The Influence of Roadway Characteristics on Potential Safety Benefits of Lane Departure Warning and Prevention Systems in the U.S. Vehicle Fleet

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Abstract: **Nearly one-third of all fatal crashes in the U.S. are a result of road departures. Lane departure warning (LDW) and lane departure prevention (LDP) have the potential to mitigate crashes and seriously injured drivers that result from road departures. However, the effectiveness of these systems are dependent on roadway characteristics, such as shoulder width and the presence of lane markings. In the U.S., road shoulders are often narrow, and lane markings are frequently not present. The objective of this study was to determine the limiting influence of shoulder width and lane markings on the effectiveness of LDW and LDP. Real-world road departure crashes were simulated without LDW/LDP, with LDW, and with LDP. These crashes were then simulated again on roads with improved infrastructure, i.e. with lane markings and a 3.6 m shoulder width. LDW and LDP were estimated to prevent 53% and 68% of crashes, respectively, when the shoulder width was at least 3.6 m. In contrast, when no shoulder was present (29% of departure crashes), LDW was found to have no effectiveness and LDP was estimated to prevent only 1% of crashes. When the crashes were simulated again with roadway infrastructure modifications, the number of crashes that could be prevented with LDW/LDP were found to double. The results of this paper highlight the importance of roadway characteristics on potential safety benefits of LDW and LDP, and should inform policy on roadway design.**

Keywords: **Safety Impact Assessment of Active Safety Devices, On-Board Sensing Driver Assistance Systems, Lane departure warning, lane departure prevention, roadway design**

1. INTRODUCTION

Road departure crashes are among the most deadly crash modes in the United States, accounting for nearly one-third of all fatal crashes (Kusano and Gabler 2014). Lane departure warning (LDW) and lane departure prevention (LDP) systems are active safety systems that have the ability to mitigate crashes and injuries by alerting drivers of a lane departure and/or directly modulating vehicle trajectory.

Deficient roadway infrastructure, such as narrow shoulders or the absence of lane markings, may restrict the effectiveness of LDW and LDP. Lane markings give a positional reference for LDW and LDP, which enable these systems to activate when a lane departure is imminent or has occurred. Although advancements in road edge detection algorithms may eventually solve the issue of no lane markings, a lack of adequate shoulder width for recovery is less easily solvable and extremely costly.

Previous works (Kusano and Gabler 2014, Scanlon et al. 2015) have examined road departure crashes from a database containing a U.S. nationally representative sample of road departure crashes. Figure 1 shows a breakdown of shoulder widths on the roadways where these road departures occurred. A majority of road departure crashes happen on roadways with shoulder widths less than 0.3 m (1 ft) wide. Additionally, this dataset also indicated that only 70% (shown in Figure 2) of vehicles crossed over lane markings prior to road departure crashes. The objective of this study was to investigate the impact of roadway design on the predicted safety benefits of LDW and LDP if all vehicles in road departure crashes in the U.S. fleet were equipped with either system.

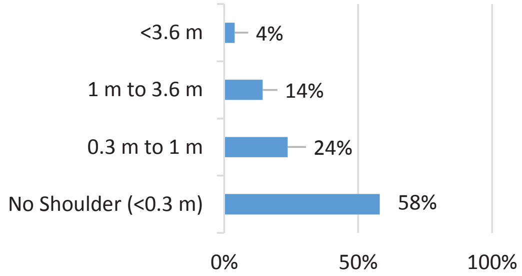

Fig. 1. Distribution of Shoulder Widths in U.S. road departure crashes (NASS/CDS 2012).

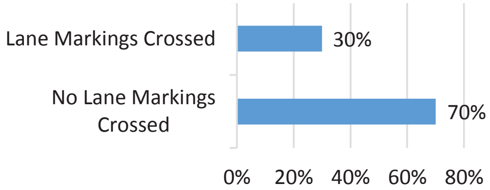

Fig. 2. Road markings crossed prior to U.S. road departure crashes (NASS/CDS 2012).

2. METHODS

2.1 *Modelling Framework*

Figure 2 summarizes the process for the LDW and LDP benefits computations developed for this project. Two sets of simulations were run in this study. First, road departure crashes from a U.S. nationally representative database were retrospectively simulated as if the vehicle had been equipped with an LDW or LDP system. Second, crashes were simulated again with improved roadway infrastructure. Specifically, all non-curbed roadways were assumed to have lane markings present and a shoulder width of 3.6 m (highway lane width maximum in the U.S.). No roadway infrastructure modifications were assumed to be made if the road had a curb. In summary, this set of simulations aimed to determine how effective LDW and LDP would be if these road infrastructure improvements were made.

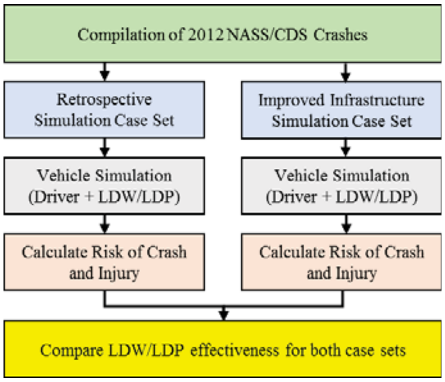

Fig. 2. Modelling framework used to estimate the effectiveness of LDW/LDP with and without roadway infrastructure improvements.

2.2 Data Source

The 2012 National Automotive Sampling System Crash Worthiness Data System (NASS/CDS) was used to formulate the simulation case sets. The database is comprised of approximately 5,000 new U.S. crashes each year, and includes detailed medical records and information from the crash environment, such as road characteristics. In order to be included in this database, at least one vehicle involved in the crash had to be towed away from the scene. Each case is additionally assigned a national weight factor, which was used in this paper to make the results nationally representative.

This study exclusively analysed single vehicle crashes where the driver drifted out of their lane and departed the roadway. Crashes that involved control loss or animals in the roadway were excluded.

2.3 Formulating a Simulation Case Set

Two pieces of information were required for formulating a simulation case set for this study. First, the NASS/CDS database contains much of the information required to run the simulations in this study. In order to effectively model each crash, a review of event records from each case was performed. Three parameters were determined during the review, including the travel lane of the vehicle, the presence of lane markings, and road shoulder width. Second, statistical models were used to determine departure conditions, i.e. departure angle and speed. These methods have been previously described Kusano et al. (2014) and Scanlon et al. (2015).

Because most crashes occurred on two-lane undivided roads, determining travel lane was typically unnecessary. In road departure cases on multi-lane roads, the scene narrative and scene diagram prepared by the crash investigator were used to determine the initial travel lane.

The lane marking was identified at the approximate location of the first lane departure. No evaluation of the painted lane marking clarity or quality was made.

Shoulder width was estimated from scene photographs showing the location of vehicle departure. Shoulder width was divided into four separate categories, including (1) less than 0.3 m wide, (2) between 0.3 and 1 m wide, (3) between 1 and 3.6 m wide, and (4) over 3.6 m wide. The 3.6 m threshold was selected because a typical U.S. highway lane is no wider than 3.6 m. For the retrospective simulation case set, crashes with labelled shoulder widths of 0.3 m to 1 m and 1 m to 3.6 m were simulated twice, once with each width to account for uncertainty in the actual should width. Shoulder widths less than 0.3 m were assumed to be negligible, and were simulated as 0 m. Shoulder widths greater than 3.6 m were simulated as being 3.6 m wide.

Departure conditions, i.e. departure angle and velocity, were determined using statistical models generated from the National Cooperative Highway Research Program (NCHRP) Project 17-22. The dataset consists of 890 reconstructed road departure crashes of cases included in the NASS/CDS database. One-way ANOVAs were then used to determine predictor variables that significantly influence each departure conditions. Last multivariate linear regression models were formed that maximized the adjusted-R^2. These models are presented in Kusano et al. (2014).

2.4 Performing Vehicle Simulations

Vehicle kinematics simulations were performed using CarSim vehicle simulation software. Driver control was modelled using a previously implemented driver recovery model developed by Volvo, Ford, and University of Michigan Transportation Research Institute (VFU) through the Advanced Crash Avoidance Technologies (ACAT) Program (Gordon et al. 2010). As the vehicle approaches the edge lines of the road, the driver model considers the yaw of the vehicle, identifies if that yaw will cause lane departure, and makes a proportional change to the yaw rate to maintain vehicle position in the lane. Driver steering was assumed to begin after the driver departed the paved roadway or after being alerted by LDW or LDP.

The LDW system was modelled as alerting the driver at the instance the leading wheel touched the lane markings. The LDP system was assumed to work in conjunction with the LDW system, i.e., the driver was alerted of a lane departure. Additionally, when LDP became active and prior to driver steering, the system was assumed to directly modulate steering wheel angle. The LDP system was assumed to linearly increase lateral acceleration over a 0.5 s interval to a maximum of 0.1 g, which is depicted in Figure 3.

2.5 Benefits Estimates

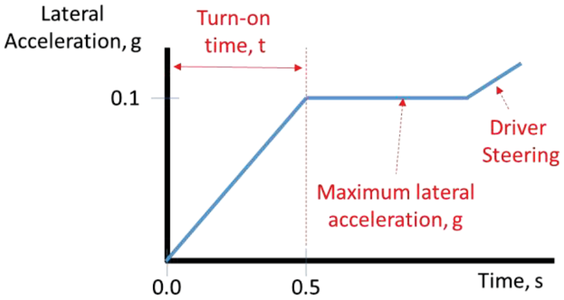

Fig. 3. LDP lateral acceleration kinematics.

Benefits estimates were performed in three steps. These steps are illustrated in Figure 4. These methods have been previously detailed by Kusano et al. (2014) and Scanlon et al. (2015).

First, a probability of crash was computed for each of the simulated trajectories. Trajectories from NCHRP Project 17-22 were used to estimate collision risk. Probability of a crash was assumed to be dictated by 1) the distance travelled laterally from the road, and 2) the total distance travelled off-road. In summary, Using the number of crashes in each of the roadside zones (C_k), the distance travelled in each of the roadside zones (γ_k), and the total simulated trajectory length in each zone k ($L_{i,k}$) the probability of a crash $P[Crash_i]$ for a given trajectory could be calculated using Equation 1.

$$P[Crash_i] = 1 - \prod_{k=1}^{K} \exp\left(-\frac{C_k L_{i,k}}{\gamma_k}\right) \tag{1}$$

Second, probability of a seriously injured driver (Maximum Abbreviated Injury Score of 3 or greater, MAIS3+) was estimated from previously developed logistic regression functions. Departure velocity and seat belt were used as predictors for the model, and serious injury was the dependent variable. After determining the probability of a serious injury, $P[injury_{IC}]$, the injury probability for the simulated trajectory, $P[injury_i]$, could be calculated using Equation 2.

$$P[Injury_i] = P[Injury_{IC}]\, P[Crash_i] \tag{2}$$

Third, benefits estimates were computed to determine the proportion of crashes and seriously injured drivers that could have been prevented if the vehicle had been equipped with LDW/ LDP. An effectiveness measure, ε, was used to compute the proportion of crashes or injuries reduced given the presence of LDW or LDP. Equation 3 shows the calculation of this effectiveness measure and utilizes counts of the number of crashes with LDW/LDP, $N_{\text{with LDP/LDP}}$, and the number of crashes without LDW/LDP, $N_{\text{without LDW/LDP}}$.

$$\epsilon = \frac{N_{without\ LDW/LDP} - N_{with\ LDW/LDP}}{N_{without\ LDW/LDP}} \tag{3}$$

3. RESULTS

A total of 478 crashes from NASS/CDS 2012 were used in this study. These crashes are representative of 147,662 crashes nationally in the U.S. Approximately 20% (30,167 nationally) of these crashes resulted in the driver being seriously injured.

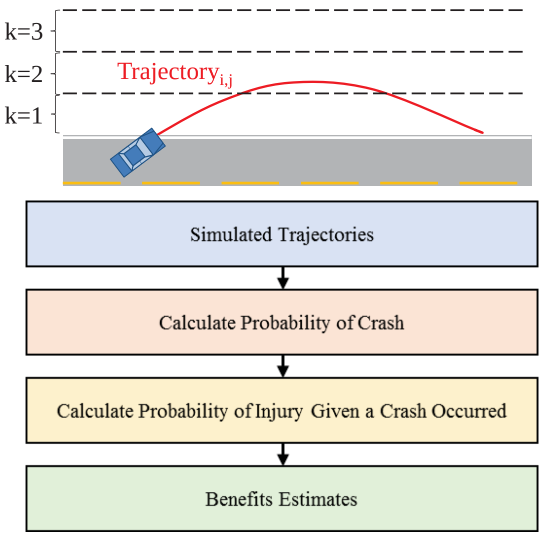

Fig. 4. Overview of methods for generating benefits estimates.

Table 1 gives a breakdown of the cases in the dataset by shoulder width. Over half of the departure crashes happened on roadways with no shoulder width. Only 3.9% of the roadways had shoulder widths greater than 3.6 m.

Lane markings were found to be present in 70.5% (103,511 nationally) of road departure crashes. Of the crashes without lane markings, 60.5% of the crashes occurred roadways with curbs.

Table 2 lists the number of crashes and injuries without LDW/LDP systems along with the predicted effectiveness of LDW and LDP systems. The retrospective simulation of real-world crashes and the simulation of crashes with improved roadway infrastructure are both shown in the table.

Figures 5 and 6 show the effectiveness of LDW and LDP by shoulder width for the retrospective simulation case set. Only simulations that had no adjacent travel lanes crossed prior to departure, i.e. traveling in rightmost or leftmost lane, are tabulated to isolate the effect of shoulder width from number of lanes crossed before departure. In total, three-fifths (63%) of the road departure crashes occurred without any adjacent travel lanes being crossed.

Table 1. Breakdown of Cases by Shoulder Width.

Shoulder Width Category	Count	Proportion
No Shoulder (<0.3 m)	85,730	58.1%
0.3 m to 1 m	34,937	23.7%
1 m to 3.6 m	21,195	14.4%
<3.6 m	5,800	3.9%
Total	**147,662**	**100.0%**

4. DISCUSSION AND LIMITATIONS

The potential benefits of LDW and LDP were found to be dramatically influenced by the presence of lane markings and shoulder width. A total of 30.9% of road departures took place on roadways without lane markings. On roads with no lane markings, LDW and LDP were assumed to not activate. This indicates that, if an LDW/LDP system requires lane marking to be present, a maximum of 69.1% of crashes could have been prevented by LDW/LDP.

LDW and LDP were estimated to prevent 59% and 67% of crashes, respectively, when the shoulder width was at least 3.6 m. In contrast, when no shoulder was present, LDW was found to have no effectiveness and LDP was estimated to prevent 1% of crashes. The influence of shoulder width on benefits is especially important when considering that 29% of crashes occurred on roads with no shoulder. On roads with lane markings but no shoulder, only LDP was assumed to be activated.

Our simulations indicate that LDW and LDP would be substantially more effective if all roadways included lane markings and had expanded shoulders (> 3.6 m). The number of crashes that could be prevented by LDW with these roadway infrastructure modifications was found to double (28.4% to 59.2% of crashes prevented). Likewise, the number of crashes that could be prevented by LDP with these roadway infrastructure modifications was found to nearly double as well (32.1% to 63.2% of crashes prevented).

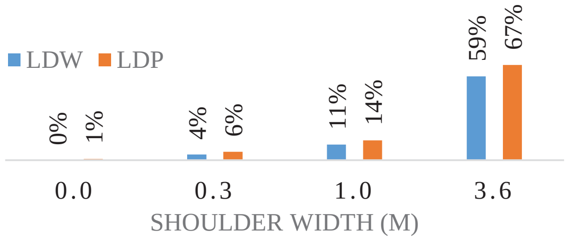

Fig. 5. Effectiveness of LDW/LDP in reducing the number of crashes as a function of shoulder width.

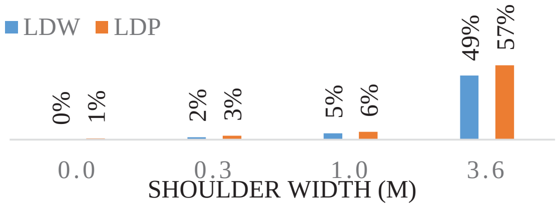

Fig. 6. Effectiveness of LDW/LDP in reducing the number of seriously injured drivers as a function of shoulder width.

It is important to note that instituting the roadway infrastructure improvements discussed in this study would be extremely costly. Specifically, expanding roadway shoulders to be the width of a highway lane would not be practical. However, this analysis highlights the importance of these roadway attributes for the effectiveness of LDW and LDP. Additionally, this analysis shows the opportunities for greatly enhancing the effectiveness of LDW/LDP by developing systems which can detect the road edge in the absence of lane markings.

There were some limitations to the model. First, the modelled LDW and LDP systems were assumed to function independent of visibility (e.g. fog or snow). LDW and LDP currently rely on video-based lane detection, which makes them highly dependent on the clarity of the line and visibility issues. These issues were not considered in this study. Second, not all equipped vehicles will have LDW or LDP enabled, because some drivers may disable the systems. Third, modifying roadway infrastructure may prevent some road departures for

Table 2. Effectiveness of LDW/LDP by Simulation Case Set.

Measure	**Values**	**Effectiveness (% Improvement)**	**Measure**	**Values**	**Effectiveness (% Improvement)**
Baseline Infrastructure			*Lane Markings + Expanded Shoulder Width*		
Crashes					
No LDW or LDP	147,662	---	No LDW or LDP	147,662	---
with LDW	105,657	28.4%	with LDW	60,314	59.2%
With LDP	100,261	32.1%	With LDP	54,279	63.2%
Injuries (MAIS3+)					
No LDW or LDP	30,167	---	No LDW or LDP	30,167	---
with LDW	23,871	20.7%	with LDW	14,711	51.5%
with LDP	21,722	27.8%	with LDP	13,390	55.9%

vehicles not equipped with LDW or LDP. This model assumed that drivers without either system would not be alert until the road departure occurs. However, this additional time prior to a road departure may have allowed some drivers to realize an imminent crash and steer back into the lane.

5. CONCLUSIONS

The results of this paper highlight the crucial influence of roadway characteristics on potential safety benefits of LDW and LDP. Federal and state transportation agencies seeking to maximize the benefit of emerging fleets with automated crash avoidance technologies, e.g. LDW or LDP, should consider the effect of these infrastructural characteristics when planning roadway improvements. This work also highlights the opportunities for LDW/LDP developers to improve the crash and safety benefits of these systems by determining ways to detect road edges on roadway without lane markings.

6. ACKNOWLEDGEMENTS

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