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Evaluation of advanced curve speed warning system for fire trucks

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ABSTRACT

A curve speed warning system (CSWS) for firetrucks was developed and tested in this study. The CSWS algorithm was developed based on guidelines in the public domain for general vehicles and modified for firetrucks for their configuration and emergency driving. Twenty-four firefighters participated in the test in a driving simulator. The results show that the CSWS was effective in issuing preemptive warnings when the drivers were approaching curves with unsafe speed during emergency responses. Drivers reduced their driving speed at curve approaching and entering phases for most challenging curves, without affecting the overall time in completing the test route. Drivers had reduced number of severe braking and decreased average in-curve distance traveled over the safety speed limits, when the CSWS was in use. Drivers also rated the CSWS as assisting, effective and useful. In summary, the CSWS can enhance firetruck safety during emergency driving without sacrificing drivers' precious response time.

1. Introduction

Transportation-related injuries of firefighters during emergency response are a persisting occupational safety problem. In 2017 there were an estimated 15,430 collisions involving fire department emergency vehicles, while firefighters were responding to or returning from incidents. These collisions resulted in 1005 firefighter injuries, not including civilian and firefighter injuries during the use of personal vehicles (common among volunteer fire fighters) (Evarts and Molis, 2018). In addition, in 2017, vehicle crashes were the third leading cause of fatal firefighter injuries – 10 firefighters lost their lives due to vehicle crashes. Four of these deaths were a result of rollover incidents, involving one fire engine and three fire tankers (water tenders); and at least in two of the cases, the rollover incidents occurred while the driver/firefighter was negotiating a curve (United States Fire Administration (USFA), 2018).

Among the heavy fire emergency vehicles, fire tankers are more prone to rollover crashes due to high center of gravity (Federal Emergency Management Agency (FEMA), 2003). Tankers represent only 3 percent of all fire apparatus in the United States, but they were involved in 21.9% of all fire vehicle fatal crashes that took place in the period 1990 to 2001 (FEMA, 2003). Rollover crashes are the most common and most deadly incident for fire tankers – of the 63 crashes with 73 deaths involving tankers in the period 1977–1999, 77.8% of the crashes and 74.0% of the deaths involved a rollover (National Institute for Occupational Safety and Health (NIOSH), 2002).

Excessive speed inside a curve has been identified as one of the major contributing factors for fire vehicle crashes and rollovers (FEMA, 2003; IAFF, 2010) and therefore several strategies are used/proposed to deal with it. Many fire departments have established policies on the maximum speed at which the vehicle may be driven during an emergency response. However, many State motor vehicle codes or fire department operating procedures allow emergency vehicles to exceed the posted or cautionary speed limit during an emergency response (FEMA, 2003). FEMA advised emergency vehicle drivers to familiarize themselves with tricky curves in their response district or potential mutual aid areas and know what the safe speeds are for negotiating them (FEMA, 2003). When driving on unfamiliar roads, drivers should be alert for yellow road signs indicating upcoming curves with suggested speeds, usually placed at the bottom of these signs (FEMA, 2003). However, it has been reported that these signs have no effect in reducing speeds on the most dangerous curves (Vest et al., 2005). Furthermore, these speeds are generally intended for passenger cars traveling on a dry road and are too high for a fire department tanker to safely negotiate the curve

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(FEMA, 2003).

The best strategy for safely negotiating curves is to maintain control of the vehicle by entering the curve at a reasonable, safe speed. The auto industry and the vehicle safety research community have been developing and testing technological solutions to assist with curve speed control. One such solution is the in-vehicle curve speed warning system (CSWS) (Pomerleau et al., 1999). The CSWS is an advanced driver assistance system (CSWS-ADAS) that provides advance warnings, based on the need to adapt to the safety speed limits for an upcoming curve. The CSWS-ADAS can be variable or dynamic speed limit system with abilities to adapt to road geometry and weather conditions (Jimenez et al., 2012)), and can use standard GPS technology (Chowdhury et al., 2020) or connected vehicle technology (Wang et al., 2020), and be adaptive to individual driver behavior (Ahmadi and Ghanipoor Machiani 2019). Previous studies on CSWS-ADAS have shown promising results in terms of improved safety outcomes and satisfactory driver acceptability (Jimenez et al. 2008, 2012)), as well as significant age and gender differences on some safety effectiveness measures (Ahmadi and Ghanipoor Machiani 2019; Wang et al., 2020). Furthermore, the systems that exercise a greater control over the driver (i.e. automatic speed reduction) are seen to be most beneficial, as opposed to simple advisory systems. However, these controlling systems are not necessarily appreciated by drivers (Young et al., 2010). Among a few other challenges with such systems are acceptability of the system warnings, driver adaptation and system overreliance.

Most of the existing research on CSWS-ADAS has been done on passenger cars and under normal driving conditions. The driving conditions and the environment of a passenger vehicle (including vehicle characteristics, ancillary equipment, and safety speed requirements) are very different from that of a heavy fire truck. The mental frame of mind of a fire truck driver who is responding to an emergency call also can be very different from that of a passenger vehicle driver in normal driving conditions.

The CSWS-ADAS algorithms described in the literature use the curve apex as speed control point (Jimenez et al. 2008, 2012) allowing the vehicles to enter and drive well into the curve at higher than the curve safety speed. The larger and heavier firetrucks may need to reduce their speed earlier in the curve (IAFF, 2010) which defines a need for shifting the speed control point before the apex. In previous research critical slide-out speed has been extensively used in the CSWS-ADAS algorithms (Jimenez et al. 2008, 2012). However, for a top-heavy firetruck, a rollover is the most likely crash scenario on a curve in dry environmental (FEMA, 2003) which defines the need to design and test CSWS-ADAS algorithms using rollover critical speed. Finally, while the CSWS-ADAS have been tested in normal driving conditions, their performance under emergency response driving conditions remains largely unknown.

In this study, a CSWS was designed by carefully modifying the published guidelines on warning algorithms for passenger vehicles to meet the specific requirements of firetruck driving under emergency response conditions. The system was tested in a driving simulator with firefighters recruited from local fire departments.

2. Methods

2.1. Participants

Twenty-four male active (career or volunteer) firefighters were recruited for this study. Participants had an average age 36 years (SD = 10.1 years), average height 182.9 cm (SD = 4.8 cm), and average weight 103.5 kg (SD = 16.8 kg). The requirements for participation in the study were 18 years of age or older, more than 6 months of experience driving a firetruck, capable to follow the study protocol and giving informed consent, having a valid driver's license, and no symptoms of motion sickness. All participants were screened using a motion sickness questionnaire (Hoffman et al., 2003) to identify any conditions that might make them unfit for the study. The goals of the study, the experimental procedures, and possible risks were explained to the participants and they signed an informed consent form approved by the Institutional Review Board (IRB) of the National Institute for Occupational Safety and Health (NIOSH).

2.2. Equipment

2.2.1. Driving simulator

The study was conducted at the NIOSH Vehicle Safety lab, which is equipped with a motion-base simulator (Mechanical Simulation, Ann Arbor, MI) featuring three 178 cm (70 in) high-definition display screens, a high-fidelity sound system for realistic sound effects, a precision steering system, commercial grade foot controls, and a reconfigurable instrument cluster. Four linear actuators at the base of the simulator provide three degrees of freedom of motion (roll, pitch and heave) to give users a realistic physical experience while driving in a virtual 3D traffic environment. Two high performance computers control and integrate all the systems in the simulator. The simulator runs TruckSim (Mechanical Simulation, Ann Arbor, MI) vehicle dynamics software, which is integrated with the Unity (Unity Technologies, San Francisco, CA) software, to specify vehicle models properties, develop road geometry, and create interactive driving scenarios with advanced graphic design and performance.

2.2.2. Warning system interface

The interface for the CSWS was provided on a 312 mm touch screen tablet (Windows Surface Pro 4, Microsoft, Redmond, WA). The tablet was set up in portrait orientation, which allowed the CSWS graphic user interface (GUI) to be located at the top half of the screen and the firetruck emergency signals controls at the bottom. The CSWS GUI provided data on the current speed of the vehicle, the posted speed for the current route section, and the safety speed for the upcoming curve. The GUI also had a color-coded indication for the CSWS status: "System Inactive" (blue), "Normal" or "OK" (green), "Caution" (yellow) for warnings with frequency 2.6–3.1 beeps/s accompanied by a blinking arrow in the direction of the upcoming turn, and "Danger" (red) for the warnings with frequency 3.2–4.0 beeps/s with steady arrow in the direction of the upcoming turn.

The touch screen display was placed to the right of the steering wheel (Fig. 1b and c), and was adjusted to be within the driver's field of view at a conveniently reachable distance since it was also used to control the lights and sirens of the firetruck. The preliminary tests indicated that during the visually demanding emergency response driving task, the warnings were predominantly perceived by the auditory component of the warning.

The audible warnings, delivered by two external speakers, had a pulse duration of 200 ms and variable inter-pulse interval (185-50 ms). To indicate increasing danger, when speed reduction was insufficient or absent, the warning signal was issued with increasing frequency, which was a function of increasing values of the calculated deceleration required to reach the safety speed within the distance to target zone ("speed control zone"). The audio warning signal had a fundamental frequency of 300 Hz and 15 harmonic components (Gonzalez et al., 2012). The audible warning signals were accompanied by synchronized vibration signals at the steering wheel (actuated by the power steering system).

2.3. Experimental setup

2.3.1. Truck model

The study used a model of a fire tanker presented in Fig. 1a. The tanker model was a 3-axle fire truck, tested in a "laden" condition with full tank of water (11,356 l/3000 gallons), for a total weight of 26,822 kg (59,008 lb.). According to the National Fire Protection Association (NFPA), 2008 standard, the maximum speed of tankers over 22,680 kg (50,000 lb.) gross vehicle weight rating (GVWR) is limited to 96 km/h

Fig. 1. Selected simulations: (a) fire tanker model; (b) view from the cab, with active CSWS while driving on a straight section within the safety speed limits (green screen); (c) approaching a curve with inappropriate speed – the active CSWS is issuing a warning (red screen). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(60 mph) (NFPA, 2008). The truck model, developed by Mechanical Simulation (Ann Arbor, MI), featured accurate dynamic performance including truck dimensions, geometry, mass distribution, engine power, acceleration, steering and braking performance, suspension and tire-road interaction (friction). It also possesses accurate outside and inside visual characteristics including a virtual dashboard, active (with simulated synchronized image) back-view mirrors, and sirens which could be turned on and off from a control touch-screen panel.

2.3.2. Driving environment (route map, visuals)

Two test routes for the study were specified by NIOSH and developed by Mechanical Simulation (Ann Arbor, MI). A pre-test route (Route A) was used for drivers to become familiar with the simulator, the operation of the vehicle, and responding to warnings. The route was 11.126 km (6.91 miles) long with 14 curves which have radii (R) in the range of 51–612 m. Eight of the 14 curves were with R < 200 m and 5 of the eight were with R < 100 m. The road map used for the actual test (Route B) is presented on Fig. 2. The route was 12.640 km (7.900 miles) long with 18 curves with R in the range of 45–1229 m. Eleven of the 18 curves were with R < 200 m and 7 of the 11 with R < 100 m (Table 1). Curves with radius <200 m were considered critical and were included in the analysis since they required a noticeable safety speed drop (>5 km/h or > 3 ml/h). Curves with radius <100 m were considered as especially challenging since they required a substantial safety speed drop (>35 km/h or > 20 ml/h). The driving environment consists of a rural two-lane (lane width = 3.36 m/11 ft) road on a hilly terrain with varied vegetation which partially occluded some of the upcoming curves. The test route is a compilation of curve segments with fixed radius approximated to actual curves from the road network of rural West Virginia (using Google Maps). All the critical curves were signaled with curve signs and speed limit signs (V_{post} in Table 1). Examples of the visual environment, including a curve, are provided in Fig. 1b and c.

2.3.3. Development of warning algorithm (a set of rules for the experimental CSWS)

The curve speed warning system (CSWS) algorithm was developed following the general guidelines for CSWS described in Pomerleau et al. (1999). The algorithm continuously calculates the deceleration value (a) (Eq. (1)) required to reduce the vehicle current speed (V) to the approaching curve safety speed level (V_s) within the distance (d) from the vehicle to the curve apex (or a V_s target location); the algorithm issues a warning when the calculated deceleration value becomes higher than a preset average deceleration value (1.5 m/s^2) representing the average deceleration rate at which drivers reduce their speed (Pomerleau et al., 1999) (Fig. 3). To adapt the system to the heavy firetruck vehicle and to emergency response driving on a dry road, the algorithm was modified by adjusting the curve safety speed level for the risk of rollover and establishing a curve safety speed zone by moving the safety speed target location to the midpoint of curve entry and curve apex. These modifications provided early warnings when curve approach and entry speeds were unsafe and also allowed the firetruck drivers to drive safely and as fast as possible during emergency response. These modifications also eliminated unneeded warnings and produced desirable driver system acceptance.

$$a = \frac{V^2 - V_s^2}{2(d - t_r V)} \qquad \text{Eq.(1)}$$

where:

V = the vehicle's current approach speed.

V_s = the maximum safe speed of the curve

T_r = driver reaction time (assumed to be 1.5 s) (Pomerleau et al., 1999).

D = the distance between the current vehicle position and apex of the curve (or a V_s target location).

The Vs values may be too conservative if based on the side friction factor assumed for highway design (assuming wet and icy conditions) and the CSWS may issue many unnecessary warnings during fire emergency driving in dry road conditions. Recognizing that the most critical speed-related crash event in a curve for a heavy truck on a dry road is a rollover, the safety speed profile (V_s) for the test was derived (as 90%) from the rollover critical speed of this vehicle (Pomerleau et al., 1999). The rollover critical speed ($V_{roll.cr}$) was determined following the

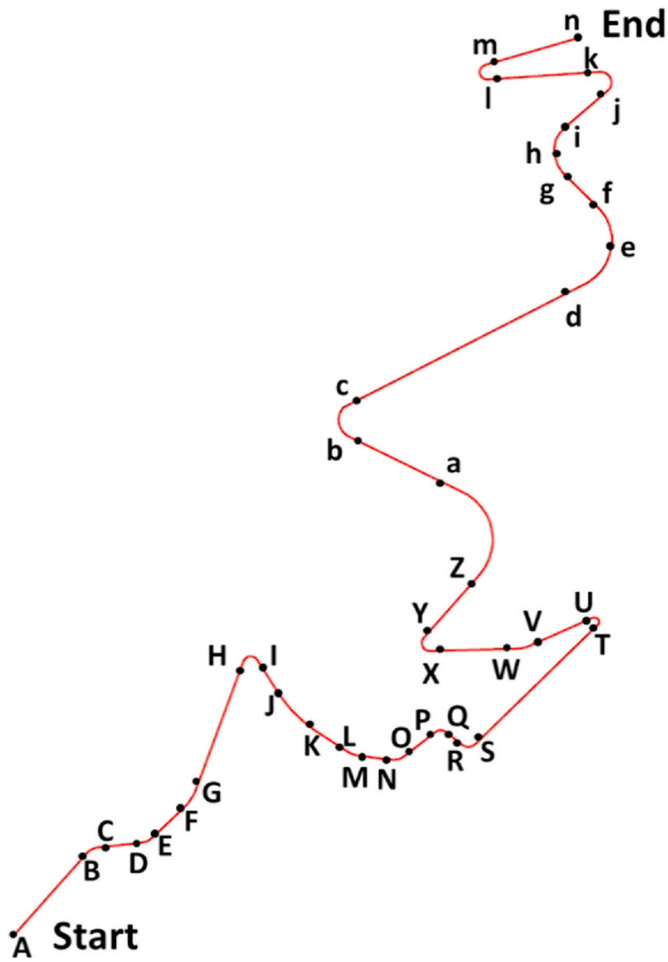


Fig. 2. Map of the test route with alphabetically indicated road segments (curves: BC, DE, FG, HI, JK, LM, NO, PQ, RS, TU, VW, XY, Za, bc, def, ghi, jk, lm).

general guidelines (Pomerleau et al., 1999) according to (Eq. (2)). The maximum lateral acceleration ($a_{lat.max}$) for the vehicle model was measured with a swept steer test at 40 mph (64 km/h) in TruckSim using Proving Grounds (Unity Scene). In the test (performed by Mechanical Simulation, Ann Arbor, MI), the truck model was accelerated to the target speed along a straight path and then started turning at a slow rate so that lateral acceleration increases at no more than 0.1 g (0.98 m/s^2) per second. The steering wheel input was applied until the vehicle tipped up indicating the maximum (critical) lateral acceleration ($a_{lat.max}$).

$$V_{roll.cr} = \sqrt{Ra_{lat.max}}, \ldots V_{roll} = 0.9\ V_{roll.cr} \qquad \text{Eq.(2)}$$

$$V_{slip.cr} = \sqrt{gRf_{slip}}, \ldots.. V_{slip} = 0.9\ V_{slip.cr} \qquad \text{Eq.(3)}$$

$$V_{comf} = \sqrt{gR\frac{a_{lat.comf} + e_{sup}}{(1 - a_{lat.comf}e_{sup})}} \qquad \text{Eq.(4)}$$

where:

R = curve radius, m

$a_{lat.max}$ = maximum lateral acceleration for the vehicle = 0.39g (3.82 m/s^2).

g = gravitational constant = 9.8 m/s.^{2}

f_{slip} = side friction factor.

$a_{lat\cdot comf}$ = maximum lateral acceleration tolerance (for comfort) = 3.5 m/s^2 (Jimenez et al., 2012).

e_{sup} = super-elevation of the road segment (%), which provides an added safety margin like a car racetrack.

The rollover safety speed (V_{roll}) values (safety speed profile) used in the algorithm for the most challenging curves are provided in Table 1. The calculation did not include the curve super-elevation to provide an additional safety margin (and because rural roads often do not have this feature). The table includes values for the posted speed (V_{post}), slip-related safety speed (V_{slip}) (Eq (3)), and comfort speed (V_{comf}) (Eq (4)) based on lateral acceleration tolerance of 3.5 m/s^2 (Jimenez et al., 2012). For straight sections and larger radius curves for which V_{roll} exceeded 96 km/h, the maximum allowable speed of 96 km/h was used as safety speed.

It must be noted that the safety speed profile is dynamic in nature and has to reflect the lowest critical speed for the current environmental conditions – for example, in slippery driving conditions the safety speed profile will have to be based on the critical speed for the vehicle slipping (on a wet or icy road) ($V_{slip} = 0.9V_{slip.cr}$) (Table 1). It should further be noted that the comfort speed (V_{comf}) based on lateral acceleration (3.5 m/s^2) (and including the super-elevation in the calculations) for driving

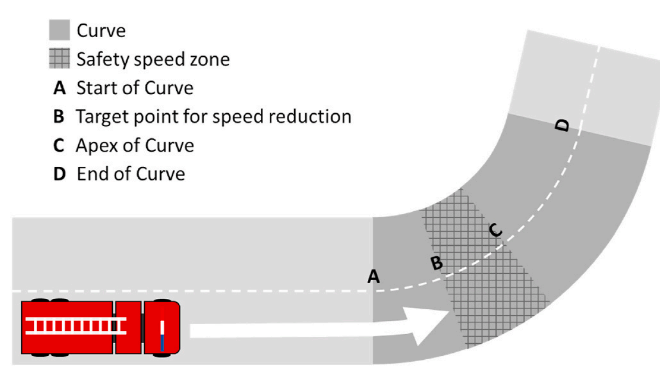


Fig. 3. Schematic representation of a curve with approaching firetruck. CSWS issues a warning if $a > 1.5$ m/s^2 (Eq. (1)); furthermore, within the safety speed zone, CSWS issues a warning when $V > Vs$.

Table 1
Characteristics and safety speeds of the most critical curves.

Name	Radius, m	Length, m	Super-elevation, %	Max Friction	Vpost, km/h	Vslip, km/h	Vroll, km/h	Vcomf, km/h
BC	120	61	2.74	0.18	56.0	47.1	69.4	76.2
DE	186	131	1.50	0.16	64.0	55.3	86.3	93.0
HI	75	134	4.38	0.20	48.0	39.3	54.9	61.7
NO	196	167	0.57	0.16	64.0	56.8	88.7	94.2
PQ	77	111	3.68	0.20	48.0	39.8	55.7	62.0
RS	98	133	0.00	0.20	48.0	44.9	62.7	66.0
TU	46	95	4.66	0.23	40.0	33.0	42.9	48.5
XY	74	151	4.76	0.20	48.0	39.0	54.4	61.6
bc	170	292	3.10	0.16	64.0	52.9	82.6	91.3
jk	97	254	0.00	0.20	48.0	44.7	62.5	66.0
lm	67	194	0.00	0.23	40.0	39.8	51.7	54.6

in curves is higher than both V_{roll} and V_{slip}. In this regard, with this vehicle, the driver will not be able to "sense" the danger of a rollover or sliding in a curve based on discomfort from lateral acceleration.

According to the guidelines (Pomerleau et al., 1999), mostly applicable to light passenger vehicles, the target point for speed reduction to the safety speed (V_s) is the curve apex (beyond which no warnings are issued). Recognizing that when negotiating a curve, a heavy truck driver must reduce vehicle speed (and reach V_s) much earlier in the curve (IAFF, 2010), the target point in the algorithm for this study was set (arbitrarily) at the middle (50%) of the entry-apex curve section (Fig. 3). This setting created a de-facto requirement for a "safety speed zone" between the target point and the apex in which the truck speed must remain at or below V_s. Therefore, the algorithm included an additional simple control logic to issue a warning if the vehicle speed exceeded the curve safety speed in the "safety speed zone" after the target point.

2.4. Procedure

When a participant arrived at the lab, the investigators described the study and the tasks that the participant was to perform and answered any questions regarding the study. The participant signed an informed consent form approved by the NIOSH IRB. Participants were then screened for susceptibility of motion sickness using a questionnaire (Hoffman et al., 2003) and the information was used as a baseline for the subsequent motion sickness monitoring. Participants also completed a baseline standing balance test (semi-tandem Romberg test – Cobb 1999; Simeonov et al., 2011) as additional precautionary measure.

To get the participants familiar with the simulator environment and the driving task, including the controls and the dynamics of the truck model, the participants performed a pre-test drive on Route A for 10–15 min. Participants wore their firefighter protective pants and boots. Before the test, a researcher explained the purpose and the function of the CSWS to the participants as follows: "when approaching a curve at unsafe speed you will get sound and visual warnings and you will need to reduce the vehicle speed until the warnings disappear". The participants were then asked to complete a Driver Satisfaction Survey (Van der Laan et al., 1997) based on their perceived expectation for the CSWS. The pre-test drive was also used to let the participants experience and react to several random cautionary warnings. Participants' reaction time and deceleration rate were measured during the pre-test with an average reaction time of 1.06 s (SD = 0.21 s) and an average deceleration rate of 1.67 m/s^2 (SD = 1.47 m/s^2). The pre-test drive was performed under normal driving conditions, i.e., not responding to an emergency call, and therefore without warning lights and sirens. Throughout the test, participants were monitored closely for any symptoms of motion sickness using the same questionnaire (Hoffman et al., 2003) described in the initial participant screening. Rest breaks (10 min) were provided after each trial and additionally as needed to assure that the participants were not negatively affected by any simulator-related motion sickness.

For the emergency response driving test, participants were instructed to drive "as fast as possible, but safely" and to respond to the warnings by gradually reducing (to avoid sudden braking) the vehicle speed until the warnings stop. To set the stage for the emergency driving task, a radio emergency dispatch message was played before the driving trial. The participant had to turn on the emergency lights and sirens. The emergency of the task was reinforced later by two more messages providing additional information on the incident to which the unit was responding. Throughout the test, participants were monitored closely for any symptoms of motion sickness using the same questionnaire (Hoffman et al., 2003) described in the pre-test. Rest breaks (10 min) were provided after each trial and additionally as needed. All participants completed all the trials of the experimental design. Trials in which a participant experienced a virtual crash were restarted. After completion of the test session, the participants had to again complete the Driver Satisfaction Survey reflecting on their experience with the CSWS and were also given the opportunity to provide some comments. Finally, the participants completed a standing balance test (semi-tandem Romberg test – Cobb 1999; Simeonov et al., 2011) as an additional precautionary measure for no symptom of carry-over motion sickness before they were compensated for their time spent in the survey and released.

2.5. Variables

2.5.1. Independent variables

The independent variables included the CSWS status and curve radius – in a "within subjects" experimental design, i.e., where every participant completed all experimental conditions. The status of the CSWS had two levels: system "off" and system "on". The system "off" setting was used as a control or baseline and system "on" was used to evaluate the effect of CSWS on all the dependent variables. The effect was mostly derived as the absolute difference between the two levels ("on" - "off") and for a few dependent variables, as the relative difference/change (as % of the baseline). The curve radius (R, m) was considered in the range 46 m–196 m including the 11 critical curves for which the safety speed was smaller than the maximum speed allowed at straight sections (Vs < 96 km/h) (Table 1).

2.5.2. Dependent variables

Three groups of dependent variables were used to evaluate the effect of CSWS on driving performance, safety outcomes, and system acceptance.

2.5.2.1. Driving performance variables. *Driving performance for the whole route*: was characterized by the *route average speed* ($V_{avr\text{-}route}$, km/h) and the *route maximum speed* ($V_{max\text{-}route}$, km/h).

Driving performance at the most critical curves: The most critical curves were the 11 curves with R < 200 m (R = 46–196 m and corresponding V_s drop = 50 to 1.8 km/h). The speed-related driving performance for each of these curves was characterized by the a*verage speed at curve approach in the 200 m section* (Polus et al., 2000, Bella, 2014) (V_{apr}, km/h) and the *curve entry speed* (V_{ent}, km/h). The effect of the CSWS was assessed as the relative average speed change at curve approach (dV_{apr}) and curve entry (dV_{ent}) between CSWS "on" and "off" conditions. The braking behavior during curve approach was characterized by the number of braking events arranged by the level of speed-reduction (dV) – mild and moderate (dV < 40 km/h) or severe (dV > 40 km/h); and by the number (and %) of severe braking events (dV > 40 km/h) which start within 100 m of the curve or which end in the curve.

2.5.2.2. Safety outcome variables. *Over-speeding distance in curves:* The variable "over-speeding distance in curves" (D_{ovs}, m) reflects the distance (in meters) or the relative distance (in %) traveled above the safety speed in curves (in the range curve start to apex) at three different levels of over-speeding: above safety speed (>0%), above 5% over the safety speed, and above 10% over the safety speed.

Maximum speed in curves: The variable maximum speed in curves (V_{max}, km/h) in the range curve (start to apex) can be regarded as a safety outcome measure when compared to the safety speed for the corresponding curve.

2.5.2.3. System acceptance variables. *System acceptance*: The system acceptance was assessed using the Driver Satisfaction Survey developed by Van der Laan et al. (1997). The survey consists of nine 5-point rating scale items. These items can be used to obtain usefulness and satisfaction scores.

2.6. Statistical analysis

Repeated measures analyses of variance (ANOVAs) were performed using the SAS MIXED procedure to evaluate the effects of curve radius (including the 11 most critical curves and treated as a continuous variable), warning system status (“on” vs “off”), and their interactions on the driving performance variables: curve approach speed (Vapr), curve entry speed (Vent), and maximum speed in curve (Vmax). In the mixed model approach the participant was used as a random effect. The significance level (α) used for this study was set at 0.05. Statistical Analysis System (SAS) software (SAS Institute Inc., Cary, NC, USA) was used to perform all data analyses.

Regression analyses were performed to determine the relationships of curve approach speed (V_{apr}) and the effect of CSWS on curve approach speed (dV_{apr}) with curve radius (R); curve entry speed (V_{ent}) and the effect of CSWS “on” in curve entry speed (dV_{ent}) with curve radius (R); and maximum speed in curve (V_{max}) and the effect of CSWS on maximum speed in curve (dV_{max}) with curve radius (R). A paired *t*-test was used to test the effect of CSWS on the variable relative over-speeding distance in curves (D_{ovs}). For other variables, descriptive statistics was used to compare CSWS “on” and “off” conditions.

3. Results

3.1. Effects of CSWS on driving performance

3.1.1. Driving performance for the whole route

The warning system did not have a significant effect on the average speed ($V_{avr\text{-}route}$) and the maximum speed ($V_{max\text{-}route}$) for the whole route. With system “on” the $V_{avr\text{-}route} = 74.8$ km/h (SD = 3.0 km/h) and $V_{max\text{-}route} = 108.2$ km/h (SD = 5.0 km/h) while for system “off” the $V_{avr\text{-}route} = 74.3$ km/h (SD = 3.3 km/h) and $V_{max\text{-}route} = 107.3$ km/h (SD = 5.3 km/h).

3.1.2. Average speed at curve approach (V_{apr})

Repeated measures ANOVA revealed significant main effects of CSWS status (“on” vs. “off”) (p = 0.0313) and curve radius (in the range 46 m–196 m) (p < 0.0001) as well as their significant interaction (p = 0.0342) on V_{apr}. With CSWS “off”, V_{apr} varied with curve radius in the range 57.6 km/h to 92.2 km/h (Fig. 4a), while with CSWS “on” V_{apr} varied with curve radius in the range 56.3 km/h to 93.3 km/h, but without well-defined trends in both conditions. The interaction of the CSWS status and curve radius revealed that the effect of the CSWS expressed as the difference in speed between system “on” and system “off” (dV_{apr}) varied with curve radius, from 7.2 km/h speed reduction in approaching the most challenging curve (with radius 46 m) to 1.7 km/h speed increase in approaching the least challenging curve (with radius 196 m) (Fig. 4b).

Regression analysis demonstrated that with the CSWS “off” V_{apr} was not associated with curve radius ($R^2 = 0.023$) (Fig. 4a), with an average of 74.0 km/h, which is 18 km/h less than the max safety speed on the route. The regression analysis further demonstrated that the effect of the warning system (dV_{apr}) can be best represented as an exponential function of curve radius ($R^2 = 0.89$), with effects changing from slight speed increase for curves with radius > 100 m to substantial speed decrease for curves with radius < 100 m (Fig. 4b).

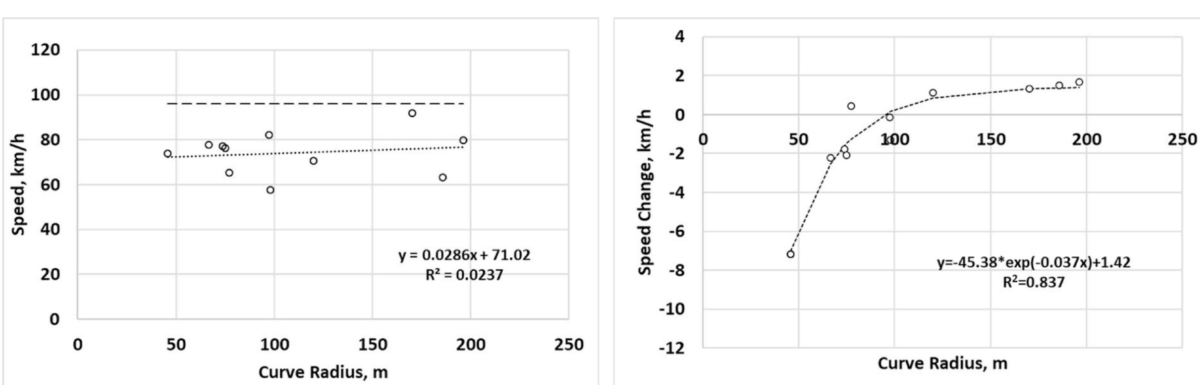
3.1.3. Curve entry speed (V_{ent})

Repeated measures ANOVA revealed significant main effect of curve radius (in the range 46 m–196 m) (p < 0.0001) and a significant interaction of CSWS status (“on” vs. “off”) with curve radius (p = 0.0295) on V_{ent}. With CSWS “off” V_{ent} increased with curve radius in the range of 40.6 km/h to 72.2 km/h (Fig. 5a), while with CSWS “on” V_{ent} increased with curve radius in the range of 37.1 km/h to 74.2 km/h. The interaction demonstrated that the effect of the CSWS on V_{ent} expressed as the difference in speed between system “on” and system “off” (dV_{ent}) was also dependent on the curve radius. The dV_{ent} ranged from 3.5 km/h speed reduction in entering the most challenging curve (with radius 46 m) to 1.94–3.4 km/h speed increase in entering some of the less challenging curves (with radius ranging in 170–196 m) (Fig. 5b). There was an exception from this trend for a curve with radius 67 m with dV_{ent} of 3.9 km/h increase.

Regression analysis demonstrated that with CSWS “off,” the curve entry speed (V_{ent}) was highly correlated with curve radius ($R^2 = 0.782$); and for curves with smaller radius (<100 m) V_{ent} approached the safety speed limits (V_s) (Fig. 5a). The regression analysis further demonstrated that the effect of the warning system (dV_{ent}) showed a weak linear trend ($R^2 = 0.358$) with curve radius (Fig. 5b). Overall, for less demanding curves (with radius > 100 m and speed drop <30 km/h) the effect of CSWS on dV_{ent} was a speed increase, while for the more challenging curves with radius < 100 m (and safety speed drop > 30 km/h) the effect was a speed decrease.

3.1.4. Braking behavior during curve approach

In approaching the curves on the test route, with CSWS “on”, the cumulative number of mild (speed drop 20–30 km/h) and moderate (speed drop 30–40 km/h) braking events was higher as compared to the system “off” condition (150 vs 105); while the number of severe braking events (speed drop > 40 km/h) was substantially reduced (nearly three times) as compared to system “off” condition (21 vs 59 braking events) (Fig. 6). Furthermore, with the CSWS “on” the overall number of severe braking events starting in the vicinity of the curve entry (within 100 m) was considerably reduced (8 vs 33), and also the number of severe braking events ending within the curve was considerably reduced (9 vs 38) as compared to the system “off” condition (Fig. 7).



a b

Fig. 4. Speed at curve approach (V_{apr}) (200 m section): (a) V_{apr} with system “off” is not associated with curve radius; (dotted regression line); (dashed line is the safety speed for the approach section, Vs = 96 km/h); (b) effect of CSWS on curve approach speed (dV_{apr}) an exponential function of curve radius (dotted regression line).

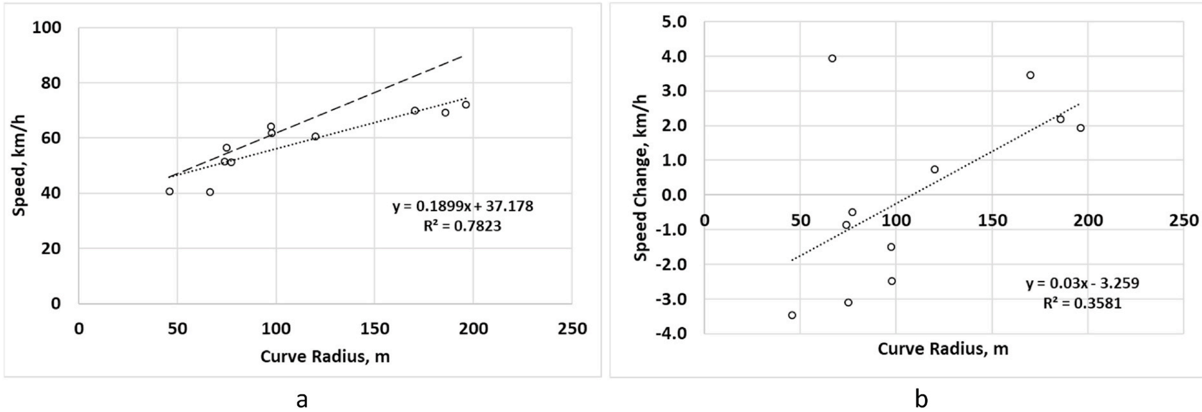


Fig. 5. Curve entry speed (V_{ent}): (a) V_{ent} with system "off," follows a linear trend with curve radius; (dotted regression line); (dashed line is the safety speed limit, V_s); (b) effect of CSWS on curve entry speed (dV_{ent}) follows a weak linear trend with curve radius (dotted regression line).

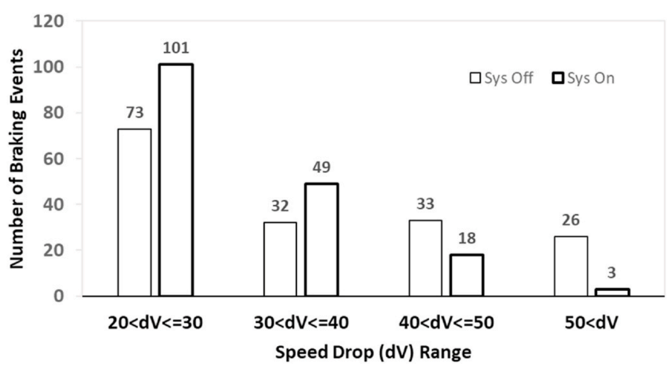


Fig. 6. Effect of CSWS on the number of braking events by speed-drop (dV) range: The use of CSWS resulted in increased number of mild and moderate braking events (speed drop of 20–40 km/h) and reduced number of severe braking events (speed drop of >40 km/h). There were 171 recorded braking events when the CSWS was "on" and 164 when the CSWS was "off."

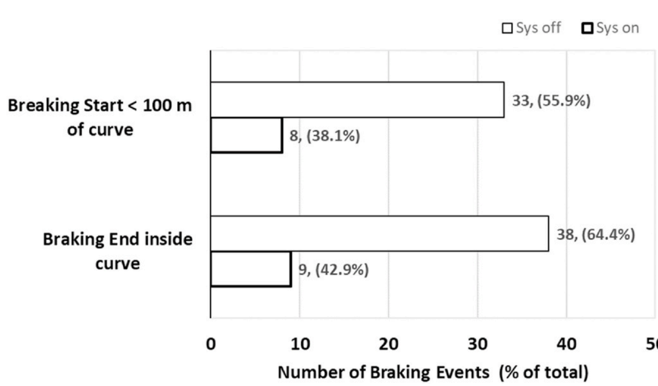


Fig. 7. Effect of CSWS on the number and % of severe braking events (dV > 40 km/h) which start within 100 m of the curve or which end in the curve: The use of CSWS resulted in reduced number (and %) of braking events starting within 100 m of the curve and number (and %) of braking events ending in the curve.

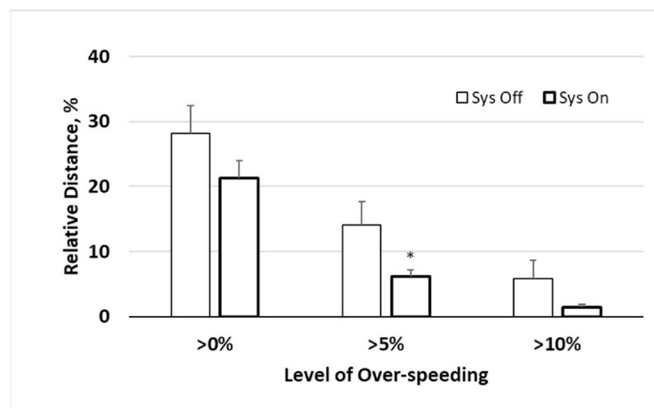


Fig. 8. Cumulative over-speeding distance (as % of start to apex, average across all curves) for all critical curves in the test route; *p < 0.05.

3.2. *Safety outcomes*

3.2.1. *Over-speeding in curves*

The cumulative relative over-speeding distance in curves (D_{ovs}) (expressed as % of the start to apex distance for all curves with $R < 200$ m) on average for all participants is displayed in Fig. 8. A paired *t*-test demonstrated that D_{ovs} was significantly reduced ($p = 0.05$) when the CSWS was "on" for the medium level of over-speeding (5%–10% over Vs) as compared to when the CSWS was "off". The over-speeding distance was not significantly different between the CSWS "on" and "off" condition for the low level (0%–5% over Vs) and high level (>10% over Vs) of over-speeding.

3.2.2. *Maximum speed in curves (V_{max})*

Repeated measures ANOVA revealed significant main effects of CSWS status ("on" vs. "off") ($p = 0.0048$) and curve radius (in the range 46 m–196 m) ($p < 0.0001$) as well as their significant interaction ($p = 0.0030$) on V_{max}. With CSWS "off" V_{max} increased with curve radius in the range of 44.2 km/h to 75.7 km/h (Fig. 9a); while with CSWS "on" V_{max} increased with curve radius in the range of 40.9 km/h to 77.7 km/h. The interaction demonstrated that the effect of the CSWS on V_{max} expressed as the difference in speed between system "on" and system "off" (dV_{max}) was also dependent on the curve radius. The dV_{max} ranged from 3.30 km/h speed reduction in the more challenging curves to 2.0 km/h speed increase in the less challenging curves (Fig. 9b).

Regression analysis demonstrated that with the CSWS "off", the curve maximum speed (V_{max}) was highly correlated with curve radius ($R^2 = 0.883$); and at sharp curves (with radius < 100 m), V_{max} approached and even surpassed the safety speed limits (V_s) (Fig. 9a). The effect of the warning system (dV_{max}), also showed a linear trend ($R^2 = 0.613$) with curve radius (Fig. 9b). Overall, for less demanding curves (with radius > 100 m and speed drop <30 km/h) the effect of CSWS on dV_{max} was a speed increase, while for the more challenging curves with radius < 100 m (and safety speed drop > 30 km/h) the effect was a speed decrease.

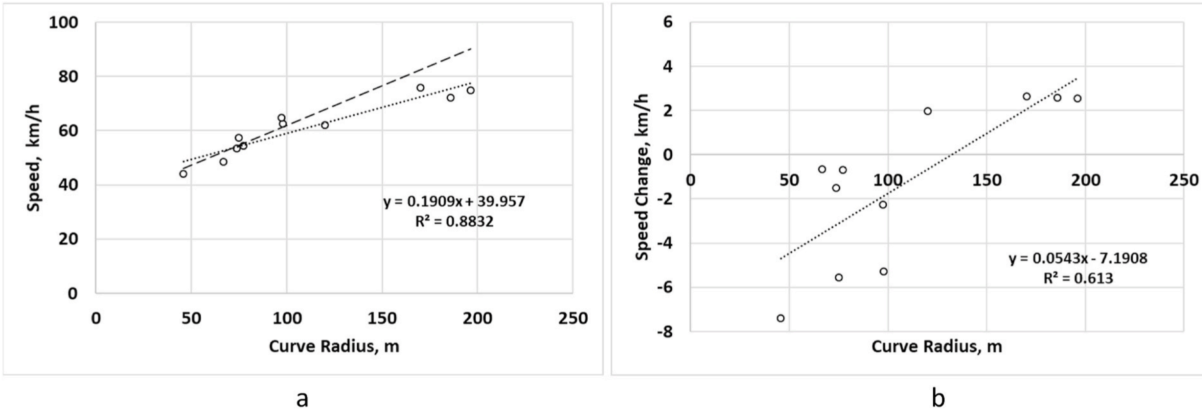


Fig. 9. Maximum speed in curves (V_{max}): (a) V_{max} with system "off" follows a linear trend with curve radius (dotted regression line), with values at or above the safety speed (dashed line, V_s) for the sharp curves (with lower radius values); (b) effect of CSWS on max speed (dV_{max}) in curves represented as a linear function of curve radius (dotted regression line).

3.3. Acceptance

Overall, the warning system was well accepted by the participants. They found the warning system was useful (alerting, assisting, effective, good, and useful) and satisfying (desirable, likable, nice, and pleasant) with scores increasing after testing the system as compared to their pre-test ratings based only on a system description (Fig. 10).

After testing, some of the participants made comments on the system. Some of the positive comments included: "the system gave confidence", "felt like a safety net", "provided a buffer zone", "felt like someone who knows the road is assisting you". The participants also considered the system as especially good for driving in unfamiliar routes and for inexperienced drivers. Participants also felt that they could start relying on the system and felt more cautious when system was "off" due to lack of assistance. With the system "on", other participants felt like driving more aggressively, being more alert to speed, and more cautious around curves. Some of the negative comments included: "may be a nuisance for experienced drivers", "you can use your own judgement to negotiate curves", "prefer relying on the road signs", and "system may need some adjustments to fix too early or too late warnings".

4. Discussion

4.1. Effects of warning system on driving behavior

The observed speeding behavior, described by the average speed at curve approach, curve entry, and curve max speed, provides a direct evidence of the effectiveness of the CSWS to change drivers' behavior when and where needed and to improve driving safety without affecting overall driving efficiency.

There was no significant effect of the warning system on the average speed across the whole route. This is consistent with other studies on curve speed warning systems for passenger vehicles (Jimenez et al. 2008, 2012) which reported no significant change in average speed on the test route between system "on" and "off" conditions. Jimenez et al. (2012) suggested that the warning system enables the distances traveled above the safe limit to be considerably reduced without penalizing the average speed because the system induces acceleration and deceleration at more suitable points. It is also possible that to some extent this outcome is due to overreliance on the system, a compensatory behavior which enables higher speeds in the less critical route sections while reducing the speed at the most critical curves.

The average speed during curve approaching with CSWS "off" was not affected by curve radius. This finding is consistent with earlier research on curve negotiation. On unfamiliar roads, the driver often does not have enough visual information for estimating the curve radius and the associated safe speed. In these conditions, the anticipatory speed adjustments are based on perceived road curvature, driver estimate of the vehicle characteristics, and driver steering competence (Godthelp 1986; Van Winsum and Godthelp 1996). When entering a curve, as additional visual information becomes available, the speed can be further adjusted using proprioceptive information from tactile and vestibular inputs to maintain a safety margin of lateral acceleration (Reymond et al., 2001). In emergency driving, these last-moment "in-the-curve" speed adjustments may be a significant challenge for a heavy fire truck vehicle driver.

The lack of curve radius effect on average curve approaching speed with CSWS "off" in this study further highlights the danger for heavy

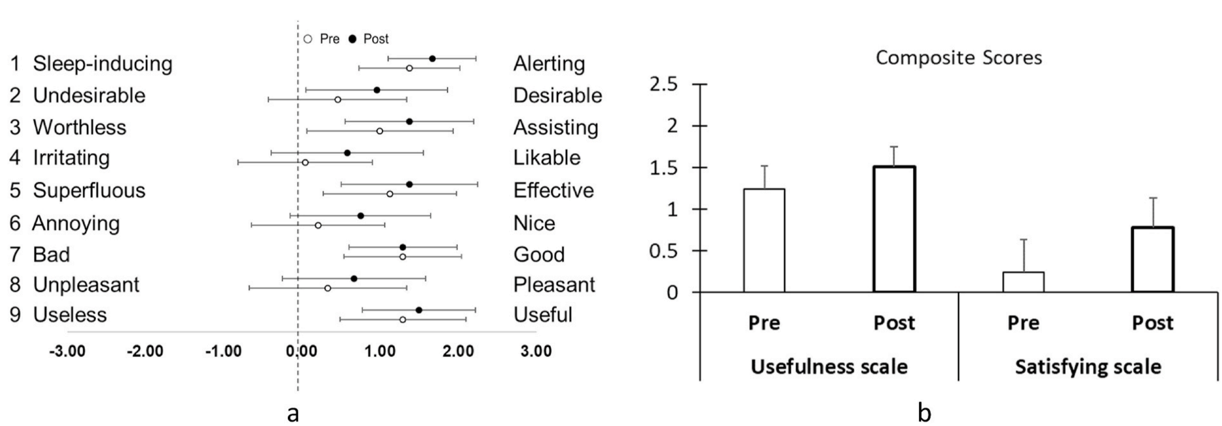


Fig. 10. Warning system acceptance measures (a) survey data; (b) composite results (useful = 1, 3, 5, 7, 9; satisfying = 2, 4, 6, 8).

firetrucks considering that many State motor vehicle codes or fire department operating procedures allow emergency vehicles to exceed the posted or cautionary speed limit during an emergency response (FEMA, 2003). Without a proper warning, some firetruck drivers may approach and enter a curve with excessive speed based on improper judgement and may end up with the need for last moment speed adjustments. Furthermore, the posted or cautionary speed limits, even if followed, are based on passenger vehicle rather than large and heavy truck criteria (FEMA, 2003). In addition, for heavy vehicles like fire tankers the Vroll is less than Vcomf which will increase the risk of misjudging the safety speed and may increase the risk of overturn crashes.

The effect of CSWS on curve entry speed was a function of curve radius – with speed decrease for sharp curves (R < 100 m) and small speed increase for less challenging curves (R > 100 m). This speed pattern can be explained by the interplay of three competing behavioral tendencies in negotiating a curve with an active CSWS. The first evident tendency is speed reduction in response to actual warnings – a direct function of the CSWS performance. The second tendency is anticipatory preemptive reduction in speed to avoid getting a warning. The third tendency is an increase in speed as a result of over-reliance on the CSWS – a compensatory behavior in line with the homeostasis risk theory (Wilde 1988). This interpretation is consistent with the study of Comte and Jamson (2000), who evaluated several traditional and innovative speed reducing measures for curves. In their study, Comte and Jamson (2000) noted an increased speed at curve approach with a speed limiter system; drivers appeared to be reliant on the system for deceleration and may have been adapting their behavior to maintain the maximum speed for as long as possible in planning for lower than desired speeds at other sections in route.

When approaching a curve with the CSWS “on” in this study, the firetruck drivers braked more often earlier and gentler as compared to the system “off” condition. This is a logical outcome for drivers in response to the preemptive warnings issued by the system or to avoid getting a warning. With the warning system “off”, most of the severe braking events occurred within 100 m of curve entry and ended within the curve. This is similar to the observation of Comte and Jamson (2000) who tested several speed-reduction measures for curves. They reported that in a curve approach under a no-assist-device condition, a clear reduction in speed was not observed until approximately 100 m before the curve entry, and the deceleration at this point was heavy into the curve. The emergency response driving without the CSWS in this study revealed such behavior of late and heavy braking into the curve. The merit of the CSWS becomes obvious at this stage.

4.2. Effects of warning system on safety outcomes

The CSWS was successful in reducing the over-speeding distance (distance driven with speed above the safety speed) and the maximum speed at the most challenging curves – two useful safety indicators for reduced risk of speed-related crashes in curves.

The results for reduced curve over-speeding distance in this study suggest a safer curve negotiation with the CSWS. These results are consistent with Jimenez et al. (2008) who studied the effect of an in-vehicle dynamic speed assistance system (ISA) with normal driving of light vehicles in real rural road conditions. They found a significant decrease (31%) in the distance traveled above the legal speed limits when driving with as compared to without the ISA system. Similarly, Jimenez et al. (2012), in testing an improved ISA, found statistically significant differences between driving with and without the system for the distance traveled at a speed above the safe limit (6.3% with the system and 21.5% without the system). The reduced maximum speed at sharp curves with the CSWS in this study further suggests improved overall driving safety at the most challenging curves with the CSWS. The effect of CSWS on maximum speed at curves can be attributed to the same behavioral mechanisms described above in the discussion about the curve entry speed.

4.3. Acceptance

A CSWS warning system may be perceived as helpful or annoying, depending on how closely the system design matches the driver’s style and expectations. An overall positive acceptance rating for the CSWS, along with many helpful and constructive comments, were observed in this study, suggesting that the tested algorithm was well balanced and matched the firefighter participants’ driving style and expectations. The increase in the acceptance rating results in the post-as compared to the pre-testing phase are consistent with a study on acceptance of mandatory intelligent speed adaptation systems (ISA) (Katteler 2005). This increase in an overall acceptance rating suggests that the system performance exceeded the drivers’ expectations per the tested acceptance parameters.

4.4. Suggested directions for future work

During the simulated emergency response in this study the firetruck drivers experienced a few virtual crash events. All the virtual crash events were associated with driving in curves above the safety speed limit. Further in-depth analysis of the firetruck crash events would provide meaningful guidance to improve the CSWS algorithms which can subsequently be tested in the future studies.

Preventing nuisance alarms is difficult because there is no commonly accepted benchmark for “correctly” negotiating a curve (Pomerleau et al., 1999). Considerable variation in driver behavior, and specifically in speed profiles when negotiating a curve, necessitates the development of an adaptive CSWS. A sophisticated adaptive CSWS may model an individual driver’s curve negotiation behavior, including measures such as driver’s reaction time, brake onset time, deceleration rate, and tolerance for lateral acceleration (Pomerleau et al., 1999; Ahmadi and Ghanipoor Machiani 2019). To fine-tune the optimal speed profiles, an innovative CSWS may use artificial intelligence (AI) by implementing learning algorithms based on data from previous driving runs through a specific route of vehicles with similar dynamic characteristics and emergency response tasks.

4.5. Limitations

This study used a driving simulator to model and test the CSWS. In this regard, the possible study limitations may be related to the fidelity of the driving simulation and participants’ previous gaming experience. Along with many benefits, such as experimental control, efficiency, low expense, safety, and ease of data collection, driving simulators have some important limitations, e.g., lack of realism associated with low risk perception, limited physical laws (i.e., lack of appropriate vestibular and motion cues), moderate behavioral validity, and potential motion sickness (Nilsson 1993; Godley et al., 2002). On the other hand, the validity of using driving simulators for speed research have been well established, both for generating and generalizing relative speed in testing road-based speeding countermeasures (Godley et al., 2002) and for studies on curve negotiation in two-lane rural roads (Bella 2008). At the same time, it is worth noting that participants initiate braking later and brake much harder in a driving simulator as compared to real roads (Boer et al., 2000); and also that curve-entry speed in a simulator was faster in less challenging curves (R > 582 m) and slower in the most difficult curves (R < 146 m) as compared to real roads (Bittner et al., 2002).

Some participants with extensive car-racing gaming experience may have been more accustomed to the simulated driving environment and could drive more aggressively than average persons. In this study, participants’ previous gaming experience was not assessed. During the test session, some participants commented on their car-racing gaming experience (and real-life car-racing experience) and how it may have affected their performance. In video-racing games, drivers are reinforced for driving recklessly and systematically breaking traffic rules, and as a result, video-racing games experience may increase risk-taking driving behaviors (Fischer et al., 2009).

In this study all participants performed all the experimental conditions in a balanced order. It is expected that in the relative differences between experimental conditions used to evaluate the CSWS effects, most of the abovementioned limitation's effects would likely be canceled out.

5. Conclusions

A curve speed warning system (CSWS) was tested in this study for fire-tanker drivers during emergency response driving using a driving simulator. The results demonstrated that the CSWS was effective in issuing preemptive warnings when drivers were approaching curves at an unsafe speed. The use of CSWS did not affect the overall travel time to complete the whole route, and improved driver performance at sharp curves where most of the speed warnings occurred. The CSWS improved the braking timing and reduced the number of severe braking events in approaching some of the most dangerous curves. The CSWS also reduced the average distance traveled at speeds over the safety speed limits and the maximum speed at the entry-to-apex section of a curve. In addition, the CSWS was well accepted in general and was rated as assisting, effective and useful by the firetruck drivers. Along with these benefits from the CSWS during the emergency response driving, there was a tendency for over-speeding at some less-challenging curves most likely due to over-reliance on the CSWS Overall, the study findings indicate that the proposed CSWS can enhance the safety under emergency driving conditions without compromising the driving time.

6. Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH or CDC. In addition, citations to websites external to NIOSH do not constitute NIOSH endorsement of the sponsoring organizations or their programs or products. Furthermore, NIOSH is not responsible for the content of these websites.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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