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Evaluation of advanced curve speed warning system to prevent firetruck rollover crashes

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Abstract

Introduction: A disproportionately high number of deadly crash-incidents involve fire-tanker rollovers during emergency response driving. Most of these rollover incidents occur at dangerous horizontal curves ("curves") due to unsafe speed. This study examined the effects of a curve speed warning system (CSWS) on fire tanker drivers' emergency response behavior to develop system improvement suggestions.

Method: Twenty-four firefighters participated in driving tests using a simulator. A fire tanker model, carrying a full tank of water, was used in emergency driving tests performed with and without CSWS. The CSWS was designed using the algorithm for passenger vehicles with a few initial modifications considering the unique requirements of heavy fire tanker and emergency driving.

Results: The results indicated that the CSWS was effective in issuing preemptive warnings when the drivers were approaching curves with unsafe speed during emergency response. Warnings occurred more frequently at curves with smaller radius. Although the CSWS improved driving performance, it did not significantly reduce the number of rollover events. A detailed analysis of the rollover events provided suggestions for improvement of CSWS algorithms.

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Conclusions: To further improve the CSWS algorithm, the following may be considered: including increased safety speed margin below the rollover critical speed, moving the speed warning trigger from the curve apex to the curve entry point, extending the safe speed-control zone to cover the entire curve, and employing artificial intelligence to accommodate individual driving styles.

Practical Applications: Fire tankers continue to be at increased risk of rollover during emergency response due to unsafe negotiation of dangerous curves. Development and use of advanced driver assist systems such as CSWS evaluated in this study may be an effective strategy to prevent deadly rollover crash-incidents. The knowledge generated by this study will be useful for system designers to improve the CSWS specifically designed for heavy emergency vehicles.

Keywords

fire tanker; horizontal curves; emergency response; speeding; overturn

1. Introduction

Transportation-related injuries remain a significant problem for firefighters in US. In 2019, an estimated 15,350 collisions resulting in 575 firefighter injuries were directly related to emergency vehicles responding to or returning from incidents (Campbell and Evarts 2020). A disproportionately high number of these incidents involve fire tankers. Tankers represent only 3 percent of all fire apparatus in the United States but 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 incidents 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 (NIOSH 2002).

Fire tankers, defined as “mobile water supply apparatus” (FEMA 2003), are some of the heaviest apparatus operated by a fire department. The water carry capacity of typical fire tankers is in the range 5678 to 11356 liters (1,500 to 3,000 gallons) and weigh more than 25 tons (55,000 lb.) (NFPA 2008). Furthermore, fire tankers have high center of gravity and are often referred as “top-heavy” vehicles. Vehicles that have a high center of gravity are more challenging to maneuver and control. Specifically, top-heavy fire trucks driven at an unsafe speed through a horizontal curve (“curve”) have a tendency to rollover. The tendency of a vehicle tipping/rolling over while moving through a curve is a matter of simple physics involving inertia and momentum - as the vehicle negotiates the turn, its weight leans in the direction opposite to which the vehicle is turning (FEMA 2003).

Road-related factors, such as the curve radius and road banking or super-elevation, provide adequate drainage and facilitate safe and comfortable negotiation of the curve at a reasonable speed (FEMA 2003). The smaller the radius of a curve the larger the tipping forces for the same speed of the vehicle. Flat curves, or curves without super-elevation are more challenging and require additional speed reductions to avoid the vehicle sliding or rolling over. The risk further increases if the roadway is banked toward the outside of the turn (i.e., the curve with negative super-elevation). The effects of these road geometry-related factors can be controlled if the vehicle is operated within an adequate speed. The real danger for a rollover is when the driver attempts to negotiate a dangerous curve at an unsafe speed, which may happen during emergency driving.

A critical review on rollover of heavy commercial vehicles (Winkler 2000) revealed that “the rollover threshold of loaded heavy trucks extends well into the ‘emergency’ maneuvering capability of the vehicle and sometimes into the ‘normal’ maneuvering range, and it is relatively hard for truck drivers to perceive their proximity to rollover while driving. Rollover is very much like walking up to a cliff with your eyes closed: as you approach the edge, you are still walking on solid ground but once you’ve stepped over, it’s too late. Further, the rollover threshold of a commercial truck changes regularly as the load changes, so drivers may not have the chance to get used to the stability of their vehicle.” Driving a tanker carrying fluid (which may shift and slosh in the tank) under emergency conditions poses several additional challenges regarding rollover threshold and vehicle stability, due to the associated time pressure and excessive speed.

Excessive speed for specific driving conditions has been identified as a major contributing factor for vehicle-related firefighter fatalities (FEMA 2003). Emergency responders are commonly allowed to travel at speeds above the posted limits (FEMA 2003). Speeding associated with emergency response driving increases the amount of risk imposed upon firefighters and the apparatus in which they ride. Therefore, firefighters should be trained in safe driving practices, including getting to know the dangerous routes and curves in their response area. Furthermore, some fire apparatuses are equipped with safety technology such as speed limiters and data collection black boxes, and most of the modern fire apparatuses have stability control systems (NFPA 2008). Despite these measures, the risk of speed-related crashes and injuries for firefighters riding in fire apparatus remains high.

A promising technological approach to assist fire apparatus drivers in controlling speed in curves may be the use of a curve speed warning system (CSWS) (Pomerleau et al., 1999); however, its effectiveness in emergency driving of heavy vehicles such as fire tankers has not been well studied. The CSWS is an advanced driver assistance system (CSWS-ADAS) which uses information from digital maps and the vehicle’s current location and speed from a global positioning system (GPS) to issue a warning when the vehicle approaches a curve at an unsafe speed. The system calculates the required deceleration and estimates the distance ahead of the curve at which to issue a warning such that the driver can safely reduce the vehicle speed before entering the curve. A great advantage of the CSWS-ADAS is that it can use variable or dynamic speed limits with the ability to adapt to different road and weather conditions (Jimenez et al., 2012). Furthermore, it can be based on standard GPS (Chowdhury et al., 2020) or connected vehicle technologies (Wang et al., 2020), and be adaptive to individual driver behavior (Ahmadi and Ghanipoor Machiani 2019).

The CSWS-ADAS has also been occasionally referred to as an intelligent speed assistance/adaptation (ISA) system. ISA is a generic term for a class of ADAS in which the driver is warned and/or vehicle speed is automatically limited when the driver is, intentionally or inadvertently, traveling over the posted speed limit, or some other pre-defined (fixed) speed threshold (Young et al 2010). The benefits of ISA technology are well documented to reduce speed, speed variability, speed violations, and injury and fatal crashes (Young et al 2010).

Devices that exercise a greater control over the driver 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). Several negative effects have been observed with ISA. Two key issues are (1) acceptability of the system warnings and (2) driver adaptation or system over-reliance. System over-reliance is a particular concern as faster speeds in curves by some drivers have been observed. Research on ISA use in heavy trucks remains limited (Fitzharris et al 2011), and it is not clear if the described ISA effects during the operation of general vehicles are applicable to heavy fire trucks.

Recently, Simeonov et al. (2021) evaluated the effectiveness, safety outcomes, and driver acceptance of a CSWS-ADAS during emergency response of a fire tanker using a driving simulator. The research findings suggested that the 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. Furthermore, drivers had a 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. Overall, the study demonstrated that the CSWS can enhance firetruck safety during emergency driving without sacrificing drivers’ precious response time.

In the study of Simeonov et al (2021), the algorithm for the CSWS was adapted from the guidelines of Pomerleau et al. (1999) and was further modified to meet the demands (for reducing the risk of rollover) of a heavy fire tanker in emergency driving conditions. The working principle in the CSWS algorithm is based on estimating the maximum curve safety speed and using it to calculate the warning distance (Pomerleau et al, 1999). In the existing studies, which are predominantly related to passenger cars (with a low center of gravity), the safety speed profiles were determined based on the risk of sideslip considering the factors such as curve radius, road superelevation, and friction factor (Jimenez et al., 2012, Wang et al., 2020, Chowdhury et al., 2020). The warning distance estimation in most of these studies was based on the curve apex serving as the curve safety speed target location, which is adequate for passenger cars since drivers usually continue decelerating well into the curve (Bella 2014).

While formulating the CSWS algorithm for the fire tankers (with an elevated center of gravity) driven under emergency conditions, the factors such as mass distribution and rollover susceptibility were considered to estimate the safety speeds. Based on the recommendation that heavy trucks require earlier speed reduction to safely negotiate a curve (IAFF 2010), the in-curve target for reducing the vehicle speed (at or below the curve safety speed) was moved from the curve apex to the entry-apex mid-point, thus establishing a safety speed zone (from the entry-apex mid-point to the curve apex). Despite these enhancements, during the simulated emergency responses, no significant difference in the rollover crash events was observed with and without CSWS conditions signifying a need for further improvement in the CSWS algorithm. Therefore, in this study an in-depth analysis of the firetruck rollover crash events was conducted with a goal of developing meaningful guidance for further improving the CSWS algorithms for emergency driving of heavy firetrucks.

2. Methods

2.1 Participants

The study participants were active members (career or volunteer) of the fire departments in Morgantown, WV, and the surrounding area. The inclusion and exclusion criteria consisted of age >=18 years, a valid driver's license, more than 6 months of experience driving a firetruck, ability to follow the study protocol and give informed consent, and no symptoms of motion sickness. Mean age, height and weight of the participants were 36 years (SD=10.1 years), 182.9 cm (SD=4.8 cm), and 103.5 kg (SD=16.8 kg), respectively.

2.2 Equipment

2.2.1 Driving simulator—A motion-base simulator (Mechanical Simulation, Ann Arbor, MI) with three degrees of freedom motion (roll, pitch, and heave) was used in this study. The simulator consists of 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. A TruckSim (Mechanical Simulation, Ann Arbor, MI) based tanker model with a 3-axle fire truck in a "laden" condition, i.e., carrying full tank of water (11356 liters/3000 gallons) with a total weight of 26,822 kg (59,008 lb.) was used in this study (Figure 1a). The model featured accurate dynamic performance of a heavy firetruck tanker, including truck dimensions, geometry, mass distribution, engine power, acceleration, steering and braking performance, suspension, and tire-road interaction (friction). Unity (Unity Technologies, San Francisco, CA) software was used to develop road geometry and create interactive driving scenarios with advanced graphic design and performance.

2.2.2 Warning system interface—The CSWS graphic user interface (GUI) provided data on the current speed of the vehicle, the posted speed limit for the current route section, and the safety speed for the upcoming curve. The system status was shown using color-codes: blue – system inactive; green – normal or OK, yellow – caution with sound warnings with frequency 2.6–3.1 beeps/s accompanied by a blinking arrow in the direction of the upcoming turn, and red with a steady arrow in the direction of the upcoming turn – danger with sound warnings with frequency 3.2–4.0 beeps/s. A touch screen tablet (Windows Surface Pro 4, 312 mm, Microsoft, Redmond, WA) was used to display the CSWS GUI (Figure 1 b, c).

The audible warning was with a fundamental frequency of 300 Hz and 15 harmonic components (Gonzalez et al. 2012). The audio warning had a pulse duration of 200 ms and variable inter-pulse interval (185–50 ms). The inter-pulse duration was regulated to increase the frequency of audio pulses to indicate increasing danger when speed reduction was insufficient or absent. The warning signal was issued with an increasing frequency, which was a function of increasing values of the calculated deceleration required to reach the safety speed to avoid a rollover event. In the situations with increasing danger, synchronized vibration signals at the steering wheel (actuated by the power steering system) were provided along with the audible warning signals.

2.2.3 Warning algorithm—The original curve speed warning system (CSWS) algorithm, mostly applicable to light passenger vehicles, is based on the following equation (Pomerleau et al 1999):

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

where:

a = deceleration required to reach V_s at curve apex

V = vehicle speed

V_s = curve maximum safe speed

d = distance between vehicle position and curve apex

t_r = driver reaction time (assumed to be 1.5 s) (Pomerleau et al 1999)

Based on this algorithm, a warning is issued when the calculated deceleration value becomes higher than a preset average deceleration value (1.5 m/s^2). Considering the specific requirements of a firetruck driving under emergency conditions, the following modifications were made to the algorithm (Figure 2) (Simeonov et al 2021):

1. 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 (Vs) was set as 90% of the rollover critical speed. The rollover critical speed (Vroll.cr) was determined according to (Eq. 2). The maximum lateral acceleration ($a_{lat.max}$) was measured with a swept steer test at 40mph (64 km/h) in TruckSim using Proving Grounds (Unity Scene) (by Mechanical Simulation, Ann Arbor, MI) (Simeonov et al 2021).

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

   The rollover critical speed is higher than the posted speed and the slip-related safety speed (based on the side friction factor assuming wet and icy conditions) and thus aids with reducing unnecessary warnings during an emergency response driving on a dry road.

2. The Vs target location was shifted from the curve apex to the middle (50%) of the entry-apex curve section. This alteration was made knowing that a heavy truck driver must reduce vehicle speed (and reach Vs) much earlier in the curve (IAFF 2010) compared to light passenger vehicles.

3. Between the Vs target location and the curve apex, a “speed control zone” was established. Within this zone a simple control logic was implemented to issue a warning if the vehicle speed exceeded the curve safety speed.

2.3 Procedure

The data collection begun with the investigators describing the study and the experimental tasks to the participants, answering their questions, and obtaining their signatures on the informed consent forms approved by the NIOSH IRB. Participants were screened for susceptibility to motion sickness and to obtain baseline scores for the subsequent motion sickness monitoring (Hoffman et al., 2003).

Each of the 24 participants completed a pre-test driving task followed by the main test – an emergency response driving task completed in two trials – one with CSWS “on” and one with CSWS “off” (for a total of 48 trials). The participants completed the CSWS “on” and “off” trials in a balanced order – half of the participants started with CSWS “on” followed by a trial with CSWS “off”; for the other half of the participants this order was reversed. Before each trial the participants were informed/instructed about the status (“on” or “off”) of the CSWS. The participants wore their firefighter protective pants and boots during the driving tasks. The pre-test task lasted for 10–15 minutes and was primarily designed to help the participants get familiar with the simulator environment. The pre-test route was 11.126 km (6.9 miles) long with 14 curves having radius (R) in the range of 51–612 m. Eight of the 14 curves had an $R < 200$ m and 5 of the eight had an $R < 100$ m.

For the emergency response driving task, the route was 12.640 km (7.9 miles) long with 18 curves having R in the range of 45–1229 m. Eleven of the 18 curves had an $R < 200$ m and 7 of the 11 had an $R < 100$ m (Figure 3). The driving environment consisted 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 simulated task began with a radio emergency dispatch message. The participants then turned on the emergency lights and sirens and started to drive as fast as possible, but safely. The participants were instructed to address the warnings by gradually reducing the vehicle speed until the warnings stop. During the driving task, two additional incident-specific messages were provided to convey the emergency of the task. In case of a rollover crash event, the trial was restarted from the location of the crash.

Throughout the tests, participants were monitored closely for any symptoms of motion sickness (Hoffman et al., 2003). Rest breaks (10 min) were provided after each trial and additionally as needed at the request of study participants. After completion of the test session, the participants completed a standing balance test (semi-tandem Romberg test – Cobb 1999, Simeonov et al 2011) as an additional precautionary measure for no symptoms of carry-over motion sickness before they were compensated for their time and released.

2.4 Variables

2.4.1 Independent variables—

The independent variables included the CSWS status and curve radius. 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 the CSWS on the dependent variables. The curve radius (R) 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 ($V_s < 96$ km/h).

2.4.2 Dependent variables—Two groups of dependent variables were used to evaluate and describe the CSWS performance and its effect on the safety outcomes (the occurrence of simulated rollover crashes) in fire tanker emergency driving.

2.4.2.1 CSWS performance variables

Warning occurrence: The warning occurrence (W_{occ}) variable indicates if any warning was issued when approaching and entering a curve. The warning occurrence is described using a binary value with 1 – indicating that a warning was activated, independent of the number or the duration of warnings issued for a specific curve, and 0 – indicating that no warnings were issued. The distance range analyzed for warning occurrences was from 200 m before the curve entry (Polus et al 2000, Bella 2014) to the curve apex. The cumulative W_{occ} from all participants for each curve was expressed as a percentage (cumulative relative warning occurrence) of the total warning occurrences possible (24 for all study participants).

Intensity of Warning occurrence: The Intensity of Warning occurrence (W_{int}) was defined as the cumulative relative warning occurrence (%) per meter of the total distance with active warnings (%).

2.4.2.2 Safety outcome variable: *Rollover crashes at curves*: The count, location, and circumstances of rollover crashes with CSWS “on” and “off” were analyzed to obtain clues/ guidance for system improvement.

2.5 Statistical analysis

Regression analyses were performed to determine the relationships of the variables warning occurrence (W_{occ}) and warning intensity (W_{int}) with curve radius (R). For the safety outcome variable “rollover crashes in curves”, descriptive statistics was used to compare CSWS “on” and “off” conditions.

3. Results

3.1 CSWS performance

The cumulative warnings issued by the CSWS are displayed along with the average vehicle speed and the reference curve safety speed (V_s) for the test route in Figure 4. The figure demonstrates that warnings were triggered by participants’ driving behavior at the approaches of most curves. The cumulative warnings had a pattern culminating before the curve with different intensities for the individual curves.

3.1.1 Warning occurrence and intensity—To further characterize the performance of CSWS, the cumulative relative warning occurrence (W_{occ}) and intensity of waning occurrence (W_{int}) was regressed as a function of curve radius (R) for the 11 curves with R < 200 m. The cumulative relative warning occurrence (W_{occ}) increased with a decrease in curve radius (R), representing nearly perfect linear relation (R^2=0.95) (Figure 5a). On the other hand, the intensity of warning occurrence (W_{int}), increased exponentially (R^2=0.86) with a decrease of curve radius (Figure 5b).

3.2 Rollover events in curves

The emergency response tasks in the simulated driving environment resulted in a total of 19 rollover events (Table 1). Of the 19 rollover events, 10 occurred with the CSWS “off” and 9 with the system “on”. The rollover events were experienced by 13 out of the 24 participants: 6 drivers had rollovers only with system “off”, 4 only with system “on”, and 3 drivers experienced rollovers both with system “off” and “on”.

Rollovers occurred on 5 out of 18 curves. There was a trend for rollovers to occur at the ending section of the route (i.e., at the last two curves: “j-k” and “l-m”). Six out of 10 rollovers occurred at the last two curves when the CSWS was “off” and 8 out of 9 when the CSWS was “on” (Figure 6). All rollovers occurred on curves with $R < 100$ m (safety speed drop > 30 km/h). There was also a tendency for rollovers to occur at longer curves without super-elevation (the last two curves: “j-k” and “l-m”). The lengths of the curves alone, however, were not correlated with the rollover outcomes.

All rollover events (both with CSWS “on” and “off”) were associated with in-curve max speed (V_{max}) at or above the curve safety speed limits (V_s) (Table 2, Figure 7). For rollover events with CSWS system “off”, there was a trend for higher curve entry speed (V_{ent}) and V_{max} as compared to rollover events with CSWS “on”. The V_{max} associated with rollovers with CSWS “off” was > 10% over V_s for most events, while V_{max} associated with rollovers with CSWS “on” was < 10% over V_s (Table 2, Figure 7). There was an outlier for V_{max} with CSWS “on”, where the curve entry speed was 26% above the safety speed limits, in which case there was a proper warning, but the driver ignored the warning. In all other rollover events with CSWS “on”, no warnings were issued by the CSWS.

In analyzing the rollovers at which the CSWS was “on” and warnings were not issued, we identified two distinct types of rollover events that were not prevented – at curve “entry” and at curve “exit” sections. In the 5 “entry” cases (Cases # 1–5, Table 2, and Figure 7), the V_{max} was slightly above the safety speed limit V_s (0%−6%) within the first 20% of the entry-apex section. In all of these cases, warnings were not issued because over-speeding ($V_{max} > V_s$) was relatively small and sufficiently far from the target speed control zone for the algorithm. In 3 of the five cases (Cases # 3–5, Table 2, and Figure 7), the vehicle was accelerating after the curve entry. In the 3 “exit” cases (Cases # 7–9, Table 2, and Figure 7), the rollover was associated with acceleration and over-speeding ($V_{max} > V_s$) after the curve apex which was not a target zone for speed control and therefore no warnings were issued.

More detailed descriptive analyses for four representative cases of rollover events are presented in the next section which could be considered to improve CSWS algorithms. The case examples include rollover events for curve “Entry-Apex” section with CSWS “on” and “off” and for curve “Apex-Exit” section with CSWS “on” and “off”.

3.3. Analysis of circumstances (case study) of rollover events

Case #1: An example of a curve “Entry – Apex” rollover event with CSWS “on” is presented in Figure 8. It represents 5 similar cases of “no adequate warning” after curve entry (cases # 1–5, Table 2, and Figure 7). The rollover event in this case is characterized with insufficient speed reduction at curve entry and no adequate warning. The vehicle was approaching the curve at a high speed (~94.0 km/h); the driver (Participant S1) received an advanced warning (at about 150 m before the curve) by the CSWS; in response (41 m later) the driver applied the brakes (for about 60 m) and drastically reduced the vehicle speed (with ~40 km/h) to a level at which the warning stopped. The vehicle continued coasting and entered the curve at speed 54.8 km/h which was above the curve safety speed (Vs=51.7 km/h). Soon after entering the curve the vehicle lost control, and despite the last-minute braking, the vehicle crashed in a rollover (at 55 m into the curve). The CSWS did not issue an additional warning at the curve entry since the algorithm targeted control zone was from the mid-point of the curve-entry to apex (48.5 m) section to the curve apex (97 m), for which the required speed reduction (of 3.1 km/h) could be achieved at the nominal braking rate (1.5 m/s^2). The analysis of this rollover event suggests the need for CSWS algorithm improvements by extending the targeted speed control zone (potentially to the curve entry), reducing the curve safety speed (using a safety margin > 10%, i.e., 15%), or using a combination of the two measures.

Case #7: An example of an “Apex - Exit” rollover event with CSWS “on” is presented in Figure 9. It represents 3 similar cases of “no warning” after curve apex (cases # 7–9, Table 2, and Figure 7). The rollover event in this case is characterized with accelerating after curve entry and coasting at the curve safety speed before and after the curve apex and no adequate warning. The vehicle was approaching the curve at the maximum for the straight section safety speed (~96.0 km/h). The driver (Participant S6) received an advanced warning by the CSWS (at about 163 m before the curve); in response (22 m later), the driver applied the brakes (for about 42 m) and substantially reduced the vehicle speed (with ~25 km/h) to a level at which the warning stopped. The vehicle continued coasting at ~69 km/h and upon getting closer to the curve received another short warning (at about 35 m before the curve); the driver applied the brakes (at about 33 m and all the way to curve entry) and entered the curve at speed 48.4 km/h which is below the curve safety speed (51.7 km/h). After curve entry, the driver accelerated back to approximately the curve safety speed (51.7 km/h) and continued with this speed all the way through and beyond the curve apex. The vehicle lost control and crashed in a rollover at 148 m from curve entry which is 51 m after the curve apex. The CSWS issued no warnings after the curve entry, since the vehicle never exceeded the curve safety speed in the speed control zone, and the algorithm did not include any control measures after the apex. This case suggests the need to increase the safety speed margin to > 10% (i.e., 15%), extend the safety speed control zone beyond the curve apex and possibly all the way to the curve exit, or use a combination of these two measures. The algorithm may also be enhanced to include in-curve acceleration detection logic to predictively issue warnings if the vehicle is approaching the curve safety speed.

Case #16: An example of a curve “Entry – Apex” rollover event with CSWS “off” is presented in Figure 10. It represents 7 similar cases of entering a curve with speed higher than the curve safety speed and coasting/decelerating in which a warning could have potentially helped (cases # 10–16, Table 2, and Figure 7). The rollover event in this case is characterized with insufficient speed reduction during curve approach and at curve entry. The vehicle was approaching the curve with a speed above the safety speed for the straight section (~100.0 km/h); in approaching the curve, the driver (Participant S15) started to reduce the speed by applying the brakes 3 consecutive times (at 209 m before the curve for about 49 m, at 151 m for about 23 m, and at 117 m for about 55 m) thus reducing the speed by ~25 km/h. The vehicle continued coasting and entered the curve at ~75 km/h which is substantially higher than the curve safety speed (54.9 km/h); shortly (8–10 m) after entering the curve, the driver applied the brakes, but lost control and the vehicle crashed in a rollover just 3.2 m before the curve apex (at 63.8 m in the curve). The existing CSWS algorithm model indicated that an active CSWS would have issued appropriate warnings and possibly prevented this rollover event.

Case #18: An example of an “Apex - Exit” rollover event with CSWS “off” is presented in Figure 11. It represents 3 similar cases of acceleration above V_s within the curve after the apex (cases # 17–19, Table 2, and Figure 7). The rollover event in this case is characterized by hard braking at curve entry followed by acceleration in the curve to above the curve safety speed after the apex. The vehicle was approaching the curve at the maximum (for the straight section) safety speed (~96.0 km/h) and coasting; in curve vicinity (47 m before curve entry), the driver (Participant S14), started applying the brakes (for about 62 m including 15 m in the curve) thus drastically reducing the speed by ~47 km/h. The vehicle entered the curve at 55.9 km/h and within 15 m in the curve the speed was reduced to 37.8 km/h, which is substantially below the curve safety speed of 51.7 km/h. Immediately after that, the driver accelerated and continued accelerating after passing the curve Apex to reach speed of 56.1 km/h, well above the curve safety speed limit. At that time the driver lost control and despite the last-minute braking, the vehicle crashed in a rollover at 184 m in the curve (87 m after the curve Apex). The existing CSWS algorithm model suggested that a warning with increasing urgency (beeping frequency) could have been properly issued if the CSWS was active, and thus preventing the aggressive braking during the curve entry. The existing CSWS algorithm model however could not have detected the acceleration to above the safety speed after the curve Apex, indicating the need for further improvements as suggested at the end of the descriptive analysis of case #7 above.

4. Discussion

4.1 Warning system performance

When approaching curves in an emergency response mode without a CSWS, firetruck drivers are likely to speed through the curve and may underestimate the need for a timely speed reduction. Furthermore, the study results of the baseline condition (CSWS “off”) confirmed that this driving behavior is independent of the curve radius (Simeonov et al 2021). The evaluation of CSWS performance by the warning occurrence measure reflects the binary probability for a driver to receive or not receive any warning (independent of the number of warnings) when approaching a curve. The results indicate that this probability increases in a linear fashion with a decrease of the curve radius. The probability for a driver to receive a warning can be regarded as a result of the interaction between driver behavior and the CSWS algorithm. In the algorithm, the safety speed limit at a curve is a near-linear function of the curve radius.

The exponential increase of warning intensity (cumulative warning probability for each curve) associated with the decrease of curve radius further highlights the extent of driver behavior deviation from the algorithm predictions. The CSWS algorithm assumed a linear behavior in speed reduction using a constant deceleration rate to calculate the warning timing and duration. As compared to the linear CSWS prediction, drivers adjust the vehicle speed in a non-linear fashion – usually in the last moments before a sharp turn, which can trigger an increased number of warnings and with a longer total warning duration. Previous research on speed-reducing measures for curves (for passenger vehicles and non-emergency driving) has reported that clear reduction in speed in the baseline condition is not observed until approximately 100 m before a curve entry, and after this point, the deceleration becomes heavy into the curve (Comte and Jamson 2000).

4.2 Effects of warning system on safety outcomes

The test route for this study was designed to be challenging for the firetruck drivers with many sharp turns preceded by long relatively straight sections. There was a total of 19 rollover crashes during the driving trials, of which 10 with CSWS “off” and 9 with CSWS “on”. While the CSWS has been helpful in reducing the average distance traveled at speeds over the safety speed limits at the entry-to-apex section of a curve (Simeonov et al 2021), the overall rollover counts suggested a need for further improvements in the warning system algorithms. An in-depth analysis showed that all rollovers occurred at or above the safety speed which reflects an accurate vehicle model and safety speed calculations. Most of the rollovers in the simulation could be preventable if the vehicle speed is maintained below the safety speed limits. The tendency for more rollovers to occur later in route (8 of 9) when the system was “on” as compared to the CSWS “off” condition (6 of 10) may indicate an increased driver risk-taking behavior with over-reliance on the CSWS later in route, which also suggests the need for improvements of the CSWS.

The safety speed limit for the CSWS algorithm in this study was derived from the vehicle rollover speed ($V_s = 0.9*V_{roll}$), in contrast to previous research using slide-out speed (Pomerleau et al 1999). Considering the emergency response driving and the dry-road conditions where the leading crash risk for the heavy fire tanker is rollover, this setting was selected to minimize the unneeded false warnings, reduce drivers’ annoyance, and improve system acceptance. However, this safety speed setting also leaves little room for errors and may be one of the causes for the observed rollovers with system “on”. Furthermore, at some of the sharp curves, the driver’s comfort speed limit (based on lateral acceleration) for the tested fire tanker was higher than the rollover speed which leads to “undetectable risk” conditions for rollovers. Therefore, one possible direction for improvement of the CSWS algorithm is to lower the V_s to below $0.9*V_{roll.cr}$ levels (e.g., increase the safety margin to more than 10%, i.e., 15%).

Analysis of the rollover circumstances indicated that in 6 (out of 9) of the rollovers with system “on”, drivers lost control before the curve apex. In one case a warning was issued but ignored, and in 5 cases, warning was not issued since the drivers entered the curve at speeds close to the safety speed (V_s) and accelerated within the curve at a timing which did not trigger the algorithm. The existing guidelines (Pomerleau et al 1999) set the trigger point at the curve apex. In contrast, in this study, the speed control zone for the algorithm was set to start (trigger) at mid-distance of the curve entry-apex to accommodate heavy emergency vehicles which need to reduce speed earlier in the curve (IAFF 2010). This setting in the algorithm may need to be adjusted, since it allowed entering the curve at a speed above the safety speed and missed detecting some in-curve accelerations at speeds above V_S before the trigger point. To address this issue, the trigger point can be moved from the mid-distance of the curve entry-apex section to the curve entry in the CSWS algorithm.

In 3 out of 9 rollovers with the CSWS system "on", the drivers lost control at locations after the curve apex, usually due to acceleration within the curve at speeds above V_S. Obviously, to reduce the risk of these rollovers, the truck speed must be maintained below the safety speed limits even after the apex, especially for heavy emergency response trucks and long curves. Possible measures to reduce the risk of rollovers after the apex may include reducing the curve safety speed (as discussed above) and extending the safety speed control zone beyond the apex (or for the whole curve).

4.3 Suggested CSWS modifications, challenges, and directions for future work

The analysis of the rollover crash circumstances suggested the following modifications for improvement of the CSWS algorithm: (1) reduce the safety speed to below $0.9V_{roll.cr}$, (2) move the trigger point to curve entry, (3) extend the safety speed-control zone beyond the apex (to possibly cover the whole curve), and (4) check for acceleration behavior to calculate and predictively issue a warning if speed will reach the safety speed limit while in curve. Implementing just one or a couple of these measures may be sufficient to reduce rollover crashes. It must be noted that some of these measures may introduce additional challenges, such as sub-optimal (too early or too late) warnings that may increase driver annoyance, reduce system acceptability, and result in compensatory (rebound) speeding behavior.

Preventing nuisance alarms is difficult because there is no commonly accepted benchmark for "correctly" negotiating a curve (Pomerleau et al 1999). An effective way to reduce nuisance warnings is the development of an adaptive CSWS which can account for the considerable variation in driver behavior, and specifically in speed profiles when negotiating a curve. 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 Machiani 2019). An innovative CSWS may also use artificial intelligence (AI) to fine-tune the optimal speed profiles by implementing learning algorithms using data from previous driving runs through specific routes of vehicles with similar dynamic characteristics and emergency response tasks.

4.4 Limitations

The use of a driving simulator as a modeling research tool in this study is associated with several limitations, related to the fidelity of the simulation and the previous gaming experience of the participants. The benefits of using driving simulations in vehicle safety research are well known. Simulators allow for a better control over the experimental conditions, lower expense and better efficiency, improved safety for participants and researchers, and convenience in data collection. However, driving simulations also have some major limitations, such as 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). Nevertheless, driving simulations have been validated for generating and generalizing relative speed in testing road-based speeding countermeasures (Godley et al 2002) and in studies on curve negotiation in two-lane rural roads (Bella 2008). However, previous research has shown that in a driving simulator, participants initiate braking later and brake much harder as compared to real roads (Boer et al 2000); and, in a driving simulator as compared to real roads, the curve-entry speed was faster in less challenging curves (R > 582 m) and slower in the most difficult curves (R < 146 m) (Bittner et al 2002).

Participants with extensive car-racing gaming experience may have been more used to simulated driving environments and drive more aggressively as compared to the average person. This study did not assess the gaming car-racing experience of the participants. However, during the tests some of the participants provided comments on their gaming car-racing experience (and real-life car-racing experience) and their perceptions of 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 gaming experience may increase risk-taking driving behaviors (Fischer et al 2009).

This study used a balanced experimental design in which all participants performed all the experimental conditions in a balanced order which should help in cancelling out most of the effects of the abovementioned limitations.

5. Conclusions

A curve speed warning system (CSWS) was tested in this study for its effectiveness in preventing fire tanker rollover crashes at risky curves during simulated emergency response driving. The results demonstrated that the CSWS was effective in issuing preemptive warnings when drivers were approaching curves at an unsafe speed. Warnings were more likely to occur at curves with radius smaller than 200 m and occurred more often at sharper curves. There is limited information on developing a warning system for heavy emergency vehicles in preventing curve speed-related rollover crashes. While the CSWS algorithms tested in this simulation study did not show a significant reduction in the number of rollover crashes, the study results provided valuable suggestions for improving the CSWS algorithm, including programming a safety speed with a more than 10% safety margin below the rollover critical speed, establishing a speed warning trigger at the curve entry point instead of the midpoint between the curve entry and apex, extending the safe speed-control zone to cover the entire curve beyond the apex point, and employing artificial intelligence technologies to accommodate individuals with different driving styles.

6. Practical Applications

Fire tankers are top-heavy vehicles that continue to be at increased risk of rollover during emergency response due to unsafe negotiation of dangerous curves. Development and use of advanced driver assist systems such as CSWS evaluated in this study may be an effective strategy to prevent deadly rollover crash-incidents. The knowledge generated by this study will be useful for system designers to improve the CSWS specifically designed for heavy emergency vehicles.

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Figure 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)

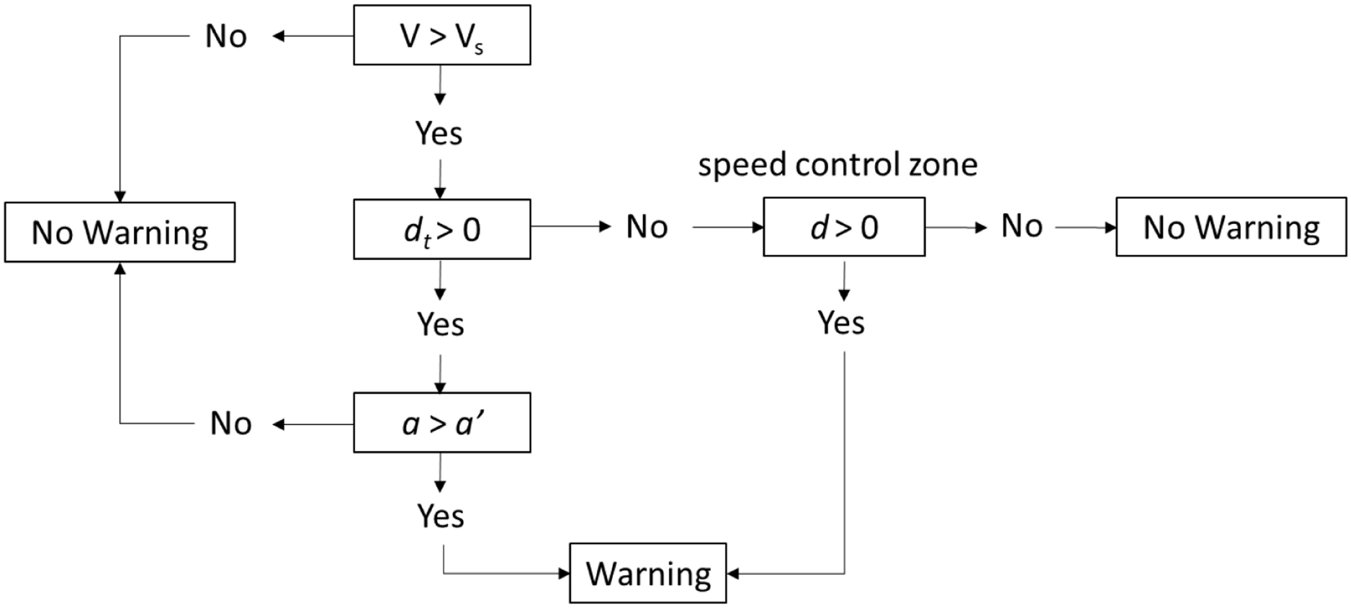


Figure 2.

Flow chart on working logic of the CSWS system.

V = vehicle speed

V_s = curve maximum safe speed

d_t = distance between vehicle position and curve trigger point

(trigger point = mid-point between curve entry and apex)

d = distance between vehicle position and curve apex

a = deceleration required to reach Vs at curve trigger point

(from equation (1) using trigger point instead of apex)

a' = average deceleration (a'= 1.5 m/s^2)

Speed control zone - between trigger point and curve apex

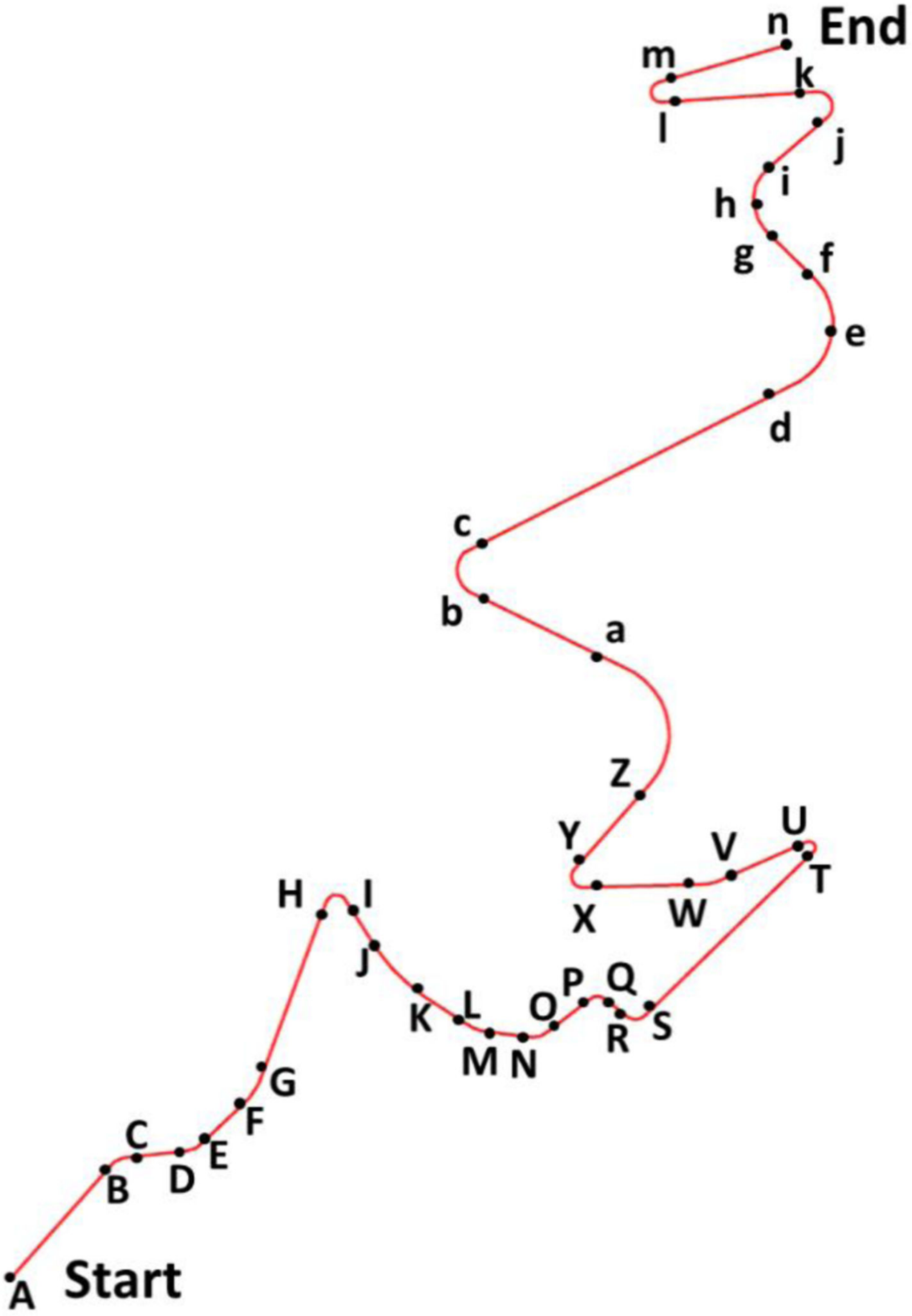


Figure 3.

Map of the test route with alphabetically indicated road segments

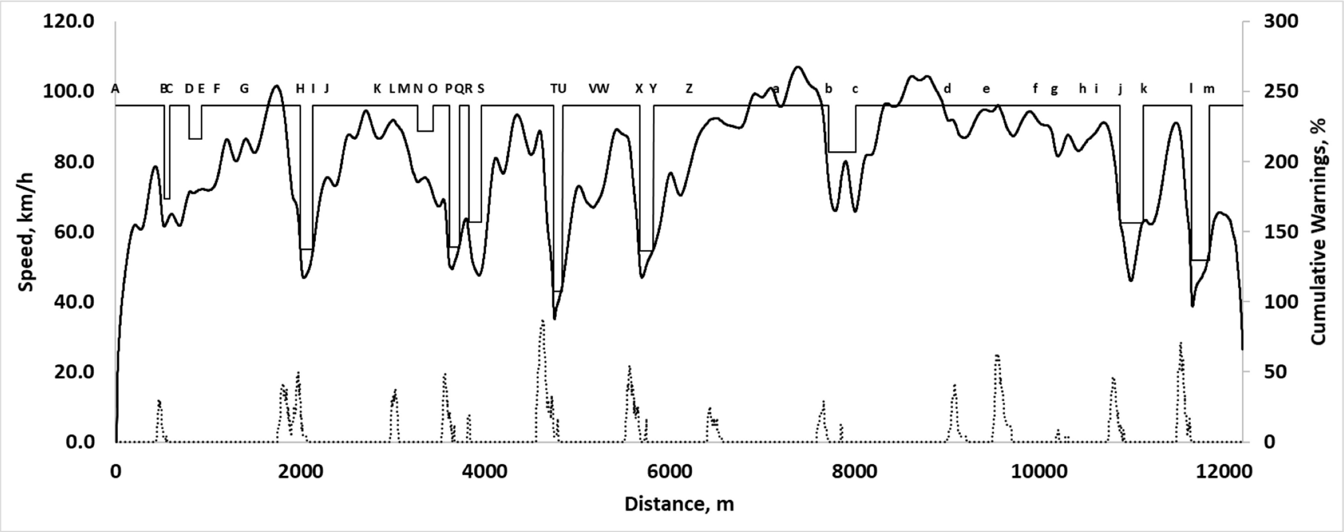
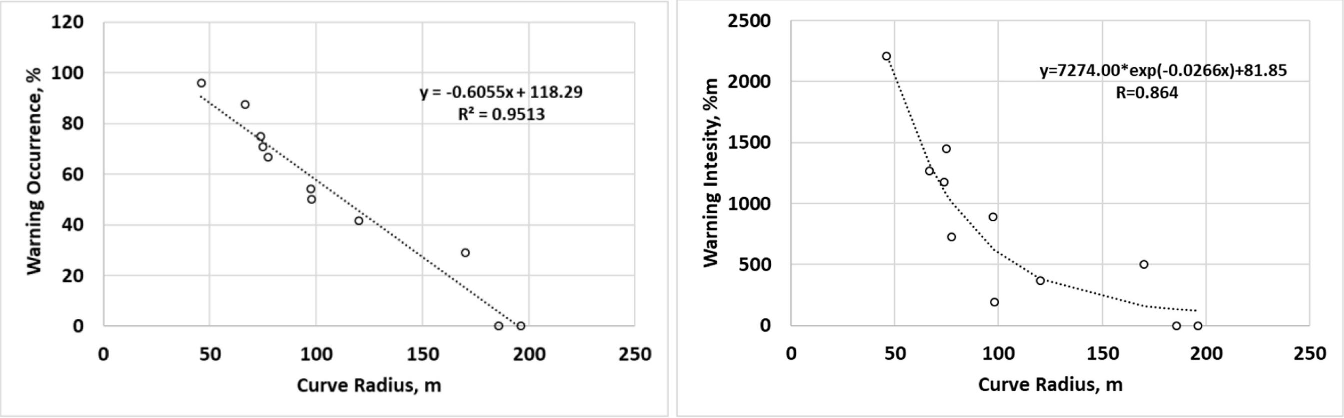


Figure 4.

Cumulative warnings (dotted line at the bottom) along the test route (plotted using secondary axis on the right) together with safety speed (V_S) (thin line at the top) and average speed (V) (thick line) (plotted using primary axis on the left).



a b

Figure 5.

Warning occurrence and warning intensity: (a) warning occurrence (W_{occ}) as a negative linear function of curve radius; (b) intensity of warning occurrence (W_{int}) as a negative exponential function of curve radius

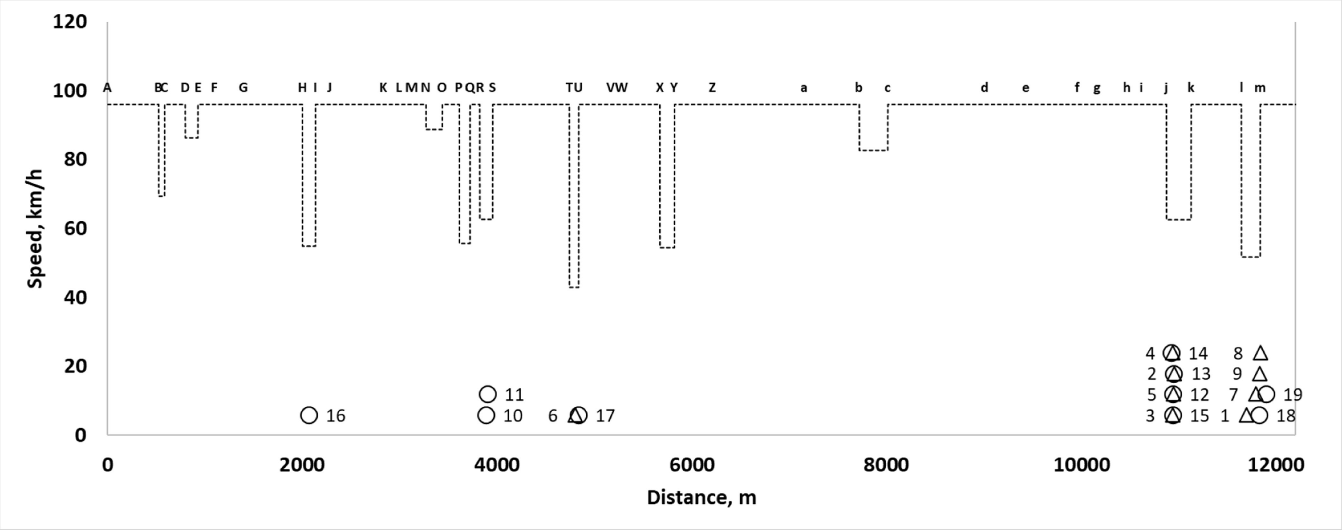


Figure 6.

Rollover events by on-route location (each symbol represents one rollover-crash occurrence: circle – system "off", triangle – system "on"). Labels next to each symbol (to the right for circles and to the left for triangles) indicate the rollover event case number as described in Table 2 and Figure 7.

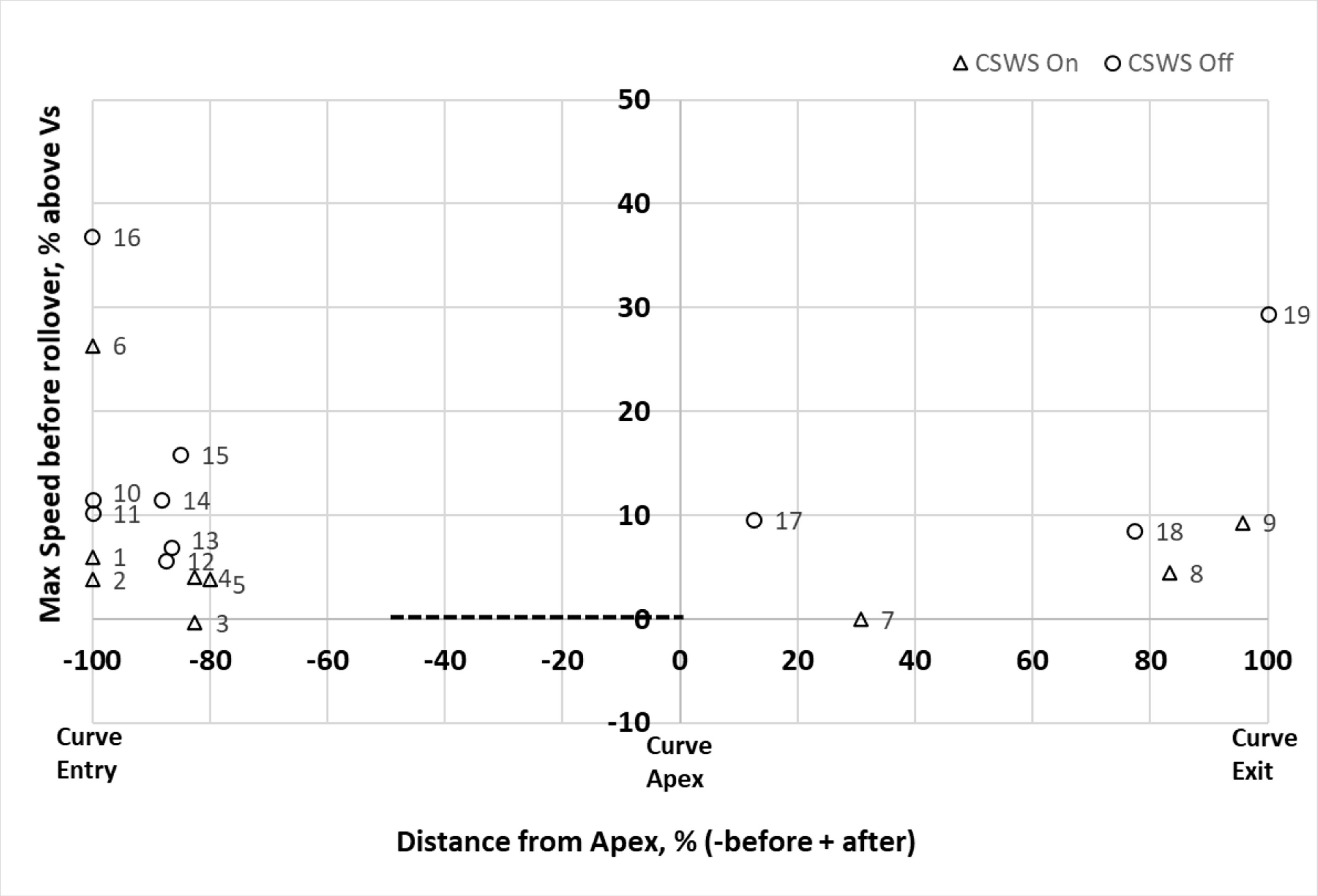


Figure 7.

Rollover event-related maximum speed (V_{max}) as % over safety speed limit (V_s) and its relative location within the curve; dashed line indicates the CSWS algorithm-targeted “speed control zone”; labels next to (the right of) each symbol (circle – CSWS “off”, triangle – CSWS “on”) indicate the rollover event case number as described in Table 2.

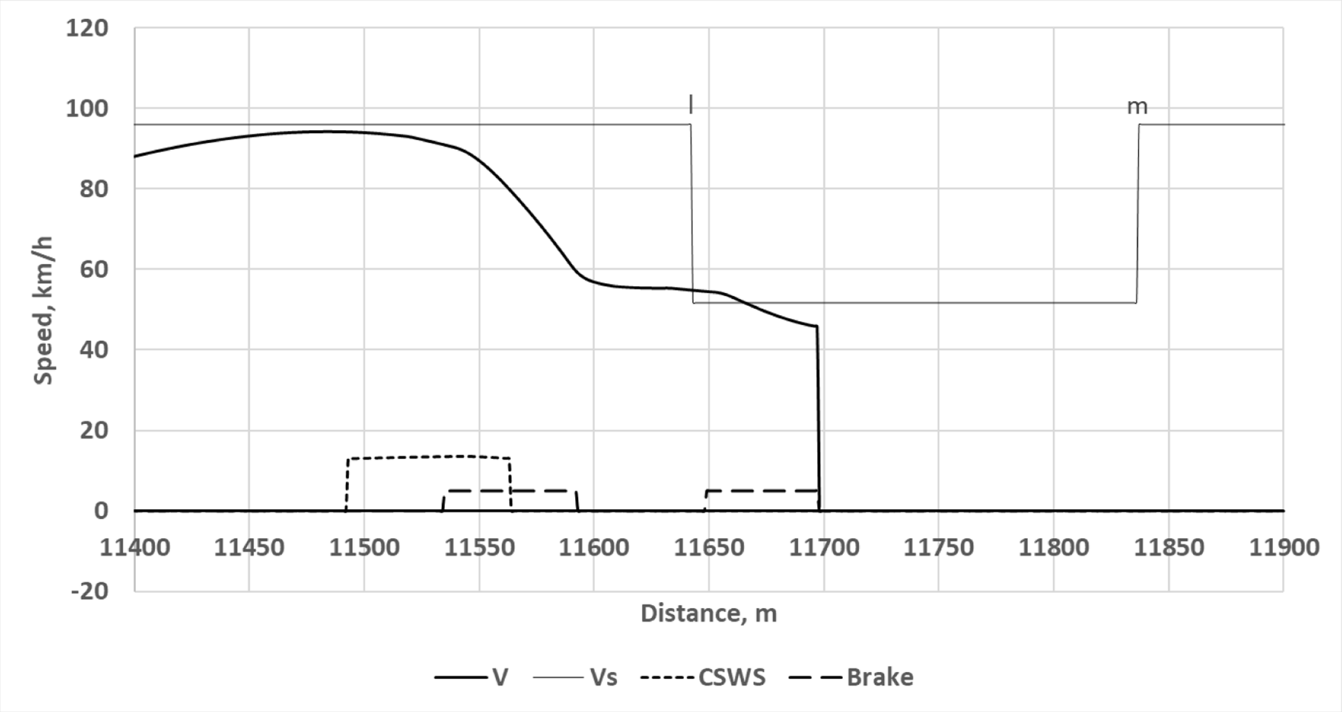


Figure 8.

Case #1: An example of an “Entry-Apex” overturn event with CSWS “on” for participant S1; the overturn occurred in the “Entry-Apex” zone of curve “l-m”. Legend: thin line at the top indicates the safety speed (Vs) at the different road sections; thick line reflects the vehicle speed (V) for this trial; dashed line indicates where the brake was applied (using an arbitrary value of 5); dotted line reflects where a warning was issued by the CSWS, as a function of beeping frequency (values x5).

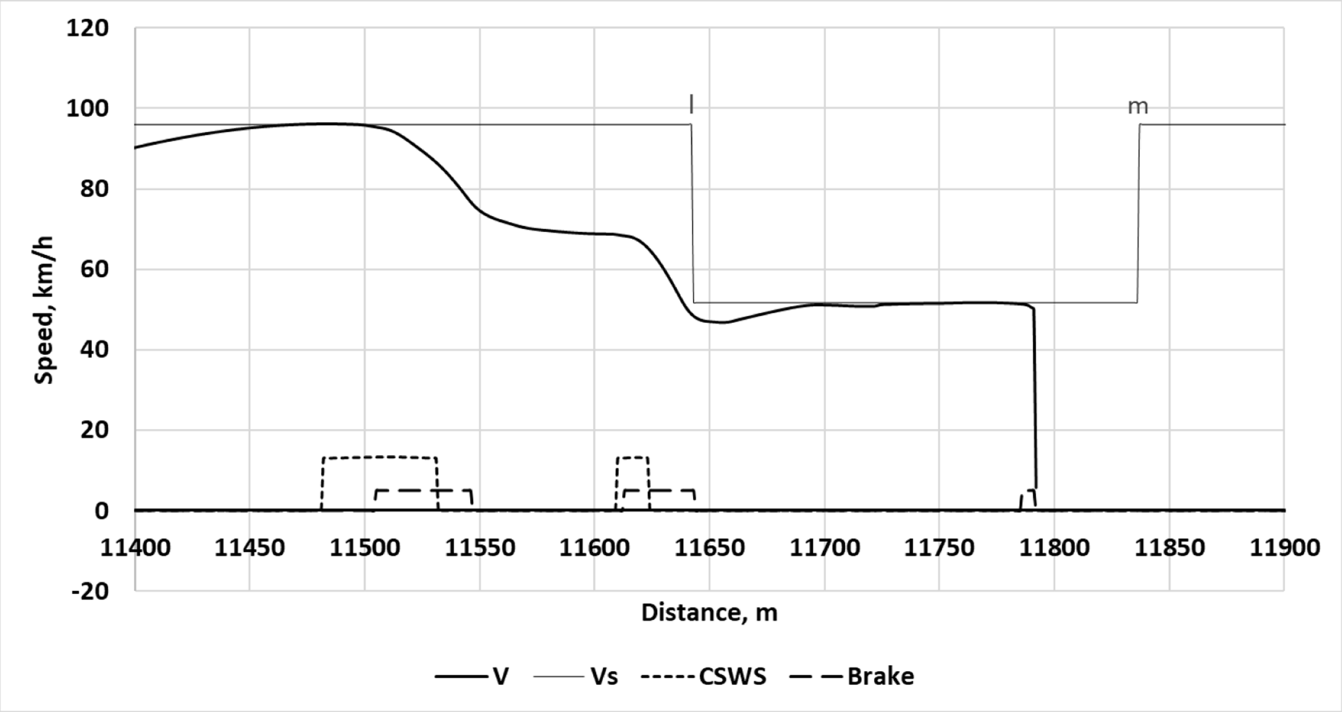


Figure 9.

Case #7: An example of an “Apex-Exit” overturn event with CSWS “on” for participant S6; the overturn occurred in the “Apex-Exit” zone of curve “l-m”. Legend: thin line at the top indicates the safety speed at the different road sections (Vs); thick line reflects the vehicle speed for this trial; dashed line indicates where the brake was applied (using an arbitrary value of 5); dotted line reflects where a warning was issued by the CSWS, as a function of beeping frequency (values x5).

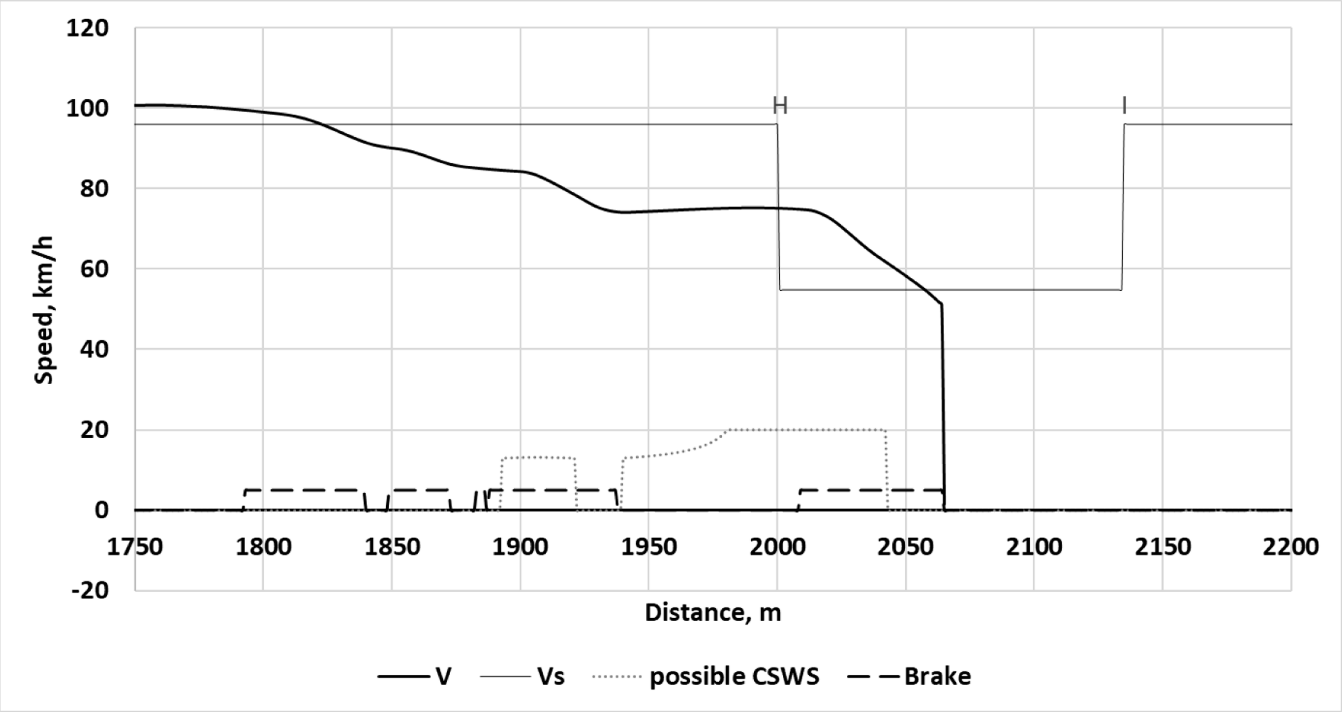


Figure 10:

Case #16: An example of an “Entry-Apex” rollover event with CSWS “off” for participant S15; the rollover occurred in the “Entry-Apex” zone of curve “H-I”. Legend: thin line at the top indicates the safety speed at the different road sections (Vs); thick line reflects the vehicle speed for this trial; dashed line indicates where the brake was applied (using an arbitrary value of 5); dotted line reflects where a warning could be issued by the CSWS if it was “on”, as a function of beeping frequency (values x5).

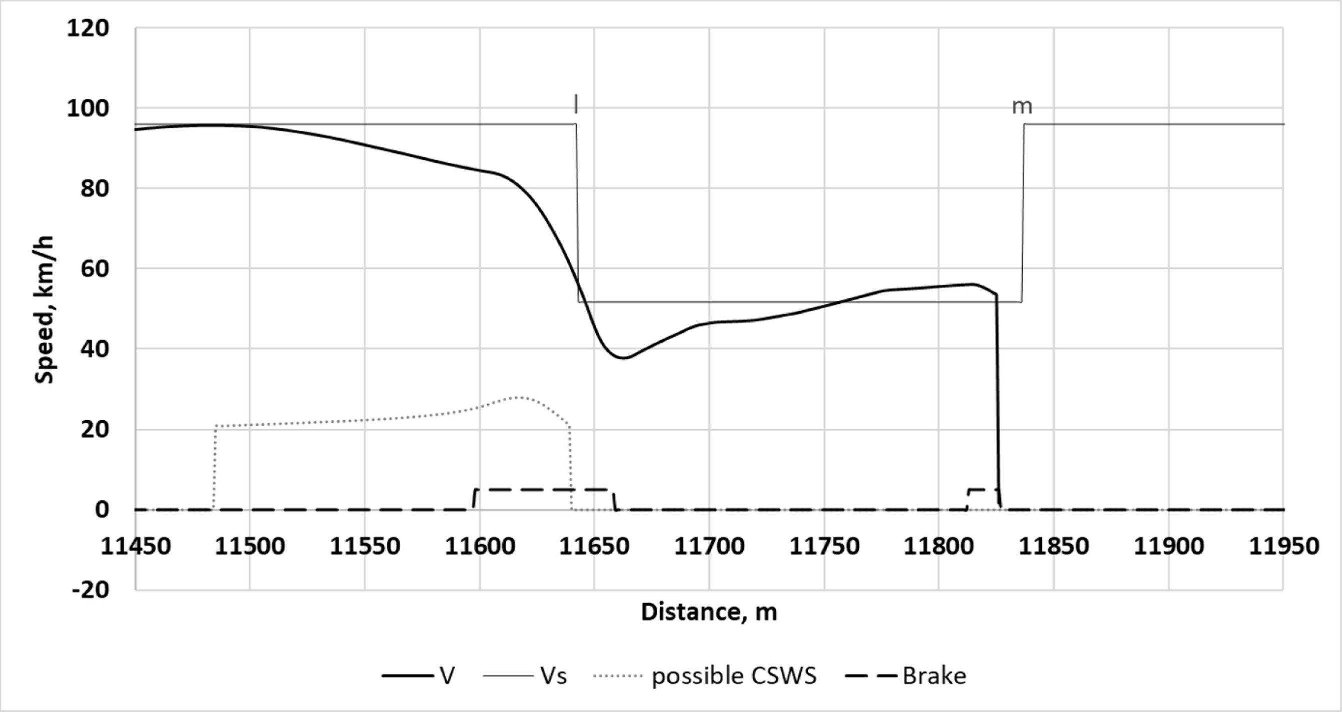


Figure 11:
Case #18: An example of an "Apex-Exit" rollover event with CSWS "off" for participant S14; the rollover occurred in the "Apex-Exit" zone of curve "l-m". Legend: thin line at the top indicates the safety speed at the different road sections (Vs); thick line reflects the vehicle speed for this trial; dashed line indicates where the brake was applied (using an arbitrary value of 5); dotted line reflects where a warning could be issued by the CSWS if it was "on", as a function of beeping frequency (values x5).

Table 1.

Study participants who experienced rollover events during the emergency response driving trials

Study	**CSWS Off**		**CSWS On**		**Rollovers**
Participant	**Rollovers**	**Event #**[*]	**Rollovers**	**Event #**[*]	**Total**
S1	1	#10	1	#1	2
S5	1	#13			1
S6	1	#17	2	#6, #7	3
S7	1	#14	1	#9	2
S10			2	#4, #8	2
S11	1	#11			1
S14	1	#18			1
S15	1	#16			1
S17	2	#15, #19			2
S18	1	#12			1
S20			1	#3	1
S22			1	#5	1
S24			1	#2	1
Total	10		9		19

[*] Event # - provided for cross-referencing with Table 2 and Figure 7

Table 2.

Circumstances of rollover events and suggested measures for CSWS improvement

Event	Curve	V_s	V_{max}	V_{max}%	Dist,%	Circumstances and Behaviors	Suggest CSWS improvements
Rollover Events with CSWS “On” in the Curve Entry-Apex Section							
1	1-m	51.7	54.8	6.0	−100	$V_{ent} > V_s$, breaking, no in curve warning	Trigger at Entry /Reduce V_s
2	j-k	62.5	64.9	3.8	−100	$V_{ent} > V_s$, coasting, no in curve warning	Trigger at Entry /Reduce V_s
3	j-k	62.5	62.3	−0.3	−82.5	$V_{ent} \sim V_s$, accelerating, no warning	Trigger at Entry /Reduce V_s
4	j-k	62.5	65.0	4.0	−82.5	$V_{ent} \sim V_s$, accelerating, no warning	Trigger at Entry /Reduce V_s
5	j-k	62.5	64.9	3.8	−80	$V_{ent} > V_s$, coast/accel, late in curve warning	Trigger at Entry /Reduce V_s
6	T-U	42.9	54.2	26.3	−100	$V_{ent} >> V_s$, decel, adequate warning - no response	No suggested change
Rollover Events with CSWS “On” in the Curve Apex-Exit Section							
7	1-m	51.7	51.7	0.0	30.8	$V \sim V_s$, coasting, no in-curve warning	Test after Apex/Reduce V_s
8	1-m	51.7	54.0	4.4	83.3	$V > V_s$, accelerating, no in curve warning	Test after Apex/Reduce V_s
9	1-m	51.7	56.5	9.3	95.7	$V > V_s$, accelerating, no in curve warning	Test after Apex/Reduce V_s
Rollover Events with CSWS “Off” in the Curve Entry-Apex Section							
10	R-S	62.7	69.9	11.5	−100	$V_{ent} > V_s$, coasting; CSWS could help	No suggested change
11	R-S	62.7	69.1	10.2	−100	$V_{ent} > V_s$, decelerating; CSWS could help	No suggested change
12	j-k	62.5	66.0	5.6	−87.5	$V_{ent} > V_s$, coast/accel; CSWS would be too late	Trigger at Entry /Reduce V_s
13	j-k	62.5	66.8	6.9	−86.6	$V_{ent} > V_s$, accel/coast; CSWS would be too late	Trigger at Entry /Reduce V_s
14	j-k	62.5	69.7	11.5	−88.2	$V_{ent} > V_s$, decelerating; CSWS could help	No suggested change
15	j-k	62.5	72.4	15.8	−85	$V_{ent} > V_s$, coast/accel; CSWS could help	No suggested change
16	H-I	54.9	75.1	36.8	−100	$V_{ent} >> V_s$, decelerating; CSWS could help	No suggested change
Rollover Events with CSWS “Off” in the Curve Apex-Exit Section							
17	T-U	42.9	47.0	9.6	12.5	$V > V_s$, accelerating to Vmax; CSWS not effective	Test after Apex/Reduce V_s
18	1-m	51.7	56.1	8.5	77.3	$V > V_s$, accelerating to Vmax; CSWS not effective	Test after Apex/Reduce V_s
19	1-m	51.7	66.9	29.4	100	$V > V_s$, accelerating to Vmax; CSWS not effective	Test after Apex/Reduce V_s

“V_{max}” = in-curve maximum speed associated with a rollover event

“V_{max}%” = $(V_{max}-V_S)/V_S*100$

“Dist,%” = Distance from Apex; Curve Entry = −100%, Curve Exit = 100%

“Reduce V_S” = Reduce Safety Speed to 0.85 of V_{roll} (currently = $0.9V_{roll}$)

“Trigger at Entry” = Move the algorithm trigger point to the curve entry point

“Test after Apex” = Provide a warning for $V > V_S$ after Apex; and early warning for acceleration to $V > V_S$