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in

MACHINE AND VEHICLE SYSTEMS

Traffic Safety Potential and Effectiveness of Lane Keeping Support

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ABSTRACT

In the road transport system, crashes due to lane departure account for a large proportion of the most severe crashes that passenger car occupants are exposed to. While Electronic Stability Control (ESC) effectively prevents lane departure due to loss of control, lane departure due to unintentional drifting has not been addressed to the same extent. This thesis is based on four papers providing knowledge of lane keeping support integrated in vehicles and road infrastructure. More precisely, the safety potential and effectiveness of Lane Departure Warning (LDW) was studied as well as the effectiveness of centreline rumble strips (CLRS). Also, the potential safety benefits of Emergency Lane Keeping (ELK) and Autonomous Emergency Steering (AES) with enhanced lateral vehicle positioning were studied. Reviewing real-world in-depth data of 138 fatal crashes in Sweden 2010 and 114 in 2017, the results show that virtually half of the single vehicle and head-on crashes involved unintentional drift-out-of-lane, where LDW, ELK and AES should have had the potential to prevent the majority of these crashes. Estimating the effectiveness of LDW by analysing 1,853 police reported real-world injury crashes during 2007–2015 extracted from the Swedish Traffic Accident Data Acquisition (STRADA) database and applying the induced exposure method, it was found that LDW halved the risk of being in a head-on or single passenger car injury crash. Posted speed limits were at 70 km/h and above and the road surface had not been covered by ice or snow. Estimating the effectiveness of CLRS by merging STRADA injury crashes during 2011–2016 involving 7,490 cars with the National Road Database in Sweden (NVDB) and applying the induced exposure method, the results show a reduction in head-on and single car crashes. Crashes involving drift-out-of-lane to the left were reduced by 40% (19–56%) for ESC-equipped cars, and by 29% (11–44%) for cars without ESC. It could be confirmed that in-depth data with high detail can provide benefits in evaluating future road safety features. Furthermore, it was found that merging STRADA, NVDB and individual vehicle equipment data has significant methodological benefits in combination with data efficient methods such as the induced exposure approach.

LDW provided by the vehicle industry and detectable lane markings provided by road authorities are parts of a system showing significant traffic safety benefits. As both components are dependent on each other, this makes safety the responsibility of both road authorities and the vehicle industry. Not only do LDW and CLRS complement each other, they also complement ESC and are able to avoid critical situations. LDW and CLRS are two of the most important traffic safety features for the foreseeable future, in which the share of unintentional lane drifting crashes is expected to increase. ELK will in the near future be mandatory for new cars, hereby detectable lanes and lateral vehicle position awareness will be even more important. Future research should focus on increasing the synergy between car and infrastructure interventions, holistically and systematically utilising the integrated safety chain.

KEYWORDS: Lane keeping, Lateral positioning, LDW, CLRS, ELK, AES, Effectiveness, Traffic Safety

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Lastly, I would like to thank my beloved wife Annika.

Simon Sternlund

Norrköping, May 2020

LIST OF APPENDED PAPERS

- Paper 1** Sternlund, S. (2017). The safety potential of Lane Departure Warning systems – a descriptive real-world study of fatal lane departure passenger car crashes in Sweden. *Traffic Injury Prevention*, 18(sup1):S18-S23. DOI: 10.1080/15389588.2017.1313413.
- Paper 2** Sternlund, S., Strandroth, J., Rizzi, M., Lie, A., & Tingvall, C. (2017). The effectiveness of Lane Departure Warning systems – a reduction in real-world passenger car injury crashes. *Traffic Injury Prevention*, 18(2):225-229. DOI: 10.1080/15389588.2016.1230672.
- Contribution of Paper 2:* Sternlund made the data collection, the analysis and authored the paper with feedback from J. Strandroth, M. Rizzi, A. Lie and C. Tingvall.
- Paper 3** Sternlund, S. (2019). The effectiveness of Centerline Rumble Strips (CLRS) on two-lane carriageways in Sweden on injury accident risk for cars equipped with Electronic Stability Control (ESC) and cars without ESC. *Traffic Injury Prevention*, 20(8):880-885. DOI: 10.1080/15389588.2019.1669790.
- Paper 4** Sternlund, S. (2020). The safety potential of enhanced lateral vehicle positioning. *Submitted to Accident Analysis & Prevention*

DEFINITIONS AND ABBREVIATIONS

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
AEB	Autonomous Emergency Braking
AES	Autonomous Emergency Steering
AIS	Abbreviated Injury Scale
CLRS	Centreline Rumble Strips
DAC	Driver Alert Control
ELK	Emergency Lane Keeping
ESC	Electronic Stability Control
Euro NCAP	European New Car Assessment Programme
FARS	Fatality Analysis Reporting Systems
LDW	Lane Departure Warning
LKA	Lane Keeping Assist
MAIS	Maximum Abbreviated Injury Scale
NASS-CDS	National Automotive Sampling System Crashworthiness Data System
NASS-GES	National Automotive Sampling System General Estimates System
NVDB	National Road Database in Sweden
STRADA	Swedish Traffic Accident Data Acquisition

INTRODUCTION

BACKGROUND

Health loss in the road transport system is one of the leading global health problems. Worldwide, about 1.35 million road traffic fatalities occur annually and up to another 50 million people sustain non-fatal injuries, which for many people result in permanent medical impairment. Road traffic injury is the leading cause of death among children and young adults aged between 5 and 29 years. According to the World Health Organization (2018), crashes in the road transport system are the eighth leading cause of death worldwide.

Health loss in the road transport system is also a major global socio-economical problem impacting extensively on society as a whole, besides imposing much suffering and substantial economic loss to individuals. For most countries, the cost of road transport system crashes is around 3% of their gross domestic product (Ibid).

Despite improvements in recent years in the European Union, health loss in the road transport system still represent a major societal problem. In 2018, about 25,100 people died in the European Union road transport system (European Commission, 2019). In addition to the fatalities, about five times as many individuals were seriously injured (Maximum Abbreviated Injury Scale (MAIS) 3+) on European roads (European Commission, 2019). Statistics show that passenger car occupants accounted for a substantial part of the exposed casualties, at 46% of the fatalities within the European Union (European Commission, 2018). Similarly, in Sweden, a large part of road traffic fatalities involved passenger car occupants. Between 2010 and 2019, an average of 273 fatalities occurred annually in road traffic, out of which just over half (52%) were passenger car occupants. The new road transport safety strategy Vision Zero, adopted by the Swedish parliament in 1997, states that it is not acceptable for society to have a transport system that kills and seriously injures people. The long-term goal is that no one should sustain fatal or serious injuries within the road transport system (Swedish Parliament, 1997).

Lane departure crashes account for a significant part of fatalities and serious injuries for passenger car occupants in most countries. The magnitude and characteristics of lane departure crashes may be regarded as part of a necessary problem formulation preceding any suggested solutions. While Electronic Stability Control (ESC) effectively prevents lane departure due to loss of control, lane departure due to unintentional drifting has not been addressed to the same extent. Therefore, this thesis focus on unintentional drifting and its prevention strategies.

From a systematic point of view, drift-out-of-lane can be analysed on a timeline in relation to other critical events such as loss of control. In relation to other critical events, drifting would belong in the emerging stages of a situation, from which the severity of the situation would increase (Fig. 1). Lane drifting can be prevented in the emerging stages of a situation while loss of control is preventable in the critical stage. The integrated safety chain, shown in Fig. 1, is introduced and explained in a following chapter.

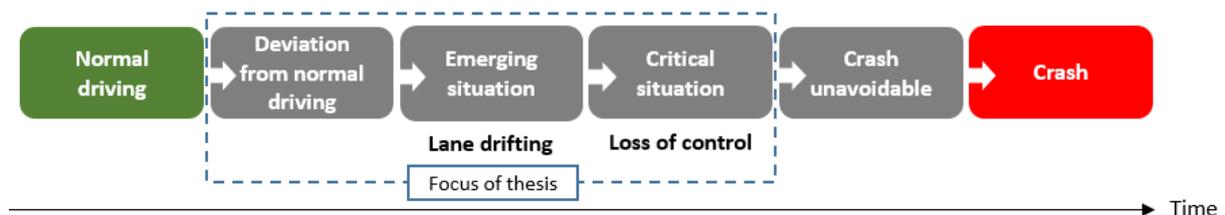


Figure 1: Focus of thesis in the integrated safety chain, adopted from Tingvall (2008), Lie (2012b) and Strandroth (2015).

Passenger cars represent the most common transport mode in fatal crashes in the European road transport system. According to the Community Road Accident Database (CARE), categorised by transport mode

in the EU, 46% of fatalities accounted for passenger car and taxi occupants (European Commission, 2017a), Fig. 2. Additionally, cars are also often involved in vulnerable road user fatalities.

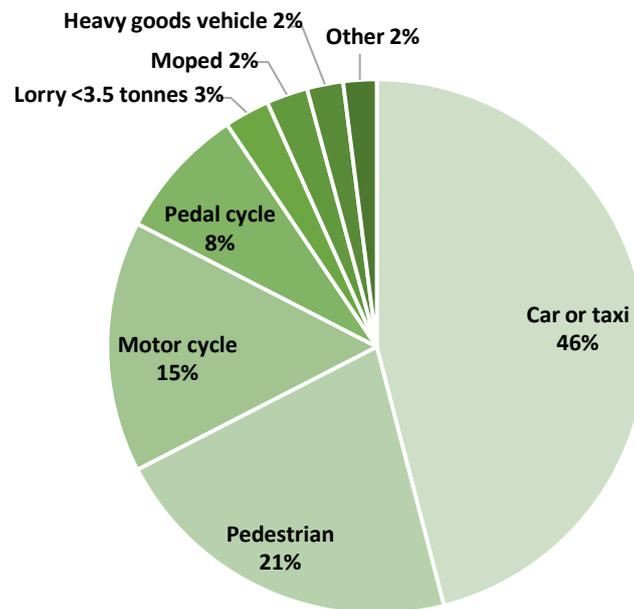


Figure 2: Distribution of fatalities by transport mode in the European Union. Source: CARE (European Commission, 2017a).

Even though car crashes occur in all traffic environments, most car occupant fatalities in the European Union countries occurred outside urban areas, on rural roads, non-motorways (68%), where the speed limit typically was 70 km/h and above (European Commission, 2017b). This is because fatality rate is related to kinetic energy. Corresponding results were found for serious injuries (MAIS 3+) during 2014 in national road accident databases within the European Union (European Commission, 2016). The European Commission (2016) study also found that the crash process (chain of events leading to a crash) involved loss of control in 40–58% of the crashes involving seriously injured car occupants. Two-thirds of the fatally injured car occupants were males and about two-thirds to three-quarters of the seriously injured persons were drivers.

Sweden had an early, rapid and high installation rate of the in-vehicle safety system Electronic Stability Control (ESC), reaching 98% in 2008 (Krafft et al., 2009). During the same year the installation rate within the European Union was 48% (FIA Foundation, 2008). The installation rate for the United States (US) was similar (53%) to the European Union, and on a global level the ESC installation rate was lower, at 33% 2008 (FIA Foundation, 2008). ESC has been found to be up to 74% effective in reducing fatal loss of control crashes in certain road conditions (Lie, 2012a). The year 2012, the European Union legislated ESC fitment in all new cars as of 2014 (European Commission, 2008). When the number of ESC equipped cars in traffic increases, the proportion of loss of control crashes would be expected to decrease, compared to crashes not due to loss of control, i.e., drift-out-of-lane crashes. Therefore, it will be important to focus on reducing lane departure crashes due to drift-out-of-lane as ESC systems are permeating the traffic.

CRASH SITUATIONS RELATED TO LANE DEPARTURE

It is logical that drivers leave the lane either intentionally or unintentionally. Overtaking, avoidance manoeuvres or lane changes are common types of intentional lane departure. However, there are multiple causes of unintentional lane departure as well. Staying in lane is important as it generally is a precondition for safe driving. From a vehicle dynamics perspective, unintentional lane departure may be the result of either loss of control or drift-out-of-lane, where driver fatigue, distraction or unawareness

are typical causes of unintentional drift-out-of-lane. Head-on or single car crashes are consequences of loss of control or drift-out-of-lane, and represents the majority (on average 76% between 2010 and 2019) of passenger car occupant fatalities in Sweden (Fig. 3) (Trafikanalys, 2020).

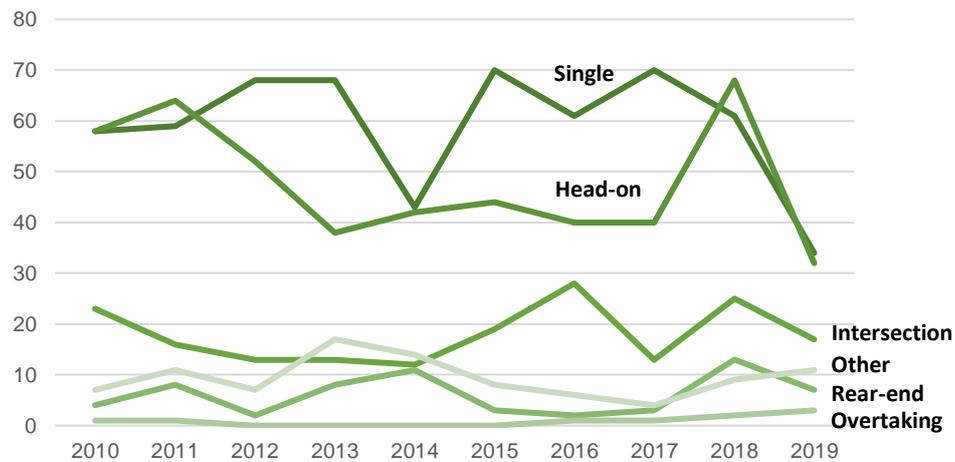


Figure 3: Passenger car occupant fatalities in Sweden during 2010-2019 (Trafikanalys 2020).

Additionally, head-on crashes represent one of the most lethal crash types involving high deceleration (Høye et al., 2010). Almost 7% of head-on crashes involving passenger car occupant injury resulted in a fatality, while corresponding fatality rates in other crash types were significantly lower; single vehicle: 1.5%, intersection: 1.2%, overtaking: 0.7% and rear-end: 0.3% (police reported crash records extracted from the Swedish Traffic Accident Data Acquisition (STRADA) 2010–2019, n=87,321).

Based on police data from the US National Automotive Sampling System General Estimates System (NASS-GES), Najm et al. (2002) found that road departure crashes without previous loss of control represented 55% (525,000 crashes) of all road departure crashes and the remaining 45% were related to loss of control. Of the road departure crashes without loss of control, 65% occurred on straight roads, 22% in curves and 13% were related to evasive manoeuvres. Later, Najm et al. (2007) showed that the road edge departure without prior vehicle manoeuvre was the second most common pre-crash scenario, accounting for 20% of single light vehicle pre-crash scenarios. The dataset included road motor vehicle crashes with property damage, injury or fatality. The study showed that a typical scenario occurs in rural speed areas (posted speed limit ≥ 55 mph corresponding to ≥ 89 km/h) while road alignment was identified as straight in 74% of the crashes. The most common (28%) single light vehicle pre-crash scenario was loss of control without prior vehicle action.

German insurance data shows that lane departure accounted for 29% of German insurance collision claims between 2002 and 2006. Categorised according to first impact, 54% involved collisions with another oncoming vehicle, 24% collisions with another vehicle moving in the same direction and 22% involved a vehicle leaving a carriageway (Kuehn et al., 2009).

In Sweden, lane departure also accounts for a large proportion of the most severe crashes. Strandroth (2015) estimated, through a retrospective case-by-case analysis of in-depth studies, that 31% of the passenger car fatalities in 2010 involved unintentional drift-out-of-lane. It should be noted that crashes involving drifting prior to loss of control, and thereby potentially prevented by ESC were not included in the 31%. Consequently, a larger proportion of crashes would have involved lane drifting, however, the actual number remains unidentified. To fully understand the magnitude of the problem it is essential to identify the total amount of unintentional drift-out-of-lane crashes with and without loss of control.

LANE DEPARTURE INTERVENTIONS

INFRASTRUCTURAL INTERVENTIONS

As described in the previous paragraph, lane departure crashes represent a significant problem in the road transport system. The risk of serious injury as a result of lane departure can be prevented in many ways. Several road infrastructure features provide guidance to help drivers avoid unintentional lane departure and related crashes. Lane markings and road posts, serving as visual guidance, have been available for an extended period of time. Improved guidance has the potential to result in changing driving behaviour. A simulation study concluded that improved visual guidance as delineation increased the driving speed and the number of collisions with unexpected objects on the road (Sharfi and Shinar, 2014). A meta-study (Høye et al., 2010) of centre road markings showed no statistically significant reduction of crashes. The same lack of significant results was found with regard to side lane markings. However, the combination of centre and side road markings was estimated to reduce injury crashes by 24% (11–35%, confidence interval [CI] 95%). Road posts exclusively showed no crash reduction. The combination of road posts, centre and side road markings, was found to reduce injury crashes by 45% (32–56%, CI 95%). The meta-study by the Institute of Transport Economics (TØI), Norwegian Centre for Transport Research, (Høye et al., 2010) argues that improved road standard, i.e., lane markings and road posts, could result in increased travelling speed. Further, the placement of lane markings may have a bearing on travelling speed. Narrow lanes may imply lower travelling speed (Johansson, 2009).

Before the introduction of 2+1 roads (a three lane road separated by a median barrier into two lanes in one direction and one lane in the other, alternating after a certain distance), early road design addressed the lane keeping problem by building wide and straight roads (Johansson, 2009). In Sweden, the general design of long distance high traffic volume roads was 13 m wide with two lane single carriageways and a posted speed limit of 90 km/h (Carlsson, 2009). The road design attributes, wide and straight, addressed the frequency of lane departure but not the crash severity in any eventual crashes. Merged data extracted from STRADA and NVDB for the period 2010–2016 showed that the head-on fatality rate per vehicle-km on these 90 km/h roads, was about 2.5 times higher than on 70 or 80 km/h roads (*Fig. 5*). The difference in risk can partly be explained by the speed differences. According to the Power Model (Elvik, 2009) a speed increase from 70 to 90 km/h results in a 3.2 times higher fatality risk given that everything else is kept unchanged, $(90/70)^{4.6} = 3.2$. The Power Model describes the relationship between relative change in speed and number of crashes or injured individuals of different severity where the exponent used for fatalities is 4.6.

$$\frac{\text{fatalities after}}{\text{fatalities before}} = \left(\frac{\text{speed after}}{\text{speed before}} \right)^{4.6} \quad (1)$$

Moreover, as these wide 90 km/h roads were located in high volume traffic areas, this type of road design has been the cause of significant harm. Even though most high volume 90 km/h roads had been converted to 2+1 before 2010, undivided 90 km/h roads show high risk (*Fig. 5*). It should be noted that *Fig. 5* involves a mix of undivided and divided roads. However, during 2010–2016, an average of 97% of the 90 km/h road length had undivided opposing lanes and 98% for 80 km/h roads respectively.

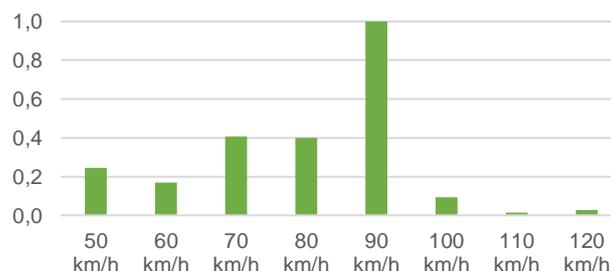


Figure 4: Head-on fatalities per traffic volume (vehicle kilometre) in relation to 90 km/h roads. Data extracted from STRADA and NVDB 2010–2016.

Rumble strips

Singing safety lanes provide warning for motorists was the headline in the *Popular Mechanics Magazine* in 1953. This was one of the first attempts of using rumble strips as a traffic safety feature. The rumble strips were made of corrugated concrete and placed on the side of the 165 mile expressway in New Jersey in 1952 (*Fig. 6*). Those were also used as a replacement for the centreline on two-lane roads. Later, milled rumble strips have been used by road transport designers as haptic and acoustic guidance to address drift-out-of-lane issues. Before and after studies of centreline rumble strips (CLRS) on rural two-lane roads in the North America showed reductions in head-on and opposing-direction sideswipe crashes by 30%, injury crashes by 25–30% and fatal crashes by 44%

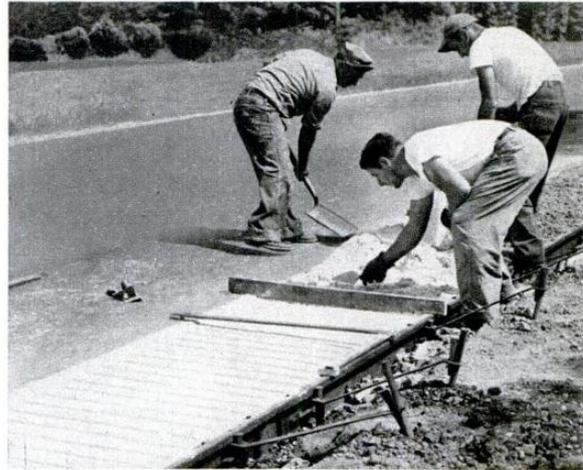


Figure 5: Singing safety lanes, Popular Mechanics Magazine (1953).

(Persaud et al., 2004; Torbic et al., 2009; Sayed et al., 2010). Among other factors, they were controlled for traffic volume and regression to the mean. The combination of both CLRS and edge line rumble strips reduced head-on, sideswipe-opposite-direction and single vehicle run-off road, for all severity crashes by 21–35% and injuries by 40% (Sayed et al., 2010; Torbic et al., 2013; Lyon et al., 2015). Edge line rumble strips alone also showed positive effects, at 14–26% reduction in run-off road crashes (Marvin, 2003; Sayed et al., 2010).

A Norwegian study of milled CLRS on two-lane roads with posted speed limits of 70, 80 or 90 km/h, also showed reductions in injury crashes (Ragnøy & Skaar, 2014). Head-on crashes were reduced by 32% and single vehicle run-off road to the left by 54%. The period before implementation (2007–2009) was compared to the period after (2011–2013), and the results were adjusted for regression to the mean and road safety trends due to general vehicle improvement.

Different types of milled rumble strips have been tested in simulation studies (Anund et al., 2005; Anund et al., 2008). The length of the strips varied between 2–30 cm, depth 1–2 cm, width 17.5–50 cm and the distance between 13–105 cm. The studies found no significant differences in the alerting effect of the different types of rumble strips.

A meta-study (Høy, 2015) of rumble strips analysed the results of several studies. The study concluded that CLRS reduced the total number of crashes resulting in injuries by 10% (5–14%, CI 95%) and injury crashes categorised as head-on, run-off road to the left and side-impacts in the opposite lane to the left, by 37% (31–42%, CI 95%). Concluding, the studies referenced above shows that the estimated effectiveness of CLRS on two-lane roads differ depending on crash severity, crash type and country specifics, within a range of approximately 10–50%.

To avoid external noise pollution in Sweden, the Swedish Transport Administration does not apply milled rumble strips closer than 150 m of urban areas. Consequently, only 70–80% of two-lane roads suitable for rumble strips have actually been equipped with rumble strips. The most prevailing CLRS implemented in Sweden is the sinus type (specification provided in Paper 3), mostly implemented between 2006–2010 (*Fig. 7*).

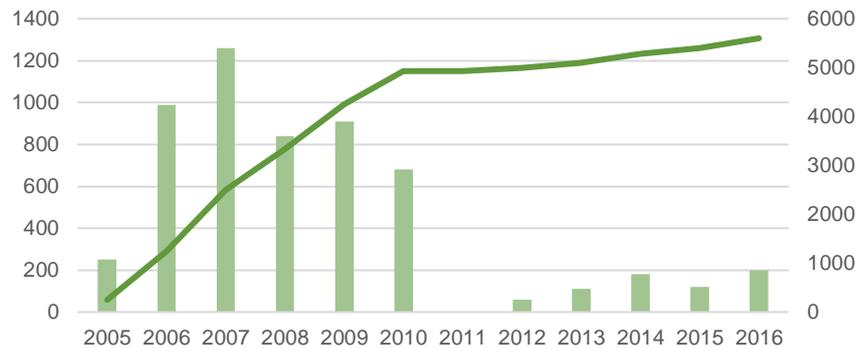


Figure 6: Implemented milled CLRS on two-lane roads in Sweden (km) and corresponding accumulated levels, adapted from the Swedish Transport Administration (2017).

Before and after studies of milled CLRS on Swedish two-lane roads showed a reduction of 15–20% (Vadeby, 2013) in the fatal and severe injury rate in police reported single vehicle crashes. Later, an update showed that fatal and severe occupant injuries had reduced by 15% for all crash types excluding crashes at intersections and 24% for single vehicle crashes comprising crash data from 2003–2013 (Vadeby & Björketun, 2016). The results were adjusted for regression to the mean and apply to two-lane roads with a posted speed limit of 90 km/h and road width up to 10 m. Milled rumble strips on the shoulder of highways were also studied (Ibid). Applying the same method, the reduction in fatal and severe injuries was 12% for all crash types, 16% for all crash types including all injury crashes, and 25% for fatal and severe injuries sustained in single vehicle crashes. However, other safety interventions on the shoulder of the road were not considered, e.g., side barriers.

In summary, rumble strips provide certain safety benefits and are not subject to selective recruitment as they address all passenger cars, not only those equipped with lateral support in-vehicle systems. However, the referenced studies above did not account for the individual in-vehicle equipment. Consequently, knowledge of how the widespread in-vehicle system ESC affects the effectiveness of CLRS is still lacking, which is of interest due to the increasing ESC implementation rate.

Median road barriers

Straight and wide road design invites drivers to exceed the speed limit (Johansson, 2009). From a Vision Zero perspective, it can be concluded that the features straight and wide exclusively do not represent successful or safe road design (Johansson, 2009). In the Vision Zero spirit it became imperative to enhance the overall safety level of road design to enable high speed driving without risking fatalities or severe injuries. As a result of the new strategies, many of the straight and wide 90 and 110 km/h roads were transformed into 100 km/h 2+1 roads, and equipped with flexible median barriers, such as wire rope barriers, which consequently increased traffic flow capacity as well as overall safety. The fatality rate was reduced by 75–80% on 13 m wide converted and improved roads (Carlsson, 2009). Implementation of median barriers on narrower road stretches (9 m wide) has resulted in a reduction of 63% in fatal and severe injuries and 28% in injury crashes (Vadeby, 2016). Median barriers and side guard rails mitigate the negative consequences of lane and road departure. However, where the road remains undivided, rumble strips or in-vehicle lane support systems such as Lane Departure Warning (LDW), Lane Keeping Assist (LKA) and Emergency Lane Keeping (ELK), have the potential to play an important role to reduce unintentional lane drifting.

IN-VEHICLE SYSTEMS

In the last ten years, new innovative lane keeping support solutions have been developed and sold by the automotive industry, where the vehicle interprets the road environment by camera. Lane support systems such as LDW and LKA represent in-vehicle technology detecting the travel lane by its lane markings and road edge lines. The primary benefit of this technology is that it can alert the driver in an effort to prevent unintentional drift-out-of-lane, typically due to driver drowsiness, distraction, or

inattention (AAA Foundation for Traffic Safety, 2016; Euro NCAP, 2017). The system issues a warning by vibrating the steering wheel or driver's seat, or through audible and visual signalling. While both the LDW and LKA systems warn drivers, without necessarily any action having to be taken by the driver, LKA systems actively assist drivers through an automatic limited steering torque, or by applying gentle brake pressure on the appropriate wheels, as the vehicle is about to drift beyond the edge line of the current lane of travelling.

Lane support systems require lane markings to be present and visible, i.e., not worn or covered by snow, or an outline contrasting significantly, such as a verge. They do not operate at low speeds, typically being activated at about 64 km/h (40 mph). There are other technical limitations to lane support systems as they do not function properly if the curve radius of the road is small or during heavy precipitation (Hummel et al., 2011; Jermakian, 2011). Other factors, such as adverse lighting as well as temporary lane markings at construction zones, could also cause the system to fail. Hence, some limitations are effects of technical issues while others the effect of attempting to avoid frequent warning signals in situations where the driver is deemed to be in control of the vehicle. In reducing the warning frequency, industry is trying to minimise the number of users disconnecting the system as well as attempting to avoid drivers becoming complacent to accurate warnings, which comes at a potential cost of reduced efficiency. It is crucial that system designs are aimed at optimising efficiency by maximising true positives while simultaneously minimising false positives (Kompass, 2012; Murphy & Kahl, 2012). Consequently, enhanced lane detection has a potential to improve lane support efficiency.

Lateral support systems were first introduced in premium cars with low sales volumes. The Japanese market was early with LKA in the 2001 Nissan Cima (Continental, 2019) and with LDW in the 2002 Toyota Caldina. In Sweden, LDW was offered as optional equipment in the 2004 Lexus LS, the 2007 Volvo S80 and the 2008 Audi A8 (Autoblog, 2008), for example. The Citroën C6 model year 2005 was the first car in Sweden to include LDW as standard equipment (Citroën, 2005). However, the widespread penetration of LDW in Sweden began with the Volvo V70II from model year 2008 (Volvo, 2009). LDW and LKA were included in the European New Car Assessment Programme (Euro NCAP) in 2014 (Euro NCAP, 2015). Although Emergency Lane Keeping (ELK) systems intervene more aggressively, they only activate in critical situations. ELK systems will intervene by resolute heading corrections if they predict an imminent road departure or drift into oncoming or overtaking traffic in the adjacent lane. ELK systems were first included in the Euro NCAP test programme in 2018 (Euro NCAP, 2017). Euro NCAP's star rating of tested new cars fitted with standard equipment has previously been proven beneficial in real-world crashes (Lie & Tingvall, 2002; Kullgren et al., 2010; Kullgren et al., 2019).

Evasive Steering Assist (ESA) systems detect swerving initiated by the driver and provides steering assistance to avoid an obstacle ahead (Volvo, 2017; BMW, 2016; Mercedes-Benz, 2017). ESA has already been introduced in traffic while Autonomous Emergency Steering (AES), initiated by the vehicle, is a technology for the future, which automatically steers the vehicle to avoid a collision when braking alone is not enough (Nissan, 2017; Strandroth, 2016; Swedish Transport Administration, 2016). Despite AES technology still being in its infancy, it has shown particular potential in avoiding single vehicle and small overlap crashes, as well as collisions involving vulnerable road users (Euro NCAP, 2019).

Safety technology such as Autonomous Emergency Braking (AEB), Intelligent Speed Assistance and ELK as well as driver drowsiness and inattention detection are expected to become compulsory as of July 2022 (European Parliament, Council of the European Union, 2019) in all new passenger cars (M1) and light commercial vehicles (N1) sold in EU. Although the systems must be in normal operational mode when activating the vehicle master control switch, it will still be possible to switch off the ELK and AEB systems, one at any given time, in a sequence of actions carried out by the driver. Additionally, it will be possible to easily suppress audible warnings, however such action must not simultaneously suppress system functions other than audible warnings, although it will be possible for the driver to override the systems. In line with the EU regulation on type-approval requirements for motor vehicles

(Ibid), the Euro NCAP (2017) test protocol states that ELK systems will only be tested and rewarded if they are activated as default at every drive cycle.

Safety potential of Lane Departure Warning systems

In conjunction with the development and introduction of LDW, by identifying the target population a number of prospective effectiveness studies have been performed. Using US data from NASS-GES 2004–2008, Jermakian (2011) estimated the safety potential of LDW for fatal head-on crashes to 40–46% (the range was defined according to the inclusion or exclusion of crashes involving speeding). Fatal single vehicle crashes showed a potential reduction of 17–31%, although if recalculated to exclude collisions with pedestrians, cyclists and animals on roadways, and only including crashes involving car occupants, the potential reduction of LDW related crashes was estimated to 24–43%. The total potential of LDW to reduce head-on and single vehicle crashes was estimated to 27–43%. A 100% effectiveness approach was taken and applied on the target population narrowed down by crash type, crash scenario specifics (excluding vehicle/road defects, avoidance manoeuvres and loss of control), speed limits of 40 mph (64 km/h) and above as well as roadways cleared from snow. Including car occupants only, it should be noted that Jermakian (2011) selected head-on, single vehicle and sideswipe possibly relevant for LDW with respective crash type constituting 12%, 78% and 10% (same direction 2% and opposite direction 8%) of the material of fatal crashes. A different composition mix was seen in the resulting relevant LDW crashes; head-on 22%, single vehicle 64% and sideswipe 13% (same direction 3% and opposite direction 10%).

To identify target populations for a number of Advanced Driver Assistance Systems (ADAS), Kusano and Gabler (2014) used NASS-GES, NASS Crashworthiness Data System (NASS-CDS), and the Fatality Analysis Reporting Systems (FARS), comprising fatal and non-fatal crashes in the US. The study concluded that the potential crashes possibly prevented by LDW, i.e., road departure, lane departure opposite direction, and lane departure same direction crashes, accounted for 44% of fatal crashes, 39% of MAIS 3+ crashes, and 14% of all severity crashes. In the National Motor Vehicle Crash Causation Survey database they found that 24% of all crashes involved distraction. They assumed that the distribution of the National Motor Vehicle Crash Causation Survey data also holds for NASS-GES, NASS-CDS and FARS. Thereby, they concluded that the LDW relevant crashes involving distraction (excluding excessive speeding, performance error, judgement error, non-performance, illegal manoeuvre, and other) accounted for 10% of fatal crashes, 9% of MAIS 3+ crashes, and 3% of all severity crashes.

Scanlon et al. (2016) showed that the roadway infrastructure influences the prospective effectiveness of LDW and LKA. This study used 478 real-world drift-out-of-lane crashes from the 2012 NASS-CDS database which represented 147,662 crashes in the US for simulation. Departure angle, departure velocity, road radius of curvature, shoulder width, and driver reaction time were replicated. The study concluded that supporting and intervening lane keeping systems, i.e., LDW and LKA, have a higher safety potential if all roadways are equipped with lane markings or expanded shoulders. The systems could prevent up to 78% of drift-out-of-lane road departure crashes if lane markings were present and the shoulders were expanded to 3.6 m. It was also concluded that even though providing expanded shoulders would be less practical than providing lane markings, missing lane markings could possibly be addressed by an in-vehicle road edge detection algorithm.

Concluding, the studies referenced above shows that the magnitude for safety potential of LDW differ depending on crash severity and study population, within a range of approximately 15–50% reduction in fatal crashes.

To precisely estimate the safety potential of lane support systems such as LDW, the main challenge is to identify the target population. A precondition for narrowing down crash data to the true target population involves accessing detailed pre-crash data relevant to LDW. The level of detail of Swedish

mass data of injury crashes (i.e., STRADA) is lower than in-depth data of fatal crashes which are rich in detail and should preferably be used to estimate the potential safety benefits of LDW.

Effectiveness of Lane Departure Warning systems

Few published studies have been able to evaluate the retrospective effectiveness of LDW and/or LKA building on real-world crashes. Analyses performed by the Highway Loss Data Institute (2012) for the Insurance Institute for Highway Safety in the US did not observe any drops in claim frequency of property damage liability or bodily injury liability coverage for LDW equipped cars in 2012. Further analyses by the Highway Loss Data Institute (2015) observed a drop in claim frequency for both types of coverage; property damage liability by 9.9–14.0% and bodily injury liability by 24.2–39.5% for Honda Accord model year 2013–2015 equipped with Forward Collision Warning combined with LDW. Analyses carried out at a later stage by the Highway Loss Data Institute (2018) into claim frequency observed inconsistency across manufacturers (Audi, Mercedes-Benz and Mazda) and across measurements (bodily injury liability, medical payment coverage, personal injury protection, property damage liability and collisions). The LDW equipment was combined with other crash avoidance technology, hence it was not possible to separately analyse the effect of LDW. Information about the specific vehicle equipment was known, but crash type was not known. These analyses demonstrate the consequences of lacking precise crash characteristics information. Reductions in the frequency of bodily injury claims, property damage claims and collision claims for BMW cars, model year 2013–2017, were revealed in more recent analyses by the Highway Loss Data Institute (2020). The combination of Forward Collision Warning, LDW and AEB were associated with reductions of 16% (bodily injury claims), 11% (property damage claims) and 5% (collision claims). The Driving Assistance package including updated versions of these systems, and also Adaptive Cruise Control, has been associated with reductions of 37% (bodily injury claims), 27% (property damage claims) and 6% (collision claims). The Driving Assistance Plus package adding lane centring and front cross-traffic alert was not associated with any additional claim frequency reductions compared to the Driving Assistance package in the study.

Hickman et al. (2015) also showed safety benefits of LDW systems. LDW equipped heavy goods vehicles (Class 7 and 8) in the US had a 48% lower LDW-related crash rate of all severities than non-equipped trucks. LDW-related crashes considered include run-off road, head-on and sideswipe crashes. Vehicle-miles travelled were used as exposure. The data were collected from 14 carriers, comprising 88,112 crash records and 151,624 truck-years that had travelled 13 billion miles over the observation period. This study focused on the effectiveness of LDW in heavy goods vehicles rather than in passenger cars.

Cicchino (2018) succeeded in merging real-world police reported crashes in the US and specific car equipment data matched by vehicle identification numbers. The analysis showed that LDW systems lowered the rates of single car, sideswipe and head-on crashes of all severities (including property damage) by 11% ($p < 0.05$) and indicated a lowered rate of injury crashes by 21% ($p < 0.07$).

Concluding, it has been shown that LDW systems do have safety benefits. The referenced studies above were mainly from the international scene, and the safety benefits of LDW in Swedish conditions have not yet been explored. At the time when analysis for the appended Paper 2 was conducted no previous retrospective effectiveness study of LDW-equipped passenger cars involved in LDW-relevant crash types had been published.

Driver acceptance of lane support systems

For lane support systems to be beneficial, they must be in operational mode. Previous studies have highlighted that driver acceptance may affect the activation rate of LDW and LKA systems (Kidd et al., 2017; Reagan et al., 2018). Raising the acceptance level of the systems may potentially reduce the rate of deactivated systems. Speculating, this may be done by more refined technology, i.e., less false positives (unnecessary warnings), and improved human-machine interface, i.e., less disturbing warning

signals. It is possible that providing scientific evidence of the safety benefits would affect driver acceptance and positively influence the implementation rate. Hence, over time, user experience without false warning signals would possibly increase the acceptance.

Braitman et al. (2010) conducted an interview study into driver acceptance of different crash avoidance technologies. Eighty-six interviews involved LDW equipped Volvo cars. Sixty-nine percent said that they always keep the system in operational mode while driving, 23% sometimes do, 7% never do, and 1% were unaware of the equipment. The most common reason for turning off the LDW included finding the warning sound disturbing. Even though 43% of the users answered that they received false unnecessary warning signals, 80% reported they would like to have access to the system again and it makes them a safer driver. Sixty-seven percent reported that they drift-out-of-lane less often and 60% that they use their indicator more often. Later, in interviews (Eichelberger & McCartt, 2014) with owners of Volvo cars with model year 2010–2012, 59% said that they constantly keep the LDW system in operational mode, which is fewer than for Forward Collision Warning (89%).

Observations at dealership service centres showed the level of activation of support systems. LDW was activated in only 33% for Honda cars with model year 2013–2015 (Reagan & McCartt, 2016) while Volvo cars with model year 2010–2016 were activated in 50% of cases (Reagan et al., 2018). However, the study by Reagan et al. (2018) excluded 17 Volvo cars where the default settings were set to in operational mode at each ignition cycle. If these 17 vehicles had been included, the activation rate would be 67% (33/49) rather than 50% (16/32). Further, the activation status varied between various car models. The systems were active in 21% of Ford/Lincoln, 36% of Honda, 50% of Chevrolet, 57% of Cadillac, 68% of Toyota/Lexus, 75% of Volvo and 77% of Mazda vehicles (Lund, 2017). It was also observed that the activation level tends to show higher numbers in more active lane keeping systems, 75% for lane centring systems (providing steering correction more frequently to maintain a lateral vehicle position close to the centre of the lane), 48% for LKA systems and 46% for LDW systems (Ibid). Reagan et al., (2018) showed similar activation levels; 65%, 55% and 45% respectively, using the same material excluding three Cadillac cars. However, only Toyota/Lexus represented cars with lane centring systems (Ibid). Furthermore, for the Toyota/Lexus cars, the LKA system was more often in operational mode (74%) compared to 60% for LDW systems and 65% for lane centring systems. It is also unknown to what extent these service centre observations are valid for traffic in environments where the systems have a greater potential. The activation rate in Volvo car models in Sweden remains unknown at the time of writing. The activation level for Volvo cars showed 87% for LKA systems and 50% for LDW systems in the US (Reagan et al., 2018). While drivers have shown a preference for vibrating seats over auditory warnings (Flannagan et al., 2016; Stanley, 2006), Harkey (2018) observed the opposite, that the audible alerts (45%) were more often in operational mode compared to vibrating seats (29%) comparing alerting modality of LDW systems in Cadillac and Chevrolet cars (n=275).

Active lane keeping systems that intervene in steering, consequently have high demands for avoiding false positives. With such high requirements the lateral positioning information becomes essential. Enhanced lateral vehicle positioning may therefore gain driver trust, acceptance and ultimately usage and effectiveness.

Lane support dependent on lateral vehicle positioning

Lane support systems are dependent on technology for vehicle localisation. Therefore, it is of interest to understand the limitations of commonly used technology. Schoettle (2017) assessed the performance of different sensing devices used for automated driving systems. She concluded that the human and the human eye perform both better and worse in the driving task compared to automated vehicles equipped with different sensors, such as camera, lidar or radar, depending on the performance aspect. With regard to lane tracking, human eyes and cameras performed good, and lidars and radars performed poor. On the other hand, in the aspect of poor weather conditions, radar was the only sensor mode that performed well, while human eyes and lidars performed fair and cameras performed poor. However, connected vehicles using information from other vehicles' sensors may perform better. Hence, a robust lane

keeping system cannot solely rely on connectivity and the sensors in other vehicles (OECD, 2018). Also, global positioning systems (GPS), inertial navigation systems (INS) and digital maps are used to improve vehicle localisation. GPS/INS can achieve accuracies of approximately 1 m and be improved down to approximately 0.25 m and lower using high-resolution digital maps (Hillel, 2014). Future GPS based systems should not be ruled out. However, GPS based systems are limited by connectivity and should be considered as important complementary information for localisation.

Less commonly, localising ground penetrating radar (LGPR) systems using the relatively stationary underground geology seems like a promising technology where visual based systems are limited, for example, due to harsh weather conditions (Cornick et al. 2016). MIT Lincoln Laboratory in Massachusetts demonstrated real-time highway testing with performance of 4.3 cm quadratic mean accuracies in lateral localisation at speeds up to 100 km/h. An interesting development project called DENSE (2019) identified the need of enhanced vehicle positioning and is aiming to solve the technological positioning challenges of driver assistance systems and automated driving in all weather conditions including adverse visibility conditions in harsh winter conditions. This is planned to be done by developments in radar, infrared camera and infrared lidar technology.

Concluding, precise and reliable lateral vehicle positioning may have potential to enhance lane keeping support systems, such as LDW and ELK, and the preconditions for robust automated evasive steering including AES. The safety benefits of enhanced lateral vehicle positioning with application to LDW, ELK and AES have not yet been examined in depth. It is of interest to understand to what extent the impact of a precise and reliable lateral vehicle positioning potentially has on lane keeping as well as on lane escaping.

SYSTEMS INTEGRATED IN VEHICLE AND ROAD INFRASTRUCTURE

Previously described safety interventions have involved a certain amount of manipulation, either to the road or the vehicle. Systems equipping both roads and vehicles have been developed to enhance lateral vehicle positioning and thereby improve safety. Magnetic sensing systems and radar reflector systems are examples of such systems.

Magnetic sensing systems

Magnetic sensing systems have been used to support drivers in lane keeping. For example, snowploughs equipped with magnetic sensors and permanent ferrite magnets embedded in the road, make up a system to support the driver with information, displayed on a monitor, of the current lateral position within the traveling lane (Yen et al., 2000). The system assists the snowplough driver during harsh weather conditions including frequent storms with heavy snowfall. The maximum lateral deviation measured 1.5 cm and on average 1 cm. More recently, experiments have shown that cars equipped with magnetic sensors driving on magnet embedded roads have the ability to detect the lane with less than a 0.1 m lateral positioning error (Steверud et al., 2013; Torin & Hellman, 2015).

Radar reflector system

Studies of radar reflector systems have been conducted (Voronov et al., 2016). It was suggested that roads equipped with passive radar reflectors, together with sensor equipped vehicles, would make up a system to increase the lateral positioning where other sensing modalities are limited, for example due to heavy rain, snow or fog. It was recommended that the reflectors should be able to function together with several sensing modes, that is, radar, lidar and camera. The lateral dead reckoning course deviation was about 0.01 m for each longitudinal metre. Consequently, a 0.1 m lateral accuracy would require reflectors at every 10 m. Finnish experimental studies (Kotilainen et al., 2019) of radar reflector systems in real-world conditions, including snow and ice, also showed feasibility for this technology. It was suggested that reflectors are needed at each 20 m interval in speeds up to 80 km/h. A limitation identified during testing includes wind carried snow dust, reducing the reflector detectability and on-coming vehicles blocking line of sight. However, the system has the potential to improve the level of redundancy with regard to lane keeping.

INTEGRATED SAFETY CHAIN

When evaluating safety features using crash data it is of particular importance to understand how crashes and safety features relate to each other. When evaluating a particular safety feature most often a combination of several other safety features affect the evaluation. A systematic approach is required to increase understanding of overlapping and correlating properties of preventive countermeasures. Particularly useful is a framework for safety potential analyses where crash process phases of different levels of critical severity must be considered. Also, regarding application of the induced exposure method (Evans, 1998) where the crucial part of using the induced exposure method is to identify sensitive and non-sensitive crashes. Here, a systematic framework is needed to provide a structure for this identification and a link between the crashes and safety features (Strandroth, 2015).

William Haddon Jr. was early to realise the need of a systematic approach to epidemiological risk in the field of road traffic safety. This led to the development of the Haddon matrix, used to identify risk factors, injury mechanisms and to develop injury prevention strategies. Dr. Haddon's approach is one of the most recognised examples of injury prevention theories and is used for road traffic safety as well as in other areas. For road safety application, the main injury mechanism was defined as harmful transfer of mechanical energy. Haddon (1980a; 1980b) used a timeline with three phases; pre-crash, crash and post-crash. For each time sequence, countermeasures were able to address the elements; road user, vehicle, physical and the socio-cultural environment. Even though Haddon gave structure to injury prevention strategies, the elements serving as targets for intervention were rather isolated.

The Haddon model has been further developed into the integrated safety chain model (Tingvall, 2008; Lie, 2012b; Strandroth, 2015) (*Fig. 4*). In the integrated safety chain, a potential crash is seen as a timeline between normal driving and a crash. The timeline is broken down into different phases where relevant countermeasures have the potential to cut the chain of events leading to crash. This approach is used in the vehicle industry (Nissan, 2005; Schöneburg & Breitling, 2005; Eugensson et al., 2011). The emphasis in this approach is on normal driving, how to design a transport system supporting the driver to stay within the normal driving phase and how to get the driver back to normal driving should the driver deviate. Energy control is also essential in normal driving and throughout the whole chain. In this approach, the integrated safety chain has been designed to enable assessment of boundary conditions to each phase. This gives the system designers a systematic approach for identifying shortcomings and allocating necessary countermeasures. As the name reveals, the safety aspect in the chain is integrated and thereby permeates all phases.

Education, motivation, cognition and social norms play a role in keeping the driver in normal driving. If the driver is deviating from normal driving, warning and support systems have the capacity to bring the driver back to normal driving. If the situation continues to the next phase, the emerging situation, any driving intervention could work as a barrier and take the driver back to normal driving. The next phase, closer to crash, is the critical situation where immediate correction of driving is essential to cut the chain of events leading to crash. In this phase a reduction of kinetic energy is important. Without correction, the incident continues and enter the phase where the crash becomes unavoidable. If there is no way back to normal driving and the crash is imminent, it becomes essential to prepare for the crash in the best way possible. The last few phases might pass by in milliseconds, and the prepared crash protection will be activated in a crash impact. Following a crash, a quick response from emergency services for rescue will be of importance, including eCall, a call issued by the vehicle automatically to local emergency services providing information such as the vehicle position, aimed at minimising emergency response times. The integrated safety chain is made up of a continuum of phases linked to one another. It should be noted that the number of situations is reduced along the chain due to safety barriers bringing the driver back to, or closer to, normal driving.

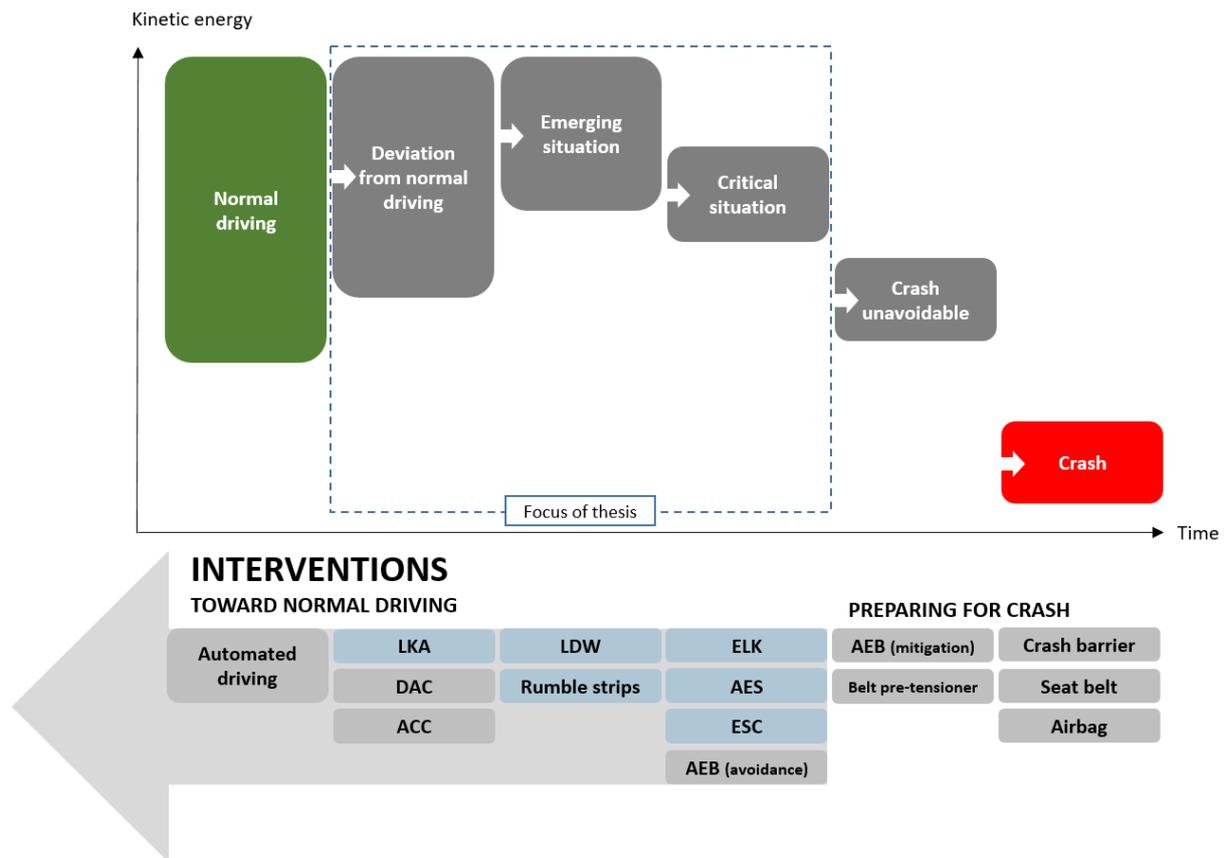


Figure 7: Safety interventions in the integrated safety chain, adopted from Tingvall (2008), Lie (2012b) and Strandroth (2015).

Of all lane departure incidents only a few result in crashes. The crashes that potentially are recorded and studied only represent the tip of the iceberg. Most deviations from normal driving do not result in crashes. Using a timeline to analyse lane departure crashes it is becoming clear that loss of control could occur after drifting out of lane. Therefore, an ESC system could potentially prevent a loss of control situation starting in drifting. The different phases in the chain are dependent on each other. Earlier phases set the preconditions for subsequent phases and provide a more or a less advantageous starting position. The combination of ESC and crash worthiness exemplifies this. As ESC prevents loss of control and the resulting rotation, it improves the likelihood of making use of the energy absorbing deformation zone in the front of the car rather than the side which would be a worse option. Combinations of safety features will potentially generate synergy in several ways. For example, Intelligent Speed Assistance supports the driver in avoiding exceeding speed limits. At excessive speeding, LDW systems and CLRS may provide limited benefits due to potentially insufficient driver reaction time. In the same way early phases set the preconditions for LDW systems and CLRS, the LDW system and CLRS sets the precondition for subsequent phases. For instance, LDW systems and CLRS support the providing of necessary friction for ESC to operate with success since the driver stays on the road. Driving off road, the driver risk insufficient friction to keep the vehicle stable.

The integrated safety chain is a model of a complex reality. As LKA systems in practice greatly differ in functionality they can therefore be present in several phases of the integrated safety chain. LKA systems incorporating more continuous lane centring features can be seen as supporting the driver in normal driving while other LKA systems, intervening later and more aggressively, may almost interfere with the definition of ELK systems associated with more critical situations. However, the safety feature emphasis of LKA are in the phase deviation from normal driving.

The emphasis of unintentional lane drifting and prevention strategies are on what the integrated safety chain refers to as an emerging situation. However, if unintentional lane drifting reaches the subsequent phase, critical situation, immediate corrections can still bring the driver back to normal driving. It is important to focus on these particular parts of the chain of events leading to crash, and more specifically by studying the safety benefits of lane support interventions such as CLRS, LDW and ELK systems. Due to limited lane detection, these interventions have limited safety benefits in unintentional lane drifting crashes involving snowy and icy road conditions or missing lane markings. Consequently, lateral vehicle positioning is a crucial factor for lane keeping and for ADAS that in critical situations intervene in steering, such as ELK and AES systems. Therefore, innovative prevention strategies, including enhanced lateral positioning, that address these crashes must be studied. Simultaneously, as enhanced lateral positioning provides improved preconditions for lane keeping, it may offer additional safety benefits in other crash scenarios, including avoiding collisions by leaving the lane, referred to as lane escaping. Altogether, it is important to study lane keeping, possible improvements of lane keeping and what additional safety benefits such improvements may result in.

AIM

The overall objective of this thesis is to increase the knowledge of unintentional drift-out-of-lane crashes and to evaluate the safety benefits of lane keeping support features preventing these crashes in real-world conditions. The specific aims are to:

- Quantifying the potential of saving lives of Lane Departure Warning systems using real-world in-depth data of fatal crashes (Paper 1)
- Evaluating the effectiveness of Lane Departure Warning systems in reducing real-world injury crashes (Paper 2)
- Evaluating the effectiveness of centreline rumble strips in reducing real-world injury crashes for cars equipped with and without Electronic Stability Control (Paper 3)
- Quantifying the potential of saving lives of enhanced lateral vehicle positioning using real-world in-depth data of fatal crashes (Paper 4)

The integrated safety chain is used as a theoretical framework to identify links between crashes and lane keeping support as well as to analyse lane keeping support as an integrated part of a holistic perspective on road traffic safety. The overview of the research plan shown in *Fig. 8* illustrates how the appended Papers 1–4 relate to the integrated safety chain, and to each other. Safety benefits of the lane support systems LDW/LKA are addressed in Paper 1, 2 and 4. Paper 3 evaluates the safety benefits of CLRS and CLRS possibly improved by ESC. Potential safety benefits of ELK and AES with enhanced lateral vehicle positioning are quantified in Paper 4. This thesis is limited to Swedish conditions and the effectiveness of LDW is based on Volvo cars.

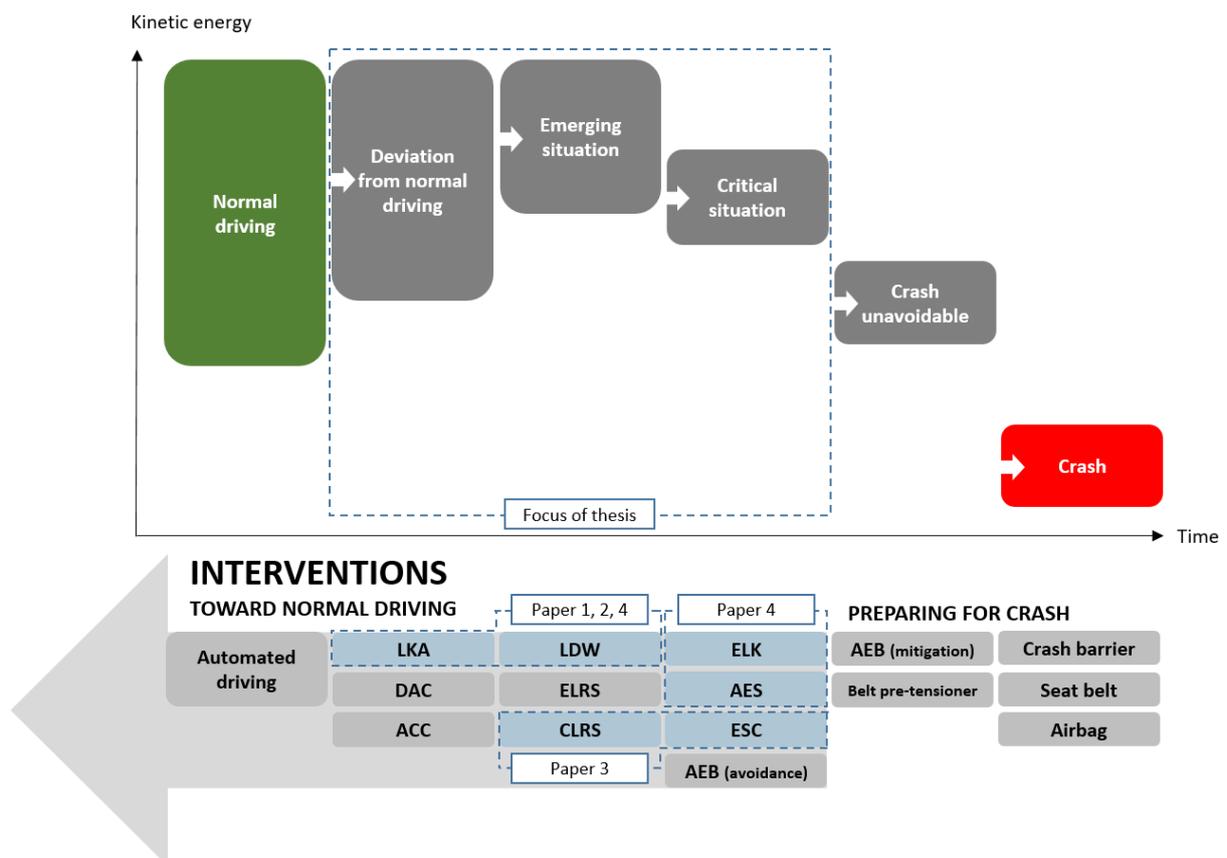


Figure 8: Overview of the research plan and the integrated safety chain. (Driver Alert Control is referred to as DAC, Adaptive Cruise Control is referred to as ACC, and edge line rumble strips are referred to as ELRS).

SUMMARY OF PAPERS

OVERVIEW OF MATERIALS AND METHODS

Several sources of material were used in the present thesis. An overview of the materials and methods is presented in *Table 1* and *Table 2*. Paper 1 and Paper 4 applied a qualitative case-by-case analytical approach where the material consisted of in-depth studies of fatal crashes in Sweden in 2010 and 2017 respectively. Paper 2 and Paper 3 applied a quantitative induced exposure method based on police reported injury crashes extracted from the STRADA.

Table 1: Overview of materials and methods for Paper 1 and 2

	Paper 1	Paper 2
Aim	Quantify the potential of saving lives of Lane Departure Warning systems using real-world in-depth data of fatal crashes	Evaluate the effectiveness of Lane Departure Warning systems in reducing real-world injury crashes
Analytical method	Qualitative case-by-case study	Quantitative induced exposure method
Data sources	In-depth studies from the Swedish Transport Administration	Police data from STRADA and vehicle data from the Swedish Road Traffic Registry
Inclusion criteria	<ul style="list-style-type: none"> Fatal passenger car occupant crashes Head-on, single car and overtaking Excl. suicide or death by natural causes 	<ul style="list-style-type: none"> Driver injury crashes Volvo passenger cars Potentially LDW/LKA equipped cars Excl. suicide or death by natural causes
Number of cases	104	1,853
Data time period	January 2010 – December 2010	January 2007 – September 2015
Injury classification	Fatal crashes	Injury crashes classified by the police

Table 2: Overview of materials and methods for Paper 3 and 4

	Paper 3	Paper 4
Aim	Evaluate the effectiveness of centreline rumble strips in reducing real-world injury crashes for cars equipped with and without Electronic Stability Control	Quantify the potential of saving lives of enhanced lateral vehicle positioning comparing the potential safety benefits of (1) Lane Departure Warning systems, (2) Emergency Lane Keeping systems with enhanced lateral positioning, and (3) Autonomous Emergency Steering systems with enhanced lateral positioning
Analytical method	Quantitative induced exposure method	Qualitative case-by-case study
Data sources	Police data from STRADA merged with the NVDB and vehicle data from Euro NCAP	In-depth studies from the Swedish Transport Administration
Inclusion criteria	<ul style="list-style-type: none"> Driver injury crashes On two-lane carriageways With at least seven metres road width In dry or wet road conditions Excl. suicide or death by natural causes 	<p>LDW/ELK:</p> <ul style="list-style-type: none"> Fatal passenger car occupant crashes Head-on and single car Excl. suicide or death by natural causes <p>AES:</p> <ul style="list-style-type: none"> Fatal passenger car occupant crashes Fatal collisions between motor vehicles and vulnerable road users Excl. suicide or death by natural causes
Number of cases	7,490	165
Data time period	January 2011 – December 2016	January 2017 – December 2017
Injury classification	Injury crashes classified by the police	Fatal crashes

SUMMARY OF PAPER 1

AIM

The aim was to identify and characterise fatal lane departure without prior loss of control crashes, and thereby differentiate between unintentional drifting, intentional lane change and evasive manoeuvre, and identify loss of control post lane departure. The aim was also to quantify potential safety benefits of Lane Departure Warning (LDW) systems in fatal crashes by identifying the target population.

METHODS AND MATERIALS

A qualitative case-by-case analysis was carried out and lane departure crashes were identified and characterised using in-depth studies of fatal crashes carried out by the Swedish Transport Administration. A total of 154 passenger car occupant fatalities involving 138 crashes occurred in Sweden during 2010. The present study was based on 104 fatal passenger car crashes classified as single passenger car (n=48), head-on (n=52) and overtaking (n=4) crashes. These were the crash types identified as relevant for possible lane departure, while only single passenger car and head-on crashes were relevant for possible unintentional drift-out-of-lane. The potential crash prevention of LDW systems was quantified by identifying the target population, whereby the target population constitutes of crashes the system is designed to address, assuming 100% effectiveness in these relevant crashes.

RESULTS

Of all crashes resulting in 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 (Fig. 9). The remaining 41 crashes were related to loss of control. Unintentional drift-out-of-lane accounted for 81% (51/63) of all lane departure without prior loss of control crashes, which correspond to 37% (51/138) of all fatal passenger car occupant crashes. Approximately half (51/100) of all head-on and single vehicle crashes were related to unintentional drift-out-of-lane. LDW systems were found to potentially prevent 33 to 38 of the 100 fatal head-on and single vehicle crashes. These crashes involved drift-out-of-lane and occurred on roads with visible lane markings, sign posted speed limits of ≥ 70 km/h and without rumble strips on the corresponding lane departure side. The range (33–38) is due to the inclusion or exclusion of excessive speeding crashes for which LDW systems may have had limited effect on due to potentially insufficient reaction time. Resulting characteristics of the 51 unintentional drift-out-of-lane crashes are described as follows. The majority (44/51=86%) of the unintentional drifting crashes occurred with no loss of control post-lane departure. The road conditions were dry in 36 crashes, wet in 10 crashes, thin ice but a visible road surface in four crashes and in one crash the road was covered in snow. No crashes occurred on roads equipped with both median and side barriers. Centreline rumble strips were present in three crashes, out of which two involved departure to the left. Of the remaining 48 crashes without centreline rumble strips 33 were departure to the left. Edge line rumble strips were present in three crashes, out of which one

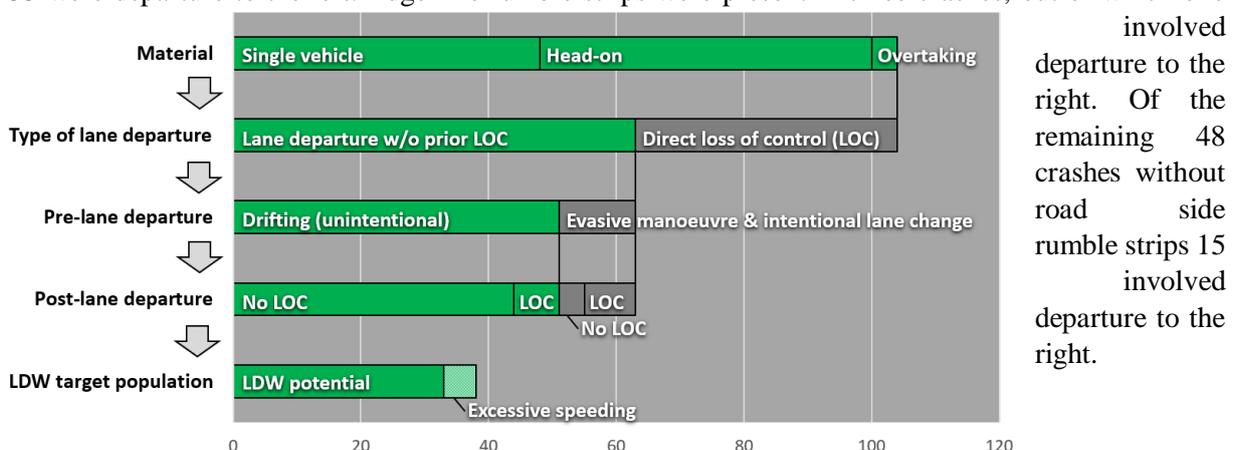


Figure 9: Number of fatal crashes, from material to resulting LDW target population through exclusion of non-relevant crashes.

involved departure to the right. Of the remaining 48 crashes without road side rumble strips 15 involved departure to the right.

SUMMARY OF PAPER 2

AIM

The aim of this study was to estimate the effectiveness of Lane Departure Warning (LDW) systems in reducing relevant real-world passenger car injury crashes.

METHODS AND MATERIALS

The study is based on driver injury crashes reported by the police to STRADA, which contains all police reported crashes incorporating at least one injury. STRADA holds a selection of information including (a) injuries: fatal, severe and minor injuries, (b) crash type (determined by police attending the crash scene): single vehicle, head-on, rear-end, intersection, overtaking, collision with animal, pedestrian, cyclist, rail traffic and others, (c) road characteristics: posted speed limit, road surface condition (i.e., dry, wet, ice or snow covered), etc., and (d) vehicle data: model, model year, vehicle registration number, etc. To identify whether a specific car was equipped with LDW or LKA, vehicle registration numbers were extracted from STRADA and vehicle identification numbers (VIN) were collected from the Swedish Road Traffic Registry and then matched by registration number and car technology equipment information, i.e., LDW, LKA, City Safety, Adaptive Cruise Control, Forward Collision Warning, Driver Alert Control, Blind Spot Information System and Collision Mitigation by Braking, was identified through a spare parts register and matched by VIN.

A total of 1,853 Volvo cars, potentially equipped with LDW/LKA and involved in a driver injury crash during the period 2007–2015 were selected for this study. In order to harmonise the case and control groups with respect to technologies addressing the exposure crashes, only models equipped with City Safety (low-speed AEB system) were included for further analysis comprising 843 cars. Out of these City Safety cars, 146 were equipped with LDW and 11 cars were equipped with LKA. The study used an induced exposure method where crash types not addressed by LDW/LKA were used as a measure of exposure, i.e., rear-end impacts.

RESULTS

The analysis showed a positive effect of LDW/LKA systems in reducing relevant real-world passenger car injury crashes. LDW/LKA systems were estimated to reduce head-on and single car driver injury crashes on Swedish roads with posted speed limits between 70–120 km/h and with dry or wet road surfaces, i.e., not covered by ice or snow, by 53% with a lower limit of 11% (CI 95%). This reduction corresponds to a reduction of 30% for all head-on and single car driver injury crashes including all speed limits and all road surface conditions.

SUMMARY OF PAPER 3

AIM

The aim of this study was to estimate the effectiveness of centreline rumble strips (CLRS) on two-lane roads in reducing relevant real-world injury crashes for passenger cars equipped with and without Electronic Stability Control (ESC).

METHODS AND MATERIALS

Police reported injury crashes during 2011–2016 were extracted from STRADA and merged with cases from the NVDB containing information regarding road design and road use parameters. The analysis includes crashes on two-lane carriageways in Sweden with a width of at least seven metres in dry and wet road conditions, that is, road surface not covered by ice or snow. The crashes involved a total of 7,490 cars with injured drivers, in 39% of cars being equipped with ESC.

The effectiveness estimates were calculated for injured drivers involving drift-out-of-lane to the left (CLRS-sensitive) resulting in head-on and single car crashes, and posted speed limits of 80 and 90 km/h. The analysis was carried out by applying the induced exposure approach in which rates of cars involved in crashes sensitive and non-sensitive to CLRS were compared at sites with and without CLRS. The non-sensitive crashes (exposure) comprised cars in rear-end, intersection, overtaking and animal collisions, non-sensitive head-on and non-sensitive single car crashes. The non-sensitive head-on and single car crashes involved lane departure to the right or loss of control prior to lane departure. The non-sensitive crashes were matched by ESC car equipment.

RESULTS

For ESC-equipped cars, the analysis showed a reduction in CLRS-sensitive crashes by 40% (19–56%, CI 95%) where CLRS had been implemented, and a reduction by 29% (11–44%, CI 95%) for cars without ESC-equipment. No statistically significant difference was found between cars with and without ESC. Nevertheless, the results are not rejecting the idea that a lane drifting driver being alerted by CLRS can be supported by ESC to safely steer the car back into the lane, without losing control, and hence ESC has the potential to enhance the effectiveness of CLRS. However, the results show that implementing CLRS as a low cost road safety measure would significantly reduce the number of injury crashes.

SUMMARY OF PAPER 4

AIM

The aim was to estimate the additional potential safety benefits of Emergency Lane Keeping (ELK) and Autonomous Emergency Steering (AES) systems with enhanced lateral positioning compared to Lane Departure Warning (LDW) systems by identifying the target populations.

METHODS AND MATERIALS

A case-by-case analysis of relevant fatal crashes from the Swedish Transport Administration's in-depth studies was carried out. The in-depth studies include detailed information of involved vehicles, users and the crash scene. Crash investigators at the Swedish Transport Administration systematically inspect and photograph any vehicle involved and record vehicle trajectory, location and direction of impact, vehicular intrusion, etc. Furthermore, crash sites are photographed and inspected to facilitate investigation of road characteristics, collision objects, skid marks, etc. Information about injuries is provided by forensic examinations, i.e., autopsy reports. Further witness statements are collected from the police as are reports from the emergency services.

The target population of LDW systems was identified as: (1) head-on and single vehicle crashes, (2) unintentional drift-out-of-lane, (3) posted speed limits of ≥ 70 km/h (43 mph), (4) excessive speeding presented separately (30 km/h over the posted speed limit estimated by the investigator), (5) visible lane markings, (6) without rumble strips on the departure side.

The target population of ELK systems with an assumed enhanced lateral vehicle positioning, functioning with non-visible or absent lane markings was identified similarly as to the LDW target but without criteria (5) and (6) above.

AES systems would be integrated with both lane keeping and lane escaping (evasive steering) functionalities. The target population for evasive steering features of AES systems was identified by the following limiting factors. The composition of relevant crash types included collisions within the current lane of travelling: (1) Head-on, intersection, rear-end, overtaking, animal and motor vehicles colliding with pedestrians, cyclists, moped users or motorcyclists, (2) Sufficient escape zone (fitting the vehicle), (3) Sufficient road friction (excluding road conditions with ice/snow), (4) Without excessive speeding.

RESULTS

ELK with enhanced lateral vehicle positioning could potentially avoid 33–45 out of 91 (36–49%) head-on and single passenger car crashes resulting in passenger car occupant fatalities, which corresponds to another 18% (5/28) compared to traditional lane support, (i.e., LDW). The range is due to the inclusion or exclusion of crashes involving excessive speeding. The improved lane keeping was addressing crashes involving non-visible lane markings (covered by snow or absent).

The lane escaping feature of AES with enhanced lateral vehicle positioning could potentially prevent 29 (25%) out of all passenger car crashes resulting in passenger car occupant fatality ($n=114$) as well as 16 out of 51 (31%) collisions between motor vehicles and vulnerable road users resulting in fatally injured pedestrians, cyclists or moped users. The target population consisted of crashes in which immediate evasive steering could potentially prevent a collision and an available escape zone could potentially have been identified. The pre-crash scenario of collisions between motor vehicles and motorcyclists did not show any relevance for being addressed by AES systems. The total potential safety benefit of AES would include both lane keeping and escaping features resulting in 42% of fatal passenger car occupant crashes, and 31% of fatal vulnerable road user collisions.

GENERAL DISCUSSION

INTRODUCTION

Lateral vehicle positioning has a crucial role in road safety, both with regard to lane keeping as well as lane escaping. Lane keeping is an important safety feature and a prerequisite for safe driving on roads. Crashes due to unintentional drift-out-of-lane account for a significant part of crashes resulting in fatalities and serious injuries, and appropriately designed lane keeping measures can potentially prevent such crashes. Focusing mainly on lane keeping, this thesis aims to evaluate the safety benefits of three safety features addressing unintentional drift-out-of-lane. Results provide evidence that lane keeping interventions have significant safety benefits in preventing crashes in circumstances the intervention was designed for, especially on rural unseparated roads. All three safety features, LDW systems, CLRS and ELK systems with enhanced lateral positioning, have been shown to provide substantial safety benefits in preventing crashes that result in health loss. These technologies are complementing each other. LDW systems provide safety on roads without CLRS and CLRS provide safety for vehicles without LDW systems. ELK systems with enhanced lateral positioning are potentially beneficial, in which both LDW systems and CLRS provide limited safety, in harsh weather conditions or when driver alertness may limit the response. Even though these safety features mainly address unintentional drift-out-of-lane, their role in how they interact is different. LDW systems are fitted in cars, CLRS are implemented on roads, and ELK systems with enhanced lateral positioning can potentially be integrated in both. A solution integrated in the vehicle as well as the road infrastructure not only expands the target population of potentially avoided crashes, it potentially increases the effectiveness of lane keeping support. Enhanced lateral positioning can be achieved in several different ways and would not only improve lane keeping systems but potentially also other types of ADAS and functionalities, such as automatic evasive steering within, and possibly also, out of lane.

RESULTS IN RELATION TO PREVIOUS RESEARCH

SAFETY POTENTIAL OF LDW SYSTEMS

The potential safety benefits found for LDW systems (Paper 1 and Paper 4) were similar to previous research findings estimating their safety potential. However, the material in Paper 1 and Paper 4 had a higher proportion of head-on crashes (52% and 34%), which also holds for the LDW relevant crashes (61% and 61%) compared to the Jermakian (2011) study, 12% and 22%, respectively. The studied Swedish material, although limited and only spanning one year, did not identify any fatal sideswipes, unlike the crash-type composition mix in the Jermakian (2011) study material which consisted of 10–13% fatal sideswipes. However, the initial impact has the potential to result in loss of control and consequently a secondary impact with opposing vehicles, obstacles on the road or rollover. Differences in the crash type composition mix may partly be explained by how crashes have been classified; approximately 77–80% of the sideswipes included a vehicle in the opposite direction.

Historically, crashes classified as overtaking have not been a big issue in Sweden due to the low number of fatalities in such crashes (*Fig. 9*). It is worth noting that a convenient method of identifying sideswipe crashes in the police reported mass data, STRADA, is not currently available. Moreover, Jermakian (2011) had adopted an approach similar to the one used in Paper 1 and Paper 4. Combining parameters held on the US database NASS-GES, crashes not addressed by LDW system limitations or involving non-relevant circumstances were excluded. As per Paper 1 and Paper 4, crashes involving loss of control, avoidance manoeuvres, speed limits of less than 40 mph (64 km/h) and snow or ice on the road were excluded. Crashes on interstate highways, involving more than two vehicles, vehicle/road defects and non-passenger vehicle out-of-lane crashes, were also excluded. The target population in Paper 1 and Paper 4 did not include any crashes of this kind.

The single vehicle crashes in the Jermakian (2011) study include other proportions of certain particular vehicle handling factors. For instance, approximately 16% of fatal single vehicle crashes involved avoidance manoeuvres in the Jermakian (2011) study compared to 12% in Paper 1 and 10% in Paper 4.

Remarkably low, only approximately 4% involved loss of control compared to almost half of the single passenger car crashes in Paper 1 and a bit above half in Paper 4 (57%). Additionally, Sweden has a higher rate of ESC-equipped cars in traffic than the US. This raises the question if loss of control crashes in the US are underreported.

Even though the crash-type composition mix may differ between countries, these studies corroborate in showing that lane support potentially offers significant safety benefits.

EFFECTIVENESS ESTIMATE OF LDW SYSTEMS

Few studies have been able to estimate the effectiveness of LDW in real-world traffic. Paper 2 was the first retrospective effectiveness study on LDW. However, only one other retrospective effectiveness study has been found since Paper 2 was published, which is a study of road crashes in the US by Cicchino (2018) showing promising results indicating a 21% ($p < 0.07$) reduction of real-world injury crashes. Explanations of the different effectiveness sizes between the Cicchino (2018) study and Paper 2 may relate to differences in the material, method or country specifics, e.g., LDW activation rate. Differences between the US and Sweden may, for instance, relate to the road environment, such as the visibility and of lane markings and the road surface material, i.e., concrete roads are more common in the US compared to Sweden. One factor influencing the extent of the effectiveness estimate may be that Swedish drivers possibly keep the LDW systems in operational mode more often than American drivers. The Cicchino (2018) study material includes somewhat newer car models (2008–2016) from several vehicle manufacturers in contrast to model year 2007–2015 in Paper 2. However, any Volvo cars included in the Cicchino (2018) study were of model year 2008–2010. All Volvo models in both studies were equipped with an easily accessible LDW switch.

Another factor influencing the size of the effectiveness estimate may be differences in the methodology adopted. The limited availability of appropriate data suitable for exposure is a general issue regarding effectiveness estimates of in-vehicle safety systems. Cicchino (2018) solved this issue by using insured vehicle days as exposure while Paper 2 adopted the induced exposure method. This induced exposure method has advantages with regard to driver behaviour aspects compared to using the exposure of insured vehicle days or even the more common exposure, vehicle kilometres travelled. While using the exposure of insured vehicle days or vehicle kilometres travelled there is a risk of overestimating the effectiveness due to selective recruitment. If safety conscious drivers drive cars equipped with LDW to a greater extent than cars without LDW, some of the effect may be due to differences in driver behaviour. However, using the Poisson regression model, Cicchino (2018) used statistical methods to control for demographic variables (driver age, gender, marital status, insurance risk level, state, calendar year and vehicle density at garaging ZIP code). LDW-equipped vehicles had significantly lower involvement rates in all severity crashes (18%), in injury crashes (24%) and in fatal crashes (86%) when not accounting for driver demographics. It is difficult to quantify how much of the driver behaviour factors the demographic variables may be controlled for.

Another factor possibly influencing the comparison between effectiveness estimates is differences in data quality. For example, to safeguard accuracy in the identification of suicide and death by natural causes, analyses can be based on medical data, i.e., autopsy reports, as is done in Sweden. Highly accurate data improve the quality of studies, facilitating more reliable effectiveness estimates

When narrowing down crash data to the most relevant conditions and type of crashes addressed by LDW systems, it is evident that higher effectiveness estimates would be found compared to estimates on a broader less relevant study population. The possibility of narrowing down previous studies to relevant crashes has been varied. Taking discussed differences into consideration, it can be concluded that results from both Cicchino (2018) and Hickman et al. (2015) were in line with results from Paper 2; LDW systems have been shown to reduce a significant amount of injury crashes.

COMPARISON BETWEEN SAFETY POTENTIAL AND EFFECTIVENESS (PAPER 1 AND PAPER 2)

Both the target population in Paper 1 and the study population in Paper 2 include crashes that have occurred on roads with visible lane markings and sign posted speed limits of 70 km/h and above. The level of detail of the lane marking information differed in that the police reported crashes in Paper 2 included information about the road surface such as icy, snow covered, wet or dry, while each crash site in Paper 1 also included detailed descriptions and photographs. However, in Paper 1, it was possible to identify more relevant LDW crash scenarios by differentiating between leaving the initial lane by unintentional drifting, intentional manoeuvring or loss of control, while Paper 2 included all crash scenarios, see *Table 3*.

Paper 1 identified the target population based on the assumption of 100% effectiveness in those crashes which resulted in 33 (38 if including excessive speeding) identified relevant crashes out of 100 fatal head-on and single vehicle crashes. Paper 2, on the other hand, identified a broader population, i.e., 56% of head-on and single vehicle crashes, but estimated the effectiveness to 53%. To enable a comparison of the results in the two papers, the results of Paper 2 was applied to all head-on and single vehicle injury crashes regardless of speed limits and road conditions. This would correspond to a reduction of 30% (0.53×0.56) of all head-on and single vehicle injury crashes. In the material, out of 418 head-on and single car crashes with known posted speed limits and road conditions, 236 crashes were on roads with posted speed limits between 70–120 km/h and with dry or wet road surfaces making up the 56% (236/418).

Table 3: Comparison of the results of Paper 1 and Paper 2

	Paper 1	Paper 2
Safety feature	LDW	LDW
Study approach	Safety potential analysis	Effectiveness estimate
Severity	Fatal crashes	Injury crashes
Population description	Target population <ul style="list-style-type: none"> • Head-on and single vehicle crashes • ≥ 70 km/h • Visible lane markings • Unintentional drift-out-of-lane • Excl. rumble strips • Excl. excessive speeding 	Study population <ul style="list-style-type: none"> • Head-on and single vehicle crashes • ≥ 70 km/h • Dry or wet road conditions (lane markings not covered by snow or ice)
Population size	33 relevant cases out of 100 fatal head-on and single vehicle crashes	56% of head-on and single vehicle injury crashes
Effectiveness	100% (assumed) in 33% of fatal head-on and single vehicle crashes	53% (calculated) in 56% of head-on and single vehicle injury crashes
Safety benefit	33% reduction of fatal head-on and single vehicle crashes	30% reduction of head-on and single vehicle injury crashes

Although it may appear that LDW systems are preventing almost all head-on and single vehicle crashes in the target population, this conclusion is not supported by the studies. A comparison of the above populations reveals that the injury levels differ; Paper 1 comprise fatal crashes while Paper 2 comprise injury crashes. Road safety features tend to show higher effects for crashes of more serious severity, which applies to speed calming measures (Elvik, 2009), improved crashworthiness (Kullgren et al., 2010), ESC (Lie et al., 2006) and LDW (Cicchino, 2018), for instance. In addition, the crash type distribution differs between injury crashes and fatal crashes. For example, head-on and single vehicle crashes in Sweden during 2016 (STRADA, 2016) were reported nearly 50% more frequently among crashes with passenger car occupant fatalities, compared to passenger car occupant injuries. The comparison of results from Paper 1 and Paper 2 is therefore not straightforward. Furthermore, LDW is a crash avoidance system rather than a crash severity mitigation system, which may add complexity to the comparison. However, a decent comparison would probably be found within the confidence interval.

It should be noted that the estimated effectiveness in Paper 2 was based on a number of preconditions. Paper 2 comprised only ESC-equipped passenger cars while the identified safety potential population

of crashes in Paper 1 constitute a mix between equipped and non-equipped passenger cars. Comparing the proportion of drift-out-of-lane and loss of control crashes, an ESC-equipped car population would be involved in less loss of control crashes and therefore a higher proportion of drift-out-of-lane crashes than a non-equipped car population. In this aspect, it appears that the effectiveness estimate of LDW was not overestimated for the ESC-equipped car population.

Comparing potential studies and effect estimate studies in general, a potential analysis usually results in higher safety benefits than effect calculations. Despite applying the two most different approaches; (Paper 1) a potential analysis, and (Paper 2) an effectiveness estimate calculation, their results align showing results of the same magnitude. The studies complement each other with one study applying a qualitative approach with descriptive results, and the other study dealing with mass data and applying a quantitative method. Therefore, the effectiveness estimate (Paper 2) in comparison to the identified target population (Paper 1) may indicate a high activation rate in Sweden.

However, the true safety benefit may fluctuate. It is possible that crash types other than the identified population could have been affected by the LDW system. For example, using the indicator more frequently may, to some extent, result in less intersection crashes, which will not be shown in these results. The resulting effectiveness estimate may be underestimated if the exposure used of rear-end impacts is not perfectly non-sensitive to LDW.

The identified target population (Paper 1) is rather tight, where the effectiveness estimate (Paper 2) implies safety benefits in a broader population. However, to a certain degree, LDW is also a warning system addressing fatigue at the early stages of the integrated safety chain. Therefore, LDW could be expected to offer safety benefits also in other crash types not directly relevant to a drift-out-of-lane event, e.g., rear-end and intersection crashes.

However, these two studies differ in study approach and population composition, such as injury severity, crash scenario as well as level of detail in the material. Still, these studies show results corroborating each other.

EFFECTIVENESS ESTIMATE OF CLRS

In line with previous research (Høye, 2015; Ragnøy & Skaar, 2014; Lyon et al., 2015; Sayed et al., 2010) Paper 3 shows resulting injury crash reduction estimates, which have been evaluating the effectiveness of CLRS. The material used in the other studies may differ from the material used in Paper 3 regarding factors such as crash severity, crash type, road layout, and vehicle equipment. Studies showing lower effectiveness levels typically also have lower precision targeting CLRS-sensitive crashes. For instance, Vadeby & Björketun (2016) showing a lower effectiveness level were targeting single vehicle crashes to the left and to the right. However, the meta-study (Høye, 2015) showed effectiveness levels of head-on, run-off road to the left and side-impacts in the opposite lane to the left much similar to results in Paper 3. Although no previous published study has evaluated CLRS for cars with and without ESC separately, there are good reasons for that. It is difficult to find and extract appropriate exposure data using the traditional approach. Such data, expressed in vehicle kilometres, would preferably be separated by the fitment of ESC and occurrence of CLRS. Questions such as how many vehicle kilometres ESC-equipped cars drive on CLRS would need to be answered. Cicchino (2018) used insurance days to evaluate the effectiveness of LDW systems. Unfortunately, using insurance days as exposure would only partly solve this problem. Eventually, in the future, all cars will be equipped with ESC, which may result in the effectiveness of CLRS increasing over time. However, when the car fleet changes, new effectiveness estimates will be required.

SAFETY POTENTIAL OF LANE SUPPORT WITH ENHANCED LATERAL VEHICLE POSITIONING

Lane support with precise and reliable lateral vehicle positioning has a beneficial role where traditional visual based systems are limited, which may occur simultaneously with the driver's vision becoming limited and lane detection support being required. Paper 4 shows that robust lateral positioning improves

the potential safety benefit of lane keeping systems as well as increases the redundancy in lane detection. With enhanced lateral positioning the preconditions for in-vehicle lane keeping systems are improved and hence make them able to perform precise steering correction of required magnitude bringing the driver back to normal driving from critical or less critical situations, or, supporting the driver to maintain within normal driving.

Previous studies of the safety benefits of enhanced lateral positioning has not been found. However, Jermakian (2011) estimated the safety potential of LDW systems by excluding non-relevant crashes. Crashes not addressed by LDW due to snow on the road represented only 4% out of the fatal crashes potentially addressed by LDW. However, sideswipe-opposite-direction crashes involved a higher proportion of snow related crashes than on average, 12%. Similarly, the target population of LDW, identified in Paper 1 and Paper 4, would increase by 12% and 14% respectively, if snow covered roads were included in the LDW target population. However, no studies have been found that show quantified safety benefit estimates of lane keeping or lane escaping systems in critical situations, such as ELK and AES.

The Insurance Institute for Highway Safety (2018) tested the active lane keeping functionality in five SAE Level 2 cars (SAE International, 2018) model year 2017–2018 equipped with lane centring and Adaptive Cruise Control activated at the same time. A driver, still responsible for driving, was monitoring the driving. The test showed limitations in staying within lane, with great variation, on curves or on hills for most or all car models. Hence, the researchers concluded that the systems are not yet a robust substitute for human drivers.

METHODOLOGICAL REFLECTIONS

Early and robust evaluation of new safety systems can strongly influence the take up rate of new systems (Krafft et al., 2009). However, early evaluation of new safety systems is challenging due to limited access to high quality data from relevant crashes. Computer simulations and laboratory testing could be used in the early system development and evaluation phases. Simulations and laboratory testing typically focus on technical aspects and may exclude how ordinary drivers will use and adapt to a system. Ideally, safety system benefit estimates should be evidence based whereas it would be preferable that real-world data evaluate their performance. Although, systems have a technical aspect, the aspect of how people use them also play a role. For example, the level of trust in a system may affect the level of activation. The lowest possible level of benefit has to be when the driver turns a safety critical system off. If the driver develops a particular type of behaviour related to increased risk taking or unwanted compensatory behaviour, it must be identified and prevented. Therefore, it is also essential to evaluate systems in real-world traffic when possible. Real-world evaluation can estimate the effects although often experience problems in understanding why these effects occur. Close multidisciplinary collaboration and solid data could in the longer perspective possibly provide an understanding and explain how users interact with technology.

INTEGRATED SAFETY CHAIN

As a theoretical framework, this thesis has used the integrated safety chain (Tingvall, 2008; Lie, 2012b; Strandroth, 2015), facilitating analyses of LDW, LKA, ELK and AES systems and CLRS in relation to each other and to other safety features, for instance, ESC, AEB and crashworthiness (*Fig. 10*). This structure was used to identify links between crashes and interventions. As has been mentioned before, the emphasis of drift-out-of-lane is in the emerging situation. Likewise, slight lane drifting can relate to an earlier phase as well, and more critical lane drifting may relate to a later phase, while loss of control can also occur after lane drifting. However, in Paper 1 it was identified that 86% of the fatal lane drifting crashes did not involve loss of control. As several interventions assist in bringing the driver back to normal driving the number of incidents are reducing and only few ends up in crash statistics.

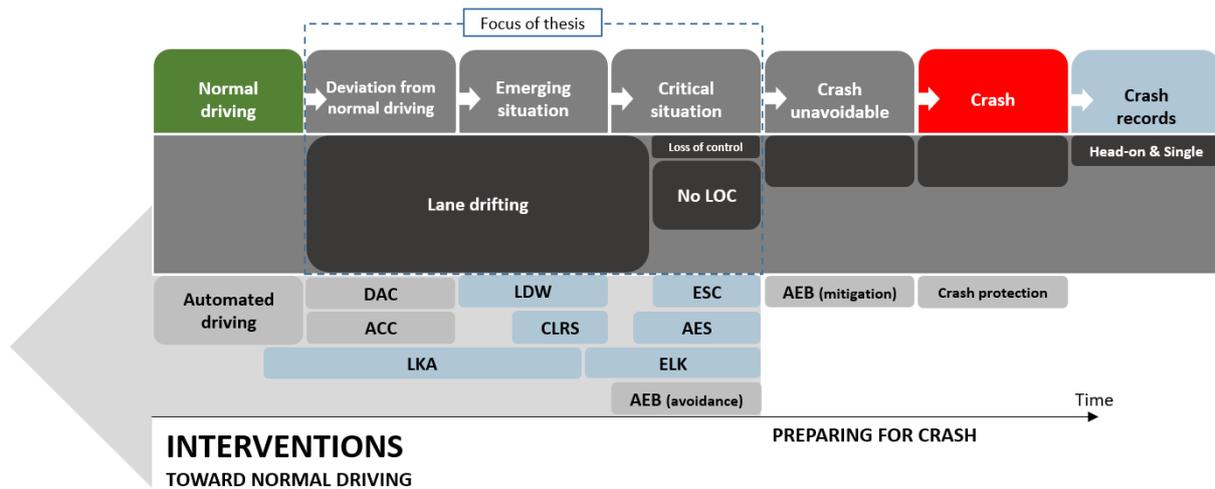


Figure 10: Lane drifting and interventions in the integrated safety chain.

While analysing crash statistics, i.e., head-on and single vehicle crashes, the analysis reached back in time identifying lane drifting (Fig. 9). The integrated safety chain demonstrates this time span with a decrease in cases, which show that the actual number of lane drifting events is higher than identified in crash databases.

The phenomenon of systems making one or the other more effective, seems to work both ways. For example, such tendencies were seen in Paper 3, in that the effectiveness of CLRS tended to be higher for cars equipped with ESC systems compared to cars without ESC systems. A possible explanation would be that drivers can handle lane drifting warnings better with ESC systems. Similarly, this synergy may also apply to in-vehicle lane support systems, both warning and steer-intervening systems, where more aggressive heading corrections issued from the ELK systems would predominantly depend on provided stability from the ESC systems. However, it can be challenging to measure the additional benefit of ESC systems in real-world traffic because cars with lane support systems are generally also equipped with ESC systems. Ideally, from an evaluation point of view only, it would be desirable to have access to LDW/ELK-equipped cars without ESC as control cars. However, this is unrealistic as ESC must be considered a cornerstone in the continued development of safety.

Additionally, when selecting a particular crash type as exposure for the induced exposure method, it is preferable if it is rather clean, i.e., without a complicated crash scenario. It is also important to keep other safety systems under control addressing system relevant/non-relevant crash types as proxy for system relevant/non-relevant events along the chain. Rear-end crashes usually do not involve many driver handling issues compared to intersection crashes, for instance, and may therefore be a preferable crash type choice to use as exposure. Furthermore, it is important to make sure that the configuration of the system equipment is similar and have the same influence on the results for all cases and control groups, for instance, AEB and ESC in Paper 2. In this thesis, similar study cars with similar equipment levels were used.

LIMITED REAL-WORLD CRASH DATA FOR EFFECTIVENESS ESTIMATES

Few studies based on real-world crashes have been able to estimate the retrospective effectiveness of LDW and/or LKA, possibly due to the systems being fitted in a limited number of car models as standard. However, the sparse crash data is not the only limiting factor. Reliable knowledge of the equipment status of individual vehicles is also an issue. Lateral support systems have often been sold as optional equipment, which is an obstacle when identifying relevant vehicles and evaluating the systems. The required level of detail of the vehicle equipment is seldom available in today's crash databases. To make precise retrospective effectiveness estimates it was suggested that manufacturers provide information to crash data registers about the specific equipment through a vehicle identification number (Blower, 2014). However, it was recognised that this practice could raise privacy and proprietary data

issues. Beside the identification of a specific vehicle's equipment, it is of importance to identify crash characteristics of involved vehicles to evaluate the effectiveness of any in-vehicle system. Even though Swedish in-depth data are rich in detail, they exclusively involve fatal crashes which are not yet constituting enough cases for quantitative retrospective effectiveness estimates of LDW systems. As lane support systems are entering the market at a rapid pace, possibilities of making enhanced benefit estimates in the near future are increasing. More timely and precise studies would be viable had crash data to a greater extent been made available from other countries.

When using crash data to evaluate the safety benefits of an in-vehicle system, the analysis is limited to crashes and not the triggering of the system. In the future, it would be desirable to have access to data closer to the lane drifting event for the safety benefit analysis. In such cases, a more refined study of the lane keeping effect of LDW systems and CLRS would be possible. One could ask if it would be possible to use a different method for analysing lane departure effects if in-vehicle data on how often and in what situations the LDW system did intervene had been accessible. However, ultimately, it is of interest to analyse the safety benefits of LDW systems reducing injury crashes in real-world traffic and while the system is in the hands of ordinary drivers.

COMPARISON BETWEEN PAPER 1 AND PAPER 4 BASED ON IN-DEPTH STUDIES

The target population and thereby also the potential safety benefit of LDW showed similar levels in Paper 1 and Paper 4. The potential safety benefit of ELK with enhanced lateral positioning (ELK+) showed a noticeably higher safety benefit including crashes involving absent or visibly non-detectable lane markings. While AES systems incorporate both lane keeping and lane escaping features only the ELK+ and LDW systems are included in the following comparison (*Table 4*).

The comparison shows corroborative results of the potential safety benefit of LDW systems. A slight difference of safety benefits should be expected based on 2010 compared to 2017 data. However, statistical conclusions must not be drawn from results based on qualitative data.

Table 4: Comparison of some results from Paper 1 and Paper 4

	Paper 1	Paper 4
Safety feature	LDW	LDW and ELK+
Study approach	Safety potential analysis	Safety potential analysis
Severity	Fatal crashes	Fatal crashes
Population description	Target population <ul style="list-style-type: none"> • Head-on and single vehicle crashes • Unintentional drift-out-of-lane • ≥ 70 km/h • Visible lane markings • Excl. rumble strips • Excl. excessive speeding 	Target population of LDW <ul style="list-style-type: none"> • Head-on and single vehicle crashes • Unintentional drift-out-of-lane • ≥ 70 km/h • Visible lane markings • Excl. rumble strips • Excl. excessive speeding Target population of ELK+ <ul style="list-style-type: none"> • Head-on and single vehicle crashes • Unintentional drift-out-of-lane • ≥ 70 km/h • Excl. excessive speeding
Population size	33 relevant cases out of 100 fatal head-on and single vehicle crashes	28 (LDW) and 33 (ELK+) relevant cases out of 91 fatal head-on and single vehicle crashes
Safety benefit	33% reduction of fatal head-on and single vehicle crashes	31% (LDW) and 36% (ELK+) reduction of fatal head-on and single vehicle crashes

Paper 1 and Paper 4 used the full population over one year and represents a full year. For instance, the representativeness over time would require a longer series of longitudinal data, since doubling the material would only be expected to marginally provide added value. Although these studies are based on qualitative research over one year each, potentially the results may also have some bearing on the

general case of the identified magnitude of potential crash avoidance, for other particular years. The potential safety benefit of LDW was similar using material from two different years, (Paper 1, Paper 4).

INDUCED EXPOSURE

Real-world data and confounding factors

When estimating the effectiveness of safety features, an exposure variable is required. However, availability of appropriate data to use as exposure variable is often limited. Furthermore, when data is available, it may not be divisible by case and control group. Nevertheless, the exposure variable shall provide a control for factors that differ between groups and are not associated with the performance of the safety feature under evaluation. The challenge is to catch the performance of the safety feature alone, isolated from possible safety benefits from other safety features. Real-world data are preferable in the sense that the safety feature performs in circumstances where the feature aims to operate. Data quality, and accessibility is fundamental factors to overcome this challenge. Some factors are difficult to control for, such as behaviour change or usage (activation rate). While these factors may not be known or registered for the specific driver or car, other factors such as driver demographics, car model year and road conditions may be more straightforward to access and control for. The induced exposure method uses exposure variables that include driver behavioural changes thereby incorporating possible changes in driver behaviour, which may be considered as a methodological strength. This variable is rather difficult to catch using other approaches. Yet, the induced exposure method produces an effectiveness measure that are commensurate with actual activation rate, similar to other approaches. Even more interesting is the issue of selective recruitment, which is not exclusively driver behaviour related, although rather challenging to control for. Traditional methods of traffic volume or insurance day exposure have been aiming to compensate for group differences using available data as proxy. Cicchino (2018) was using a considerable set of control variables; driver age, gender, marital status, insurance risk level, state, calendar year and vehicle density at the garaging ZIP code. Although, the induced exposure method has benefits of directly incorporating the behavioural differences issuing selective recruitment. For example, if safety conscious drivers tend to drive safety equipped cars to a higher degree than less safety conscious drivers, this would be a difficult factor to control for not using an exposure that can pick up this phenomenon.

Consistency in injury severity

Another challenge is to achieve consistency in injury severity. For instance, fatalities in relation to the general traffic volume is a comparison of very different populations where the population of fatalities involve a higher proportion of excessive speeding and unbelted drivers under the influence of alcohol or drugs, driving cars that on average are older, than the population of cars in general traffic. Logically, fatalities in relation to fatalities could be a somewhat more consistent risk measure. The induced exposure method has the possibility to use this form of consistency in injury severity.

Conservative approach

Methods that result in overestimated effectiveness levels can be problematic to manage. Therefore, a conservative result may be preferable, and the induced exposure method tends to give conservative estimates. The challenge is to identify exposure crashes non-sensitive to the safety feature under evaluation. If the exposure crashes are not completely non-sensitive, consequently the difference between the number of sensitive and non-sensitive crashes would decrease and thereby result in an underestimated effectiveness estimate. This also applies to incorrect crash type classification, which again, stresses the importance of high quality data.

Concluding, the induced exposure has a number of advantages. However, the challenge of using the induced exposure is to identify frequent crashes non-sensitive to the system under evaluation and links between crashes and safety features to isolate one safety feature's performance from another, and the success of that is highly dependent on the quality of data.

Combined systems

It may also be challenging to isolate the safety benefits of different systems in cars equipped with several systems. However, cars equipped with systems addressing different crash types are generally manageable using crash type and any commonly used exposure. For instance, difficulties due to lacking crash type data were demonstrated with Forward Collision Warning combined with LDW (Highway Loss Data Institute, 2015). However, it is more challenging to manage combinations of safety features addressing the same type of crash. In fact, using the induced exposure method as well can be challenging when the control cars of several systems are the same. Assume that you identify three groups of cars; cars with LDW, cars with LKA, and cars without LDW/LKA. To allow use of perfect control car models, hypothetically, the best case scenario would be to use data comprising car models that can only be equipped with LDW or LKA, not both. However, data are seldom perfect. This was the case in Paper 2, where in reality, the car models may have been equipped with any of the systems, rendering the control group of cars identical for the two types of equipped cars. Therefore, excluding LKA cars would result in methodological issues that would make it impossible to separate LKA control cars from LDW control cars. Notice, of the cars equipped with LDW/LKA, in Paper 2 most of the cars were equipped with LDW (93%) rather than LKA (7%).

Paper 2 and Paper 3

Paper 2 and Paper 3 estimate an effectiveness measure by using mass data and the induced exposure method showing that the population description differs between the studies (*Table 5*). Paper 3 comprises a narrower selection of data due to the more limited application of CLRS (18%) compared to LDW systems (56%). However, for a fair comparison one must keep in mind that CLRS address vehicles regardless of their equipment while LDW systems must be installed and not deactivated to provide any direct benefit.

When comparing the effectiveness measure (best estimate) between LDW systems (53%) and CLRS (40%) it should be noted that both effectiveness calculations were based on ESC equipped cars.

The total safety benefit (reduction of head-on and single vehicle injury crashes) of LDW (30%) assumes that all vehicles are fitted with LDW systems. The Swedish guidelines for implementing CLRS is limited to roads with posted speed limits of 80 km/h and above. Had CLRS been implemented on 70 km/h roads and shown similar effectiveness measures as higher speed limits, the total safety benefit would significantly increase. However, effectiveness calculations of CLRS on 70 km/h roads were included in the appendix of Paper 3 and shows less effectiveness, which may be due to the lack of material, while the lack of material may be due to a low implementation rate of CLRS on 70 km/h roads.

Table 5: Comparison of the results of Paper 2 and Paper 3

	Paper 2	Paper 3
Safety feature	LDW	CLRS
Study approach	Effectiveness estimate	Effectiveness estimate
Severity	Injury crashes	Injury crashes
Population description	Study population <ul style="list-style-type: none"> • Head-on and single vehicle crashes • ≥ 70 km/h • Dry or wet road conditions (w/o snow or ice) 	Study population <ul style="list-style-type: none"> • Head-on and single vehicle crashes • Lane departure to the left • 80 & 90 km/h • Two-lane carriageways • ≥ 7 m road width • Dry or wet road conditions (w/o snow or ice)
Population size	56% of head-on and single vehicle injury crashes	18% of head-on and single vehicle injury crashes
Effectiveness	53% in 56% of head-on and single vehicle injury crashes	40% (with ESC) in 18% of head-on and single vehicle injury crashes
Safety benefit	30% reduction of head-on and single vehicle injury crashes	7% reduction of head-on and single vehicle injury crashes

IMPLICATIONS OF RESULTS

LIMITATIONS

The available techniques for lateral lane support are extensive. It involves several aspects with potential benefits and challenges. However, this thesis has been limited to focus on the safety aspects as well as a few chosen safety features; LDW, CLRS, ELK and AES.

Generally, the included safety features were studied in their present mode in real-world traffic, meaning that specific modifications in the configuration for LDW or CLRS systems have not been studied. However, regarding ELK and AES systems, as a precondition it was assumed that their lateral positioning was enhanced, although specific technologies for achieving this has not been extensively studied. A few technologies were mentioned as examples for realisation and as examples for practical application, mainly serving as subjects for principle discussions. Hence, enhanced lateral positioning may be achieved in a number of other ways, not mentioned in this thesis. While evaluating potential safety benefits of ELK and AES with enhanced lateral positioning, it was assumed that the systems were in operational mode and worked as intended. This may not necessarily have been the case in all crashes included.

Similarly, when potential safety benefits of LDW were being identified, it was also assumed that the LDW system was in operational mode and worked as intended, and that drivers had enough time to respond correctly to the warning. As for the ELK and AES, this may not necessarily have been the case in all crashes included. However, the effectiveness estimate of LDW is commensurate with the actual real-world activation rate and driver behaviour.

Results in this thesis are based on Swedish crash data. The resulting effectiveness estimate is naturally specific for the Swedish geographical location, road design principles, vehicle fleet properties, i.e., the effectiveness of LDW is based on Volvo cars, and other factors possibly relevant. However, current research literature, which is limited regarding LDW and more extensive regarding CLRS, supports generalisation, showing similar safety benefit levels.

Further work that aims at increasing the safety benefits of lane keeping intervention is still required. To increase the target population, it is essential to safeguard that lanes are easily identifiable by LDW systems, i.e., through effective snow clearance. Some systems are capable of detecting the lane, regardless of the presence of lane markings, based on recognition of roadway edge or shoulder. For these systems, for example, a clear snow verge along the roadway may be facilitating lane detection.

IMPLEMENTATION OF LANE SUPPORT

The results of this thesis show that there is a substantial amount of crashes potentially addressed by lane support systems such as LDW and ELK systems. The results have also shown that LDW systems as implemented in Volvo car model years 2007–2015 had a significant effectiveness in reducing injury crashes, which should require accelerated LDW implementation as standard equipment in new car models. However, the availability rate of new cars equipped by LDW systems as standard has been limited. In Sweden, only 7.1% of new passenger car models on the market in 2016 were equipped with LDW systems as standard in all versions (Ydenius & Kullgren, 2019). This percentage increased to 20.7% in 2017 and 28.8% in 2018. Considering the fitment rate of actually sold car models in Sweden, it has been an encouraging increase of LDW as standard in all versions from 2.8% in 2017 to 62.8% in 2019. Models with LKA sold in 2019 show high fitment rate numbers, 41.0% as standard in all versions (A. Ydenius, Folksam, personal communication, January 31, 2020). However, estimates of the fitment rate of LDW in traffic is still low, i.e., 5% of the traffic volume in Sweden in 2019 (Swedish Transport Administration, 2020). Hence, rapidly reaching full implementation of lane support systems is of public interest and in the interest of the European Parliament as well as the Council making ADAS, such as ELK, mandatory in new cars. Additionally, an increase in LDW fitment on the car aftermarket may be achieved retrofitting LDW. However, for optimal functionality the LDW system requires access to the turn direction indicator (Scholliers et al., 2020).

Setting the LDW effectiveness in a larger perspective and looking at a broader crash scenario, the consequence of a 53% reduction in head-on and single car crashes on roads with speed limits of 70–120 km/h and clear of snow or ice, would correspond to the following proportion of reductions assuming no adverse effects in the wider populations.

- 13% reduction of injuries in passenger cars
- 20% reduction of injuries in passenger cars on 70–120 km/h roads
- 30% reduction of all head-on and single car injury crashes
- 40% reduction of all head-on and single car injury crashes on 70–120 km/h roads

If all cars today had been equipped with LDW, of the effectiveness evaluated in this thesis (Paper 2) the effectiveness would correspond to approximately 30 fewer fatalities, 250 fewer severely injured persons and 1,400 fewer persons suffering minor injuries, annually in Sweden (based on estimates using crash records from STRADA, 2016).

IMPLEMENTATION OF CLRS

This thesis shows that implementing CLRS as a low cost road safety measure would significantly reduce the number of injury crashes. Today, only approximately 30% of two-lane carriageways in Sweden with a width of at least seven metres, AADT of at least 2,000 and posted speed limit of 80 km/h are equipped with CLRS. The corresponding figure for roads with a posted speed limit of 90 km/h is approximately 50%. Based on the results of this thesis (and assumptions of even crash distributions) approximately 44 car occupants would avoid injuries and three car occupants would avoid fatal injuries annually, if the remaining two-lane carriageways of approximately 3,700 km were equipped with CLRS. The results imply an accelerated implementation of CLRS.

AUTOMATED LANE KEEPING

Results show that precise and reliable lateral vehicle positioning combined with automation is important as it has the potential of preventing crashes (Paper 4). The requirements of lateral vehicle positioning awareness for safety systems such as ELK or AES that may engage in critical situations, often only a few times throughout the lifespan of the car, are high. As automated driving requires 100% functionality at all times and in all driving modes, it is evident that lateral control is highly essential for automated driving as well. However, progressive development is necessary where more advanced systems, such as lane centring, show high effectiveness levels in real-world conditions before automated driving is implemented. As a first step, results in this thesis show that the effectiveness of rather simple technology (LDW) is fairly high (Paper 2). To ensure that the development towards fully automated vehicles is moving in a safe direction, Level 2 systems must demonstrate effectiveness in real-world evaluations.

It has been shown that early implementation of a less complete automated vehicle policy would result in some, although less fatalities, than without the implementation. Such implementation would be preferable in a utilitarian perspective (Kalra & Groves, 2017). However, it would prove problematic gaining social acceptability of an automated vehicle policy that allows mistakes leading to fatal crashes. Justifying that the vehicle performs the driving task safer than the average human driver will be difficult to convince society, since the demand for safety increases once the control is removed from the individual user and directed elsewhere. An automated vehicle policy, allowing machine errors leading to fatalities, cannot not be accepted even if it is preferable from a utilitarian perspective.

The safe system approach would be to increase the redundancy. Safety is built by combining several safety barriers/nets. If one safety barrier fails, another safety barrier preventing injury, must engage. Improved redundancy is achieved through increasing the number of safety barriers bringing occupants back to what the integrated safety chain calls normal driving. The application of the safe system approach entails that the entire road transport system, accounts for possibly errors in automated lane keeping as well as automated driving.

DRIVER ACCEPTANCE

Lane support systems

Reagan et al. (2018) and Lund (2017) presented activation levels of lane support systems, which were based on US data. However, the high effectiveness level shown in Paper 2 indicates a high activation level in Sweden. In contrast, if the activation level in Paper 2 would be on the same level as the US data indicate, then the effectiveness of the LDW feature appears to be extremely effective for those who keep it activated. Speculating, the resulting effectiveness estimate in this thesis compared to US results in the Cicchino (2018) study indicates possibly higher activation levels in Sweden. Furthermore, driver monitoring alert systems, such as Driver Alert Control systems, and LDW systems as a warning system addressing fatigue in the early stages of the chain of events leading to crash, would affect the US results to a higher extent than the results in this thesis, due to differences in methodology (incorporated in the induced exposure method). Therefore, this aspect indicates a higher activation rate in Sweden compared to the US. Additionally, the US study by Reagan et al. (2018) involved cars of a somewhat newer model year and possibly improved human-machine interface. However, the estimate of effectiveness in the US study (Cicchino, 2018) involved older Volvo cars, model year 2008–2010. Still, newer cars from other manufacturers were included.

It is imperative that the human-machine interface is suitably designed so that drivers appreciate the system, keeping it in operational mode, and providing drivers with the opportunity to react appropriately and in time when a warning signal is issued. System developers attempt to avoid false warnings could result in calibration compromises affecting the end effectiveness. To reduce this problem robust and precise information about the lateral position of the vehicles is required.

CLRS

A simulator study by Eriksson et al. (2013) concluded that driver acceptance and performance was high for both LDW systems and rumble strips (edge and centreline) in unintentional lane departure events. No significant difference between using LDW systems and rumble strips was found in lane departure distance or in time to get the car back in lane.

The driver acceptance may be a less relevant factor when it comes to gaining the benefits of CLRS. CLRS cannot be deactivated by the driver. Passenger car drivers have no issues of false positives or unclear factors in the human-system interface that require careful calibration. CLRS are rather straightforward in the interpretation of warning signals, static in activation and robust. However, we have to accept that CLRS are not effective when the road surface is covered with snow or ice. Yet, we must not accept unintentional lane departure leading to fatalities in such road conditions.

The Swedish guidelines for applying CLRS recommend a road width of at least seven metres. Applying CLRS on narrow roads may imply issues of false positive-like character for drivers of heavy trucks that may have difficulties avoiding the CLRS, due to the width and length of the vehicle. This indicates a need of other safety measures to support lane keeping at narrow roads.

INTEGRATED SAFETY

Rather than being a confined issue, or indeed an afterthought, the safety aspect within integrated safety is always expected to permeate the whole system, holistically. In this holistic approach, for instance; active and passive safety, safety interventions in road infrastructure and cars, or, early and late safety interventions in the integrated safety chain, are not viewed separately. For instance, factors early in the integrated safety chain are seen to set the safety preconditions in subsequent phases, although it is sometimes also possible to observe this synergy in reverse order. Attempts to identify such synergies were exemplified where ESC systems may enhance the safety benefits of CLRS (Paper 3). Similarly, it is reasonable that ESC systems enhance the safety benefits of LDW systems since all LDW-cars are supported by an ESC system. However, the combined effectiveness of two safety interventions can result in the sum of the individual effectiveness measures (independent interventions), more than the sum (synergetic interventions), or less than the sum (overlapping interventions). Synergy provides additional

safety benefits however overlapping intervention generates redundancy. It is of interest to discuss the characteristics of the combined safety aspect of LDW and CLRS. Unintentional drift-out-of-lane is addressed by both LDW and CLRS. While LDW systems only support drivers in LDW-equipped cars (on most roads), CLRS support drivers in all cars, but only where CLRS are implemented. In this aspect, the interventions are complementing each other addressing different target populations seen as independent. Additional limitations of each intervention are described. As LDW systems are visually based, visual obstructions such as heavy rain, fog or dust would cause the system to fail while CLRS would be less affected. In these conditions CLRS can be a complement to LDW. However, it is of interest to understand the safety benefits of the combination of LDW and CLRS. As discussed, dependent on certain conditions the level of how much these systems are complementing each other is changing. Hence, these interventions cannot be treated as independent except in specific situations. However, in more ideal conditions a driver may benefit from both LDW and CLRS. In the integrated safety chain both LDW and CLRS relate to the emerging situation (*Fig. 8*). If the LDW system alert the driver before hitting the CLRS then LDW should be placed earlier in the integrated safety chain than the CLRS (*Fig. 10*). However, the LDW alerting time can vary between different manufacturer calibrations while the placement of lane markings and CLRS can also vary. In this scenario where interventions are being stacked within the same time slot addressing the same target, redundancy is produced.

Clarifying the capabilities of LDW, it shows that CLRS would have advantages when the visual lane detection of LDW fails. Similar reasoning would be applied to the combination of CLRS and ELK systems. As both CLRS and ELK address drift-out-of-lane they generate redundancy. If the driver fails to respond in time when alerted by the CLRS, then the ELK system would engage. Dependent on trigger configuration and CLRS placement, an opposing scenario may arise whereby the ELK/LKA are supposed to engage earlier but fails, in which case the CLRS would alert the driver.

Another example of producing redundancy in injury prevention, involves an integrated car technology approach in which an AES system is connected to the AEB system optimising the intervention of steering and braking. However, this type of integration could also be expected to provide synergy as has been shown previously, as speed reduction has properties enhancing other interventions (Strandroth et al., 2011; Sternlund, 2011; Strandroth, 2015).

FUTURE RESEARCH NEEDS

In this thesis, safety benefits of lateral supporting features have been studied, and significant safety benefits have been revealed. However, in-vehicle lateral support (LDW, LKA, ELK, and AES) is part of a system dependent on car safety technology and road infrastructure being harmonised. In the last few years car safety technology has improved rapidly, whereby cars have been better adapted to the roads and responsibility for safety has increasingly been assigned to the car. To increase the potential effectiveness and robustness of lateral support systems, road infrastructure innovations adapted to support future cars are desirable. Therefore, it is required that further research focus on enhanced lateral positioning and its development, testing and evaluation in environments relevant to real-world traffic conditions. Vehicle and road integrated positioning technology such as magnetic sensing systems and radar reflector systems need further considerations. Ground penetrating radar is a positioning technology that requires less changes to the infrastructure and therefore it may have advantages in scalability. Further research is needed on the feasibility of implementing lateral support based on ground penetrating radar.

To achieve the goal of increasing the knowledge of a holistic and systematic view of lateral positioning support, it is essential that the infrastructure interface is considered with regard to providing detectable lanes to support the cars. Utilising the integrated safety chain as a framework would further identify safety gaps and increase the synergy between car and infrastructure interventions. Further research is

still needed to evaluate the safety benefits of in-vehicle lateral support systems, in real-world traffic, as well as a variety of markets, manufacturers and system specifications for future road and infrastructural interventions.

CONCLUSIONS

Overall, lane keeping support features have substantial safety potential and high effectiveness preventing unintentional lane drifting, specifically:

- Crashes involving unintentional drift-out-of-lane account for approximately half of the fatal passenger car occupant head-on and single car crashes.
- This thesis shows that the safety potential of Lane Departure Warning (LDW) is profoundly significant in saving lives and that it is effective in reducing real-world injury crashes.
 - › Lane Departure Warning systems were found to potentially prevent one third of all head-on and single vehicle crashes resulting in passenger car occupant fatality, which corresponds to two thirds of the drift-out-of-lane crashes.
 - › Lane Departure Warning systems were estimated to reduce head-on and single vehicle injury crashes by half on Swedish roads with posted speed limits between 70–120 km/h and with dry or wet road surfaces.
- Centreline rumble strips (CLRS) are an effective infrastructure intervention in preventing relevant head-on and single vehicle crashes.
 - › On roads with centreline rumble strips the number of injured drivers in cars fitted with Electronic Stability Control (ESC) were reduced by 40% (19–56%).
 - › The number of injured drivers in cars without Electronic Stability Control were reduced by 29% (11–44%).
- Precise and reliable lateral vehicle positioning has the potential of saving lives.
 - › Enhanced lane keeping systems increase the potential of saving lives compared to traditional Lane Departure Warning systems.
 - › Enhanced Autonomous Emergency Steering (AES) systems potentially addressing a wide range of crash types would prevent approximately 42% of all crashes involving passenger car occupant fatality.
 - › Enhanced Autonomous Emergency Steering systems would have the potential to save the life of 31% of pedestrians, cyclists and moped users in collisions with motor vehicles.

RECOMMENDATIONS

- Organisations and road safety stakeholders should promote the fitment of in-vehicle lane support systems in new cars and accelerate the implementation in the vehicle fleet.
- Road authorities should accelerate the implementation of centreline rumble strips on roads without a median barrier.
- Further research should focus on developing technology supporting a precise and reliable lateral vehicle positioning functioning in both harsh and more normal conditions.
- It is imperative that the lane support system avoids false positives without losing effectiveness by calibration compromises and is suitably designed so that drivers appreciate it and keep it in operational mode.
- Modern cars are equipped with sensor technology, i.e., Lane Departure Warning, with the ability to localise unreadable or missing lane markings and Electronic Stability Control that can detect low friction on the road. This sensor technology could potentially be used to collect data concerning the readability of lane markings. This data should be reported and made available to increase the effectiveness of road maintenance.
- To make precise retrospective effectiveness estimates it is suggested that manufacturers provide information to crash data registers about the specific equipment through a vehicle identification number.
- If the number of real-world crashes involving cars with lane support systems in a single country is still too low for statistical analysis identifying performance differences between manufacturers and technical solutions it is recommended to attempt using multi-national crash data.
- Interventions isolated to the infrastructure or isolated to the car technology are not delivering safety most efficiently. Future research on the role and effectiveness of lateral supporting systems should consider an integrated approach, taking into consideration the role of both road infrastructure and vehicle systems, in dialogue between road authorities and the vehicle industry.
- Further research and development should focus on maximising safety benefits through combinations of safety features generating synergy and at the same time identify system boundary conditions of a future safe road transport system.

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