Traffic Safety Benefit of A Lane Departure Warning System

- A Retrospective Assessment of the Crash Avoidance Effect Based on Real World Crash Data in Sweden -

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**ABSTRACT:** Lane departures can have serious consequences when resulting in run-off-road and oncoming crashes and effective countermeasures are of utmost importance. The objective of this study was to evaluate the real-world crash avoidance effectiveness of a Lane Departure Warning (LDW) crash avoidance system, introduced as optional mounted equipment in Volvo car models in 2008. Situations addressed by the LDW system—single-vehicle run-off-road and oncoming crashes in which the driver unintentionally leaves the lane without loss of control—were identified in insurance claims data. To evaluate the crash avoidance effect, crash rates were calculated and compared for vehicles with and without LDW. The rate of run-off-road crashes without traction loss was reduced by 30% if the vehicle had LDW (RD = 0.20, 80% CI [0.03, 0.37]). There were not enough oncoming crashes to evaluate them statistically. The analysis revealed that the system has a large crash avoidance effect in real-world traffic, and the findings are promising for further refinement of these technologies, which target the avoidance of run-off-road and oncoming crashes.

**KEY WORDS:** Safety, Active Safety, Effectiveness Study, Lane Departure Warning, Real World Crash Data [C1]

1. Introduction

Lane departures occur when a vehicle crosses a lane marking, either near the road edge or in the center of the road. Crashes resulting from lane departures represent a high proportion of all severe road crashes and casualties worldwide. In traffic accident statistics, these crashes are often described generally as ‘single crashes’, ‘run-off-road crashes’ or ‘oncoming crashes’. The focus in this study is on the active safety technologies developed to prevent or mitigate crashes initiated by unintended lane departures. Hence, both conflict situation identification and pre-crash factor analysis were essential for defining the target crash situations.

A large number of studies have investigated pre-crash factors for single-vehicle run-off-road (from now on, run-off-road) and oncoming-crash situations.

In 2002, police-reported crashes in US were analyzed, using data from the National Automotive Sampling System, General Estimates System (NASS-GES), it was found that 37% of run-off-road crashes were preceded by loss of control. Vehicle technologies such as Electronic Stability Control (ESC) and Antilock Brake System (ABS) have been shown to be promising countermeasures to reduce the incidence of loss-of-control situations.

Other pre-crash factors unrelated to loss of control which were frequently found to contribute to run-off-road crashes are driver distraction, inattention, or fatigue. A study of run-off-road crashes and near-crash events concluded that the most frequent contributing factor among run-off-road events was distraction. One technology implemented to help avoid run-off-road crashes which considers these pre-crash factors is lane departure warning (LDW), a technology that monitors the position of the vehicle with respect to the lane boundary. The LDW alerts the driver with a warning if the car begins to drift out of the lane; it relies on lane markings (lines at the road edge or between lanes) to operate. Although the system does not provide any intervention, some Lane Keep Assist systems supplement the warning with interventions to help the vehicle stay in the lane. The LDW is not designed to work on unpaved roads or roads without lane markings. Further, if the roadway is covered with snow or leaves (for example), the system may not be able to detect the markings. An overview of different LDW systems is provided in.

Volvo Cars’ LDW system was introduced as an optionally mounted system in 2008. In the first generation, an audio signal warned the driver; in the most recent, a haptic warning is also available. If the driver uses the turn indicator or makes an active steering movement, the warning is inhibited. LDW is active from 65km/h–200km/h (40mph–124mph), although it can be turned off by the driver. In some of the later models, the LDW system was accompanied by Lane Keeping Aid (LKA), providing steering assist to help prevent a lane departure. The safety performance evaluation in this study does not specifically look at LKA.

Only a few real-world follow-up studies of LDW based on crash data have been presented. In a study analyzing insurance data (including all crash situations), LDW systems were associated with both higher and lower claim rates. In another study, police-reported crashes involving Volvo cars in Sweden in which at least one person was injured was analyzed, using the induced exposure method to evaluate LDW. A reduction of 53% with LDW for
head-on and single-vehicle crashes on dry roads and at speed limits from 70–120 km/h was found.

Although the system has been on the market for many years, finding adequate datasets to evaluate the system remains a challenge. Few vehicles are equipped with the optionally mounted LDW system, and detailed data sufficient to control for relevant parameters such as conflict situation are hard to come by. In addition, it is a major issue to access relevant exposure data for this kind of traffic safety evaluation.

The objective of this study was to evaluate the crash avoidance effect of Volvo Cars’ LDW system using real-world data based on insurance claims in relevant target situations.

2. Method.

Cars with and without the technology were compared in relevant crash situations collected from insurance claims data. The selected crash situations were lane departures resulting in unintentional run-off-road crashes or oncoming crashes (the types of crashes that LDW is designed to mitigate). To evaluate the real-world crash avoidance effect of the LDW system, crash rates for cars with and without the LDW technology were compared.

2.1. Data

Data claims reported to the insurance company If/Volviva through the car damage warranty (CDW) have information on crashes for all new Volvo cars (21–22). The CDW covers damages to the policyholder’s car for the first three years and includes information about optionally mounted equipment for individual vehicles. For cars older than three years, collision damage insurance replaces the CDW. Third party liability insurance, compulsory for all cars in Sweden, covers personal injuries and damage to other vehicles and property.

Run-off-road crashes were identified by selecting single-vehicle crashes (no other motor vehicle was involved). These claims were available via the CDW coverage unless the vehicle was more than three years old, in which case they were found via the collision damage coverage. The available information, including costs for damage to the policyholder’s own car, was coded as described in Section 2.1.2 below. Lane departures resulting in oncoming crashes (head-on collisions with another vehicle) were identified from the third party liability insurance. The selection of these crashes is also further described in Section 2.1.2 below.

Insurance data include crashes at all levels of severity, from minor crashes with little/no property damage to severe crashes with fatal injuries and heavily damaged cars. A large, representative data sample of crashes is available relatively soon after the introduction of new crash-avoidance technologies, making insurance data valuable for real-world follow-up safety performance assessments.

2.1.1. Data Selection

Crashes in Sweden with the Volvo car models V70 and XC70, MY 2008–2016, were collected from January 1, 2012 to December 31, 2015. The two models were built on the same platform and are of similar size.

Vehicles with (LDW) and without (noLDW) the LDW technology were identified. Approximately four percent of the cars had the LDW option in the model years 2008 to 2013. From MY 2014, the number of LDW cars increased, and by MY 2016 all Volvo V70 and XC70 cars were equipped with the technology.

For the selected dataset, the total exposures were 41,154 and 345,786 insured vehicle years (IVY) for LDW and noLDW cars, respectively. The exposures were calculated as the sum of insured vehicle years for cars in traffic during the four-year period of data collection.

2.1.2. Specification of LDW target situations

Run-off-road crashes addressed by the LDW technology were identified using data from single vehicle crash insurance claims. The crashes were sorted by the cost of the damage claim settlement. Single vehicle crashes were frequent when all levels of crash severity were included. Table 1 shows the number of crashes sorted by claims cost for LDW and noLDW cars.

Table 1 Number of single vehicle crashes sorted by claims cost for LDW and noLDW cars.

| cost (1000 SEK) | cost (USD) | Number of crashes |
|----------------|------------|-------------------|
|                |            | LDW cars | noLDW cars |
| 0 <           | 0 <        | 1108     | 11521    |
| 10 <          | 1150 <     | 872     | 7582    |
| 25 <          | 2900 <     | 322     | 2764    |
| 50 <          | 5775 <     | 98      | 873     |
| 75 <          | 8650 <     | 58      | 504     |

Most (76%) of all single crashes have claims costs below 25,000 SEK. For these less severe crashes, common causes include minor contacts with objects (e.g., a pole or a stone in a parking situation) or situations occurring in traffic without involving other motor vehicles.

Since the LDW technology is active at higher speeds (65kph–200kph), the coding of pre-crash factors for each case was performed for all crashes with claims costs above 75,000 SEK (approx. 8650 USD), to select crashes where LDW was most likely to be activated. This was done by manually reviewing each case. The dataset included 58 crashes with LDW cars and 504 crashes with noLDW cars.

For the analysis, three different categories of crashes were identified in a stepwise process as described in Figure 1.

Single-vehicle crashes in which the car did not depart from the road were the result of a collision with an object or animal on the road, or other (rare) situations—e.g., vehicle failure such as engine stop due to water on the road.

Loss-of-control crashes were identified by indicators in the claims on e.g. skidding due to slippery road. Speeding, illness, intoxication or vehicle failure were indicators for crashes not included in the target lane departure crashes.
The number of crashes for LDW cars and noLDW cars in each of the categories, together with the exposure in IVY, are presented in Table 2.

Table 2  Number of run-off-road crashes for LDW and noLDW cars per category and exposure in IVY.

| Category                                      | LDW cars | noLDW cars |
|-----------------------------------------------|----------|------------|
| All single-vehicle crashes                    | 58       | 504        |
| All single-vehicle crashes with claims cost above 75,000 SEK | 35       | 364        |
| Left lane, run-off-road                       |          |            |
| All single-vehicle crashes                    | 19       | 230        |
| Left lane, without loss of control            |          |            |
| run-off-road, LDW target situation           | 41,154   | 345,786    |

Table 3 provides descriptive statistics for driver age and gender for the three categories defined in Figure 1.

| Category                                      | mean age (year) | std age (year) | % male | % female |
|-----------------------------------------------|-----------------|----------------|--------|----------|
| All single-vehicle crashes                    | 44.4            | 14             | 91     | 9        |
| All single-vehicle crashes with claims cost above 75,000 SEK | 46.2            | 15.3           | 85     | 15       |
| Left lane, run-off-road                       | 44.0            | 16.3           | 93.9   | 6.1      |
| All single-vehicle crashes                    | 46.4            | 16.6           | 82.2   | 17.8     |
| Left lane, without loss of control            | 47.2            | 17.1           | 82     | 18       |

Oncoming crashes were selected from the third party liability claims. According to the way these crashes are regulated in Sweden, the policyholder was at fault for leaving the lane of travel and crashing into a vehicle traveling in the opposite direction. As with run-off-road crashes, oncoming crashes were sorted by claims cost and three categories were defined.

Table 4  Number of oncoming crashes for LDW and noLDW cars per category and exposure in IVY.

| Category                                      | LDW cars | noLDW cars |
|-----------------------------------------------|----------|------------|
| All oncoming crashes                          | 7        | 66         |
| Oncoming crashes with claims cost above 75,000 SEK | 0        | 10         |
| Left lane                                     |          |            |
| Oncoming crashes with claims cost above 75,000 SEK | 0        | 3          |
| Left lane, without loss of control            |          |            |
| Exposure (IVY)                                | 28,430   | 214,961    |
2.2. Statistical methods

The evaluations were conducted by comparing the rate of run-off-road crashes per 1,000 IVY for the three different categories of cars with and without the technology under study. The rate of run-off-road crashes for LDW cars was defined as:

\[ \text{Rate}_{LDW} = \frac{n_{LDW}}{VY_{LDW}} \]  

where

\( n_{LDW} = \) Number of run-off-road crashes for LDW cars  
\( VY_{LDW} = \) Number of IVY for cars with LDW

The rate of run-off-road crashes for noLDW cars was defined in the same way. The number of claims occurring can be considered using a Poisson distribution, and 95% and 80% confidence intervals for the rate were calculated by using a normal approximation to this distribution.

\[ \text{Rate}_{LDW} \pm z_{\alpha} \frac{\text{Rate}_{LDW}}{\sqrt{VY_{LDW}}} \]

where

\( \alpha = \) Significance level; (confidence level=1- \( \alpha \))  
\( z = \) The critical value to get a symmetric confidence interval of (1- \( \alpha \)) %, obtained from the Normal distribution table.

To evaluate whether LDW vehicles have a different rate of run-off-road crashes, the difference between the rates for vehicles with and without the system was calculated together with a 95% and a 80% confidence interval.

\[ RD = \text{Rate}_{\text{noLDW}} - \text{Rate}_{LDW} \]

A test-based method were used to construct the confidence interval (23).

\[ \chi^2 = \left( n_{LDW} - \frac{mVY_{LDW}}{VY} \right)^2 / \left( \frac{mVY_{LDW}VY_{\text{noLDW}}}{VY^2} \right) \]

Where

\( m = \) the total number of events observed  
\( VY = \) the total number of insured vehicle years

The confidence limits were then calculated by

\[ RD_L = RD \pm z_{\frac{\alpha}{2}} \frac{\sqrt{RD^2 + \chi^2}}{2} \]

The effectiveness of LDW was calculated as a difference between rates for cars without and with LDW divided by the rate for cars without LDW.

\[ e = \frac{\text{Rate}_{\text{noLDW}} - \text{Rate}_{LDW}}{\text{Rate}_{\text{noLDW}}} \]

3. Results

In this study, a 30% reduction was found for the single run-off-road crashes when evaluating the LDW target situation (no prior loss of control and damage claims cost above 75 000SEK) for LDW cars compared to noLDW cars. The rate of run-off-road crashes per 1000 IVY was 0.46 for LDW cars and 0.66 for noLDW cars, resulting in a rate difference: RD = 0.20, 80% CI [0.03, 0.37]. Rates and rate differences, including confidence intervals, are presented in Table 5 and illustrated in Figure 3.

When all single-vehicle run-off-road crashes were evaluated (without considering the specific LDW conflict situation), there was a reduction of 19% for LDW cars. When loss of control was included, these situations have a crash rate of 0.85 and 1.05 per 1000 IVY for LDW and noLDW cars, respectively, with a rate difference of 0.2 (Table 5 and Figure 3).

Finally, studying all single vehicle crashes above 75,000 SEK, the reduction was 3%. The crash rate was 1.41 for LDW cars and 1.46 for noLDW cars, with a rate difference of 0.05 (Table 5 and Figure 3).
4. Discussion

To a great extent, previous studies on LDW systems dealt with evaluating specific effects, that can affect crash reduction. For example, it has been shown that LDW contributed to an increase in turn signal use and improved lane-keeping ability (24-27). These studies are important for understanding how new technologies work and how they are received and used by drivers. However, crashes are relatively rare in relation to miles driven, and safety impacts are primarily evaluated by near-crashes or critical events instead of real crashes in these studies. In contrast, the value of the retrospective real-world study in this report lies in its use of real crashes in these studies. In this kind of study, based on the entire variation of a car population in traffic, can the overall benefit of in-vehicle safety technologies be evaluated.

In a real-world study of police-reported crashes (20), it was estimated that the overall safety benefit was a 53% reduction of head-on and single vehicle injury crashes on Swedish roads with speed limits between 70-120 km/h and surfaces free of ice or snow. This result is somewhat different from the findings in the present study, which found a 30% reduction of crashes for the most comparable analysis (oncoming and run-off-road crashes as a result of a lane departure with no prior loss of control with a claims cost above 75,000 SEK). Different data sources with different sampling criteria may explain the different results: In the study based on police-reported crashes they examined crashes in which at least one person was injured, while this study considered crashes above a certain claims cost independent of personal injuries. Furthermore, different data classification and analysis methods were used. In this study, in which exposures were available, the effect was estimated by rate differences; in the other study they applied an induced exposure method.

This study, as well as previous findings (20, 28) show that the ability to stratify data to match the technology’s operational scope is essential; this study targeted oncoming and run-off-road crashes preceded by a lane departure without traction loss, the scope of LDW’s intended benefit. This approach highlights and clarifies possible effects more fully than analyses using general baselines. Otherwise, the effect of a system designed for a limited situation could remain hidden. The results of this study demonstrated that the crash-reducing effect was ten times higher in the target run-off-road situations for LDW cars than in all reported single vehicle crashes of the same severity (Figure 3). This finding might explain the results using all kind of crashes (29). For safety performance evaluation studies, the selection criteria of crashes need further discussion. If police-reported crashes (with at least one injured person) are used, the data would not provide details of property-only crashes, which crash-avoidance technologies are also expected to mitigate. On the other hand, studies using naturalistic driving study (NDS) data can include events such as curb strikes in the crash classification. In a study in 2015, it was concluded that curb strikes occurred at a wide range of travel speeds in the NDS dataset analyzed (29). Further, another study pointed out the different results obtained using NDS datasets versus police reported crashes, because of different crash severities in the datasets (30). The obvious question is whether curb strikes are relevant for traffic safety performance evaluations (they probably do not pose a problem to the driver or any damage to the car). In contrast, insurance claims data provide an intuitive, straightforward definition of crashes relevant for safety evaluation, since all crashes causing some kind of harm to the driver (including financial harm) are included.

A number of limitations of this study have to be mentioned. Although many major factors were controlled for (such as conflict situation and whether traction was lost, and car model), other pre-crash factors not available from crash claims data might have influenced the results.

Table 5. Rates and rate differences including 80% and 95% confidence limits for the different categories of single-vehicle and oncoming crashes.

| Category                        | Crash rate | LDW cars | noLDW cars | Crash rate difference |
|---------------------------------|------------|----------|------------|-----------------------|
|                                 |            | CL 95%   | CL 90%     | CL 95%                | CL 90%     | RD        | CL 95% | CL 90% |
| all > 75 kSEK                   | all oncoming > 75 kSEK | 1.14     | 1.05-1.14  | 1.17-1.24  | 1.46     | 1.33-1.59  | 1.37-1.54  | 0.05     | <0.0-0.44  | <0.0-0.30 |
| run-off-road                    | all oncoming > 75 kSEK | 0.85     | 0.67-1.10  | 0.46-1.29  | 1.05     | 0.92-1.20  | 0.99-1.12  | 0.20     | <0.0-0.54  | <0.0-0.42 |
| run-off-road                    | all oncoming > 75 kSEK | 0.46     | 0.25-0.70  | 0.30-0.60  | 0.66     | 0.50-0.76  | 0.61-0.72  | 0.20     | <0.0-0.46  | <0.0-0.37 |

*Figures in bold are significant*
Some examples of factors which were not controlled for, but which are nonetheless directly related to LDW functionality performance, include driving speed and lane marking presence and status, as well as the size of the roadside area, light and weather conditions. Additionally, driver status (e.g., drowsiness) and ability (e.g., years of driving experience) are also important factors when it comes to the driver’s reaction to the warning. Furthermore, understanding driver acceptance of the system is crucial to an accurate, detailed analysis of the system performance: is the system turned on or off? In different surveys and FOT studies, drivers are reported being annoyed with LDW systems and even deactivate them, which would clearly result in reduced safety benefits. However, the large crash reducing effect found in this study indicates that a large portion of the drivers do keep the system activated during driving.

Environmental circumstances influence the results; this study was performed in Sweden, where snow and icy conditions during winter can result in skidding situations. Also, the presence of rumble strips in the roads and different types of lane configuration could be considered in further analysis. In Sweden, a recent and quite common solution for reducing oncoming crashes is the so-called 2 + 1 road: it alternately has one or two lanes, with a median barrier separating oncoming traffic.

Finally, other collision avoidance features might also affect claim frequencies. Driver Alert Control (DAC) is a technology that partly addresses the same conflict situations as LDW and coexists with LDW in almost all of the cars in this study. DAC monitors the car’s movements between the road markings and assesses whether the vehicle is being driven in a controlled way. If it is not, then the driver is alerted.

These and other factors are important for improving the understanding of the real-world effects of the LDW system and should be further investigated in the future. This study, however, focused specifically on the total crash avoidance effect of the system in real-world traffic.

5. Conclusion

A homogeneous dataset in terms of car model, conflict situation and traction was used to evaluate the safety performance of the LDW system. Insurance data of sufficient quantity provided crash details as well as exposure data for a retrospective traffic-safety performance estimation.

LDW reduces a large portion of crashes. Future enhancements of the system, including steering aids, are promising technologies for further avoidance and mitigation of run-off-road and oncoming crashes.

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