and* exceeding the speed limit by 5 mph, it began to cross the road at a constant speed of 2 ft per second. Stationary pedestrians (non-targets) were displayed with an exact ratio of 1:3 (target: non-target). An approaching vehicle in the other lane appeared 1000 ft from the driver every 1000 ft he/she travelled. These approaching vehicles always followed the speed limit throughout the trial. All target and non-target road events are randomly presented for each participant.

2.3. Apparatus

The driving task was completed using a STISIM® driving simulator (STISIM DRIVE M100K). The STISIM simulator was installed on a Dell Workstation (Precision 490, Dual Core Intel Xeon Processor 5130 2 GHz) with a 256 MB PCIe × 16 NVIDIA graphics card, Sound Blaster® X-Fi™ system, and Dell A225 Stereo System. The driving scenario was presented on a 27-inch LCD with 1920 × 1200 pixel resolution. The driving simulator also included a Logitech Momo® steering wheel with force feedback, a gas pedal and a brake pedal.

The speed assistance system (ISA, ISPS or combined system) was displayed on a 12.1 inch ELO screen which was located 50 cm from the participants’ right hand and 91 cm from their eyes. The visual angle of the touch screen was 13.1° and controlled by a Dell PC (OPTIPLEX 745), which was connected to the driving simulator via a Labjack® system.

2.4. Experimental procedure

Upon arrival, participants were asked to sign a consent document and fill out a set of self-reported measures before engaging in the driving task. The first questionnaire was designed to capture the participant’s demographic characteristics (e.g., age and gender) and driving history (e.g., estimated annual driving mileage and the year a US driver’s license was first obtained). Then, participants were asked to construct a subjective value metric that measures a driver’s attitude towards the cost-benefit tradeoff of speeding (Zhao and Wu, 2012, Tech Report 03-2012-A). Finally, a short form of the Revised Eysenck Personality Questionnaire (EPQR-S; Eysenck et al., 1985) was administrated to divide all drivers into three categories: normal drivers (those characterized as E+ and N−, or E− and N+), impulsive drivers (those characterized as E+ and N+), and non-impulsive drivers (those characterized as E− and N−). The decision making reference (derived from the subjective value metric) and personality characteristics (collected from the EPQR-S) served as the inputs of the data processing module in the PRE and COM systems.

Participants then went through four consecutive practice blocks of the driving task without any speed assistance system to familiarize themselves with the driving simulator and different road events. They were asked to operate the driving simulator as if they were driving a real vehicle on the road. Each practice block lasted for 15–20 min. This relatively long period of practice (1–1.5 h in total) was expected to control confounding learning effects on driving behaviors so that participants could form relatively steady driving patterns. Driving signals (e.g., speed, acceleration, etc.) were collected online and analyzed immediately after each practice block to train the data processing module in the PRE and COM systems. The optimal parameters for model inputs (e.g., window size, overlap between windows, magnitude) were selected after the entire practice session. During the formal test, participants in the ISA, PRE, and

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[2] The rate of acceleration was calculated using a linear transition from the vehicle’s initial speed when the transition begins until it reaches the specified speed at the end of the transition period.

COM system condition completed two test blocks given the support of the corresponding speed assistance system, while those in the BAS system group completed the same two test blocks without any system.

After each test block, all participants were asked to assess their mental efforts and perceived risks. Participants in the ISA, PRE, and COM system conditions were also asked if they would be willing to accept and use the corresponding speed assistance system in general and under certain specific conditions (e.g., driving in a hurry). The entire experiment lasted for 2–2.5 h. Participants were paid $10 per hour.

2.5. *Measurement*

Several driving behavioral measures were automatically collected from the driving simulator. Two types of accidents which may occur in the simulated driving environment were recorded: (1) a pedestrian-related accident, when a driver did not respond quickly enough and, therefore, hit a simulated pedestrian who was crossing the road; (2) a vehicle-related accident, when there was any collision with a vehicle on the road. Driving speed (in meters per second) and speeding measures (frequency, duration, and magnitude of speeding) were also collected. The first 30-s intervals from the beginning of each test block and each program startup due to an accident as well as the 30-s intervals starting at each target lead vehicle began to decelerate were excluded from the analysis. Frequency of speeding indicated the number of times a vehicle's speed exceeded the pre-defined speed threshold. Duration of speeding provided the amount of time (in s) that a driver spent above the specific speed threshold. Magnitude of speeding reported the speed deviations (in m/s) from the pre-defined speed threshold. Minimum time-to-collision (i.e., the shortest time-to-collision during a braking event; TTC) was calculated by assuming the driver was to continue in the same path at the same velocity. Minimum TTC is an important indicator of the safety outcome of a braking event (Donmez et al., 2006).

Subjective measures, including mental effort, perceived risk, and attitudes towards the system acceptance and usage, were assessed. The mental effort questionnaire (Zijlstra, 1993) was on a scale of 0 (absolutely no effort) to 150 (extreme effort). The perceived risk questionnaire (Zylstra et al., 2003) was on a scale of 1 [driving on an easy road perfectly alert] to 10 [driving with eyes closed]. The system acceptance questionnaire (Van Der Laan et al., 1997) consisted of nine questions along a scale of −2 to +2, investigating two dimensions of acceptance: usefulness and satisfaction. Finally, participants were asked if they were willing to use the speed assistance system in general and under certain conditions, such as driving in a hurry, when there are speed cameras on the road, and when there are no speed cameras on the road. The responses were collected using a five-point Likert scale.

2.6. *Data analysis*

One-way analysis of variance (ANOVA) was used to examine group differences in demographic factors (e.g., age) and driving history (e.g., annual mileage and the year a US driver's license was first obtained). Partial correlations were performed to investigate the within-subject correlations of the driving behavioral and subjective measures. A repeated measures ANOVA was then performed on the continuous dependent variables with the system type as a between-subjects factor and the speeding criterion as a within-subjects factor. Significant findings were followed-up with Univariate analysis to assess the magnitude of the effects that each independent variable has on the dependent variables, and Bonferroni's test for post hoc comparison.

Table 1
Pair-wise comparisons for the average driving speed.

Pair-wise comparisons	*p*-Value	*i*–*j* (95% CI)
Lower speeding criterion (posted speed limit plus 1 mph)		
BAS (*i*) vs. ISA (*j*)	$p < .001$	2.56 (1.31, 3.81)
BAS (*i*) vs. PRE (*j*)	$p < .001$	3.66 (2.41, 4.9)
BAS (*i*) vs. COM (*j*)	$p < .001$	4.24 (2.99, 5.48)
ISA (*i*) vs. PRE (*j*)	*NS*	
ISA (*i*) vs. COM (*j*)	$p = .004$	1.68 (.43, 2.92)
PRE (*i*) vs. COM (*j*)	*NS*	
Higher speeding criterion (posted speed limit plus 5 mph)		
BAS (*i*) vs. ISA (*j*)	*NS*	
BAS (*i*) vs. PRE (*j*)	$p = .003$	1.81 (.48, 3.13)
BAS (*i*) vs. COM (*j*)	$p < .001$	2.67 (1.34, 4)
ISA (*i*) vs. PRE (*j*)	*NS*	
ISA (*i*) vs. COM (*j*)	$p = .004$	1.77 (.44, 3.1)
PRE (*i*) vs. COM (*j*)	*NS*	

3. Results

3.1. *Demographic factors, driving history, and descriptive statistics*

One-way ANOVAs were used to examine group differences in demographic factors and driving history. There were no significant differences among the four system groups for age ($F_{3,36} = .7$, $p = .561$), annual mileage ($F_{3,36} = .72$, $p = .549$), or the year a US driver's license was first obtained ($F_{3,36} = .2$, $p = .892$). Descriptive statistics (e.g., sample means and standard deviations) were provided to describe the main features of the sample for each measurement (see Appendix I).

3.2. *Driving speed and speeding measures*

Partial correlation analysis demonstrated strong correlations between driving speed and magnitude of speeding ($r = .76$, $p < .001$) and moderate correlations between driving speed and frequency of speeding ($r = .38$, $p = .02$). Because these dependent variables were correlated, multivariate tests were performed on these measures to control for inflation of the Type I error. Both main effects of the system type (Wilks' $\lambda = .11$, $F_{9,83} = 13.34$, $p < .001$) and the speeding criterion (Wilks' $\lambda = .55$, $F_{3,34} = 9.39$, $p < .001$) were significant. According to the univariate analyses reported below, the main effect of the system type was contributable to the differences observed in driving speed, frequency of speeding, and magnitude of speeding. However, the main effect of the speeding criterion was only due to the differences observed in driving speed.

A repeated measures ANOVA was performed on the seven of the driving behavioral and subjective measures. These measures were driving speed, frequency, duration, and magnitude of speeding, minimum TTC, mental effort, and perceived risk. Frequency of accidents did not enter the repeated measures ANOVA as dependent variables, as there were only two collisions with a lead vehicle and one collision with a simulated pedestrian across all test blocks and subjects.

3.2.1. *Driving speed*

A significant system type × speeding criterion interaction was revealed for average driving speed ($F_{3,36} = 4.22$, $p = .012$) (see Fig. 2). Pair-wise comparisons showed that both PRE and COM systems led to significantly slower driving speeds than the baseline condition at both levels of speeding criteria (*ps* < .01) (see Table 1). Participants using the COM system drove significantly slower than those using the ISA system across different speeding criteria (*ps* = .004), indicating the better performance of the combined system in regulating a driver's speed compared to the post-warning system. The ISA system showed its advantage of reducing driving speeds over

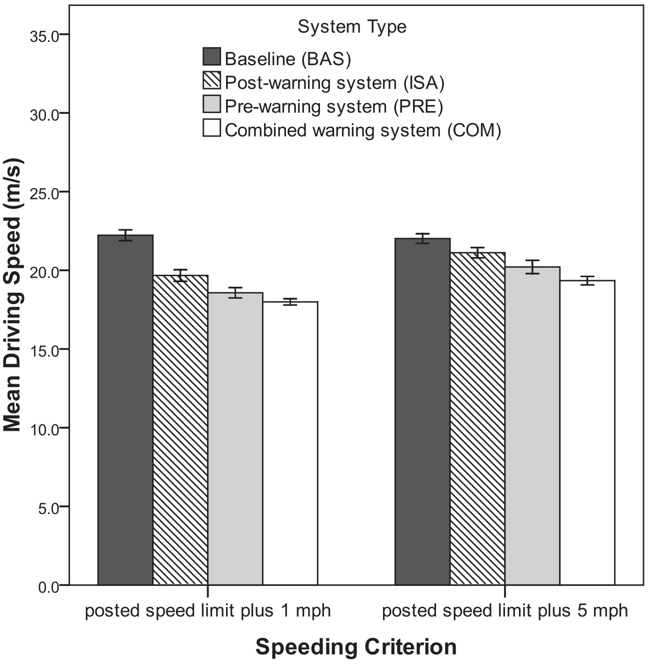

Fig. 2. A comparison of the average driving speed for the four systems (error bars indicate ±1 standard error).

the baseline condition only at the lower level of speeding criterion ($p < .001$). This suggested that the existing ISA technology was more effective in reducing driving speeds when the pre-defined speeding threshold was stricter. Additionally, both main effects of the system type ($F_{3,36} = 35.41$, $p < .001$) and speeding criterion ($F_{1,36} = 25.86$, $p < .001$) were significant for the average driving speed.

3.2.2. *Frequency of speeding*

The main effect of the system type was significant for the frequency of speeding ($F_{3,36} = 18.37$, $p < .001$) (see Fig. 3). Pair-wise comparisons indicated that participants using the combined system were less likely to exceed the speeding criteria than those without using any speed assistance system ($p = .001$) (see Table 2). The ISA system led to more speeding exceedances compared to PRE and COM condition ($ps < .001$). As one would expect, the ISA system cannot detect and avoid speeding, but it may force people to reduce driving speeds below the speed threshold by repeating warning messages, which lead to more speeding exceedances. Moreover, there were fewer speeding exceedances in the baseline condition compared to the ISA condition ($p = .04$). One possible reason was that people tended to speed for a long time without post-warning messages. The main effect of the speeding criterion and the system type × speeding criterion interaction were not significant for this measure.

Table 2
Pair-wise comparisons for speeding measures.

Pair-wise comparisons	*p*-Value	*i*–*j* (95% CI)
Frequency of speeding		
BAS (*i*) vs. ISA (*j*)	$p = .04$	−4.05 (−7.98, −.12)
BAS (*i*) vs. COM (*j*)	$p = .001$	6.1 (2.17, 10.03)
ISA (*i*) vs. PRE (*j*)	$p < .001$	6.5 (2.57, 10.43)
ISA (*i*) vs. COM (*j*)	$p < .001$	10.15 (6.22, 14.08)
Duration of speeding (s)		
BAS (*i*) vs. ISA (*j*)	$p = .014$	141.71 (21.31, 262.12
BAS (*i*) vs. PRE (*j*)	$p = .002$	171 (50.59, 291.4)
BAS (*i*) vs. COM (*j*)	$p < .001$	238.53 (118.13, 358.93)
Magnitude of speeding (m/s)		
BAS (*i*) vs. ISA (*j*)	$p = .007$	1.02 (.21, 1.82)
BAS (*i*) vs. PRE (*j*)	$p < .001$	1.84 (1.04, 2.65)
BAS (*i*) vs. COM (*j*)	$p < .001$	2 (1.2, 2.81)
ISA (*i*) vs. PRE (*j*)	$p = .043$	.82 (.02, 1.63)
ISA (*i*) vs. COM (*j*)	$p = .01$	.98 (.17, 1.79)

3.2.3. *Duration of speeding*

There was a significant main effect of the system type on the duration of speeding ($F_{3,36} = 10.84$, $p < .001$) (see Fig. 4). Pair-wise comparisons showed that three speed assistance systems led to shorter speeding duration compared to the baseline condition ($ps < .05$) (see Table 2). These results suggested that both post-warning and pre-warning technologies were beneficial for the

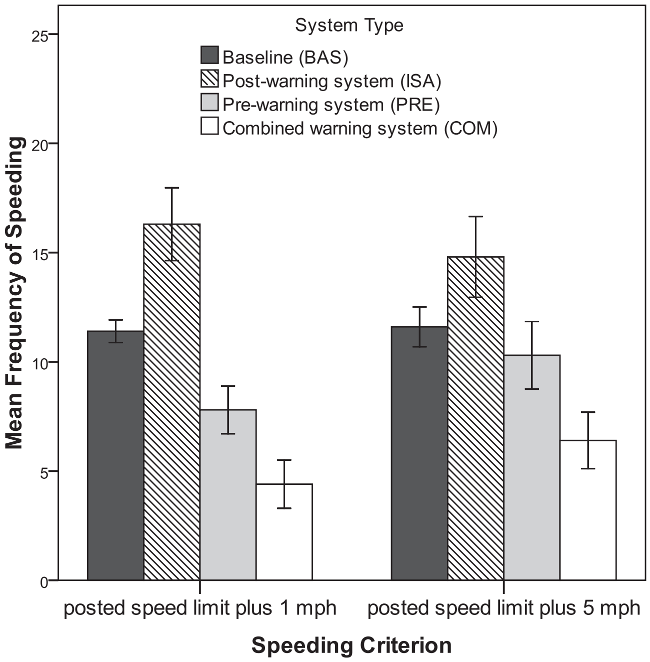

Fig. 3. A comparison of the frequency of speeding for the four systems (error bars indicate ±1 standard error).

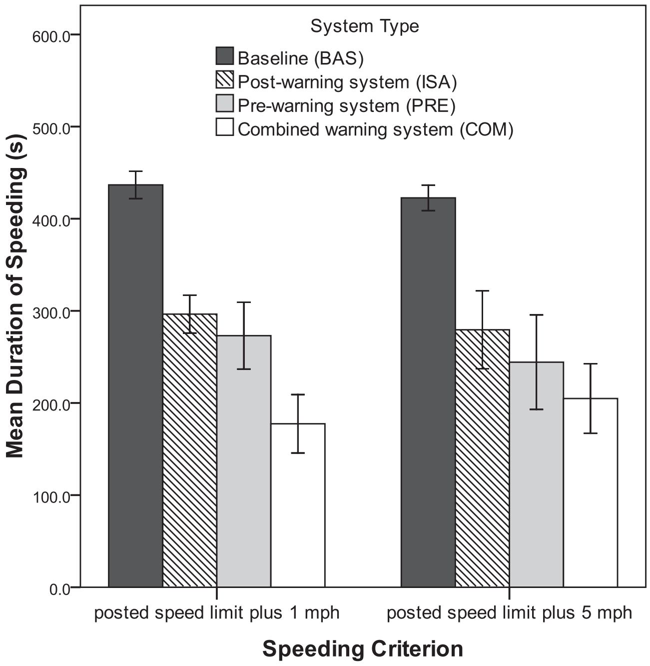

Fig. 4. A comparison of the duration of speeding for the four systems (error bars indicate ±1 standard error).

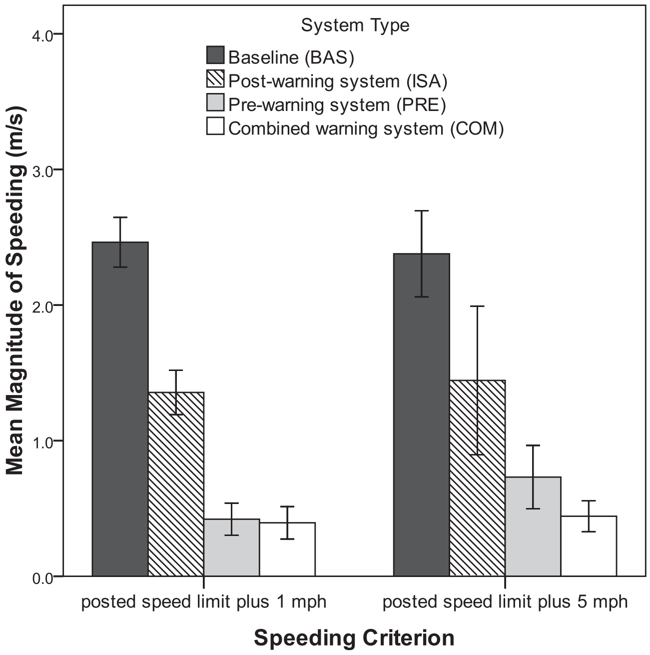

Fig. 5. A comparison of the magnitude of speeding for the four systems (error bars indicate ±1 standard error).

reduction of speeding duration. The main effect of the speeding criterion and the system type × speeding criterion interaction were not significant for the duration of speeding.

3.2.4. *Magnitude of speeding*

The main effect of the system type was significant for the magnitude of speeding ($F_{3,36} = 20.26$, $p < .001$) (see Fig. 5). Pair-wise comparisons showed that three speed assistance systems resulted in smaller speed deviations compared to the baseline condition ($ps < .01$) (see Table 2). Participants using the PRE and COM systems exceeded the speeding criteria by smaller magnitudes than those using the ISA system ($ps < .05$), indicating the better performance of the pre-warning technology in reducing speeding magnitude. The main effect of the speeding criterion and the system type × speeding criterion interaction were not significant for this measure.

3.3. *Lead vehicle braking response*

We found a significant main effect of the system type on the minimum TTC ($F_{3,36} = 69.31$, $p < .001$) (see Fig. 6). Pair-wise comparisons revealed that three speed assistance systems resulted in greater minimum TTC compared to the baseline condition ($ps < .01$) (see Table 3). The COM system provided the driver longer time to avoid a collision than the PRE system which was better than the ISA system ($ps < .001$), indicating the better safety outcome of the combined pre-warning and post-warning technology in response to a lead vehicle breaking event. There was no significant main effect of the speeding criterion or the system type × speeding criterion interaction for this measure.

Table 3
Pair-wise comparisons for the minimum TTC.

Pair-wise comparisons	*p*-Value	*i*–*j* (95% CI)
BAS (*i*) vs. ISA (*j*)	$p = .007$	−.63 (−1.3, .03)
BAS (*i*) vs. PRE (*j*)	$p < .001$	−2.05 (−2.72, −1.39)
BAS (*i*) vs. COM (*j*)	$p < .001$	−3.12 (−3.78, −2.45)
ISA (*i*) vs. PRE (*j*)	$p < .001$	−1.42 (−2.08, −.75)
ISA (*i*) vs. COM (*j*)	$p < .001$	−2.48 (−3.15, −1.82)
PRE (*i*) vs. COM (*j*)	$p < .001$	−1.06 (−1.73, −.4)

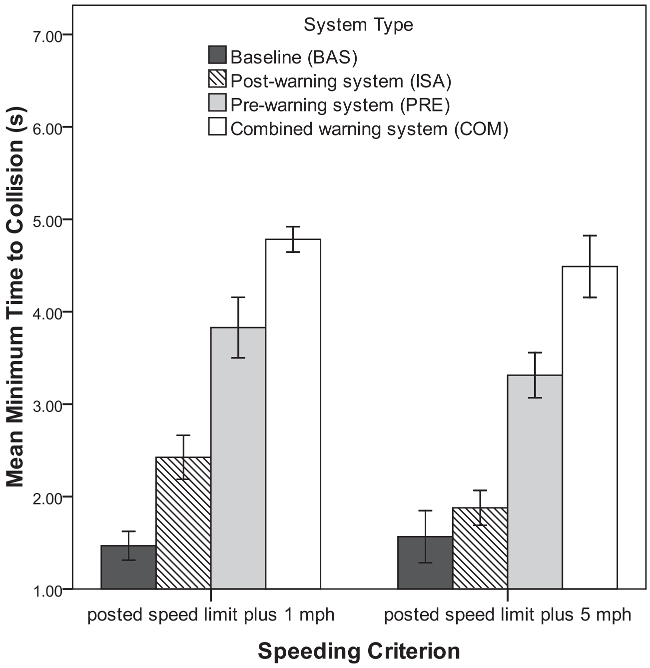

Fig. 6. A comparison of the minimum TTC (error bars indicate ±1 standard error).

3.4. *Subjective measures*

There was a significant main effect of the system type on perceived risk ($F_{3,36} = 8.74$, $p < .001$) and mental effort ($F_{3,36} = 8.315$, $p < .001$) (see Fig. 7). Pair-wise comparisons suggested that participants using three speed assistance systems perceived less risk and mental effort than those without using any speed assistance system ($ps < .05$) (see Table 4). The main effect of the speeding criterion and the system type × speeding criterion interaction were not significant for perceived risk or mental effort. The 95% confidence intervals for the mean subjective usefulness scores, which excluded zero, revealed that participants generally found the three speed assistance systems to be useful (see Fig. 8). System type had a significant main effect on the mean subjective usefulness scores ($F_{2,27} = 4.76$, $p = .017$). Pair-wise comparisons suggested that the COM system was more useful than the ISA and PRE systems ($ps < .05$) (see Table 4). Speeding criterion had a significant main effect on the mean subjective usefulness scores ($F_{1,27} = 7.82$, $p = .009$) and satisfaction scores ($F_{1,27} = 3.9$, $p = .05$). Participants' attitudes toward system usefulness and satisfaction significantly degraded when the speeding criterion was reduced to a lower level. These results along with the subjective responses regarding the system usage reported

Table 4
Pair-wise comparisons for subjective measures.

Pair-wise comparisons	*p*-Value	*i*–*j* (95% CI)
Perceived risk		
BAS (*i*) vs. ISA (*j*)	$p = .016$	1.5 (.2, 2.79)
BAS (*i*) vs. PRE (*j*)	$p = .001$	2 (.7, 3.29)
BAS (*i*) vs. COM (*j*)	$p < .001$	2.1 (.8, 3.39)
Mental effort		
BAS (*i*) vs. ISA (*j*)	$p = .032$	19.6 (1.15, 38.05)
BAS (*i*) vs. PRE (*j*)	$p = .004$	24.75 (6.3, 43.2)
BAS (*i*) vs. COM (*j*)	$p < .001$	31.25 (12.8, 49.7)
Usefulness scores		
ISA (*i*) vs. COM (*j*)	$p = .045$	−.03 (−.56, .63)
PRE (*i*) vs. COM (*j*)	$p = .032$	−.64 (−1.23, −.04)

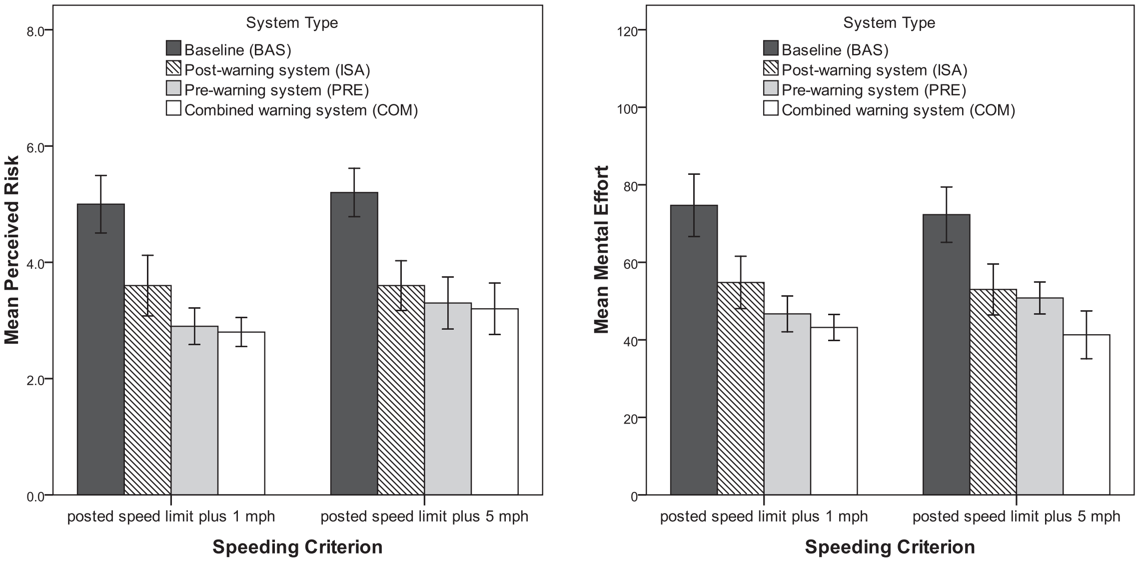

Fig. 7. Comparisons of the perceived risk (left panel) and mental effort (right panel) for the four systems (error bars indicate ±1 standard error).

below suggested that people may have their desired speed ranges which were beyond the posted speed limit and preferred to use the three speed assistance systems if the speeding criterion was defined at a higher level.When the participants were asked whether or not they would use the three speed assistance systems while driving in a hurry, 25% of them indicated they would always or often use them and 43% preferred the system with a higher level of speeding criterion (see Table 5). 70% of the participants preferred to use the three systems if there were speed cameras on the road and 57% found that the systems with a lower level of speeding criterion were more beneficial. 47% of the participants reported that they would always or often use the systems even though there was no speed camera on the road and 76% chose a higher pre-defined speed threshold. In general, 43% of the participants reported that they would use the speed assistance system regardless of the speeding criterion and 76% preferred a higher level of speed threshold.

4. Discussion

The aim of this study was to assess the effectiveness and acceptance of the ISPS. The core algorithm of the ISPS consists of a top-down driver speed control model and a bottom-up model. According to the dynamic vehicle motion signals and environmental inputs collected from in-vehicle sensors, GPS and other technologies, the two models provide quantitative predictions of speeding (e.g., the time at which the driver exceeds the pre-defined speed threshold). If a driver is going to speed, the ISPS will present visual and auditory warning messages via an in-vehicle human machine interface to prevent speeding.

We conducted an experimental study involving a driving simulator to evaluate and compare the ISPS and existing ISA technology. System type served as a between-subjects variable with four levels: no speed assistance system, pre-warning system developed based

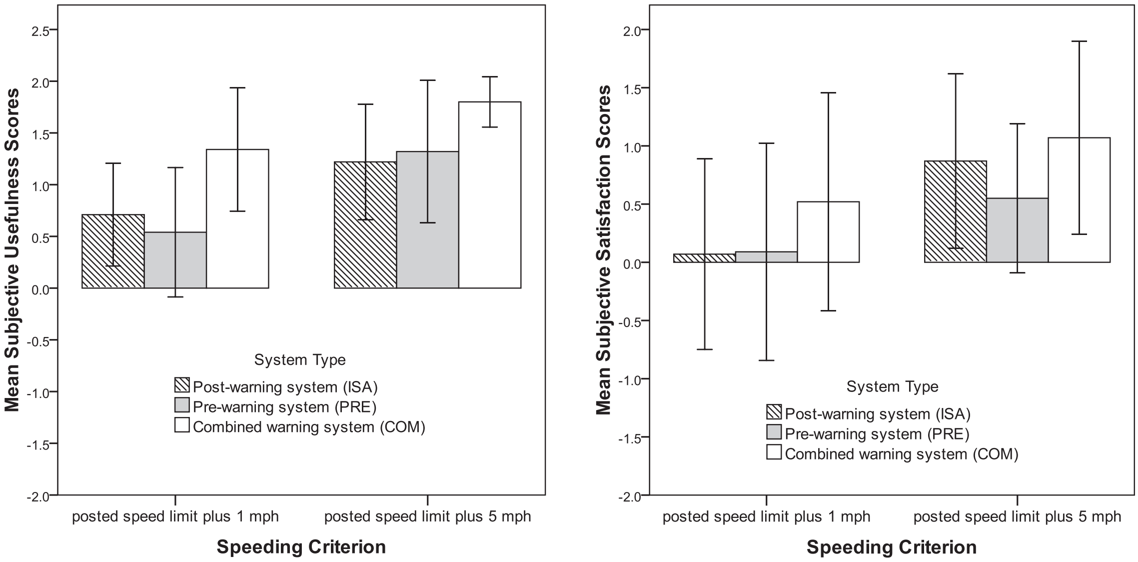

Fig. 8. Comparisons of the subjective attitudes towards system usefulness (left panel) and satisfaction (right panel) for the three systems (error bars indicate ±95% confidence interval).

Table 5
Subjective responses regarding the usage of the three systems (values in parentheses indicate subjective responses at a higher level of speeding criterion).

	Always turn it off	Often turn it off	Neutral	Often use it	Always use it
Drive in a hurry					
ISA system	6 (1)	3 (1)	6 (3)	2 (2)	3 (3)
PRE system	7 (3)	4 (2)	5 (2)	3 (2)	1 (1)
COM system	4 (1)	2 (0)	8 (4)	4 (3)	2 (2)
Percentage (%)	**.28 (.17)**	**.15 (.1)**	**.32 (.3)**	**.15 (.23)**	**.1 (.2)**
There are speed cameras at the road					
ISA system	0 (0)	1 (1)	3 (3)	7 (3)	9 (3)
PRE system	1 (1)	3 (3)	4 (3)	6 (1)	6 (2)
COM system	0 (0)	2 (2)	4 (4)	4 (2)	10 (2)
Percentage (%)	**.02 (.03)**	**.1 (.2)**	**.18 (.33)**	**.28 (.2)**	**.42 (.23)**
There is no speed camera at the road					
ISA system	4 (0)	2 (1)	4 (1)	6 (5)	4 (3)
PRE system	5 (1)	5 (1)	4 (2)	3 (3)	3 (3)
COM system	2 (0)	1 (0)	5 (1)	6 (5)	6 (4)
Percentage (%)	**.18 (.03)**	**.13 (.07)**	**.22 (.13)**	**.25 (.43)**	**.22 (.33)**
In general					
ISA system	3 (0)	4 (0)	4 (2)	5 (5)	4 (3)
PRE system	5 (1)	4 (2)	5 (2)	4 (3)	2 (2)
COM system	2 (0)	2 (0)	5 (0)	6 (5)	5 (5)
Percentage (%)	**.17 (.03)**	**.17 (.07)**	**.23 (.13)**	**.25 (.43)**	**.18 (.33)**

on the ISPS, post-warning ISA system, and combined pre-warning and ISA system. Speeding criterion served as a within-subjects variable with two levels: lower (posted speed limit plus 1 mph) and higher (posted speed limit plus 5 mph) speed thresholds. Several aspects of the participants' driving speeds, speeding measures, lead vehicle brake responses, and subjective measures were collected.

The current study found that the ISPS took advantage of its effectiveness in reducing average driving speed, speeding duration and magnitude over the baseline condition. These findings were consistent with our hypothesis H1a and indicated that the pre-warning technology has potential to manage speed behavior, increase speed limit compliance, and improve driving safety. Compared to the ISA technology, the ISPS did not show better performance in regulating driving speeds, which was inconsistent with our hypothesis H1b. A possible explanation is that the ISPS does not play warning messages after a driver exceeds the speed threshold. If some drivers stick to their acceptable speed ranges which are beyond the speeding criterion and always speed during the entire drive, the ISPS may not work. In contrast, the ISA may force these drivers to reduce driving speeds because it plays warning messages repeatedly until driving speed is below the threshold.

In this study, we designed lead vehicle braking events to measure the minimum TTC. Target lead vehicles randomly stopped at a certain deceleration rate if, and only if, the driver exceeded the specific speed threshold. We found that the ISPS led to greater minimum TTC compared to the baseline condition and ISA technology. These results were consistent with our hypotheses H2a and H2b. The ISPS is able to detect speeding before it occurs, while the ISA system only plays a warning message after the driver exceeds the speed threshold. As we expected, the ISA system might be too late to warn the driver when he/she is already speeding, and provides people insufficient time to identify and react to an emergent hazard (Elvik et al., 2009).

In general, drivers found that the ISPS was useful but were not satisfied with it, especially when the speeding criterion was defined as only 1 mph over the posted limit. A possible reason for this dissatisfaction is that the pre-warning system cannot always predict speeding with 100% accuracy. Zhao and Wu have conducted an experiment to validate the ability of the ISPS in predicting speeding. The average model sensitivity is 2.1 (sensitivity is zero if by chance) and average testing accuracy is over 86% (Zhao and Wu, 2012, Tech Report 03-2012-A). Technically, although the ISPS's sensitivity and accuracy are acceptable, it still may miss a prediction of true speeding and/or predict a false speeding and generate unnecessary warning messages. The previous studies have found that the presence of system faults or poor advice significantly diminished human reliance on the system and affected a driver's attitude towards the system acceptance (Gupta et al., 2002; Bliss and Acton, 2003). The reliance could recover, but not to the initial level of reliance (John and Moray, 1992; Bisantz and Seong, 2001).

The combined system resulted in slower driving speed, fewer speeding violations, and greater minimum TTC than the baseline condition and ISA system across different speeding criteria. These findings were consistent with our hypotheses related to driving speed and speeding measures (H1a and H1b) and hypotheses related to braking responses in emergency (H2a and H2b). Additionally, the combined system led to greater minimum TTC, and people found that the combined system was more useful than the pre-warning system. The reason may be that the combined system not only informs the driver before he/she is going to speed, but also warns the driver after he/she exceeds the specific speed threshold repeatedly. Accordingly, the combined system can detect and inform the driver of all speeding instances (no missing), and thus the driver may feel that the combined system is more reliable than the pre-warning system.

In this study, people reported that three speed assistance systems would be more useful and satisfactory when speeding criterion was defined at a higher level. This result was consistent with our hypothesis H3 and may be related to the trade-off between the effectiveness and acceptance of the speed assistance system (Van Nes et al., 2008): the stricter speed threshold, the larger effect on speed behavior but the lower system acceptance. In reality, many drivers believe that they can drive over the posted speed limit before they will be ticketed (Royal, 2003). Driver might feel uncomfortable hearing repeated warning messages while driving within his/her acceptable speed ranges (e.g., driving 2–3 mph over the posted limit). In practice, these speed assistance systems may be customized for different types of drivers. For example, drivers with good driving records may be allowed to customize the speed threshold according to their acceptable speed ranges. Drivers with poor driving records (e.g., revoked license due to prior speeding violations), inexperienced drivers, and professional drivers (e.g., school bus drivers) may be forced to use the system with a stricter speed threshold.

The previous studies of ISA technology mainly used the average speed as an indicator of safety benefits, generally with positive effects on the average speed (Hjälmdahl and Várhelyi, 2004; Várhelyi et al., 2004; Carsten and Tate, 2005; Regan et al., 2000; Vlassenroot et al., 2007; Adell and Várhelyi, 2008; Arhin et al., 2008; Van Nes et al., 2008; Warner and Aerg, 2008; Marchau et al., 2010; Young et al., 2010). In this work, we also found that the ISA system resulted in slower driving speeds than the baseline condition, which was consistent with the previous findings. In addition to average driving speed, this work also assessed the effects of speed assistance systems on the frequency, duration, and magnitude of speeding, the minimum TTC, subjective measures, including mental effort, perceived risk, and attitudes towards the system acceptance and usage. These measures provided a more comprehensive understanding of the safety benefits of these speed assistance systems.

In practice, the ISPS and combined systems have the potential to reduce excessive driving speed and improve driving safety. Because the ISPS is developed based on a set of mathematical equations, it can be easily embedded in an in-vehicle computer system to provide real-time speeding predictions. All model inputs required by the ISPS (such as pedal inputs, vehicle acceleration, and the posted speed limits) are readily available from existing in-vehicle sensors, GPS, and other technologies (e.g., on-board diagnostics system). Also, the existing ISA technologies have been implemented in the GPS system to monitor a driver's speed and provide visual/auditory warning messages via the GPS's interface. Hence, the ISA technologies can be easily embedded in the ISPS system to develop the combined system.

Despite these intriguing findings, it is necessary to consider the limitations of this study to be addressed in future work. Firstly, in this study, all participants went through a relatively long period of practice to familiarize themselves with the driving simulator and different road events. This practice session helped people form steady driving patterns to optimize the model parameters but significantly reduced the occurrences of accidents. Future investigation might reduce the length of practice or the number of road events occurred during the practice session to have a better chance to measure the number of accidents as indicators of safety outcomes in addition to the minimum TTC. Secondly, the effects of the current ISPS on regulating a driver's long-term driving behaviors and enhancing driving safety was not examined in the current experimental setting. Future naturalistic driving studies might be needed to assess the acceptance of the ISPS over extended periods of time before its widespread implementation. Also, it might be interesting to examine the safety effects of the ISPS on inexperienced drivers and professional drivers (such as taxi drivers). These drivers usually exhibit different driving patterns from normal drivers, which may lead to different safety outcomes and attitudes towards the acceptance of usage of the ISPS.

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Appendix I. The descriptive statistics of dependent variables

Table A1

Table A1
The means and standard deviations for dependent variables.

	Use the posted speed limit plus 1 mph as speeding criterion				Use the posted speed limit plus 5 mph as speeding criterion			
	BAS	ISA	PRE	COM	BAS	ISA	PRE	COM
Driving speed (m/s)	22.23 (1.09)	19.67 (1.16)	18.57 (1.03)	17.99 (.64)	22.02 (.97)	21.12 (1.03)	20.21 (1.34)	19.34 (.85)
Frequency of speeding	11.4 (1.65)	16.3 (5.27)	7.8 (3.46)	4.4 (3.5)	11.6 (2.87)	14.8 (5.85)	10.3 (4.88)	6.4 (4.09)
Duration of speeding (s)	436.71 (47.05)	296.46 (65.06)	273.06 (114.7)	177.43 (100.3)	422.63 (43.76)	279.45 (133.7)	244.29 (162.2)	204.84 (119.5)
Magnitude of speeding (m/s)	2.46 (.58)	1.35 (.52)	.42 (.37)	.39 (.38)	2.38 (1)	1.44 (1.73)	.73 (.74)	.44 (.36)
The minimum TTC (s)	1.47 (.49)	2.42 (.75)	3.83 (1.04)	4.78 (.43)	1.57 (.89)	1.88 (.59)	3.31 (.77)	4.49 (1.06)
Perceived risk	5 (1.56)	3.6 (1.65)	2.9 (.99)	2.8 (.79)	5.2 (1.32)	3.6 (1.35)	3.3 (1.42)	3.2 (1.4)
Mental effort	74.7 (25.45)	54.8 (21.37)	46.7 (14.6)	43.2 (10.62)	72.3 (22.58)	53 (20.8)	50.8 (13.07)	41.3 (19.5)
Usefulness scores	NA	.71 (.69)	.54 (.87)	1.34 (.83)	NA	1.22 (.78)	1.32 (.96)	1.8 (.34)
Satisfaction scores	NA	.07 (1.14)	.09 (1.3)	.52 (1.31)	NA	.87 (1.05)	.55 (.89)	1.07 (1.16)

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