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The safety potential of lane departure warning systems—A descriptive real-world study of fatal lane departure passenger car crashes in Sweden

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ABSTRACT

Objective: Lane departure crashes account for a significant proportion of passenger car occupant fatalities and serious injuries. Utilizing real-world data involving fatal passenger car crashes in Sweden, the characteristics of lane departure crashes were identified and the safety potential of lane departure warning (LDW) systems was quantified.

Methods: The material consisted of 104 in-depth studies of fatal passenger car crashes in 2010. The crashes were classified as single-vehicle ($n = 48$), head-on ($n = 52$), and overtaking ($n = 4$) crashes. These crash types were identified as crashes that could have potentially involved lane departure. A case-by-case analysis was carried out and lane departure crashes were identified and characterized using police reports and information collected by crash investigators at the Swedish Transport Administration; for example, inspections and photographs of the crash sites and of the involved vehicles. Lane departure crashes were separated from crashes where loss of control occurred pre-lane departure. Furthermore, loss of control post-lane departures were identified. When studying the pre-stage of lane departure without prior loss of control, crashes were categorized as unintentional drifting, intentional lane change, or evasive maneuver. Using previously published effectiveness information, the potential for LDW systems to prevent crashes was estimated.

Results: Of all crashes with passenger car occupant fatalities in Sweden in 2010, 46% (63/138) were found to relate to lane departure without prior loss of control. These crashes accounted for 61% (63/104) of all single-vehicle, head-on, and overtaking crashes. The remaining 41 crashes were due to loss of control pre-lane departure. Unintentional drifting accounted for 81% (51/63) of all lane departure crashes without prior loss of control, which corresponded to 37% (51/138) of all fatal passenger car occupant crashes. LDW systems were found to potentially prevent 33–38 of the 100 fatal head-on and single vehicle crashes. These crashes involved drifting and occurred on roads with visible lane markings, signed posted speed limits ≥70 km/h, and without rumble strips on the corresponding lane departure side. The range of potentially prevented crashes (33–38) is due to the inclusion or exclusion of crashes involving excessive speeding.

Conclusions: In this study, approximately half (51/100) of all head-on and single-vehicle crashes were identified as being a consequence of drifting, where LDW systems had the potential to prevent the majority (33–38) of these crashes. The typical lane departure crash without prior loss of control occurred on undivided roads in rural areas with signed posted speed limits ≥70 km/h, where the center and side road markings were visible.

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Lane departure; LDW; cars; safety; real-world; in-depth studies; fatalities

Introduction

Between 2010 and 2015, Sweden had on average 277 road fatalities per year. Of these fatalities, 52% were passenger car occupants (Trafikanalys 2016), with 77% due to head-on and single-vehicle crashes (Trafikanalys 2016). Lane departure crashes are mainly made up of 3 major crash types related to lateral vehicle movement: head-on, single-vehicle, and overtaking/lane changing crashes.

Lane departure crashes accounted for 29% of German insurance collision claims between 2002 and 2006. Categorized according to first impact, 54% were "collisions with another oncoming vehicle," 24% were "collisions with another vehicle moving in the same direction," and 22% were "a vehicle leaving the carriageway" (Kuehn et al. 2009, p. 3). In the United States,lane departure crashes are one of the most common crash types, accounting for 1.6 million road collisions per year. This corresponds to more than a quarter of all vehicle accidents (Mehler et al. 2014). Based on data from the United States, Najm et al. (2007, p. 20) showed that the "road edge departure without prior vehicle maneuver" was the second most common pre-crash scenario, accounting for 20% of single light-vehicle pre-crash scenarios. The data set included road motor vehicle crashes with property damage, injury, or fatality. The study showed that the typical scenario was in rural speed areas (posted speed limit ≥55 mph) and the road alignment was identified as straight in 74% of the crashes. The most common (28%) single

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light-vehicle pre-crash scenario was "control loss without prior vehicle action". The U.S. National Transport Systems Center (Volpe) and the National Highway Traffic Safety Administration (NHTSA) found that road departure crashes without loss of control (LOC) represented 55% (525,000 crashes) of all off-roadway related crashes and the remaining 45% were related to LOC (Najm et al. 2002). Of the road departure crashes without LOC, 65% occurred on straight roads, 22% on curved roads, and 13% were related to evasive maneuvers. Lane departures typically arise from driver inattention, relinquished steering, or LOC due to unfavorable road conditions, high speed, or sudden evasive maneuvers, according to Mastinu and Ploechl (2014).

Road infrastructure interventions can provide guidance to help drivers avoid unintentional lane departure and related crashes. Some interventions provide visual guidance (e.g., road markings), others provide haptic guidance (e.g., rumble strips), and physical infrastructure such as barriers and guard rails can mitigate the consequences of lane departure crashes. Furthermore, keeping roadsides clear from trees and other obstructions can help mitigate the severity of run-off-road crashes.

Lane departure warning (LDW) systems are an in-vehicle technology that utilizes a camera to detect the lane by its lane markings and road edge lines. The primary benefit of this technology is that it alerts the driver in an effort to prevent unintentional lane departure (AAA Foundation for Traffic Safety 2016). LDW systems are designed to minimize unintentional drift out of the travel lane, typically due to driver drowsiness, distraction, or inattention. There are also LDW-like systems that assist drivers to stay in the lane by steering torque.

LDW systems have limitations and do not work properly where lane markings are not visible (e.g., worn out or covered by snow), when the road has a small curve radius, at low speeds (typically below 65 km/h), in heavy precipitation, or if the system is deactivated (Automotive World 2012; Hummel et al. 2011; Jermakian 2011). There are also other factors that could cause the system to not function adequately, such as lighting, temporary lane markings at construction zones, or poor contrast between the road surface and lane markings. Some of the limitations are technical and some are an effect of attempts to avoid frequent warnings in situations where the driver is deemed to be in control of the vehicle.

There have been several attempts to estimate the potential safety benefits of LDW systems. Wilson et al. (2007) used field operational test data and suggested that LDW systems reduced scenario-specific crashes by 1–8%. Using U.S. data from the NASS General Estimates System 2004–2008, Jermakian (2011) estimated LDW systems to have the potential to reduce fatal head-on crashes by 40–46% (the range was due to the inclusion or exclusion of speeding) and single-vehicle crashes by 17–31% including collisions with pedestrians and bicyclists. When collisions with pedestrians and bicyclists were excluded from single-vehicle crashes to only include car occupant fatalities, the potential reduction was estimated at 24–43%. The total potential of LDW systems to reduce fatal car occupant head-on and single-vehicle crashes was estimated to be 27–43%.

The Insurance Institute for Highway Safety (2015) analyzed real-world crashes and observed decreases in claim frequency for property damage liability (9.9–14.0%) and bodily injury liability (24.2–39.5%) coverages for FCW/LDW equipped cars. However, it was not possible to quantify the claim frequency reduction for each individual system. To make precise estimates, Blower (2014) concluded that appropriate calculations would be possible when Vehicle Identification Numbers indicating the availability of optional equipment become available.

Based on Swedish data, Sternlund et al. (2017) conducted a real-world benefit study of LDW systems. Vehicle Identification Numbers were used to identify the specific equipment level of Volvo passenger cars. The study showed that LDW system-equipped cars experienced a reduced number of crashes. A 53% crash reduction was found for injured passenger car drivers involved in head-on or single-vehicle crashes on roads with speed limits of 70 km/h and above and when the road was not covered in snow or ice. This estimate represents a 30% reduction of all Swedish head-on and single-vehicle crashes involving injured drivers in passenger cars.

The current study identified characteristics of lane departure crashes and quantified the safety potential of LDW systems using real-world data of fatal passenger car crashes in Sweden.

Aim

The aims of this study were to

1. identify fatal lane departure crashes in Sweden that occurred without prior loss of control.
2. characterize fatal lane departure crashes in Sweden that occurred without prior loss of control.
   a. differentiate between unintentional drifting and intentional lane change or evasive maneuver.
   b. identify loss of control post-lane departure.
3. quantify the potential safety benefit of LDW systems in fatal crashes in Sweden by identifying the target population.

Material

The material consisted of in-depth studies of fatal crashes in Sweden in 2010. In-depth studies of fatal crashes are carried out by the Swedish Transport Administration (STA). STA has carried out in-depth studies for each fatal road-related crash in Sweden since 1997. Crash investigators at STA systematically inspect and photograph the vehicles involved and record vehicle trajectory, location and direction of impact, vehicular intrusion, seat belt use, airbag deployment, tire properties, etc. Crash sites are also photographed and inspected to investigate road characteristics, collision objects, skid marks, etc. Information about injuries is provided by forensic examinations (e.g., autopsy reports), witness statements from the police, and reports from the emergency services (Swedish Road Administration 2005). The autopsy reports contain information on the possible influence of alcohol and drugs on the deceased person. Information on the possible influence of alcohol and/or drugs on surviving drivers is documented in police reports, which are also included in the in-depth studies. The present study material included forensic data for fatalities, which have a higher reliability than police-reported crashes where the influence of alcohol or drugs is concerned.

In Sweden, there were 154 fatalities involving 138 crashes with passenger car occupant fatalities in 2010. The present study was based on 104 fatal passenger car crashes classified as single-vehicle (n = 48), head-on (n = 52), and overtaking (n = 4) crashes. These crash types were identified as potentially occurring as a consequence of lane departure. Other crash types—that is, intersection, animal, rear-end, and train ($n = 34$)—were excluded from this analysis. Crash types were defined according to Trafikanalys (2016). For example, a single-vehicle crash used in this study typically involved a single passenger car running off the road and colliding with a tree or other stationary object, with at least one passenger car occupant suffering fatal injuries. Collisions with pedestrians, bicyclists, or animals were not included in the single-vehicle crash type.

Methods

The focus of this study was on lane departure crashes where a vehicle left the initial lane due to a change in lateral position without prior LOC (illustrated in Figures 1 and 2). If the vehicle left the initial lane due to LOC without prior lane departure, it was referred to as direct LOC. In general, LOC was identified when oversteering or understeering occurred.

A case-by-case analysis was carried out in 3 steps. The first step was to identify lane departure without prior LOC. Secondly, the crashes were categorized as different pre-crash lane departure scenarios; that is, no maneuver lane drifting (e.g., due to driver drowsiness, distraction, or inattention) and intentional lane change or evasive maneuvers (e.g., overtaking, cutting short in a curve, or avoiding a potential collision object). Thirdly, crashes where LOC occurred after the vehicle departed from the lane were identified (illustrated in Figure 2). Examples of crash site photographs can be found in Appendix 1 (see online supplement).

Additional characteristics were identified for each crash in the analysis; that is, side of lane departure, road characteristics, traffic flow, type and condition of road markings, lighting and weather conditions, car model year, driver age, potential excessive speeding, and whether the driver was under the influence of alcohol and/or drugs. The Swedish legal limit of 0.02% blood alcohol concentration was used to identify whether individuals were considered to be under the influence of alcohol. Speed in excess of approximately 30 km/h (investigators' estimates) over the posted speed limit was defined as excessive speeding. The STA crash investigators' subjective assesments of curved roads and straight roads were used.

The potential crash prevention of LDW systems was quantified by identifying the target population. The target population

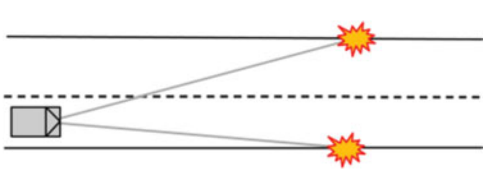

Figure 1. Illustration of initial lane departure without prior LOC.

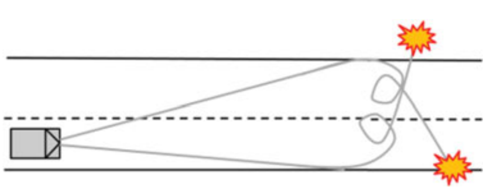

Figure 2. Illustration of initial lane departure without prior LOC, followed by LOC.

for LDW systems was drifting crashes on roads with visible lane markings and posted speed limits of 70 km/h and above. It was assumed that the LDW system was activated and worked properly and there was enough time for the drivers to respond correctly to the warning from the LDW system. However, crashes involving rumble strips were excluded from the target population and crashes involving excessive speeding were presented separately due to potentially insufficient reaction times.

Results

Identification of lane departure crashes without prior loss of control

In Sweden in 2010, there were 138 fatal passenger car crashes. Of these, 104 were single-vehicle, head-on, and overtaking crashes potentially related to lane departure. Sixty-three crashes were classified as lane departure without prior LOC, which accounted for 46% of all crashes involving at least one passenger car occupant fatality and 61% of all fatal single-vehicle, head-on, and overtaking crashes. The remaining 41 of the 104 head-on, single-vehicle, and overtaking crashes were direct LOC without prior lane departure (32 oversteering and 9 understeering).

Characteristics of lane departure crashes without prior loss of control, $n = 63$

Of the 63 crashes related to lane departure without prior LOC, 36 were head-on crashes, 25 were single-vehicle crashes, and 2 were crashes related to overtaking. The mean age of drivers in the lane departed vehicles was 42 years. In 17 crashes (27%, compared to 24% for all crash types in cars in Sweden in 2010; STA 2015), the driver in the departed vehicle was under the influence of drugs or alcohol and 8 crashes (13%) were identified as involving excessive speed.

The majority of the crashes occurred on roads with center (87%) and side (94%) line markings. Sixty-eight percent of the crashes occurred when the road conditions were noted as being dry. The majority of the crashes (92%) were on roads with posted speed limits of 70 km/h and above. Approximately half of the crashes were on high-speed roads (posted speed limit $\geq$90 km/h, 48%) and on higher traffic flow roads (annual average daily traffic $\geq$2,000, 59%). Approximately half (51%) of the crashes that related to lane departure without LOC were on straight stretches of road and the rest on curves. Seventy-one percent of the crashes involved lane departures to the left and the rest to the right. Forty-four percent of the single vehicle crashes and 89% of the head-on crashes involved lane departures to the left. The oldest passenger car among the lane departure crashes was from 1985 and the newest from 2009 and the passenger car mean model year was 1999. For further information about specific data related to lane departure crashes, see Appendices 2 and 3 (see online supplement).

Unintentional drifting out of lane, $n = 51$

Figure 3 shows how the 63 lane departure related crashes were grouped depending on the intention to leave the lane and whether lane departure was followed by LOC. It was found that

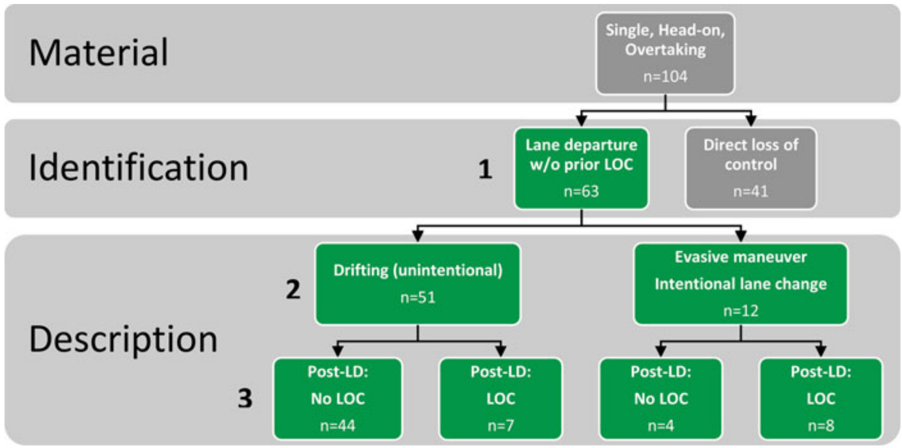

Figure 3. Illustration of the 3-step method: (1) Identification of lane departure without prior loss control and description of characteristics; (2) pre-lane departure and (3) post-lane departure.

the majority (51/63 = 81%) of the lane departures involved drifting and, of these crashes, 71% (36/51) had a driver not under the influence of alcohol or drugs and was not speeding excessively. The majority (44/51 = 86%) of the drifting crashes occurred with no LOC post-lane departure; see Figure 3. The drifting crashes accounted for 37% (51/138) of all fatal passenger car crashes in Sweden in 2010. For more information see Appendix 4 (see online supplement).

Additional characteristics of the 51 drifting crashes were as follows:

Road characteristics:

- Speed limits: 10% at 50 km/h, 22% at 70 km/h, 20% at 80 km/h, 45% at 90 km/h, 4% at 110 km/h.
- Center road markings: 78% visible, 8% snow covered, 2% worn, 12% no markings.
- Side road markings: 84% visible, 6% snow covered, 2% worn, 8% no markings.

Light:

- 62% daylight, 14% twilight, 24% darkness.

Driver age:

- 18 years: 8%, 19–24 years: 18%, 25–44 years: 27%, 45–64 years: 27%, 65–74 years: 10%, 75+ years: 10%, mean age: 43 years.

Car model year:

- Mean 2000.
- Median 2000.

Intentional lane change and evasive maneuver, n = 12

Of the 12 crashes that were identified as undertaking an intentional lane change or evasive maneuver, 8 were followed by LOC and 4 were not. Eight of these crashes involved a driver who was not under the influence of alcohol or drugs and was not speeding excessively when the impact occurred.

Potential safety benefit of lane departure warning systems

The potential crash prevention of LDW systems was quantified by identifying the target population. There were 51 drifting crashes, and 41 of these occurred on roads with posted speed limits of 70 km/h and above and with visible lane markings. When crashes with rumble strips on the same departure side were excluded from the target population, 38 crashes remained. However, if crashes with excessive speeding were excluded due to potentially insufficient reaction time, the remaining target population came down to 33 crashes. Therefore, the target population of crashes (of the 100 fatal head-on and single-vehicle crashes analyzed), where LDW systems may have been of benefit, was identified as being between 33 and 38 (depending on whether crashes involving excessive speeding were excluded or included, respectively). All except one of the 38 crashes occurred on undivided roads. Of these 37 crashes that occurred on undivided roads, approximately half occurred on roads with posted speed limits of 90 km/h (9 at 70 km/h, 9 at 80 km/h, and 19 at 90 km/h).

Discussion

In this study, almost half of all fatal passenger car occupant crashes in Sweden during 2010 were related to lane departure without prior LOC and accounted for 61% of head-on, single-vehicle, and overtaking crashes.

The typical lane departure crash without prior LOC occurred on undivided roads in rural areas with signed posted speed limits of 70 km/h and above, where the center and side road markings were visible. The majority of lane departure crashes in this study (81%) were identified as those involving drifting (i.e., unintentional lane departure) and could potentially have been avoided by an adequate lane support system. The drifting crashes seldom involved loss of control and therefore drivers were often still in the control loop and could potentially respond to warnings.

The potential crash reduction of LDW systems was found to be 33–38% for all fatal head-on and single-vehicle crashes. These crashes in the target population involved drifting and occurred on roads with visible lane markings, signed posted speed limits of 70 km/h and above, and without rumble strips on the corresponding lane departure side. The range is due to the inclusion or exclusion of crashes involving excessive speeding.

Main results in comparison to previous studies

The potential crash prevention found for LDW systems was similar to that found in previous research (Jermakian 2011;

Sternlund et al. 2017). Road safety systems tend to show greater benefit for crashes of more serious severity (Elvik et al. 2004; Krafft et al. 2009; Kullgren et al. 2010; Lie et al. 2006), and this study showed a potential that stays within the range for what could be expected of LDW systems in preventing fatal crashes.

The resulting proportion of crashes where vehicles left the initial lane without direct LOC versus with direct LOC showed comparable levels to previous research (Najm et al. 2002). However, in regards to road geometries, the analysis of Swedish crash data showed fewer crashes occurring on straight roads than those that occur on curved road segments compared to data from the United States, possibly due to the different definitions of a straight versus curved segment of road. The curve definition was unclear in the in-depth studies. Furthermore, it was found that there is a high safety potential for LDW systems on undivided rural roads in Sweden.

Similar classification methods have been used in previous studies (Najm et al. 2002, 2007), but the current study pointed out that lane departure relates to more than one part of the crash sequence. Both infrastructure and vehicle interventions can play a major role in the prevention of lane departure crashes. There is a need for a systematic approach to describe lane departure and related interventions that could be facilitated by the integrated safety chain (Tingvall 2008). Preventive interventions could break the chain of events leading to a crash at several stages to bring the driver back to normal driving. A crash that starts with lane departure and ends up in LOC could be addressed by a lateral support system or an electronic stability control system. Electronic stability control has been found to be up to 74% effective in reducing fatal LOC crashes in certain road conditions (Farmer 2010; Lie 2012). However, it should be noted that the drifting crashes in the current study were seldom followed by LOC.

Limitations

In-depth data from fatal crashes have previously been used to estimate the potential crash reduction benefits of different types of safety systems (Rizzi et al. 2009; Sferco et al. 2001; Strandroth, Rizzi, et al. 2012; Strandroth, Sternlund, et al. 2012). One limitation of these studies is that the results would have been influenced by subjective judgments. When the methodology contains subjective assessments, it needs to follow a transparent structure as was done in this study. The present study only included crash data from one year, making generalization of the results difficult. Sweden experienced a lot of snow in 2010, and analyzing other years could potentially result in a higher number of fatal single-vehicle crashes. In 2010, there were 3 fewer single-vehicle fatalities than the average for 2010–2015 and therefore the safety potential of LDW systems may be underestimated. However, the safety potential of LDW systems may also be overestimated. It was assumed that the LDW system was activated and worked properly and there was enough time for the drivers to respond correctly to the warning and this may not necessary have been the case in the crashes included for this analysis. It should be noted that no crashes occurred at construction zones.

Though it is important to reduce all types of lane departure crashes, the focus of this study was on crashes involving drifting of the vehicle, because this type of lane departure has the potential for an early intervention that can prevent the crash. Documented suicides and death by natural causes were excluded from this analysis because they are not the main target of lane-keeping technologies.

Future research

Lane-keeping systems that intervene by steering must be able to accurately detect potential lane departures and act accordingly. It is vital that the system understands at what point and to what magnitude it should intervene in a given situation. Fujishiro and Takahashi (2015) demonstrated that it is possible to reduce accidents and increase driver acceptance of a technology by calibrating the system to intervene later when the lateral speed of a vehicle is low but earlier when the lateral speed is high. There are examples of how other systems have approached the trade-off between timing and magnitude of intervention. For example, some autonomous emergency braking systems provide an early warning and if the driver does not react and a collision is expected, the system will intervene with full braking force (European New Car Assessment Program 2016). Future research should consider what the best balance is for lane-keeping systems.

Robust data about a vehicle's lateral position are a precondition for reliable automatic steering and it is essential that road infrastructure can support in-vehicle systems with this information. As steering control gradually shifts from the driver to the car, lane departures should be tackled holistically. Future research on the role and effectiveness of lane-keeping systems should consider an integrated approach, taking into consideration the role of both road infrastructure and vehicle systems.

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