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The Safety Potential and Effectiveness of Lane Departure Warning Systems in Passenger Cars

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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 two papers aimed at increasing the knowledge of the safety potential and effectiveness of lane keeping support.

Paper 1 aims to identify and characterise lane departure crashes and identify the safety potential of lateral support systems such as Lane Departure Warning (LDW) by using real-world in-depth data of fatal crashes in Sweden. Single car, head-on and overtaking crashes involving lane departure without prior loss of control were categorised into intentional lane change, evasive manoeuvre or unintentional drift out of lane. The latter category accounted for half (51/100) of the single vehicle and head-on crashes and LDW systems have the potential to prevent a majority (33 to 38) of these crashes.

Paper 2 aims to estimate the effectiveness of LDW in real-world passenger car injury crashes, extracted from the Swedish Traffic Accident Data Acquisition (STRADA). The induced exposure method and information of each individual car's equipment were used. LDW halved the risk of being in a head-on or single passenger car driver injury crash where the posted speed limits were 70 km/h and above and where the road surface was not covered by ice or snow.

This thesis shows results in line with other research considering the safety potential and effectiveness of lane keeping support. While related research used risk measure exposure such as insured vehicle days or vehicle miles travelled to estimate effectiveness of LDW, Paper 2 used induced exposure where the exposure is made up by non-sensitive crashes. The induced exposure method has advantages of incorporating possible changes in driver behaviour and usage rates in real-world traffic.

Despite applying two very different methods of analysis, the two papers synthesised in this thesis show results that corroborate each other.

In conclusion, LDW is part of a system where detectable lane markings provided by road authorities and vehicles technology have to work together and shows significant traffic safety benefits under certain conditions. As both components are dependent on each other to create safety, this makes safety the responsibility of both road authorities and the car industry.

Lane keeping support systems, such as LDW, is one of the most important safety features in the foreseeable future, where the share of unintentional drifting crashes could be expected to increase due to ESC addressing loss of control. Therefore, different organisations and road safety stakeholders should promote the fitment of LDW systems in new cars and speed up the implementation in traffic.

KEYWORDS: Lane keeping, Lane support, Lane departure, LDW, Effectiveness, Injury, Safety

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Simon Sternlund

Norrköping, May 2018

LIST OF APPENDED PAPERS

PAPER 1

Sternlund S. *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 (2017) May 29, 18(sup1):S18-S23. DOI: 10.1080/15389588.2017.1313413.

PAPER 2

Sternlund S, Strandroth J, Rizzi M, Lie A, Tingvall C. *The effectiveness of Lane Departure Warning systems – a reduction in real-world passenger car injury crashes.* Traffic Injury Prevention (2017) Feb 17, 18(2):225-229. DOI: 10.1080/15389588.2016.1230672.

Division of work between authors, Paper 2:

Sternlund, Strandroth, Rizzi, Lie and Tingvall designed the study. Sternlund made the analysis work with the help from Strandroth and Rizzi. The paper was authored by Sternlund with feedback from Strandroth and Rizzi.

DEFINITIONS AND ABBREVIATIONS

AES	Autonomous Emergency Steering
AIS	Abbreviated Injury Scale
ESC	Electronic Stability Control
Euro NCAP	European New Car Assessment Programme
FARS	Fatality Analysis Reporting Systems
GIDAS	German In-Depth Accident Study
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 1.24 million road traffic fatalities occur annually and between another 20 and 50 million people sustain non-fatal injuries which for many result in permanent disability. Road traffic injury is the leading cause of death among people aged between 15 and 29 years. According to the World Health Organization (2017), road traffic crashes are predicted to become the seventh leading cause of death by 2030, unless sustainable action is taken.

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. The cost of road transport system crashes for most countries is around 3% of their gross domestic product (ibid, 2017).

Despite improvements in recent years, health loss in the road transport system is a major societal problem also in the European Union. In 2015, more than 26,000 people died in the European Union road transport system. In addition to the fatalities, there are about four times as many permanently disabling injuries, eight times as many serious injuries (AIS 3+) and 50 times as many minor injuries estimated within the European Union (European Commission, 2017). Statistics show that passenger car occupants accounted for a substantial part of the exposed victims, at 46% of the fatalities within the European Union.

Similarly, in Sweden, a large part of road traffic fatalities involved passenger car occupants. Between 2010 and 2017, an average of 273 fatalities occurred annually in road traffic out of which approximately half (52%) involved passenger car occupants. The majority (77%) of the passenger car occupant fatalities were involved in head-on or single passenger car crashes (Trafikanalys, 2018). Year 2017, 253 fatalities occurred in road traffic, *Table 1*.

Table 1: Road traffic fatalities in Sweden 2017 (Trafikanalys, 2018)

Road user	Number of fatalities
Passenger car drivers	89
Passenger car passengers	42
Light-goods vehicle, heavy-goods vehicle and bus drivers	9
Light-goods vehicle, heavy-goods vehicle and bus passengers	3
Motorcycle drivers	36
Motorcycle passengers	3
Moped riders	1
Cyclists	26
Pedestrians	37
Others and unknown	7
Total	253

The same year 2,275 severe, and 17,385 minor, road traffic injuries were reported by the police. Fifty-five percent of the severely injured persons were passenger car occupants and 67% of the minorly injured persons were passenger car occupants (ibid, 2018).

VISION ZERO

The initiation of the Swedish Road Safety Administration in 1968 was the beginning of a systematic road safety approach. This work was successful during the 1970s. In 1966, 674 car occupants died in traffic in Sweden, *Figure 1* (Trafikanalys, 2018), and in 1983 the fatalities had decreased to 409, representing a reduction of nearly 40%. During the 1980s this decreasing trend of fatalities was interrupted and the number of fatalities began to increase with the increasing traffic. In 1989 nearly 600 car occupants died in traffic in Sweden. In the beginning of the 1990s unemployment increased and fatalities decreased. In connection with closing down the Swedish Road Safety Administration, the Swedish Road Administration was given the road safety responsibly. Keeping the unfavourable trend from the 1980s in mind, new approaches were desired (Belin, 2015). Work on developing a safe system approach was initiated at the Swedish Road Administration in 1994 (Belin et al., 2012). The development work resulted in a memorandum entitled *Vision Zero - An idea of a road transport system without health losses* (Swedish Road Administration, 1996). The government decided it was time to instigate change. In 1997, the Swedish parliament adopted a new road transport safety strategy called Vision Zero proposed by the government (Swedish Parliament, 1997a). Vision Zero states that, it is not acceptable for society to have a transport system that kills and severely injures people. The long term goal is that no one should sustain fatal or serious injuries within the road transport system (Swedish Parliament, 1997b).

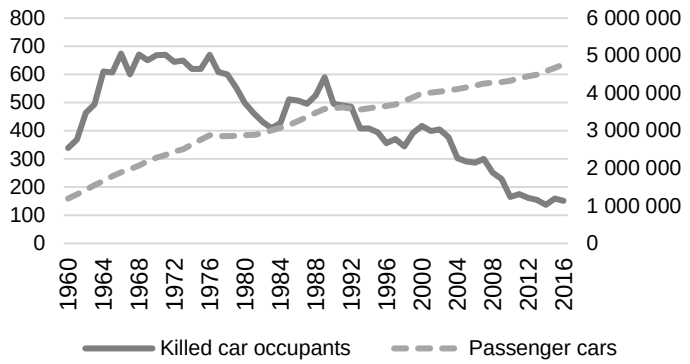

Figure 1: Car occupants killed in road traffic accidents reported by the police (Trafikanalys, 2018) and passenger cars in traffic between 1960–2016 (Bil Sweden, 2018).

Vision Zero was developed as an approach to prevent crashes causing fatalities and serious injuries, although it would not expect all accidents resulting in property damage or less serious injuries to be eliminated (Johansson, 2009). The basic idea is that humans make, and always will make mistakes and misjudge situations in the road transport system. The strategy cannot be based on eliminating the road safety issue by eliminating human error. Though, what must be eliminated is human error leading to serious consequences (Tingvall, 1995). However, mistakes should not be punished by death or impairment (Swedish Transport Administration, 2012a). Vision Zero also states that the road transport system must be forgiving and error-tolerant, designed to absorb such mistakes. Therefore, Vision Zero shifted the primary responsibility for safety in the road transport system from the individual road user to the road transport system designers (Larsson et al., 2010). System designers, who have a holistic perspective, must ensure that human exposure to external impact forces is never greater than the human tolerance to crash energy (Tingvall, 1995).

An important element of Vision Zero is having adopted a holistic approach addressing speed, road design, vehicle design and human capabilities simultaneously (Tingvall et al., 2000; Stigson, 2009). The Vision Zero approach prompted major implementation of 2+1 roads. Wide (typically 13 metre road width) high speed (typically posted speed limits of 90 or 110 km/h) roads without a median barrier was identified as a type of high fatality risk road. During the 1990s nearly 100 fatalities and 400 severe injuries occurred annually, corresponding to 25% and 20% respectively of the total amount on state roads at the time. During this period these roads held 25% of the traffic volume but only 14% of the road length. Introducing the 2+1 road design with a median barrier reduced the fatality rate by 75–80% (Carlsson, 2009). Another example is the transformation of intersections with traffic lights to roundabouts. Although there are more conflict points in a roundabout, the impact speed in case of a crash would be lower and consequently also the risk of injury (Belin et al., 2012; Swedish Transport Administration, 2012a; Elvik, 2017).

Looking at Swedish head-on crashes during 2016, almost all (95%) of the passenger car occupant fatalities occurred on roads with posted speed limits of 70 km/h, 80 km/h or 90 km/h. Even though Sweden has successfully eliminated head-on crashes on many high-speed roads using the 2+1 road design, head-on crashes still account for a significant part of the fatalities and most severe crashes on roads still undivided. Of the passenger car occupant fatalities, head-on accounted for 15% (4/26), 47% (16/34) and 48% (16/33) on roads with posted speed limits of 70 km/h, 80 km/h and 90 km/h, respectively, during 2016 (extracted from the Swedish Traffic Accident Data Acquisition, STRADA). Roads with posted speed limits of 90 km/h or less are typically undivided and the share of fatalities in single vehicle and head-on crashes on such roads is high; 65% (17/26), 79% (27/34) and 73% (24/33) of the fatalities involved head-on or single vehicle crashes on roads with posted speed limits of 70 km/h, 80 km/h and 90 km/h, respectively, during 2016 (extracted from STRADA). This problem ought to be addressed by speed management, infrastructural or in-vehicle interventions, as a matter of urgency.

A MODEL FOR SAFE CAR OCCUPANTS - THE ROAD USER, VEHICLE AND THE ROAD

To facilitate the analysis of traffic safety and to develop prevention strategies a model for safe road traffic for car occupants has been developed in accordance to Vision Zero (Linnskog, 2007; Stigson, 2009), *Figure 2*. The model is suitable for use in road transport planning, to actively aim for a safe road transport system, rather than away from an unsafe one. The model describes the interaction between the road, vehicle and road user, with speed as a regulating factor to create safe traffic. Safety criteria for each component are defined based on the mental and physical capacity of the road user, including the human biomechanical tolerance limits to external forces. The model was used to identify safety gaps between the safe reference model and the road transport situation at the time (Stigson, 2009) and to identify non-conformities (Lie, 2012a). Stigson, (2009) identified shortcomings of the criteria for complying with human tolerance limits in frontal crashes on single carriageways with a posted speed limit of 70 km/h. These shortcomings included frontal crashes with heavy goods vehicles and frontal crashes with small overlap.

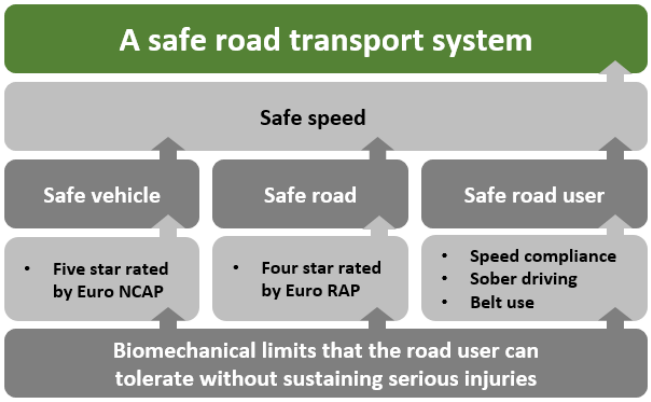

Figure 2: The Vision Zero model for safe traffic with safety criteria for road, vehicle and road user, adopted from Stigson (2009).

Stigson used European New Car Assessment Programme (Euro NCAP) five star rating as criteria for safe vehicles. Euro NCAP provides consumer rating tests and is a driving force for improving vehicle safety on the market and on roads. Euro NCAP's star rating of tested new cars with standard equipment was proven beneficial in real-world crashes for car occupants, pedestrians and cyclists (Lie, 2002, Strandroth, 2011; Strandroth, 2014). The requirements for achieving five stars are gradually raised. Both supporting and intervening lane systems such as Lane Departure Warning (LDW) and Lane Keeping Assist (LKA) were introduced in the Euro NCAP testing programme in 2014 (Euro NCAP, 2017a).

The Vision Zero model has also been used to identify *safe* traffic conditions through collaboration between Volvo Car Corporation and the Swedish Transport Administration, *Figure 3*. The focus, during the development of this scheme, was to establish boundary conditions and interfaces for future vehicles and infrastructures (Eugensson et al., 2011). Clarifying the capabilities provided increased integrated safety and opened up for the vehicle and road infrastructure design to support each other. For example, limited concern has been given to the design of road markings and road signs readable for vehicles. Therefore, the traditional driver-road-interface focus must be complemented by an interface between the vehicle and the road.

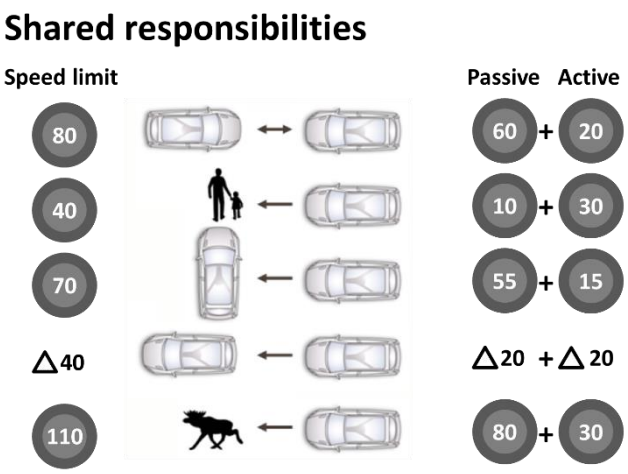

Figure 3: Example of how the responsibilities can be shared between car and infrastructure and how the vehicle´s speed can be shared between passive and active countermeasures (Eugensson et al. 2011), speed in km/h.

Also, this attempt to establish boundary conditions was based on the human biomechanical tolerance limits to violent crash forces. To ensure survivability in potential head-on crashes the speed limit on an undivided road cannot be higher than the sum of active and passive safety. If the Autonomous Emergency Braking system reduces the speed by 20 km/h, and the crashworthiness of a car front absorbs harming energy corresponding to 60 km/h, the speed limit should not exceed 80 km/h. The infrastructure design will be highly responsible for safety above this speed. One way to ensure safety is to install median barriers and side guard rails. Similar reasoning was adopted for other crash types. This attempt to set safety oriented speed limits did not include heavy goods vehicles. In-vehicle lane keeping systems would play an important role in avoiding head-on collisions with all vehicle types.

Historically most of the responsibility for road traffic safety was placed on to the road user, while lately the responsibility has shifted, in accordance with Vision Zero, towards other system components such as the car and the road (ultimately, the road designer). As mentioned before, the general idea of Vision Zero is that the transport system should be error-tolerant and absorb human errors, because humans will always be prone to making mistakes. It has been shown that problematic road user behaviour can be supported by vehicle safety systems such as seat belt reminders (Lie et al., 2008). In conclusion, the passenger car has an essential role as an integrated component of a safe road transport system.

PASSENGER CARS

Passenger cars are the most common transport mode for fatalities in the European road transport system. According to the community database of road fatalities divided by transport mode in the European Union, 46% accounted for cars and taxis in 2014 (CARE, 2016), *Figure 4*. Additionally, cars are often involved also in vulnerably road user fatalities.

Even though car accidents happen in all traffic environments, fatal car occupant crashes mostly occur outside urban areas on rural roads (70%) where the speed limit was above 40 mi/h (64 km/h) (CARE, 2016), because the fatality rate is related to the kinetic energy. Equal results were found for serious injuries (MAIS 3+) in national road accident databases within the European Union, Czech in-Depth Accident Study (CziDAS), French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR), German In-Depth Accident Study (GIDAS), Dutch Hospital Data (DHD) trauma register, and in-depth studies, STRADA, Road Accident In-depth Study (RAIDS) and On the Spot (OTS) in-depth data in England, and in-depth data from IGLAD (AT, CZ, DE, FR, IT, SE, and ES) for 2014 (European Commission, 2016). The study by the European Commission (2016) 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. Furthermore, the study identified the following crash characteristics: speeding and/or inappropriate speed (35–56%), careless/reckless behaviour (23–49%), driver under the influence (drugs/alcohol) (18%), failing to look properly (17%), road condition (wet/icy/poor surface; 14%), fatigue (driver or opponent; 10%) (Ibid, 2016). Two-thirds of the fatally injured car occupants were males and about two-thirds to three-quarters of the seriously injured persons were drivers.

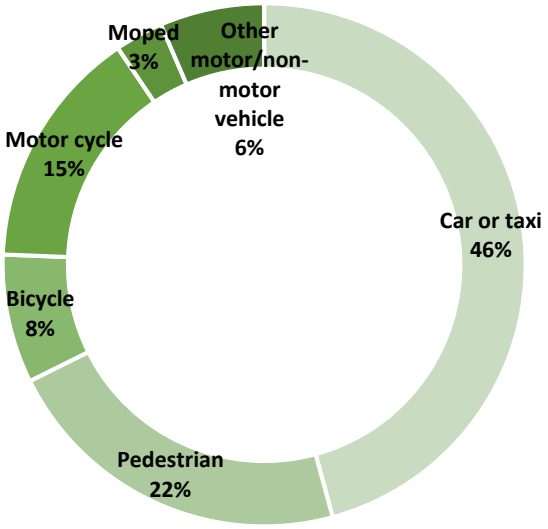

Figure 4: Distribution of fatalities by transport mode in the European Union, 2014.

Car safety has developed significantly over the last 25 years. For instance, the fatality risk for car occupants involved in a crash has reduced by an average of approximately 6% per year comparing models from the early 1980s with models launched between 2005–2010 (Strandroth, 2015; Folksam, 2017). In 2015, the average age of passenger cars in traffic in Sweden was 9.6 years, corresponding to 1.1 years less than the average for passenger cars within the European Union (ACEA, 2017). In general, a young car fleet can give a higher implementation rate of new safety systems. A way of lowering the mean age of cars in traffic involves phasing out old cars from the road transport system (Swedish Transport Administration, 2015a).

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; Bosch, 2008). ESC has been found to be up to 74% effective in reducing fatal loss of control crashes in certain road conditions (Lie, 2012a). While other countries proposed or implemented legislation, Sweden primarily adopted other methods. Stimulating the market based on scientific evidence of the ESC safety benefits, provided media with the foundation for making such evidence available and following up manufacturers and importers with regard to new cars. The government and insurance companies were signalling the importance of ESC by only using equipped cars and liaising with the car industry as well as monitoring the implementation process (Krafft et al., 2009). When the market is mature, legislation is the natural next step. 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, e.g., drift out of lane crashes. Therefore, lane departure crashes due to drift out of lane will be important to focus on as ESC systems are permeating the traffic.

While ESC is becoming common among passenger cars within the road transport system in Sweden today, national statistics show a decrease of head-on fatalities between 2010 and 2017, *Figure 5*. However, the number of single car fatalities do not show a clear decreasing trend.

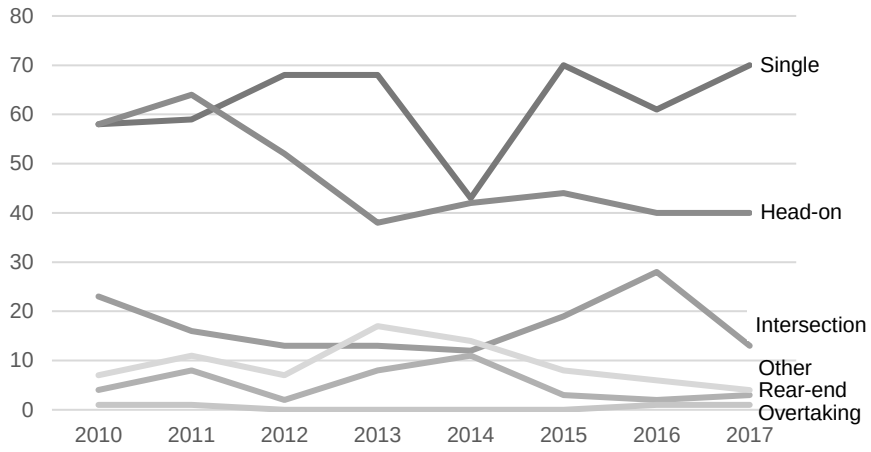

Figure 5: Passenger car occupant fatalities in Sweden during 2010-2017 (Trafikanalys 2018).

Strandroth (2015) suggested that the previous decrease (from 2000 to 2013) of fatalities in head-on and single vehicle crashes could be explained by several countermeasures. Road investments such as installing median barriers on rural high traffic volume roads, and milling rumble strips in the centre of two lane carriageways and on motorway shoulders, were made in the period. During 2009, the posted speed limits on Swedish state roads were reviewed on a large scale with the aim to adopt speed limits to each road's safety level. The posted speed limits on roads without median barriers, were reduced on approximately 18,000 km of road, mainly from 90 to 80 km/h. Approximately 2,500 km of road with a posted speed limit of 90 km/h and high traffic volume, were rebuilt to 2+1 roads with increased posted speed limits (Swedish Transport Administration, 2012b). The crashworthiness of cars was enhanced through fitting new cars with Seat Belt Reminder and as mentioned above, improved crash safety and increased fitment of ESC. However, direct or indirect external factors and seasonal differences also affected the fatality outcome (Swedish Transport Administration, 2015). The number of fatalities of car occupants experienced a substantial reduction during the period 2000–2010, *Figure 1*.

LANE DEPARTURE

Lane departure has been identified as one of the leading scenarios in police-reported road traffic crashes involving injured passenger car occupants. In the US, lane departure crashes belong to the most common crash types, accounting for 1.6 million police-reported accidents per year, corresponding to more than a quarter of all vehicle accidents (Mehler et al., 2014). Lane departure typically arises from driver inattention, relinquished steering (due to physiological reasons such as falling asleep, drug or alcohol, or seizure), or loss of control due to unfavourable road conditions, high speed, or sudden evasive manoeuvres (Mastinu and Ploechl, 2014).

It is logical that the driver leaves 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, 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 passenger car crashes are consequences of

loss of control or drift out of lane, and head-on crashes are one of the most lethal crash types involving high deceleration (Høye, 2012), *Table 2*.

Table 2: Severity rates for occupants in passenger car crashes (police reported crash records extracted from STRADA 2010–2017, n=72,095)

Crash type	Fatal crashes	Severe injury crashes	Minor injury crashes
Head-on	6.8%	21%	72%
Single	1.5%	14%	84%
Intersection	1.2%	12%	87%
Overtaking	0.6%	10%	90%
Rear-end	0.3%	8%	92%

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 off-roadway related 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 is 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 *control loss 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% were *collisions with another oncoming vehicle*, 24% were *collisions with another vehicle moving in the same direction* and 22% were *a vehicle leaving the carriageway* (Kuehn et al., 2009).

In Sweden, lane departure also accounts for a large proportion of the most severe crashes. Strandroth (2015) estimated, through retrospective analysis of in-depth studies, that 31% of the passenger car fatalities in 2010 involved unintentional drift out of lane. Although, 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 drifting, however, the actual number remains unknown. 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 interventions 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 could result in changes in the driving manners. 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 (Institute of Transport Economics, Norwegian Centre for Transport Research, 2017a) of centre road markings showed no statistically significant reduction of accidents. The same lack of significant results were 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%, CI95). Road posts exclusively showed no accident reduction. The combination of road posts, centre and side road markings, was found to reduce injury crashes by 45% (32–56%, CI95). The meta-study by Institute of

Transport Economics, Norwegian Centre for Transport Research (2017a) argue 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 the travelling speed. Narrow lanes may imply lower travelling speed (Johansson, 2009).

Before the introduction of 2+1 roads, 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 metre 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. Data extracted from STRADA and the national road database (NVDB) 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, *Figure 6*. 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 2.18 times higher fatality risk given that everything else is kept unchanged, $1 - (90/70)^{4.6}(-1) = 2.18$. 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 damage. Even though most high volume 90 km/h roads had been rebuilt to 2+1 before 2010, *Figure 6* shows high risk undivided 90 km/h roads. It should be noted that the figure involve a mix of undivided and divided roads. However, during 2010-2016, in average 97% of the 90 km/h road length had undivided opposing lanes and 98% for 80 km/h roads respectively.

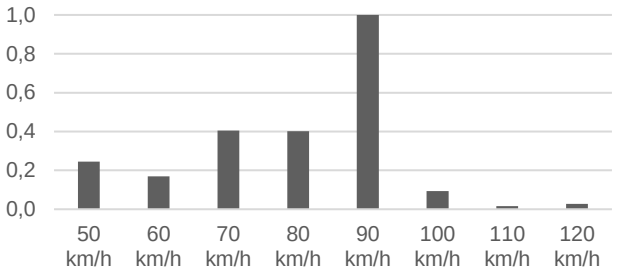

Figure 6: Head-on fatalities per traffic volume (vehicle kilometre) in relation to 90 km/h roads. Data extracted from STRADA and the national road database (NVDB) 2010-2016.

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, *Figure 7*. It was 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 on rural two-lane roads in the US showed reductions in head-on and opposing-direction sideswipe crashes by 30%, injury crashes by 25–30% and fatal crashes by 44% (Persaud et al., 2004, Donnell et al., 2009, Sayed et al., 2010). Among other factors, they were controlled for traffic volume

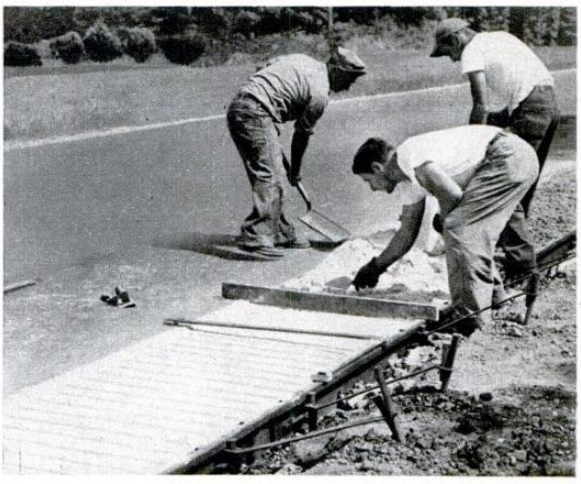

Figure 7: Singing safety lanes, Popular Mechanics Magazine (1953).

and regression to the mean. The combination of both centreline rumble strips and shoulder rumble strips reduced head-on, sideswipe-opposite-direction and single vehicle run-off road, for all severity crashes by 21–35% and fatalities and injuries by 40% (Sayed et al., 2010; Torbic et al., 2014; Lyon et al. 2015). Shoulder rumble strips alone also showed positive effects, at 14–26% reduction in run-off road crashes (Marvin, 2003; Sayed et al., 2010).

Milled centreline rumble strips on Finnish two-lane roads showed a 10% reduction in off-road to the left and head-on injury crashes (Rajamäki, 2010; Räsänen, 2011). The rumble strips were installed during 2004–2008, and the police reported crash data used in the study were from 2003–2009.

Milled centreline rumble strips on 239 km Norwegian two-lane roads with posted speed limits of 70, 80 or 90 km/h, showed reductions in injury crashes (Ragnøy et al., 2014). Head-on crashes were reduced by 32% and 54% for single vehicle run-off road to the left. The period before 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 were 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 study found no significant differences in the alerting effect of the different types of rumble strips.

A meta-study (Institute of Transport Economics, Norwegian Centre for Transport Research, 2017b) of rumble strips summarised the results of several studies. Centreline rumble strips showed a 10% (5–14%, CI95) reduction in the total number of accidents producing injuries while in a different study population, including accidents categorised as head-on, run-off road to the left and side-impacts in the opposite lane to the left, the reduction was 37% (31–42%, CI95). Studies showed that centreline rumble strips on two-lane roads has different estimated effectiveness dependent on crash severity and crash type, within a range of approximately 10–40%.

To avoid external noise pollution in Sweden, the Swedish Transport Administration does not apply milled rumble strips closer than 150 metres 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 rumble strips implemented in Sweden is the *Målilla* type. Between 2006–2010, milled centreline rumble strips were the most implemented rumble strips on two-lane roads in Sweden, *Figure 8*.

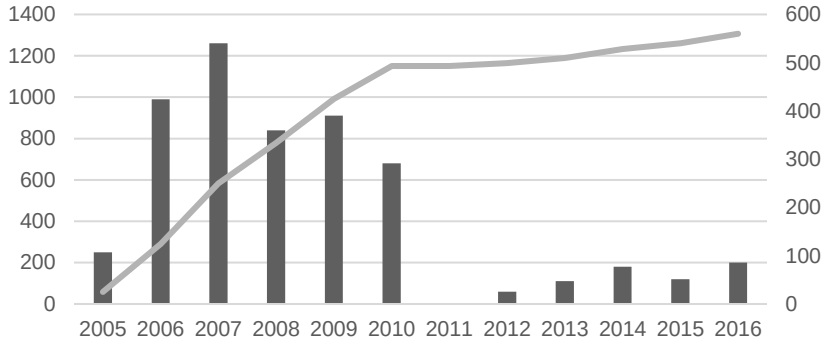

Figure 8: Implemented milled centreline rumble strips on two-lane roads in Sweden (km) and corresponding accumulated levels, adapted from Swedish Transport Administration (2017).

A before and after study of milled centreline rumble strips on Swedish two-lane carriageways showed a risk reduction of 15–20% (Vadeby, 2013) in the fatal and severe injury rate in police reported single vehicle crashes.

Vadeby and Björketun (2016) updated their study of milled centreline rumble strips using the same method but more comprehensive crash data comprising 2003–2013, and found that fatal and severe

injuries had reduced by 15% for all crash types and 24% for single vehicle crashes. In this study the results were adjusted for deviation of regression to the mean. The results apply to two-lane roads with a posted speed limit of 90 km/h and road width up to 10 metres. Milled rumble strips on the shoulder of highways were also studied (Ibid, 2016). 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 (incl. regression to the mean). 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, rumble strips do not eliminate all unintentional lane departures and therefore further countermeasures are needed to ensure safety.

Median road barriers

As mentioned before, straight and wide road design invites drivers to exceed the speed limit (Johansson, 2009). From a Vision Zero perspective, the Swedish Road Administration (STA) concluded, following the introduction of Vision Zero, that the features *straight and wide* exclusively did 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.

In an attempt to improve necessary road design characteristics, the Swedish Transport Administration used separation of opposing traffic by median crash barriers. To mitigate the severity of run-off road crashes further, side crash guard rails or cleared road side areas were used.

As a result of the new strategies, many of the straight and wide 90 km/h roads were transformed into 2+1 roads, and equipped with median wire rope barriers, which consequently increased traffic flow capacity as well as overall safety. The fatality rate was reduced by 75–80% on 13 metre wide converted and improved roads, despite the speed limit being increased to 100 km/h in most cases (Carlsson, 2009). Implementation of median barriers on narrower road stretches (9 metre 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.

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 Lane Departure Warning (LDW) and Lane Keeping Assist (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). 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 travel lane. Lane support systems are designed to minimise unintentional drift out of the travel lane.

Lane support systems require lane markings to be present and visible, i.e., not worn out or covered by snow, or a line with significant contrast such as the verge. They are not operating at low speeds, typically from about 65 km/h (40 mph). There are other limitations to lane support systems as they do not function properly if the curve radius of the road is tight or in heavy precipitation (Automotive World, 2012; Hummel et al., 2011; Jermakian, 2011). Other factors, such as adverse lighting or weather conditions as well as temporary lane markings at construction zones, could also cause the system to fail. Some

limitations are effects of technical issues 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. This comes at the potential cost of reduced efficiency.

Lateral support systems was first introduced in premium cars with low sales volumes. The Japanese market was early with LKA in the 2001 Nissan Cima 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, for example. The Citroën C6 model year 2005 was the first car in Sweden to include LDW as standard equipment. However, the widespread penetration of LDW in Sweden began with the Volvo V70II from model year 2008. As mentioned before, LDW and LKA were included in the Euro NCAP test programme in 2014 (Euro NCAP, 2017a).

Autonomous Emergency Steering (AES) is a technology for the future that automatically steers the vehicle to avoid a collision when a collision cannot be avoided by braking only (Nissan, 2017; Strandroth, 2016; Swedish Transport Administration, 2016). While AES still has not been introduced in traffic, the more prevalent Evasive Steering Assist systems detect swerving initiated by the driver and provides steering assistance to avoid an obstacle ahead (Volvo, 2017; BMW, 2016; Mercedes-Benz, 2017). In a drift out of lane head-on crash scenario the relevant moment in time for AES to potentially prevent a crash is later than the time slot for LKA to potentially prevent a crash. In such a head-on crash scenario, LKA must be overridden for the AES to be activated. In other words, while the LKA system aims to prevent drifting into the opposing lane, the AES system automatically steers the vehicle to help avoid a collision with an approaching vehicle in the opposing lane. However, AES systems are also relevant in crash types where LKA systems are not relevant, i.e., rear-end crashes.

Lateral control is essential for automated car driving. According to the SAE International (2016) standard J3016 for levels of automated driving, the LDW system would be considered as a no automation (Level 0) and LKA as a driver assistance system (Level 1). Progressively moving up in levels to full automation, Level 5 systems perform automated driving at all times and in all driving modes. Therefore, robust and reliable lane keeping is essential for automated cars.

SAFETY POTENTIAL OF LANE DEPARTURE WARNING SYSTEMS

In conjunction with the development and introduction of LDW, a number of prospective effectiveness studies have been performed by identifying the target population and applying the estimated system effectiveness as suggested in the Traffic Accident Causation in Europe (TRACE) project (Karabatsou et al., 2007). The eIMPACT project (Wilmink et al., 2008) assessed the potential benefits of lateral support systems on a European level, and found the potential to be a 15.2% reduction in all fatalities and 8.9% reduction in all injuries given fleet penetration at a 100%. The identified target population constituted mainly of the accident type *collision beside the road with pedestrian or obstacle or other single vehicle accidents* (70% reduction of fatalities and injuries) and *side-by-side collisions* (20% reduction of fatalities and injuries). The project attempted to include indirect effects of changed driver behaviour, 3% increased fatalities due to lowered alertness and drivers deactivating the system was expected. Additionally, due to increased driving exposure during difficult conditions the fatalities were expected to increase by 1%.

The eSafety project (eSafety Forum, 2006), funded by the European Commission and the Allgemeiner Deutscher Automobil-Club (ADAC) predicted LDW to reduce lane departure crashes by 17.5% (25% times 70%) and to have an overall impact by reducing traffic crashes by 2.9% when the system reaches a fleet penetration of 70%. The effectiveness of LDW was assumed to be 25%. This estimate was based on German national statistics of police reported accidents with personal injuries during 2002.

In 2008, Visvikis et al. used in-depth data (OTS) and police data (STATS19) from the United Kingdom and German In-Depth Accident Study (GIDAS) to estimate the expected benefits of LDW. For M1/N1

class vehicles, i.e., passenger cars and light trucks having a maximum mass not exceeding 3.5 tonnes, the safety benefits ranged from 16–48% for fatal accidents in the target population defined as head-on, left roadway and side collisions. The effectiveness measure of LDW, ranging from 5–30%, was identified from several earlier studies and applied to the accident types.

Wilson et al. (2007) used field operational test data, and suggested that LDW reduced scenario specific crashes by 1–8%. 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 mi/h (65 km/h) and above as well as roadways cleared from snow.

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 43% of all fatal crashes, 39% of all MAIS 3+ crashes, and 14% of all injury crashes. From the National Motor Vehicle Crash Causation Survey (NMVCCS) database they found that 24% of all accidents involved distraction. They assumed that the distribution of the NMVCCS data also holds for NASS-GES, NASS-CDS and FARS. Thereby, they concluded that the LDW relevant crashes involving distraction (excluding speed, performance error, judgement error, non-performance, illegal manoeuvre, and other) accounted for 10%, 9%, and 3% respectively.

Scanlon et al. (2016) showed that the roadway infrastructure influences the 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 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, has 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 metres. 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.

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. In Sweden, mass crash data are lacking the level of detail for this cause, but in-depth data of fatal crashes are rich in detail and could be used to reliably estimate the safety potential of LDW.

EFFECTIVENESS OF LANE DEPARTURE WARNING SYSTEMS

Few published studies have been able to evaluate the effectiveness of LDW and/or LKA building on real-world crashes. This is possibly due to the limited number of car models having the system as

standard. 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 adds difficulty when identifying relevant vehicles and evaluating the systems. To make precise effectiveness estimates it was suggested that manufactures provide information to crash data registers about the specific equipment through a vehicle identification number (Blower, 2014). It was also recognised that this practice could raise privacy and proprietary data issues. However, the necessary level of detail of the vehicle equipment is seldom available in today's crash databases. 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 involve fatal crashes only which are yet not constituting enough cases for quantitative effectiveness estimates of LDW.

Analyses performed by the Highway Loss Data Institute (HLDI) for the Insurance Institute for Highway Safety (2012) 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. In later analyses HLDI (Insurance Institute for Highway Safety, 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 cars equipped with Forward Collision Warning combined with LDW. However, it was not possible to quantify the claim frequency reduction for each individual system. Information about the specific vehicle equipment was known but crash type was not known. This study is an example of the consequences of lacking precise crash characteristics information.

Recently Cicchino (2017) succeeded to merge real-world police reported crashes in the US and specific car equipment data matched by vehicle identification numbers. Analysis of the combined information of both the individual car equipment and crash characteristics showed that LDW systems lowered the rates of single car, sideswipe and head-on crashes of all severities by 11% ($p<0.05$) and lowered the rate of injury crashes by 21% ($p<0.06$).

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.

It has been shown that infrastructural interventions and in-vehicle systems have safety benefits. The referenced studies above were mainly from the international scene, and the safety benefits of LDW in Swedish conditions has not yet been explored. However, one of the most obvious knowledge gaps considering the safety benefits of lane keeping, are how safety systems integrated in cars and infrastructure could work in combination.

THEORETICAL FRAMEWORK

THE INTEGRATED SAFETY CHAIN MODEL

William Haddon Jr. was early to realise the need of a systematic approach to epidemiological risk in the field of road traffic safety. This lead 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 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 could 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), *Figure 9*. In the integrated safety chain model 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 has the potential to cut the chain of events leading to crash. This approach is used in the automobile industry (Nissan, 2004; Schoeneburg, 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 if the driver deviates. Energy control is also essential in normal driving. In this approach, the integrated safety chain is 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. Additionally, the different phases in the integrated safety chain are dependent on each other. A previous phase sets the preconditions for subsequent phases. A previous phase could thereby put the driver in a more or less advantageous starting position in the subsequent phase, which is especially important with regard to energy control.

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 interventions 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 will without a doubt occur, 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. 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.

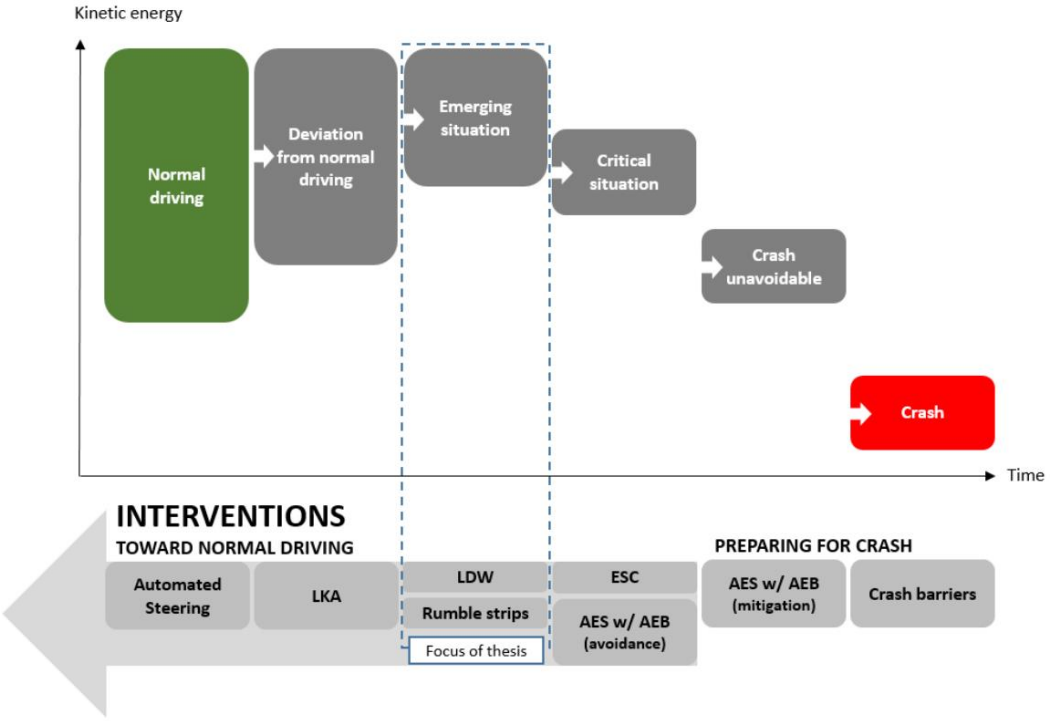

Figure 9: Focus of thesis and LDW in the integrated safety chain, adopted from Tingvall (2008), Lie (2012b) and Strandroth (2015). Detectable lanes is a precondition for lane keeping. Autonomous Emergency Braking is referred to as AEB.

Of all lane departure incidents only a few are resulting in crashes. The crashes that potentially are recorded and studied is only the tip of an iceberg. Most deviations from normal driving are not resulting 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, of happening. As mentioned before, the different phases in the chain are dependent on each other. Earlier phases set the preconditions for subsequent phases and provide a more or less advantageous starting position. The combination of ESC and crash worthiness exemplifies this. As ESC prevents loss of control and the resulting rotation it increases the likelihood of using the energy absorbing deformation zone in the front of the car rather than in the side, which is a worse option.

Unintentional lane departure and prevention strategies as such fall in the frame of what the integrated safety chain refers to as an emerging situation. It is important to focus on this particular part of the chain of events leading to crash, and more specifically by studying the safety potential and benefits of lane support systems such as LDW using Swedish in-depth and mass crash data.

AIM

The overall aim of this thesis is to increase the knowledge of lane keeping support. This thesis is based on two studies aiming to: (1) identify and describe characteristics of lane departure crashes and quantify the potential safety benefits of lane support systems such as LDW using real-world in-depth data of fatal crashes in Sweden, and; (2) evaluate the effectiveness of LDW systems in reducing real-world injury crashes using Volvo passenger cars in Sweden.

SPECIFIC AIMS OF PAPER 1

1. Identify fatal lane departure without prior loss of control crashes in Sweden.
2. Characterise fatal lane departure without prior loss of control crashes in Sweden.
   i. Differentiate between unintentional drifting and intentional lane change or evasive manoeuvre.
   ii. Identify loss of control post lane departure.
3. Quantify the potential safety benefits of LDW systems in fatal crashes in Sweden by identifying the target population.

SPECIFIC AIM OF PAPER 2

- Estimate the safety benefits of in-vehicle LDW systems in reducing relevant real-world passenger car injury crashes using Volvo passenger cars in Sweden.

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 3*. Paper 1 applied a qualitative case by case analytical approach where the material consisted of in-depth studies of fatal crashes in Sweden in the year 2010. Paper 2 applied an induced exposure method based on police reported crashes that had occurred in Sweden between January 2007 and September 2015. These crashes, involved injured drivers in Volvo passenger cars of model year between 2007 and 2015, and were extracted from the Swedish Traffic Accident Data Acquisition database (STRADA). Volvo's low speed Autonomous Emergency Braking system is referred to as City Safety in *Table 3*.

Table 3: Overview of materials and methods

	Paper 1	**Paper 2**
Aim	Identify and describe characteristics of lane departure crashes and quantify the potential safety benefits of LDW systems in Sweden	Estimate the safety benefits of LDW systems in reducing relevant real-world passenger car injury crashes using Volvo passenger cars in Sweden
Analytical method	Qualitative case by case study	Induced exposure and one-sided 95% confidence interval
Data sources	In-depth studies of the Swedish Transport Administration	Police data from the Swedish Traffic Accident Data Acquisition (STRADA) and vehicle data from the Swedish Road Traffic Registry
Inclusion criteria	• Fatal passenger car occupant crashes • Head-on, single car and overtaking • No suicide or death by natural causes	• Driver injury crashes • Volvo passenger cars • Potentially LDW/LKA equipped cars • City Safety equipped cars • No suicide or death by natural causes
Number of cases	104	843 (14% w/ LDW and 1% w/ LKA)
Data time period	January – December 2010	January 2007 – September 2015
Injury classification	Fatalities	Injury crashes classified by the police

SUMMARY OF PAPER 1

BACKGROUND

Between 2010 and 2017, the average road fatality rate in Sweden was 273 out of which 52% were passenger car occupants (Trafikanalys, 2018), with 77% due to head-on and single vehicle crashes (Ibid). 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 in Swedish conditions may be regarded as part of a necessary problem formulation preceding any suggested solutions. Lane support systems target population is an area which needs to be studied.

AIM

1. Identify fatal lane departure without prior loss of control crashes in Sweden.
2. Characterise fatal lane departure without prior loss of control crashes in Sweden.
    i. Differentiate between unintentional drifting and intentional lane change or evasive manoeuvre.
    ii. Identify loss of control post lane departure.
3. Quantify potential safety benefits of LDW systems in fatal crashes in Sweden 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. The Swedish Transport Administration has carried out in-depth studies for each fatal road related crash in Sweden since 1997 (Swedish Road Administration, 2005). 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 identified lane departure crashes were separated from crashes where loss of control occurred. When studying the pre-stage of lane departure without prior loss of control, crashes were categorised as unintentional drift out of lane, intentional lane change or evasive manoeuvre. Sweden was exposed to a total of 154 passenger car occupant fatalities involving 138 crashes in 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. The target population for LDW systems was drifting crashes on roads with visible lane markings and speed limits from 70 km/h. However, crashes involving rumble strips were excluded from the target population and crashes involving excessive speeding were presented separately due to the reaction time available to drivers might have been too limited. Additionally, LDW is potentially less beneficial in cases including extreme speeding as the driver typically is very active in these driving situations. All analysis of and interpretation of the crashes were performed by the author.

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 (in *Figure 10* referred to as LOC). These crashes accounted for 61% (63/104) of all single vehicle, head-on and overtaking crashes, *Figure 10*. 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 are related to unintentional drift out of lane. LDW 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.

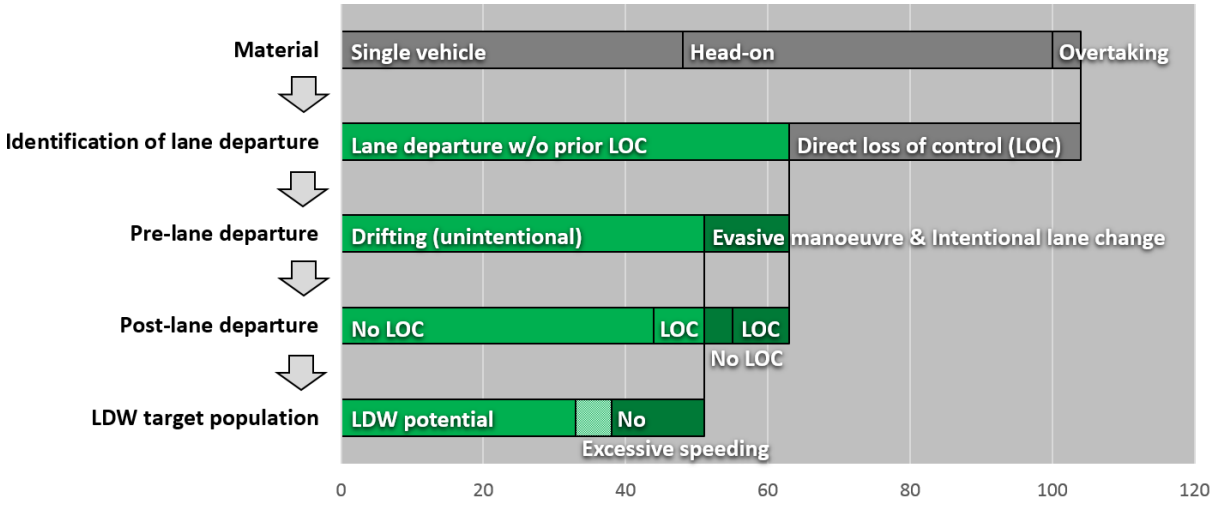

Figure 10: Number of fatal crashes, from material to described characteristics of lane departure crashes and quantified potential safety benefit of LDW systems.

Resulting characteristics of the 51 unintentional drift out of lane crashes is described as follows: The majority (44/51=86%) of the unintentional drifting crashes occurred with no loss of control post-lane departure. The consequence of the unintentional drifting includes head-on crashes in 31 cases and single car crashes in 20 cases. Twelve (12/51=24%) unintentional drifting crashes involved a driver under the influence of alcohol or drugs. Six crashes (6/51=12%) crashes involved excessive speeding. The majority (36/51=71%) of the unintentional drifting crashes involved a driver not under the influence of alcohol or drugs and was not speeding excessively. 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. Centre rumble strips were present in three crashes, out of which two involved departure to the left. In these two scenarios, where the driver drifted over the rumble strip, one resulted in a head-on crash in the adjacent lane and one in hitting a bridge pillar in concrete. Of the remaining 48 crashes without centre rumble strips 33 were departure to the left. Road side rumble strips were present in three crashes, out of which one involved departure to the right. Of the remaining 48 crashes without road side rumble strips 15 were departure to the right. Additional characteristics of the 51 unintentional drift out of lane crashes are presented in Table 4.

Table 4: Characteristics of the 51 unintentional drift out of lane crashes

Speed limits, km/h	**50**	**70**	**80**	**90**	**110**		
	10%	22%	20%	45%	4%		
Road markings	**Visible**	**Snow covered**	**Worn**	**Missing**			
Centre	78%	8%	2%	12%			
Side	84%	6%	2%	8%			
Light	**Daylight**	**Twilight**	**Darkness**				
	62%	14%	24%				
Driver age, years	**18**	**19-24**	**25-44**	**45-64**	**65-74**	**75+**	**Mean**
	8%	18%	27%	27%	10%	10%	43
Car age, years	**Mean**	**Median**					
	10	10					

SUMMARY OF PAPER 2

BACKGROUND

In some countries, lane departure has been identified as one of the leading scenarios in the most severe road traffic crashes involving passenger cars. Due to several reasons, few published studies have been able to evaluate the effectiveness of LDW systems on real-world crashes, including the limited installation rate, as yet too short implementation period being and difficulties in identifying cars with LDW systems in accident databases. In order to validate predicted effectiveness estimates of lateral support systems, evaluations based on real-world crashes are essential.

AIM

The aim of this study was to estimate the safety benefits of in-vehicle LDW systems in reducing relevant real-world passenger car injury crashes using Volvo passenger cars in Sweden.

METHODS AND MATERIALS

The study was based on driver injury crashes reported by the police to the Swedish Traffic Accident Data Acquisition Database (STRADA). STRADA contains all police reported crashes with at least one injury. For each crash, STRADA contains information including injuries, i.e.., fatal, severe and minor injuries, judged by the police in the field; crash type, e.g., single vehicle, head-on, rear-end, intersection, overtaking, collision with animal, pedestrian, cyclist, rail traffic and others; posted speed limit, road surface condition, i.e., dry, wet, ice or snow covered; and, vehicle registration number, etc.

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. However, only 843 models also equipped with City Safety, a low speed Autonomous Emergency Braking system, were included for the effectiveness estimate.

Out of these City Safety vehicles, 157 were equipped with LDW and 11 cars were equipped with LKA. The car models were fitted with different generations of the LDW technology. The Volvo models S80 (2007–2011), V70 (2008–2011), XC60 (2009–2011) and XC70 (2008–2011) were equipped with an early version of LDW called *LDW with sound warning* (LDW1). From model year 2011, a new generation of LDW was introduced with *One Line Tracking* (LDW2) meaning that LDW was not limited to the need for two visible lane markings. LDW2 also used a sound warning. Volvo introduced LKA in the V40 model year 2013 and later in the V60 model year 2014.

To identify whether a specific car was equipped with LDW or LKA, vehicle registration numbers were extracted from STRADA and vehicle identification numbers 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 vehicle identification number.

The study used an induced exposure method previously used in several studies evaluating safety technologies (Evans, 1998; Lie et al., 2006; Strandroth et al., 2012a). In this study, the relationship between crashes, sensitive and non-sensitive to LDW/LKA, were compared for cars equipped with LDW/LKA and cars without LDW/LKA. LDW and LKA are systems designed to prevent unintentional lane departure crashes. Lane departure crashes mainly result in head-on and single vehicle crashes. In this study, head-on and single vehicle crashes were considered as crashes sensitive to LDW/LKA. Crash types not addressed by LDW/LKA were used as a measure of exposure. Rear-end impacts belong to a crash type that does not involve many car-handling factors and also constitute enough cases for analysis. Therefore, rear-end impacts were used to target the exposure of LDW/LKA non-sensitive crashes in this study. Both striking and struck cars had been involved in the crashes. Also, effectiveness estimates were performed where crashes classified as rear-end, intersection, overtaking, collision with animal, pedestrian, cyclist and rail traffic were used as non-sensitive crashes for some analyses in 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 were included in the analysis. City Safety is active at speeds under 50 km/h, however, Fildes et al. (2015) showed that City Safety reduced rear-end crashes by 38% and that there was no statistical difference in the effectiveness between speed zones up to and above 60 km/h.

The effectiveness (E) of LDW/LKA was calculated as $E = 1 – (A/B) / (C/D)$ where *A* is crashes sensitive to LDW/LKA with LDW/LKA cars; *B* is crashes non-sensitive to LDW/LKA with LDW/LKA cars; *C* is crashes sensitive to LDW/LKA with cars without LDW/LKA; *D* is crashes non-sensitive to LDW/LKA with cars without LDW/LKA.

RESULTS

The analysis showed a positive effect of the LDW/LKA systems in reducing lane departure crashes. The LDW/LKA systems were estimated to reduce head-on and single vehicle 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% with a lower limit of 6% (CI 95%) for all head-on and single vehicle driver injury crashes (including all speed limits and all road surface conditions).

To estimate the overall effectiveness of LDW/LKA, Swedish national statistics were linked to the target crash type. This target crash type (head-on and single vehicle crashes on roads with higher speed limits (70–120 km/h) and on road surfaces not covered by ice or snow) corresponds to 15% of all passenger car injury crashes with known posted speed limit and road surface state (236/1527), therefore the overall effectiveness of the LDW/LKA systems was an 8% risk reduction (0.53×0.15) with a lower limit of 2% (CI 95%) for all injury crashes in Sweden.

These results were computed using rear-end impacts as exposure data. Effectiveness estimates using all non-head-on and non-single vehicle crashes showed a similar effectiveness level, 51% with a lower limit of 10% (CI 95%) for head-on and single vehicle crashes on roads with higher speed limits (70–120 km/h) and road markings not covered by ice or snow.

GENERAL DISCUSSION

INTRODUCTION

Crashes due to unintentional drift out of lane account for a significant part of head-on and single vehicle crashes. The other major part of head-on and single vehicle crashes involves loss of control. Due to high effectiveness and rapid implementation of ESC, loss of control crashes is estimated to decrease rapidly. Therefore, addressing and preventing the share of unintentional drifting crashes would be expected to become even more relevant. This licentiate thesis is based on two studies aimed at increasing the knowledge of lane keeping support by: (1) identifying and describing characteristics of lane departure crashes and quantifying the potential safety benefit of lane support systems such as LDW using real-world in-depth data of fatal crashes in Sweden; and (2) evaluating the effectiveness of LDW systems in reducing real-world injury crashes using Volvo passenger cars in Sweden.

Results provide evidence that lane keeping interventions potentially have high safety benefits in preventing fatal crashes involving unintentional drift out of lane, especially on rural undivided roads with posted speed limits of 70 km/h and above. LDW in Volvo cars as an in-vehicle safety intervention, has proven to be highly effective in circumstances the system was designed for; speeds of 65 km/h and above with visible lane markings.

The safety potential study (Paper 1) showed that the target population of LDW was 33–38% of all fatal head-on and single vehicle crashes, assuming 100% effectiveness of a lane support systems such as LDW or LKA. The effectiveness study (Paper 2) showed that LDW reduced relevant head-on and single vehicle injury crashes in a broader population, i.e., the study population, by half. However, comparison of these results will be discussed later, where differences in study approach and population composition, such as injury severity, crash scenario as well as level of detail in material are taken into consideration.

The results of these studies are based on Swedish crash data. The resulting effectiveness estimate is naturally specific for the Swedish geographic location, road design principles, speed limits, vehicle fleet properties, driving culture and other relevant factors. Regulation, education, motivation and cognition represent aspects of potential importance in regard to this issue in relation to the early stages of the integrated safety chain. However, differences in rescue routines and methods for capturing, processing and extracting accident data, e.g., emergency services, injury diagnosis, accident reporting, classification, registration, data storage structure and retrieving, may be present. Hence further research is needed to generate representative effectiveness estimates in a broader perspective.

The presented effectiveness estimates refer mainly to Volvo's first few generations of systems, given a specific human-machine interface, inactivation degree and lane recognition features, etc. Since then, the technology has been further developed. The reliability probably influences the frequency of users activating the system. Other manufacturers or generations of systems may provide higher or lower effectiveness in detecting drift out of lane situations. Different human-machine interface solutions, e.g., haptic, visual, and audible warnings signals, may also deliver differences in real-world traffic effectiveness. Additionally, driver behaviour may be influenced and affected differently by different approaches such as LDW compared to LKA. However, it is worth considering that the safety benefits in real-world traffic may not always be provided by the system that makes the greatest intervention while attempting to prevent an accident, for instance, where low acceptance rate may result in extended deactivation. Nevertheless, Paper 1 indicates clearly that an adequate LKA system would deliver significant safety benefits, assuming 100% effectiveness in the target population.

Further work aimed 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 to detect 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.

Without excluding any previous suggestions, a further approach would be to boost the effectiveness of the LDW systems. This could be achieved by enhancing the usage of LDW systems, as drivers do not always keep the system turned on. Furthermore, it is imperative that the human-machine interface is suitably designed so that drivers appreciate the system, keeping it turned on, and providing drivers with the opportunity to react appropriately and in time when a warning signal is issued. On the other hand, development of lateral support technology is moving towards steering systems less dependent on human reaction. When placing more of the lane keeping task on the vehicle, it is important to ensure that the infrastructure information is reliable, robust and detectable for the vehicle.

Another way to increase the effectiveness of lane keeping support could be a solution integrated in the vehicle and the road infrastructure. This can be achieved through dialog between road authorities and vehicle industry.

RESULTS IN COMPARISON

RESULTS IN RELATION TO PREVIOUS RESEARCH

Safety potential

The potential safety benefit found for LDW systems (Paper 1) was similar to previous research findings estimating their safety potential. In a study of crashes in the USA, Jermakian (2011) selected head-on, single vehicle and sideswipes possibly relevant for LDW with respectively crash type constituting 12%, 78% and 10% (same direction 2% and opposite direction 8%) of the material of fatal crashes. The resulting relevant LDW crashes had another mix of composition, head-on 22%, single vehicle 64% and sideswipes 13% (same direction 3% and opposite direction 10%). The material in Paper 1 had a higher proportion of head-on crashes (52%), which also holds for the LDW relevant crashes (61%). The studied Swedish material, although limited and only spanning one year, did not identify any 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.

Historically, crashes classified as overtaking have not been a big issue in Sweden due to the low number of fatalities in such crashes, see *Figure 5*. It is worth noting that a convenient way 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. Combining parameters in NASS-GES, crashes not addressed by LDW system limitations or involving non-relevant circumstances were excluded. As per Paper 1, crashes involving loss of control, avoidance manoeuvres, speed limits of less than 40 mi/h (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 did not include any crashes of this kind.

The single vehicle crashes in the Jermakian study have other proportions of some particular vehicle handling factors. For instance, approximately 16% of fatal single vehicle crashes involved avoidance manoeuvres in the Jermakian study compared to 12% in Paper 1. Remarkably low, only approximately 4% involved loss of control compared to almost half of the single passenger car crashes in Paper 1. 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.

Effectiveness estimate

Few studies have been able to estimate the effectiveness of LDW in real-world traffic. However, a recent study of road crashes in the US by Cicchino (2017) indicates some promising results. The study uses real-world police reported crashes in the US, merged with equipment data of each individual car. LDW systems were estimated to reduce the rate of head-on, single car and sideswipe crashes of all severities (including property damage) by 11% ($p<0.05$) and lowered the rate of injury crashes by 21% ($p<0.06$). Explanations of the different effectiveness sizes between the Cicchino study and Paper 2 may relate to differences in the material, method or country specifics, e.g., LDW activation rate.

There are significant differences between the US and Sweden. For instance, the road environment, such as the placement and visibility of lane markings may differ. One factor influencing the size of the effectiveness estimate may be that Swedish drivers possibly keep the LDW systems turned on more often than American drivers.

The Cicchino study material included several vehicle manufactures; Buick, Cadillac, Chevrolet, GMC, Honda, Mazda, Mercedes-Benz, Subaru and Volvo. The Cicchino study included less of the later Volvo car models, model year 2008–2010 compared to model year 2007–2015 in Paper 2. However, all Volvo models in both studies were equipped with an easily accessible on/off button. Several of the other car makes included were however newer, model year 2015 or 2016.

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 (2017) solved this issue by using insured vehicle days as exposure while Paper 2 adopted the induced exposure method. While using the exposure of insured vehicle days or even the more common exposure vehicle kilometres, the possible resulting crash reduction has to be linked to the context of usage rate to identify the effectiveness in real-world traffic. The usage rate is incorporated in the induced exposure method. Possibly resulting crash reductions identified using the induced exposure method shows the effectiveness given the actual usage rate in real-world traffic. This induced exposure method has advantages also with regard to other driver behaviour aspects compared to using the exposure of vehicle kilometres, which is discussed later. The effectiveness level showed in Paper 2 include the actual usage rate and significant additional driver behaviour influence.

There is a risk of overestimating the effectiveness of safety systems when using the exposure of vehicle insurance days or vehicle kilometres. 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 (2017) 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). Without accounting for driver demographics, vehicles equipped with LDW had significantly lower involvement rates in crashes of all severities (18%), in crashes with injuries (24%) and in fatal crashes (86%). It is difficult to quantify how much of the driver behaviour factors the demographic variables may be controlled for.

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 a broader less relevant study population. The possibility of narrowing down previous studies to relevant crashes has been varied. Taking discussed differences in consideration, it can be concluded that results from both Cicchino (2017) and Hickman (2015) were in line with results from Paper 2.

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; where 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 a more LDW relevant crash scenario 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 5*.

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 an effectiveness of 53%. To enable a comparison of the results between the 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 5: Comparison of the results of Paper 1 and Paper 2

	Paper 1	**Paper 2**
Study approach	Safety potential analysis	Effectiveness estimate
Severity	Fatal crashes	Injury crashes
Population description	Target population • Head-on and single vehicle crashes • ≥70 km/h • Visible lane markings • Unintentional drift out of lane • W/o rumble strips • W/o excessive speeding	Study population • 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

A potential conclusion is that the LDW-system is preventing almost all head-on and single vehicle crashes in the target population. However, this conclusion is not supported by the studies. A comparison of the above populations reveal that the injury levels differ; Paper 1 comprise fatal crashes while Paper 2 comprise injury crashes. Road safety systems tend to show higher effects for crashes of more serious severity (Elvik, 2009; Kullgren et al., 2010; Krafft et al., 2009; Lie et al., 2006), and 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. However, LDW is a crash avoidance system rather than a crash severity mitigation system.

The 53% estimated effectiveness in Paper 2 was calculated for a broader population, corresponding to 30% of all head-on and single passenger car crashes with injuries. 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 broader population of crashes constitute of a mix between equipped and non-equipped passenger cars. An ESC-equipped car population would probably have relatively more drift out of lane crashes than a non-equipped car. Correspondingly, the rate of loss of control crashes would in relation be less due to the ESC function reducing loss of control crashes. In this aspect, it appears that the effectiveness estimate of LDW was not overestimated for the broader population. On the other hand, LDW-equipped cars are usually also ESC-equipped.

Comparing potential studies and effect estimate studies in general, a potential analysis generally tends to result in a higher benefit than other 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 deals 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 usage rate in Sweden.

Further, the true safety benefit could be higher or lower. 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 reduced 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. 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 impacts and intersection accidents.

In an interview study 60% answered that they use the indicators more often (Braitman et al., 2010). If LDW systems encourage drivers to use the indicators to a higher extent it could be expected to reduce rear-end impacts rather than head-on or single car crashes. Since rear-end crashes were used as exposure, this may also suggest that the results are conservative.

For comparison, using mass data parameters as in Paper 2 to narrow down the in-depth material (Paper 1), i.e., basically missing out on the assessment of drifting, presence of rumble strips, assessment of visibility of lane markings and excessive speeding, may result in a potential LDW relevant population of 63% of the fatal head-on and single car crashes. Crashes included were selected by a posted speed limit of 70–120 km/h and road surface conditions dry or wet (excluding snow and ice). Comparing 63% to the more narrows LDW relevant and precise population of 33%. It would be interesting to find out more about if LDW is addressing a specific crash type with high effectiveness or a broader population with less effectiveness summing up to the same level of reduction.

METHODOLOGICAL REFLECTIONS

Early and robust evaluation of new safety systems can strongly influence the take up rate of the systems (Krafft et al., 2009). However, it is challenging to evaluate new safety systems early 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 phase. Simulations and laboratory testing typically focus technical aspects and may exclude how ordinary drivers will use and adapt to a system. Safety system benefit estimates is ideally evidence based whereas real-world data are preferable to evaluate its performance. Although, systems have a technical aspect, there is also the aspect of how people use them. 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, understood and prevented. Therefore, it is also essential to evaluate systems in real-world traffic when possible. Real-world evaluation can estimate the effects but often have problems to understand why these effects occur. Close multidisciplinary collaboration and solid data could in the longer perspective possibly understand and explain how the technology and the users interact.

SWEDISH IN-DEPTH STUDIES

In-depth studies of fatal accidents have been conducted in Sweden since 1997. These in-depth studies contain a high level of detail of crashes and are carried out to improve road safety. It is a systematic approach to offer insight into why an accident resulted in a fatal crash mapping out the series of events leading to the crash (Swedish Road Administration, 2005). The challenge in this thesis is to understand the emerging situation (*Figure 10*, in Summary of Papers) using data collected after the crash occurred. The lane departure event and its characteristics, e.g., unintentional drifting and post-loss of control was clearly described in some crashes. Other crashes were more challenging to categorise, although a significant amount of useful data with regard to the deaths was still available. Categorisation was made possible using unstructured data (report text, photographs of the crash scene and of the vehicles

involved). Therefore, this method is qualitative in its character and time-consuming. All analysis and interpretation of the crashes were performed by the author to minimise inter-observer differences.

The Swedish in-depth studies can be improved to form a better basis both for safety potential and effectiveness studies. More precise information about a car's equipment level may be retrieved from vehicle registers using vehicle identification numbers to be added to the in-depth studies. Information about the occurrence of crucial events, i.e., for each phase of the integrated safety chain, could be added in a structured and systematic manner. With minor improvements the in-depth studies have the potential to play an even more significant role for scientific evaluations.

Paper 1 used the full population over one year and represents the full year. However, the result representativeness over time would claim a longer series of longitudinal data, where, for instance, doubling the material would be expected to only marginally provide added value. Although this study is based on qualitative research over one year, potentially the results may also have some bearing on the general case of the identified magnitude of potential crash avoidance, for other particular years.

INDUCED EXPOSURE

When estimating the effectiveness of in-vehicle safety systems, an exposure method is required. However, often availability of appropriate data to use as exposure variable is 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 system under evaluation. The aim is to catch the performance of the system alone, which can be challenging. Some factors are difficult to control for, such as behaviour change or usage rate. Another challenge is isolating system performance from the benefit of other in-vehicle safety systems. 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.

In this thesis mass data from the police is used as a basis for induced exposure analysis. The induced exposure method use system insensitive crash types as exposure. This method has previously been used to evaluate the safety benefits of a multitude of safety systems (Evans, 1998; Lie et al., 2006; Lie, 2012a; Strandroth et al., 2012a).

The induced exposure method has benefits compared to the traditional exposure such as traffic volume, e.g., vehicle kilometre. The induced exposure method is capable of compensating for some confounding factors compared to the traditional method, as the result using induced exposure are given by the relative difference between equipped and non-equipped populations, i.e. selective recruitment. The effectiveness estimate in this thesis was based on real-world traffic incorporating possible driver behavioural changes and usage rate, etc., which may appear as a strength of the method. 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 using traffic volume exposure. However, it is unlikely that safety conscious drivers in general would have a selective safety conscious mind whereby certain kinds of crash types would be avoided to a greater extent than others. Taking that into account, some aspects of the induced exposure method may be viewed as advantageous.

Traditionally, the traffic volume exposure method may have used compensation for group differences with regard to driver behaviour, which presents a challenge with this particular method. Driver behaviour data in real-world traffic can be difficult to capture, and it could be even more difficult to retrieve such data categorised into drivers in cars, with or without, specific equipment. For instance, Cicchino (2017) was using control variables for driver age, gender, marital status, insurance risk level, state, calendar year and vehicle density at garaging ZIP code.

At a first sight, not much differ between the two approaches as the structure is similar but as has been discussed the application is essentially different.

Using traffic volume exposure, e.g., driven vehicle kilometre, the relative risk could be calculated as R_1/R_2 where $R_1=A/B$ is crash risk for LDW cars; $R_2=C/D$ is crash risk for cars without LDW; A is crashes with LDW cars; B is traffic volume, e.g., vehicle kilometres, for LDW cars; C is crashes without LDW cars; and D is traffic volume for cars without LDW.

Using induced exposure, e.g., insensitive crashes, the relative risk could be calculated as R_3/R_4 where $R_3=E/F$ is risk of LDW sensitive crashes for cars with LDW; $R_4=G/H$ is risk of LDW sensitive crashes for cars without LDW; E is crashes sensitive to LDW with LDW cars; F is crashes non-sensitive to LDW with LDW cars; G is crashes sensitive to LDW with cars without LDW; and H is crashes non-sensitive to LDW with cars without LDW.

Another benefit is the possibility of consistency in injury severity using induced exposure, i.e., injury crashes in the numerator (system sensitive) and denominator (exposure). This phenomenon is clear with regard to fatal crashes, a population different from injury crashes, property damage crashes or traffic in general. For instance, 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 is older, than the population of cars in ordinary traffic. To clarify, while fatalities in relation to the general traffic volume is a comparison of very different populations, fatalities in relation to fatalities could be a somewhat more consistent risk measure.

Generally, it is problematic when a method can overestimate the effectiveness. The induced exposure method gives conservative estimates. For example, if drivers frequently turn off the LDW system, the induced exposure method's resulting effectiveness would be underestimated compared to full use of the system. Also, if the rear-end collisions (exposure) were not completely insensitive to LDW, consequently the difference between risk R_3 and risk R_4 would have been underestimated using the induced exposure. This also applies to incorrect crash type classification.

However, the extent of how much the induced exposure method compensates for confounding factors is dependent on the quality of data and possibility to identify frequent crashes non-sensitive to the system under evaluation.

INTEGRATED SAFETY CHAIN

This thesis used the integrated safety chain as a theoretical framework, where the LDW system can be placed in context to other lane departure relevant safety features, for instance, rumble strips, ESC and AES. The integration could be present at several levels. For instance, in an integrated car technology approach, an AES system would be connected to an Autonomous Emergency Braking system optimising the intervention of steering and braking.

When focusing on preventing injuries every phase in the chain could be seen as an opportunity to bring the driver back to normal driving or properly prepare for crash. However, a previous phase in the chain sets the preconditions for the subsequent phases. For example, Intelligent Speed Adaptation (ISA) supports the driver to avoid exceeding speed limits. At excessive speeding, LDW may provide limited benefits due to potentially insufficient driver reaction time. In the same way early phases set the preconditions for LDW systems, the LDW system sets the precondition for subsequent phases. For instance, LDW systems 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. Further, an ESC system provides a stable and therefore a more advantageous starting point for the subsequent phase where the vehicle crashworthiness is mitigating the crash severity by correctly using the energy absorbing crash zones in the front of the vehicle.

The chain of events leading to crash may have been influenced by other safety systems before the driver reaches the crash stage and thus end up in accident data, for potential use when estimating the LDW effectiveness. However, this thesis aimed to estimate the ability of LDW avoid crash. This challenge makes it important to understand what type of crashes safety systems address.

Additionally, when selecting a crash type as exposure for the induced exposure method, it is preferable if it is rather *clean*, 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. Furthermore, making sure case and control groups have similar system equipment configuration is also important as, Autonomous Emergency Braking or ESC may influence significantly, for instance. In this thesis effectiveness study vehicles with similar equipment levels were used. Rear-end crashes usually do not involve much driver handling issues compared to intersection crashes, for instance, and may therefore be a preferable crash type choice.

When using crash data to evaluate the safety benefits of a system, the analysis is limited to crashes and not the activation of the system. In the future, it would be desirable to use 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 would be possible. Speculating, if in-vehicle data on how often and in what situations the LDW system did intervene would be accessible, another type of analysis of the lane departure event would be possible. However, ultimately, it is of interest to analyse the safety benefits of LDW reducing injury crashes in real-world traffic and while the system is in the hands of ordinary drivers.

IMPLICATIONS OF RESULTS

INCREASING NUMBER OF LANE DEPARTURE WARNING SYSTEMS IN TRAFFIC

The results of this thesis show that there is a substantial amount of crashes potentially addressed by lane support systems such as LDW 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. However, the availability rate of new cars equipped by LDW systems as standard is still limited. In Sweden, only 10% of the new passenger car models on the market in 2016 were equipped with LDW systems as standard on all versions (Ydenius, 2017). In the same year 21% of available vehicle models offered LDW as optional equipment on all versions of the model. Twenty-three percent of the models were a mix of versions where LDW systems were standard in some versions but optional or missing in others. Unfortunately, for the remaining 46% of the passenger car models it was not possible as buyer to order a LDW-equipped version. Euro NCAP has an important role, as a driving force, to increase the installation rate of LDW systems in Europe. As lane support systems are entering the market at rapid pace, there will be better possibilities to make benefit estimates in the near future. More timely and precise studies can be made if crash data from many countries would be made available.

Setting the LDW effectiveness in a larger perspective and looking at a broader accident 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

Had all cars today already been equipped with LDW of the effectiveness evaluated in this study (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).

Over time the benefits for lane support systems could change. At a time when all cars in traffic have a lane support system the road environment may have changed as well. However, rapidly reaching full implementation of lane support systems is of public interest.

DRIVER ACCEPTANCE

For lane support systems to be beneficial, they must be active. These systems cannot reach their full potential if the driver chose to keep the system turned off. However, previous studies have pointed out that driver acceptance may affect the usage rate of LDW and LKA systems (Kidd et al., 2017; Reagan et al., 2017). 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 annoying warning signals. It is possible that providing scientific evidence of the safety benefits would affect driver acceptance and positively influence the implementation rate.

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 drive with the system turned on, 23% sometimes do, 7% never do, and 1% were unaware of the equipment. The most common reason to turn LDW off included finding the warning sound annoying. Even though 43% of the users answered that they received false unnecessary warning signals, 80% reported they would like 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.

With regard to the LDW system performance it is important for system reliability and thereby also acceptance to have an acceptable amount of false warnings. However, in general, user experience without false warning signals would possibly increase the acceptance. At the same time, a low usage rate may indicate the level of acceptance.

Observations at dealership service centres showed that the level of activation of support systems, e.g., LDW, lane departure prevention functioning as LKA, and active lane centring steering, varied between various car models (Lund, 2017). 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. The activation level tends to show higher numbers in more active lane keeping systems (75%) compared to 46% for LDW and 48% for lane departure prevention.

The activation status of LDW was observed in Honda vehicles at dealership service centres (Reagan and McCartt, 2016). LDW was activated in only 32% for Honda cars with model year 2013–2015 while Volvo cars with model year 2010–2012 were activated in 59% (Eichelberger and McCartt, 2014) of cases and 50% in Volvo cars with model year 2010–2016 (Reagan et al., 2017). However, the study by Reagan et al. (2017) excluded 17 Volvo cars where the default settings were set to *turned on at each ignition cycle*. If theses 17 vehicles had been included, the usage rate would be 67% (33/49) rather than 50% (16/32). It is unknown to what extent these service centre observations are valid also for traffic in environments where the systems have a greater potential. The usage rate in Volvo car models in Sweden remains unknown at the time of writing. Reagan et al. (2017) also showed that the LKA in Volvos was more often turned on than the LDW, in 86% (60/70). The Euro NCAP (2017b) test protocol state that the system Emergency Lane Keeping that is part of the lane support systems will only be tested and rewarded if it is activated as default at every drive cycle. Emergency lane keeping apply automatic steering correction when detecting the vehicle is about to drift beyond the edge of the road or into oncoming or overtaking traffic in adjacent lane similar to AES.

The activation levels presented by Reagan et al. (2017) are based on US data. However, the high effectiveness level showed 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 suggests, then the effectiveness of the LDW feature appears to be extremely effective. Speculating, the resulting effectiveness estimate in this thesis compared to US results in the Cicchino study indicates possibly higher activation levels in Sweden. Furthermore, driver monitoring alert systems and LDW as a warning system addressing fatigue in the early stages, 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 usage rate in Sweden compared to the US. Additionally, the US study by Reagan et al. (2017) involved cars of a somewhat newer model year and possibly improved human-machine interface. This aspect supports an opposing view, with a low usage rate in Sweden. However, the effectiveness estimate in the US study (Cicchino, 2017) involved older Volvo cars, model year 2008–2010. Still, newer cars from other manufacturers were included.

System developers attempt to avoid false warnings could result in calibration compromises affecting the end effectiveness. To reduce this problem a balance of robust and precise information about the lateral position of the vehicles is required. However, false warning signals need to be minimised for LDW systems to gain trust, acceptance and ultimately, usage, without losing effectiveness in cases where human-machine interface is an important factor to take into account. Reducing false positives becomes even more essential with regard to lane keeping systems intervening in steering. The lateral positioning information used for lane keeping systems need to be robust. However, the vehicle industry wants to sell cars widely. Therefore, methods for increasing the robustness are preferably scalable and rather independent of costly additional road infrastructure investments only functioning in limited geographic conditions.

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.

Today's in-vehicle systems are mainly relying on the traditional road design properties (painted lane markings, etc.) to function. If, the road infrastructure was designed with a particular purpose to support in-vehicle intervening and/or warning lane keeping systems, it should possibly be better adapted. For example, modern cars are already equipped with radars that could be applied to navigate by radar reflectors along the road side to avoid drifting out of the lane. Another example is that the road surface could be made darker to increase the lane marking contrast which facilitate the in-vehicle camera to better detect lane markings. Furthermore, placing road magnets below the surface of the road would support cars fitted with magnetic sensors (Torin et al., 2015).

Car technology has improved rapidly in the last few years while the road infrastructure design has not changed as fast. Investments in car technology have somewhat higher flexibility than road infrastructure investments, for instance in the geographical aspect. Therefore, it is not remarkable that cars have been adapted to the roads and not the other way around. At the same time, car manufacturers want to sell cars on many markets, and if car safety systems only work in a limited geographic area where the road has been adapted to the car, that car may not be appreciated extensively. This feeds the traditional road transport system design, where most of the development takes place on cars. New scalable road infrastructure innovations adapted to future cars is desirable.

Visions Zero states that responsibility for safety is shared. For roads holding high traffic volumes safety investments on the road can be efficient in reducing injuries. Implementing median barrier was shown to be highly effective in reducing injuries on undivided roads. Where the road remains undivided, rumble strips, safety zones or new innovations could be used to represent such road investments. For vehicle investments, automated steering, LKA, LDW, ESC, AES, Autonomous Emergency Braking and improved crashworthiness could potentially reduce injuries in lane departure crashes. However, while shortcomings identified by Stigson (2009) must be addressed (frontal crashes with heavy goods vehicles and with small overlap on undivided roads with a posted speed limit of 70 km/h), the importance of penetration of new safety technology in traffic must be stressed.

Ultimately, to get the maximum safety benefit out of the transport system, it would probably be preferable that infrastructure and in-vehicle systems work together as cooperative systems, where lane keeping support is integrated in vehicle and supported by infrastructure. Innovation and research could be of importance for future integrated safety solutions. Shared goals, coordination and collaboration between road authorities and the car industry are key factors as well as allowing iterative processes for development, testing and evaluation in environments relevant to real-world traffic conditions.

It is clear that the development of passenger cars is heading towards automation, which consequently leads to the car taking on more responsibility in safety issues. Lateral support systems are already showing great effectiveness in Level 1 of the SAE International automation level scale (Paper 2; Cicchino, 2017; Hickman, 2015), which looks promising for standalone in-vehicle systems at a higher level of automation. However, as automation is enhanced the requirements of lane keeping systems increases. The systems have to sustain control, detection and response in a changeable environment, covering for all kinds of possible *situations*, and operate continuously and everywhere. This leads to the requirement of incorporating redundancy in the systems, i.e., whereby additional or duplicate systems or equipment will be activated if any part of the system fails, safeguarding continued reliability by providing backup for critical functions. To achieve increased redundancy several sources of information are essential for providing in-vehicle systems to manage the lateral position. Different types of sensors could increase the redundancy. New innovative lane keeping support solutions have been developed by the automotive industry where the car interprets the road environment, i.e., using image processing technologies to detect road edges (Volvo, 2018). Also, lidar has been suggested as complementary to the camera for lane recognition in difficult weather conditions (Lee, 2018). Furthermore, preparation of the road environment adapted to support future cars, i.e.., implementation of radar reflectors (Voronov, 2016) or road magnets, may provide accuracy in lateral positioning and increase redundancy. These new technologies seem promising and could possibly increase the safety potential of LDW-like systems.

LIMITATIONS

The main limitations of this thesis concern the limited availability and size in data. The methods applied used data efficiently, where the two papers complement each other. The material in Paper 1 was limited in size, 104 real-world crashes. Only data collected over one year was included. However, each crash involved a multitude of detailed data. The material in Paper 2 was limited to involving Volvo passenger cars only. The systems of other manufacturers may perform differently, but have as yet not been sufficiently disseminated in Sweden.

The increasingly widespread penetration of LDW in Sweden began when the Volvo V70II from model year 2008, which included LDW as optional equipment, became a popular choice of car for many consumers. The widespread penetration among Volvo car users in Sweden was the reason for exclusively examining LDW in Volvo cars, and not including any other manufacturers. Evaluations comprising a mix of manufacturers and few cases can experience difficulties due to the cases as well as the control group of such evaluation would be varied, not only the LDW features but also additional safety related equipment, needed to control for, would differ. The results were obtained with a given car population mixing newer and older cars. The results can be viewed as one measuring point, a snapshot in a continually changing world.

It is possible to generalise the results to some extent. The results of this thesis were based on crashes in Swedish conditions. Therefore, the results may not be directly applicable to conditions different from the conditions in Sweden. However, the results are expected to be relevant for countries with similar road traffic systems.

Even though the material was limited in size, two exposure approaches obtaining similar results, indicate robustness. Calculations were performed in relation to several non-sensitive crash types where a driver was injured. Calculations were also performed in relation to rear-end impacts only, which was assumed to not be affected by an LDW system to any particular extent.

It has to be mentioned that, of the cars equipped with LDW/LKA in this thesis, most of the cars were equipped with LDW (93%) rather than LKA (7%). Hypothetically in a best case scenario, it would be preferable to use data where each car model could only be equipped by LDW or LKA, not both. Then, perfect control models would be usable. However, the data is not of that character. In reality, the car models can be equipped with any of the systems, the control group of cars is therefore the same for the two types of equipped cars. Therefore, excluding LKA cars would result in methodological issues where LKA control cars cannot be separated from LDW control cars. However, calculated safety benefits are mainly related to LDW. Further research is still needed to evaluate the safety benefits of LKA systems. For instance, it is still unknown how LKA systems perform with regard to the interaction between system and driver in the hands of drivers.

A further potential limitation is the fact that the LDW/LKA-equipped cars were also fitted with a number of other safety features included in the Volvo Driver Support package. Though both the LDW/LKA- and non-LDW/LKA-equipped cars were fitted with low-speed Autonomous Emergency Braking, the former was also equipped with Adaptive Cruise Control (97% of LDW/LKA and 1% of non-LDW/LKA cars), Forward Collision Warning (98%, 1%), and Collision Mitigation by Braking (97%, 1%), which can be expected to reduce rear-end crashes constituting the exposure. Therefore, it may be suggested that the present results are conservative.

To check some significant variables that may influence the results, the distribution of LDW/LKA and non-LDW/LKA fleets were compared and average values were calculated. The comparison included cars involved in crashes on roads with posted speed limits of 70 km/h and above, without snow or ice on the road surface (n=54, n=318). The driver age for LDW/LKA and non-LDW/LKA cars had similar distributions (42.6, 41.7 years). The average car model year was 2013 for both LDW/LKA and non-LDW/LKA cars. The engine power in LDW/LKA-equipped cars was higher compared to non-equipped cars (135, 116 kW). Regarding speed limits, LDW/LKA cars were slightly more often crashing at lower speed limits (83, 85 km/h). This could indicate that incidents in the higher speed range resulted in accidents less frequently due to the activation of LDW in this speed range. There were male drivers in 72% of the LDW/LKA cars and 70% of the non-LDW/LKA cars.

FUTURE RESEARCH NEEDS

In this thesis the safety potential and the effectiveness of LDW have been studied, and significant safety benefits have been revealed. However, LDW 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 lane support systems, road infrastructure innovations adapted to support future cars are desirable. Therefore, the potential safety benefits of innovations such as road magnets and radar reflectors require further consideration.

To achieve the goal of increasing the knowledge of a holistic and systematic view of lane keeping, 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 systems, such as LKA and LDW, in real-world traffic, as well as a variety of markets, manufacturers and system specifications for future road and infrastructural interventions, such as lane markings, rumble strips and barriers.

CONCLUSION

This thesis shows that the safety potential of LDW is profoundly significant in preventing fatal crashes and that it is highly effective in reducing injury crashes.

Using Swedish in-depth data, the potential crash reduction of LDW systems was found to be 33–38% for all fatal head-on and single passenger car occupant crashes during the year 2010. These crashes in the identified target population for lane support systems such as LDW involved drifting and occurred on roads with visible lane markings, sign posted speed limits of 70 km/h and above and without rumble strips on the corresponding lane departure side. The benefit range is due to the inclusion or exclusion of a few crashes involving excessive speeding.

Almost half of all fatal passenger car occupant crashes in Sweden during 2010 were related to lane departure without prior loss of control, and accounted for 61% of head-on, single passenger car, and overtaking crashes. The majority of lane departure without prior loss of control crashes in this thesis (81%) were identified as those involving unintentional drifting. These crashes seldom involved post-loss of control, and therefore drivers were often still in the control loop and could potentially respond to warning signals, while others were not able to respond due to distraction or fatigue.

This result applies to Swedish conditions and the extent of generalisation would be examined in further research. However, it is clear that a significant portion of lane departure crashes without loss of control worldwide results in fatalities.

Swedish mass data was analysed covering real-world traffic of Volvo passenger cars, model year 2007–2015, and police-reported crashes occurred during the period January 2007 to September 2015. Volvo's LDW systems reduced head-on and single car injury crashes with speed limits between 70–120 km/h and with dry or wet road surfaces, i.e., not covered by ice or snow, by 53%. This reduction corresponded to a reduction of 30% for all head-on and single car driver injury crashes including all speed limits and all road surface conditions.

Lane support systems attempt to add additional safety along the integrated safety chain where LDW systems support the driver to stay within the lane in *normal driving*. Lane keeping is important as it generally is a precondition for safe driving on the roads. This thesis showed that LDW has significant safety benefits in real-world traffic and has a clear place in a *safe system* approach, both in the Vision Zero model and the integrated safety chain. LDW is a complement to ESC and can avoid critical situations before Autonomous Emergency Steering or Autonomous Emergency Braking kicks in.

Concluding, the LDW system, developed by the vehicle industry aiming to avoid unintentional lane drifting, is part of a system consisting of detectable lane markings, provided by the road authorities. Both components are essential and therefore the responsibility for safety is placed both on the road authorities and the vehicle industry. Based on this thesis, LDW systems have been shown to be effective in real-world traffic. In fact, the figures suggest that LDW systems is one of the most important safety technologies available. Hence, besides safeguarding that the LDW implementation rate is increased, establishing detectable lanes is also essential.

RECOMMENDATIONS

LDW assigns responsibility for safety on relatively high speed roads to the car to a greater extent. The LDW system is a safety barrier in the integrated safety chain which could be complemented by, for example, ESC, Autonomous Emergency Braking and ultimately by crashworthiness. However, the whole concept is based on drivers not exceeding posted speed limits and more support is needed in this area, e.g., automatic speed limiters connected to road sign recognition features or insurance plans connected to Intelligent Speed Adaptation.

Though the results in this thesis are promising, it is essential that future research is carried out on larger data sets involving a wider vehicle fleet, in order to estimate the safety benefits of technologies for intervening and supporting lane keeping, e.g., LKA, LDW and AES. Preferably, future research would be carried out under real-world conditions, and differentiate the effectiveness between human-machine interfaces proposed by different manufacturers, e.g., haptic, visual and audible warnings. The number of crashes involving cars with LDW systems in Sweden is still too low for statistical analysis identifying performance differences between different manufacturers and their different technical solutions. However, it is recommended to use crash data in multi-national studies for analysis of this kind. For precise effectiveness estimation it is a precondition that data on the actual car equipment is registered and made available to researchers, even if the equipment in this thesis was optional.

Lane markings became an important linking feature for roads to be readable for modern cars. Also, road design and maintenance are essential for readability. Modern cars are equipped with sensor technology, i.e., LDW with the ability to localise unreadable or missing lane markings and ESC that can detect low friction on the road. This sensor technology could potentially be used to collect data about the readability of lane markings. This data should be reported and made available to increase the effectiveness of road maintenance. Resources would be more precisely directed when more precise information of place, time and magnitude, for the need of maintenance was used.

Further, lane keeping support systems must be able to perform when they are most needed, i.e., in difficult road conditions where the lane markings are covered by snow or ice. Considering this, alternatives to painted lane marking needs to be developed and evaluated. Cameras and road edge detection algorithms are continually being improved, which must be taken into account when exploring future solutions. It is suggested that a new lane detection system could make use of already implemented sensor technologies, e.g., radar and lidar, but also to enforce road lane information and to make lanes more detectable. For efficiency, the lane keeping system has to be developed in dialogue between road authorities and the car industry.

Lane keeping systems that intervene by steering must be able to accurately detect potential lane drifting and act accordingly. It is vital that the system understands at what point and to what magnitude it should intervene in any given situation. Robust data about a vehicle's lateral position is a precondition for reliable automatic steering and it is essential that the road infrastructure can support in-vehicle systems with this information. As steering control gradually shifts from the driver to the car, lane drifting needs to be tackled holistically. Furthermore, 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 lane keeping systems should consider an integrated approach, taking into consideration the role of both road infrastructure and vehicle systems.

Lane keeping support systems, such as LDW, is one of the most important safety features for the foreseeable future, where the share of unintentional drifting crashes is expected to increase. For that reason, different organisations and road safety stakeholders should promote the fitment of LDW systems in new cars and speed up the implementation in traffic.

REFERENCES

ACEA (2017). Average Vehicle Age. *European Automotive Manufactures Association*. Available at: http://www.acea.be/statistics/tag/category/average-vehicle-age. Accessed: September 18, 2017.

Anund A, Hjälmdahl M, Sehammar H, Palmqvist G, Thorslund B (2005). Placement and Design of Milled Rumble Strips on Centre Line and Shoulder — a Driving Simulator Study. *Swedish National Road and Transport Research Institute (VTI), Sweden.* Report ID: 523A.

Anund A, Kecklund G, Vadeby A, Hjälmdahl M, Åkerstedt T (2008). The Alerting Effect of Hitting a Rumble Strip — a Simulator Study with Sleepy Drivers. *Accident Analysis and Prevention*, 40(6), 1970–6.

Elvik R (2017). Road Safety Effects of Roundabouts: A Meta-Analysis. *Accident Analysis and Prevention*, 99(A), 364–371.

Belin MÅ (2015). Nollvisionen inom Trafiksäkerhetsområdet. In: Andersson R, Nilsen P. *Personsäkerhet: Teori och Praktik.* Swedish Civil Contingencies Agency (MSB), MSB944, 249–261. ISBN: 978-91-7383-620-3.

Belin MÅ, Tillgren P, Vedung E (2012) Vision Zero – a Road Safety Policy Innovation, *International Journal of Injury Control and Safety Promotion*, 19:2, 171–179.

Bil Sweden (2018). *Statistics. Automotive holdings*. Available at: http://www.bilsweden.se/statistik/fordonsbestand. Accessed: March: 26, 2018.

BMW (2016). *The All-New 2017 BMW 5 Series: Performance, Redefined. BMW Group. Press Release: November 13, 2016*. Available at: https://www.press.bmwgroup.com/usa/article/detail/T0264802EN_US/the-all-new-2017-bmw-5-series:-performance-redefined. Accessed: December 10, 2017.

Bosch (2008). *Automotive Technology. Electronic Stability Control ESC on the Rise. Nearly Every Fifth New Car Equipped with Live-Saving Technology*. Available at: http://www.bosch.co.jp/en/press/rbjp-0907-03.asp. Accessed: September 18, 2017.

Braitman KA, McCartt AT, Zuby DS, Singer J (2010). Volvo and Infiniti Drivers' Experiences with Select Crash Avoidance Technologies, *Traffic Injury Prevention*, 11(3), 270-278, DOI: 10.1080/15389581003735600

CARE (2016). *Annual Accident Report 2016*. Community Road Accident Database. Available at: https://ec.europa.eu/transport/road_safety/specialist/statistics_en. Accessed: June 28, 2017.

Carlsson A (2009). Evaluation of 2+1-Roads with Cable Barrier. Final report. *National Road and Transport Research Institute (VTI).* Report ID: 636A.

Cicchino JB (2017). *Effects of Lane Departure Warning on Police-Reported Crash Rates*. Insurance Institute for Highway Safety, Arlington, USA. Available at: http://www.iihs.org/frontend/iihs/documents/masterfiledocs.ashx?id=2142. Accessed: December 17, 2017.

Donnell ET, Garvey PM, Bauer KM, Harwood DW, Gilmore DK, Dunn JM, … Sommer HJ (2009). Guidance for the Design and Application of Shoulder and Centerline Rumble Strips. *Transportation Research Board, USA.*

Eichelberger AH, McCartt AT (2014). Volvo Drivers' Experiences with Advanced Crash Avoidance and Related Technologies. *Traffic Injury Prevention.* 15(2), 187–195.

eSafety Forum (2006). *eSafety Compendium*. Available at: http://www.czechspaceportal.cz/files/files/storage/eSafety/esafety_compendium_may_2006.pdf. Accessed: December 10, 2017.

Elvik R (2009). The Power Model of the Relationship Between Speed and Road Safety. *Institute of Transport Economics, Norwegian Centre for Transport Research*. Report ID: 1034/2009.

Eugensson A, Ivarsson J, Lie A, Tingvall C (2011). Cars are driven on roads, joint visions and modern technologies stress the need for co-operation. Paper no. 11-0352. In: Proceedings of the 22nd International Technical Conference on the Enhanced Safety of Vehicles. Washington, DC.

European Commission (2008). Proposal for a Regulation of the European Parliament and the Council Concerning Type-Approval Requirements for the General Safety of Motor Vehicles. COM(2008) 316 final. Brussels.

European Commission (2017). *Mobility and Transport - Road Safety*. Available at: https://ec.europa.eu/transport/road_safety/specialist/statistics_en. Accessed: June 28, 2017.

European Commission (2016). *Study on Serious Road Traffic Injuries in the EU*. Available at: https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/injuries_study_2016.pdf. Accessed: June 28, 2017.

Euro NCAP (2016). *Autonomous Emergency Braking*. Available at: http://www.euroncap.com/en/vehicle-safety/the-rewards-explained/autonomous-emergency-braking/. Accessed: December 16, 2016.

Euro NCAP (2017a). *Land Rover Discovery Sport 2014*. Available at: https://www.euroncap.com/sv/results/land-rover/discovery-sport/7873. Accessed: December 10, 2017a.

Euro NCAP (2017b). *Test Protocol – Lane Support Systems. Version 2.0.1*. Available at: https://cdn.euroncap.com/media/32287/euro-ncap-lss-test-protocol-v201.pdf. Accessed: December 20, 2017

Evans L (1998). Antilock Brake Systems and Risk of different Types of Crashes in Traffic. Paper No. 98-S2-O-12. In: Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles. Windsor, ON, Canada.

FIA Foundation (2008). *FIA Foundation for the Automobile and Society, Europe Plays Catch Up with US on Key Car Safety Technology*. Press Release: May 21, 2008. Available at: http://www.chooseesc.eu/download/press/ESC%20release1%20210508.pdf. Accessed: October 13, 2017.

Fildes B, Keall M, Bos N, Lie A, Page Y, Pastor C, … Tingvall C (2015). Effectiveness of Low Speed Autonomous Emergency Braking in Real-World Rear-End Crashes. *Accident Analysis Prevention.* 81, 24–29.

Folksam (2017). *Folksam Report "How Safe is Your Car?"*. Available at: https://www.folksam.se/media/S4534_Folksams_report_How_safe_is_your_car_2017_eng_tcm5-34877.pdf. Accessed: January 12, 2018.

Haddon W Jr (1970). On the Escape of Tigers: An Ecologic Note. *Technology Review, Massachusetts Institute of Technology*, 72(7), 44–53.

Haddon W Jr (1980a). Advances in the Epidemiology of Injuries as a Basis for Public Policy. *Public Health Reports*, 95(5), 411-21.

Haddon W Jr (1980b). Options for the Prevention of Motor Vehicle Crash Injury. Israel Journal of Medical Sciences, 16(1), 45-65.

Hickman JS, Guo F, Camden MC, Hanowski RJ, Medina A, Mabry JE (2015). Efficacy of Roll Stability Control and Lane Departure Warning Systems using Carrier-Collected Data. *Journal of Safety Research*, 52, 59-63.

Hummel T, Kuehn M, Bende J, Lang A (2011). Advanced Driver Assistance Systems—An Investigation of Their Potential Safety Benefits Based on an Analysis of Insurance Claims in Germany. *German Insurance Association Insurers Accident Research*, 2011.

Høye A (2012), Trafikksikkerhetshåndboken 4 utgave. *Institute of Transport Economics, Norwegian Centre for Transport Research*. . ISBN 978-82-480-1399-0.

Institute of Transport Economics, Norwegian Centre for Transport Research (2017a). *Trafikksikkerhetshåndboken. 3.13 Vegoppmerking*. Available at: https://tsh.toi.no/doc662.htm#anchor_22179-30. Accessed: December 8, 2017.

Institute of Transport Economics, Norwegian Centre for Transport Research (2017b). *Trafikksikkerhetshåndboken. 3.26 Forsterket og Profilert Midtoppmerking*. Available at: https://tsh.toi.no/326-forsterket-midtoppmerking.htm#anchor_147175-300. Accessed: December 11, 2017.

Insurance Institute for Highway Safety, Highway Loss Data Institute (2012). *Crash Avoidance Features Reduce Crashes, Insurance Claims Study Shows; Autonomous Braking and Adaptive Headlights Yield Biggest Benefits*. Available at: http://www.iihs.org/iihs/news/desktopnews/crash-avoidance-features-reduce-crashes-insurance-claims-study-shows-autonomous-braking-and-adaptive-headlights-yield-biggest-benefits. Accessed: December 19, 2017.

Insurance Institute for Highway Safety, Highway Loss Data Institute (2015). 2013–15 Honda Accord Collision Avoidance Features. 32(33). Available at: http://www.iihs.org/media/98e59e28-6667-478c-8fb2-5dd51865fa60/. Accessed: January 15, 2016.

Insurance Institute for Highway Safety, Highway Loss Data Institute (2016). Most Honda Owners Turn Off Lane Departure Warning. 51:1. Available at: http://www.iihs.org/iihs/sr/statusreport/article/51/1/4. Accessed: December 19, 2017.

Jermakian JS (2011). Crash Avoidance Potential of Four Passenger Vehicle Technologies. *Accident Analysis and Prevention*, 43, 732–740.

Johansson R (2009). Vision Zero - Implementing a Policy for Traffic Safety. *Safety Science*, 47(6), 826–831.

Karabatsou V, Pappas M, Elslande P, Fouquet K, Stanzel M, Fildes B, Lange R (2007). A-Priori Evaluation of Safety Functions Effectiveness—Methodologies. *Deliverable D4.1.3 of the TRACE project. Project No.: 027763*. Available at: http://www.trace-project.org/publication/archives/trace-wp4-d4-1-3.pdf. Accessed: December 10, 2017.

Kidd DG, Cicchino JB, Reagan IJ, Kerfoot LB (2017). Driver Trust in Five Driver Assistance Technologies Following Real-World Use in Four Production Vehicles. *Traffic Injury Prevention*, 18(S1), S44–S50.

Krafft M, Kullgren A, Lie A, Tingvall C (2009). From 15% to 90% ESC Penetration in New Cars in 48 Months—the Swedish Experience. Paper no. 09-0419-O. In: Proceedings of the 21st International Technical Conference on the Enhanced Safety of Vehicles. National Highway Traffic Safety Administration, Washington, DC.

Kuehn M, Hummel T, Bende J (2009). Benefit Estimation of Advanced Driver Assistance Systems for Cars Derived from Real-Life Accidents. Paper no. 09-0317. In: Proceedings of the 21st International Technical Conference on the Enhanced Safety of Vehicles. National Highway Traffic Safety Administration, Washington, DC.

Kullgren A, Lie A, Tingvall C (2010). Comparison between Euro NCAP Test Results and Real-World Crash Data. *Traffic Injury Prevention*, 11, 587–593.

Larsson P, Dekker SWA, Tingvall C (2010). The Need for a Systems Theory Approach to Road Safety. *Safety Science*, 48(9), 1167–1174.

Lee U, Jung J, Jung S, Shim DH (2018). Development of a Self-Driving Car that Can Handle the Adverse Weather. International Journal of Automotive Technology 19, 191.

Lie A (2012a). Nonconformities in Real-World Fatal Crashes — Electronic Stability Control and Seat Belt Reminders. *Traffic Injury Prevention*, 13, 308–314.

Lie A (2012b). Managing Traffic Safety — an Approach to the Evaluation of New Vehicle Safety Systems. (Doctoral Thesis Karolinska Institutet, Stockholm). Accessed: December 10, 2017.

Lie A, Krafft M, Kullgren A, Tingvall C (2008). Intelligent Seat Belt Reminders — Do They Change Driver Seat Belt Use in Europe? *Traffic Injury Prevention*, 9(5), 446–449.

Lie A, Tingvall C (2002). How do Euro NCAP Results Correlate with Real-Life Injury Risks? A Paired Comparison Study of Car-to-Car Crashes. *Traffic Injury Prevention*, 3, 288–293

Lie A, Tingvall C, Krafft M, Kullgren A (2006). The Effectiveness of Electronic Stability Control (ESC) in Reducing Real Life Crashes and Injuries. *Traffic Injury Prevention*, 7, 38–43.

Lund A (2017). *Vehicle Safety Initiatives at Insurance Institute for Highway Safety: Crashworthiness, Crash Avoidance, and Automated Driving.* Automotive Safety Council Annual General Meeting; March 24, 2017. Aventura, USA.

Lyon C, Persaud B, Eccles K (2015). Safety Evaluation of Centerline plus Shoulder Rumble Strips. *Office of Safety Research and Development, Federal Highway Administration*, USA.

Mastinu G, Ploechl M (2014). *Road and Off-road Vehicle System Dynamics Handbook*. Boca Raton: Taylor & Francis Group.

Mehler B, Reimer B, Lavalliere M, Dobres J, Coughlin JF (2014). *Evaluating Technologies Relevant to the Enhancement of Driver Safety*. Washington: AAA Foundation for Traffic Safety.

Mercedes-Benz (2017). *Intelligent Drive next Level as part of Driving Assistance Package. The Extended Intelligent Drive Driving Assistance Package in the new E-Class Provides More Comfort and Less Stress on the Road through Semi-Automated Driving. Controlled avoidance for more safety*. Available at: https://www.mercedes-benz.com/en/mercedes-benz/innovation/with-intelligent-drive-more-comfort-in-road-traffic/. Accessed: December 10, 2017.

Najm WG, Koopmann J, Boyle L, Smith DL (2002). *Development of Test Scenarios for Off-roadway Crash Countermeasures Based on Crash Statistics*, Washington: NHTSA.

Najm WG, Smith JD, Yanagisawa M (2007). *Pre-crash Scenario Typology for Crash Avoidance Research*. Technical report, Washington, NHTSA.

Nissan Motor Corporation (2005) *Annual Report 2004*. Tokyo, Nissan Motor Corporation.

Nissan (2017). *Nissan Motor Corporation. Autonomous Emergency Steering System*. Available at: http://www.nissan-

global.com/EN/TECHNOLOGY/OVERVIEW/autonomous_emergency_steering_system.html. Accessed: September 18, 2017.

Persaud BN, Retting RA, Lyon CA (2004). Crash Reduction Following Installation of Centerline Rumble Strips on Rural Two-Lane Roads. *Accident Analysis and Prevention*, 36(6), 1073-9.

Popular Mechanics Magazine February (1953). Volume 99 - Number 2 by Jr. H. H. Windsor. Available at: https://books.google.se/books?id=x9wDAAAAMBAJ&printsec=frontcover&hl=sv#v=onepage&q&f=false. Accessed: December 8, 2017.

Ragnøy A, Skaar B (2014). *Trafikksikkerhetseffekt av forsterket midtoppmerking (FMO) Før / Etter – analyse*, NORTEK Conference on road markings, 2014, Lillehammer, Norway.

Rajamäki R (2010). Impact of Rumble Strips on Road Accidents, Helsingfors, ISBN 978-952-255-585-4.

Reagan IJ, McCartt AT (2016). Observed Activation Atatus of Lane Departure Warning and Forward Collision Warning of Honda Vehicles at Dealership Service Centers. *Traffic Injury Prevention*, 17, 827–32.

Reagan IJ, Cicchino JB, Kerfoot LB, Weast RA (2017). *Crash Avoidance and Driver Assistance Technologies – Are They Used?* Arlington: Insurance Institute for Highway Safety.

Räsänen M (2011). Räfflor och Markering av Breda Mittremsor som Trafiksäkerhetsåtgärder - Finska Resultat. NORTEK Conference on road markings, 2011, Rovaniemi, Finland.

SAE International (2016). *SAE International standard J3016_201609. Surface Vehicle Recommended Practice. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*. SAE International, USA.

Sayed T, deLeur P, Pump J (2010). Impact of Rumble Strips on Collision Reduction on Highways in British Columbia, Canada: Comprehensive Before-and-After Safety Study. *Transportation Research Record 2148, Transportation Research Board.* Washington, 9–15.

Sferco R, Page Y, Coz JY, Fay A (2001). Potential Effectiveness of Electronic Stability Programs (ESP)—what European Field Studies Tell Us. Paper no. 2001-S2-O-327. In: Proceedings of the 17th International Technical Conference on the Enhanced Safety of Vehicles, Amsterdam, Netherlands.

Schoeneburg R, Breitling T (2005). *Enhancement of Active & Passive Safety by Future Pre-safe Systems.* Paper no. 05-0080. In: Proceedings of the 19th International Technical Conference on the Enhanced Safety of Vehicles; Washington DC, USA.

Stanley LM (2006). *Haptic and Auditory Interfaces as a Collision Avoidance Technique During Roadway Departures and Driver Perception of these Modalities*. (Doctoral Thesis, Montana State University-Bozeman, Bozeman Montana). Available at: https://scholarworks.montana.edu/xmlui/handle/1/2338. Accessed: December 28, 2017.

Stigson H (2009). A Safe Road Transport System: Factors Influencing Injury Outcome for Car Occupants. (Doctoral Thesis, Karolinska Insitutet, Department of Clinical Neuroscience, Stockholm). Available at: https://openarchive.ki.se/xmlui/bitstream/handle/10616/38085/thesis.pdf?sequence=1&isAllowed=y. Accessed: December 28, 2017.

Strandroth J, Rizzi M, Sternlund S, Lie A, Tingvall C (2011). The Correlation Between Pedestrian Injury Severity in Real-Life Crashes and Euro NCAP Pedestrian Test results. *Traffic Injury Prevention*, (12)6, 604-613.

Strandroth J, Rizzi M, Olai M, Lie A, Tingvall C (2012a). The effects of Studded Tires on Fatal Crashes with Passenger Cars and the Benefits of Electronic Stability Control (ESC) in Swedish Winter Driving. *Accident Analysis Prevention*, 45, 50–60.

Strandroth J, Sternlund S, Tingvall C, Johansson R, Rizzi M, Kullgren A (2012b). A New Method to Evaluate Future Impact of Vehicle Safety Technology in Sweden. *Stapp Car Crash Journal*. 2012;56:497–509.

Strandroth J, Sternlund S, Lie A, Tingvall C, Rizzi M, Kullgren A, Fredriksson R (2014). Correlation Between Euro NCAP Pedestrian Test Results and Injury Severity in Injury Crashes with Pedestrians and Bicyclists in Sweden. *Stapp Car Crash Journal*, 58, 213-231.

Strandroth J (2015). *Identifying the Potential of Combined Road Safety Interventions. A Method to Evaluate Future Effects of Integrated Road and Vehicle Safety Technologies*. (Doctoral Thesis, Chalmers University of Technology, Department of Applied Mechanics, Gothenburg).

Strandroth J, Nilsson P, Sternlund S, Rizzi M, Krafft M (2016). Characteristics of Future Crashes in Sweden – Identifying Road Safety Challenges in 2020 and 2030. In: Proceedings of the International Research Council on the Biomechanics of Injury Conference, 47–60, Malaga Spain.

Swedish Road Administration (1996). *Nollvisionen – En idé om ett Vägtransportsystem utan Hälsoförluster. [Vision Zero – An idea of a road transport system without health losses]*. Borlänge, Swedish Road Administration.

Swedish Road Administration (2002). *VU94S-2. 4 Trafikteknisk standard. 4.7 Sektionsstandard*. Vägverket Publication:114. Available at: https://www.trafikverket.se/contentassets/acbe28f56ecd45e8b8a51f10830d1c0e/filer/d4_07_sektionsstandard.pdf. Accessed: December 28, 2017.

Swedish Road Administration (2005). *In-depth studies of fatal accidents save lives*. Available at: https://trafikverket.ineko.se/Files/sv-SE/10293/RelatedFiles/88654_in_depth_studies_of_fatal_accidents_save_lives.pdf. Accessed: December 16, 2016.

Swedish Road Administration (2006). *Vägar och Gators Utformning (VGU). Säker Framkomlighet*. Vägverket Publication:37. Available at: https://trafikverket.ineko.se/Files/sv-SE/11139/RelatedFiles/2006_37_vgu_saker_framkomlighet_preliminara_riktlinjer.pdf. Accessed: December 28, 2017.

Swedish Transport Administration (2012a). *Road Safety: Vision Zero on the Move*. Borlänge, Swedish Transport Administration.

Swedish Transport Administration (2012b). *Utvärdering av Nya Hastighetsgränser. Slutrapport.* Borlänge, Swedish Transport Administration.

Swedish Transport Administration (2015a). *Analysis of Road Safety Trends 2014. Management by Objectives for Road Safety Work towards the 2020 Interim Targets*. Borlänge, Sweden: Swedish Transport Administration.

Swedish Transport Administration (2015b). *Minskad Andel Alkohol och Narkotika i Trafiken—Gemensam Strategi för År 2015*–2020 [Reduced Proportion of Alcohol and Drugs in Traffic for the Years 2015 - 2020]. Borlänge, Swedish Transport Administration.

Swedish Transport Administration (2016). *Översyn av Etappmål för Säkerhet på Väg till 2020 och 2030, med en Utblick mot 2050.* Borlänge, Swedish Transport Administration.

Swedish Transport Administration (2017). *Analys av Trafiksäkerhetsutvecklingen 2016. Målstyrning av Trafiksäkerhetsarbetet mot Etappmålen 2020.* Borlänge, Swedish Transport Administration.

Swedish Parliament (1997a). *Parliament Transport and Communication Committee Report.1997/98:TU4*. Stockholm, Swedish Parliament.

Swedish Parliament (1997b). Swedish Parliament Protocol 1997/98:13. Decision on Vision Zero for road traffic safety. Stockholm, Swedish Parliament.

Sharfi T, Shinar D (2014). Enhancement of Road Delineation can *Reduce* Safety. *Journal of Safety Research*, 49, 61-68.

Tingvall C (1995). *The Vision Zero – A Road Transport System Free From Health Losses. Transportation, traffic safety and health: the new mobility*. In: Proceedings of the 1st International Conference Gothenburg, Sweden, 1995. Springer Verlag Berlin 35-57. ISBN 3-540-62524-0

Tingvall C, Lie A, Johansson R (2000). Traffic safety in planning - a multidimensional model for the Zero Vision. Proc. Transportation, Traffic safety and Health. New Mobility. 2nd International Conference, 1996. Springer Verlag Berlin 61-69. ISBN 3-540-67443-8.

Tingvall C (2008). Distraction from the View of Governmental Policy Making. In: Young K, Lee JD, Regan MA, *editors. Driver Distraction: Theory, Effects, and Mitigation.* Australia. CRC Press.

Torbic D, Bauer K, Hutton J (2014). *Delta Region Transportation Development Program: Rural Safety Innovation Program Evaluation, Final Report*, Federal Highway Administration, Washington, DC.

Torin A, Hellman S, Svensson M (2015). *Magnets in a carriageway part 2; magnetic background noise and markers pattern study.* Technical report, Gothenburg, ÅF. Available: http://www.astazero.com/wp-content/uploads/2015/10/Bergman-%C3%85F_Magnets_in_a_carriageway_part_2_-_AstaZero_Researchers_Day_short_public.pdf. Accessed December 16, 2016.

Trafikanalys (2018). Road Traffic Injuries 2010–2017 [official statistics]. Available at: http://www.trafa.se/vagtrafik/vagtrafikskador/. Accessed May 14, 2018.

Vadeby A (2016). *Traffic Safety Effects of Narrow 2+1 Roads with Median Barrier in Sweden*. Proceedings of RS5C conference in Rio de Janeiro, Brazi.

Vadeby A, Anund A, Björketun U, Carlsson A (2013). Safe Accessibility, Summarized Results. *Swedish National Road and Transport Research Institute (VTI), Sweden.* Report ID: 790.

Vadeby A. Anund A (2017). Effectiveness and Acceptability of Milled Rumble Strips on Rural Two-Lane Roads in Sweden. European Transport Research Review, 9, 29.

Vadeby A, Björketun U (2016). Safe Accessibility – Traffic Safety Evaluation 2013 and 2014. *Swedish National Road and Transport Research Institute (VTI), Sweden.* Report ID: 7-2016.

Vadeby A, Lundberg T, Gustafsson S, Ekström C, Andrén P (2016). Säker Framkomlighet. Spårutveckling på Mitträfflade, Mötesfria och Riktningsseparerade Vägar. *Swedish National Road and Transport Research Institute (VTI), Sweden.* Report ID: 10-2016.

Visvikis C, Smith TL, Pitcher M, Smith R (2008). *Study on Lane Departure Warning and Lane Change Assistant Systems*. TRL Project Report PPR 374. Wokingham, Transport Research

Laboratory. Available at: http://www.trl.co.uk/umbraco/custom/report_files/PPR374.pdf. Accessed: December 10, 2017.

Volvo (2017). *Volvo Cars' New XC60 SUV Will Automatically Steer You Out of Trouble.* Press Release: February 28, 2017. ID: 204531. Available at: https://www.media.volvocars.com/global/en-gb/media/pressreleases/204531/volvo-cars-new-xc60-suv-will-automatically-steer-you-out-of-trouble. Accessed: December 10, 2017

Voronov A, Hultén J, Wedlin J, Englund C (2016). Radar reflecting pavement markers for vehicle automation. Available at: https://doi.org/10.13140/RG.2.1.1695.8323. Accessed June 21, 2016.

Wilmink I, Janssen W, Jonkers E, Malone K, Noort M, Klunder G, … Schönebeck S (2008). *Socio-Economic Impact Assessment of Stand-Alone and Co-Operative Intelligent Vehicle safety Systems (IVSS) in Europe.* Deliverable D4 of the eIMPACT Project. Delft, Netherlands.

Wilson BH, Stearns MD, Koopmann J, Yang CYD (2007). *Evaluation of a Road-Departure Crash Warning System.* Report No. DOT HS 810 854. Washington, National Highway Traffic Safety Association.

World Health Organization (2017). *Media Centre. Road traffic injuries. Fact sheet*. Available at: http://www.who.int/mediacentre/factsheets/fs358/en/. Accessed: June 28, 2017.

Ydenius A. (2017). Personal Communication – Electronic Mail Conversation, November 23, 2017. Folksam Research, Stockholm.