Lane Departure Warning and Prevention Systems in the U.S. Vehicle Fleet

Influence of Roadway Characteristics on Potential Safety Benefits

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Road departure crashes account for one-tenth of all crashes but nearly one-third of all fatal crashes. Lane departure warning (LDW) and lane departure prevention (LDP) active safety systems could mitigate these crashes by warning the driver of a lane departure or automatically navigating the vehicle back into the lane. The objective of this study was to quantify the influence of certain roadway characteristics on the effectiveness of LDW and LDP systems within the U.S. vehicle fleet. This study used 478 real-world drift-out-of-lane road departure crashes and simulated them as if the vehicles had been equipped with LDW or LDP systems. The simulations were then repeated as if (*a*) all of the roadways had lane markings, (*b*) the roadway shoulders were expanded, and (*c*) lane markings were present and the shoulder widths were expanded. With the existing roadway infrastructure, LDW and LDP were found to potentially prevent 28% to 32% of U.S. road departure crashes and 21% to 28% of cases of serious driver injury. When lane markings were added to the roadways, LDW and LDP could prevent 32% to 36% of crashes and 27% to 31% of cases of serious driver injury. When only shoulder widths were expanded, LDW and LDP could prevent 50% to 54% of crashes and 44% to 48% of cases of serious driver injury. When lane markings were present and the shoulders were expanded, LDW and LDP could prevent 72% to 78% of crashes and 60% to 65% of cases of serious driver injury. The findings of this study highlight the important influence of roadway infrastructure on the performance of LDW and LDP.

Although comprising only one-tenth of all crashes, road departure crashes account for nearly one-third of all fatal crashes in the United States (*1*). Lane departure warning (LDW) and lane departure prevention (LDP) systems are vehicle-based active safety systems that have the potential to reduce the number of crashes and seriously injured drivers that result from these road departures. LDW can alert the driver of a lane departure and therefore allow the driver time to steer the vehicle back into the lane markings. LDP directly controls the vehicle's trajectory in the event of a lane departure.

Several previous studies have evaluated the potential crash and safety benefits of LDW and LDP through the retrospective simulation of real-world lane departure crashes as if the vehicles had been equipped with LDW-LDP systems (*2–10*). Each of these studies predicted a potential reduction in lane departure crashes if these systems were equipped throughout the entire vehicle fleet. Modifications to many elements of LDW-LDP have been investigated, including the type of warning that should be delivered to the driver (*11, 12*), when the warning should be delivered (*13, 14*), how to reduce driver annoyance at LDW alarms (*15*), and how the driver will adapt to these systems (*16*). However, no studies have analyzed how roadway infrastructure may limit or enhance the performance of these systems.

The performance of LDW and LDP is likely to be dependent on roadway infrastructure. Specifically, roads without lane markings and roads with narrow shoulders may restrict the ability of these systems to successfully prevent road departures. Current LDW-LDP systems rely on the vision-based sensing of lane markings to detect a lane departure (*17–21*). Future technologies may be capable of detecting curbs or lane edges, but current systems do not activate on roadways with missing lane markings (*22, 23*). Additionally, shoulders provide additional time and space for the vehicle to be driven back into the lane. Absent or narrow shoulders will restrict the performance of these systems. Although advancements in road edge detection technologies may solve the issue of absent lane markings, the universal widening of road shoulders would prove challenging and very costly. In the simulation case sets used by Kusano et al. (*2*) and Scanlon et al. (*3*), the distributions of the shoulder widths and lane markings crossed before the road departure were tabulated for U.S. road departure crashes, as shown in Figure 1. Nearly one-third of the vehicles departed roadways without crossing any lane markings. In addition, over half of the vehicles departed a roadway with either no shoulder or a minimal shoulder width (<0.3 m).

The objective of this study was to quantify the influence of these roadway characteristics on the effectiveness of LDW and LDP within the U.S. vehicle fleet. This study used previously developed models, designed to estimate the reduction in crashes and cases of serious driver injury attributable to LDW and LDP (*2, 3*), to enable the resimulation of these crashes with hypothetical improvements to the roadway infrastructure.

METHODOLOGY

The modeling strategy for this study can be found in Figure 2. First, a set of nationally representative road departure crashes was extracted from the 2012 National Automotive Sampling System—Crashworthiness Data System (NASS-CDS) database (*24*). Second, three simulation case sets with varying roadway infrastructure

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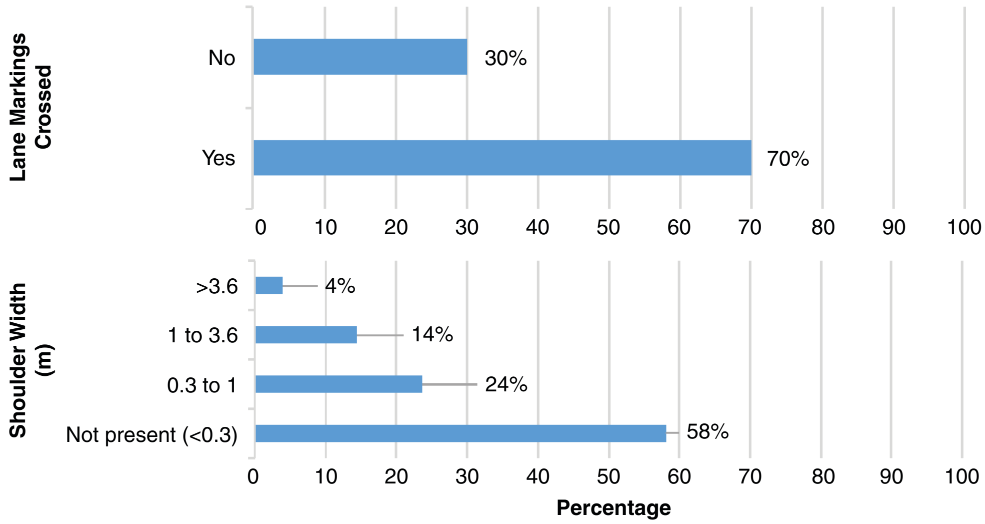

FIGURE 1 Proportion of drivers who crossed lane markings (*top*) and shoulder width magnitudes before those road departures (*bottom*) [values taken from previous studies, in which the values were generated from a collection of road departures in the National Accident Sampling System's Crashworthiness Data System 2012 (*2, 3*)].

specifications were formed from this compilation of crashes, including the crashes (*a*) as they actually occurred, (*b*) with lane markings always present, (*c*) with an expanded shoulder width (3.6 m, the maximum highway lane width in the United States), and (*d*) with lane markings always present and an expanded shoulder width. Third, each of the crashes within each simulation case set was simulated as if the vehicle was (*a*) not equipped with LDW or LDP, (*b*) equipped with LDW, or (*c*) equipped with LDP. Fourth, the probability that the driver experienced a crash or serious injury or both was estimated for each trajectory. Fifth, the proportion of crashes and cases of serious driver injury that could be prevented if the vehicle were equipped with LDW or LDP was computed for each of the simulation case sets and then compared across roadway infrastructure groups.

Data Source

The NASS-CDS 2012 database was used for this study to formulate a simulation case set. This nationally representative database is composed of 4,000 to 5,000 crashes, collected annually, that occurred

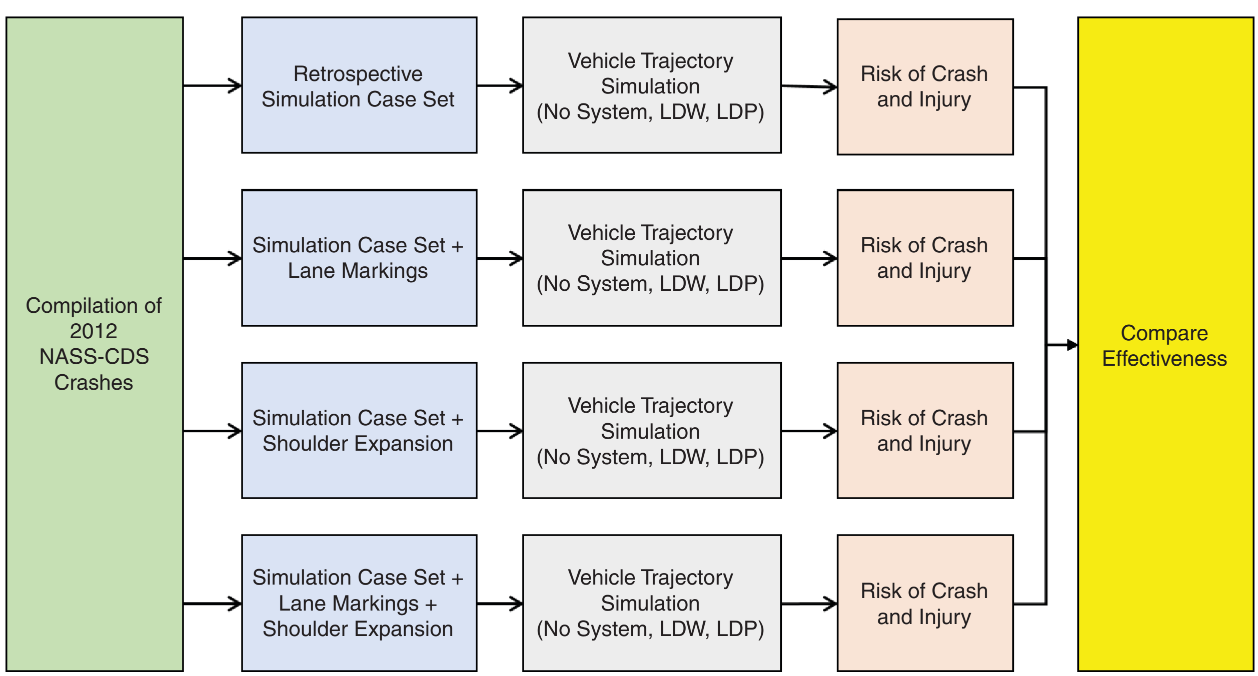

FIGURE 2 Study's overall modeling strategy, used to determine influence of lane markings and shoulder width on potential effectiveness of LDW and LDP (NASS-CDS = National Accident Sampling System Crashworthiness Data System).

at various locations throughout the United States. For a crash to be included in this database, at least one vehicle involved must have been towed away from the scene as a result of damage. This database is ideal for this study for several reasons. First, information is recorded about the occupant, the vehicle, and the environment at the time of the crash. Second, investigators prepare scene diagrams depicting the crash and take pictures of the crash location. Third, detailed medical records are provided for each occupant involved. In addition, each case is assigned a national weighting factor, which, when applied, allows for nationally representative estimates to be made from the data set.

This study specifically analyzed single-vehicle road departure crashes that occurred as a result of an initial drift-out-of-lane event. The process for identifying these cases can be seen in Table 1. First, coded variables within the NASS-CDS database were used to identify drift-out-of-lane road departure crashes and exclude crashes that may have occurred as a result of control loss or an evasive maneuver attempt (e.g., to avoid an animal in the roadway). Second, for each crash, a manual inspection of the evidence (e.g., scene diagram, scene photographs, and crash narrative) prepared by the crash investigator was performed to verify that the case was properly coded as a road departure crash. Third, cases were excluded for having a disproportionately high sample weight [cases representative of >5,000 crashes nationally could greatly skew the data (*25*)], involving departures at T-intersections, and involving road departures that occurred over multiple departure sides (e.g., the driver overcorrected and exited the opposite side of the road).

Formulation of a Simulation Case Set

Determining Parameters of Interest

The NASS-CDS database contains extensive coded information about the events leading up to a crash. However, the coded database lacks some vital information required for the adequate reconstruction of road departure crashes. For this study, these data were determined through a manual review of the event records and previously developed statistical models.

The initial travel lane before the initial lane departure was not provided within the coded NASS-CDS database. Crashes that occurred on two-lane undivided highways did not require a manual review. On multilane roads, the scene narrative and scene diagram were used to determine this initial travel lane.

The presence of lane markings and the shoulder width were additionally not coded in NASS-CDS. However, both of these parameters could be determined from scene photographs. The presence of lane markings was examined at the location of the initial lane departure. No evaluation of lane marking clarity was made. The shoulder width was estimated on the side of the lane departure. Because exact measurements could not be determined from the scene photographs, shoulder widths were categorized into four groupings: (*a*) no shoulder (<0.3 m), (*b*) 0.3 to 1.0 m, (*c*) 1.0 to 3.6 m, and (*d*) >3.6 m.

Some information from the crash, including the departure angle, the departure velocity, and the road radius of curvature, had to be determined by previously developed statistical models. In methods described in Kusano et al. (*2*), the NCHRP 17-22 database was used to formulate statistical models that could predict these three missing parameters from information about the crash. This database contained 890 reconstructed road departure crashes that occurred from 1997 to 2004, the information provided in the NASS-CDS database, and supplemental data. The statistical model development was done in two steps. First, one-way analyses of variance were used to determine the factors that were significantly correlated with each of the departure conditions. Second, multivariate analyses of variance, with combinations of these factors, were fit to the data to maximize the adjusted R^2.

Simulation Case Set Replications

Because some of the conditions of the crash had to be estimated through visual approximations or statistical models, each case was replicated multiple times to account for all of the possible scenarios. All of these replications were then given an equal probability of occurring. For any given case, up to five variables could have multiple values; these variables included the departure angle, the departure velocity, the road radius of curvature, the shoulder width, and the driver reaction time. The departure angle, the departure velocity, and the road radius of curvature (if the road was curved) were each represented by three values: the 17th, 50th, and 83rd percentiles of three equally partitioned regions of a normal probability distribution function. Cases with shoulder widths between 0.3 and 1.0 m and between 1.0 and 3.6 m were simulated twice, and the maximum possible values of each category were used. For instance, a case with a shoulder width of 0.3 to 1.0 m would be simulated with both a shoulder width of 0.3 m and of 1.0 m. Driver reaction times were always simulated with two separate values. In summary, a crash that took place on a curved road with a shoulder width of between 0.3 and 1.0 m would be simulated under 108 conditions (three radii of curvature × three departure angles × three departure velocities × two shoulder widths × two driver reaction times).

TABLE 1 Method for Compiling Drift-out-of-Lane Road Departure Crashes from 2012 NASS-CDS Database

Group	Count	Weighted Count
All crashes in CDS 2012	3,581	1,996,016
Drift-out-of-lane departures	629	293,937
Valid departure after manual inspection	556	271,810
Exclusions for valid departures		
Weight > 5,000	5	91,577
End departures	8	1,767
Multiside departures	65	30,804
Final compilation of crashes	478	147,662

NOTE: Cases were eliminated in the sequence shown.

Vehicle Trajectory Simulation

Three types of vehicle trajectory simulation were run in this study: (*a*) driver only, (*b*) driver with an LDW-equipped vehicle, and (*c*) driver with an LDP-equipped vehicle. LDW and LDP were modeled as becoming activated at the instant that the leading wheel touched the lane line. The location at which an LDW is activated, relative to the lane marking, varies by make and model but is generally within ±0.5 m of the lane markings (*26*). For simulations without an LDW or LDP system or without a visible lane or both, driver steering was assumed to begin after a certain reaction time that followed the initial road departure. For simulations in which an LDW was activated, driver steering was assumed to begin after a prescribed reaction time. For simulations in which LDP was activated, automated vehicle steering was assumed to take place, followed by driver steering after a certain reaction time.

Two equally probable driver reaction times, 0.38 and 1.36 s, were simulated in this study. These values were selected from the observed upper and lower bounds of driver reaction times after an LDW during previous driving simulation studies (*12, 27*).

Vehicle simulations were performed with CarSim vehicle simulation software. All numerical integration within each simulation was performed through the use of the fourth order Runge–Kutta method and a time step of 0.001 s. The roadway lane width was assumed to be 3.48 m for divided highways and 3.64 m for undivided highways. These lane widths were determined from average values taken from the NCHRP 17-22 database.

A driver recovery model previously developed by Volvo, Ford, and the University of Michigan Transportation Research Institute, through the Advanced Crash Avoidance Technologies Program, was used to simulate driver reaction (*4*). This model modulates steering through the use of a proportional controller that considers the current heading of the vehicle with respect to the road edge and the yaw rate required to maintain the vehicle within the roadway. The model was developed through experimental studies conducted in Ford's VIRTTEX driver simulator. The current study simulates all trajectories through a 2000 Ford Taurus CarSim model, which matches the specifications of Ford's simulator.

A general depiction of the function of the LDP system can be seen in Figure 3. At the instant the leading wheel touches the lane marking, an LDW is delivered, and automated vehicle steering begins. The system is assumed to manipulate the steering wheel angular displacement at a rate that linearly ramps up lateral acceleration (rate = 0.2 *g*/s) to a maximum value of 0.1 *g*. After some reaction time, driver steering would begin.

Estimating Crash or Serious Injury Reduction

After the trajectories had been generated for each of the cases within the simulation cases sets, the potential effectiveness of LDW and LDP could be estimated for each of the roadway infrastructure scenarios. This process was done in three main steps. First, the probability that a crash took place was calculated on the basis of the off-road vehicle trajectory. Second, given the probability that a crash occurred, the probability of the driver being seriously injured was calculated through the use of statistical models that considered the departure conditions of the crash. Third, the potential crash and serious injury reduction, or effectiveness, was calculated for each of the roadway infrastructure scenarios. These methods were previously developed and described in Kusano et al. (*2*).

Previously developed models that calculate the probability of a crash on the basis of the off-road trajectory of the vehicle were used in this study (i.e., it was assumed to be impossible for a vehicle to have experienced a crash if the vehicle had never departed the roadway). These models were developed through the use of data from the NCHRP 17-22 data set. In general, two separate factors were assumed to dictate the risk of experiencing a crash: (*a*) the distance traveled laterally away from the roadway and (*b*) the total off-road travel distance. The probability of a crash was calculated as shown in Equation 1:

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

where

$P[\text{crash}_{i,j}]$ = probability that vehicle experienced a crash during trajectory j of case i,
$L_{i,j,k}$ = total simulated distance traveled within a predefined off-road zone k,
C_k = total number of crashes from NCHRP 17-22 data within zone k, and
γ_k = total trajectory length in zone k from NCHRP 17-22 data.

The probability of a driver being seriously injured was then calculated for each trajectory. A seriously injured driver was defined to have sustained a maximum abbreviated injury score (MAIS) of three or greater (3+) according to the Abbreviated Injury Scale, 1998 version (*28*). Logistic regression models were then formulated through the use of the NCHRP 17-22 database. Given that a crash occurred, the models used seat belt use and departure velocity to predict the probability that the driver sustained an MAIS 3+ injury. The probability of an injury for the given trajectory ($P[\text{injury}_{i,j}]$) was then calculated through Equation 2, in which $P[\text{injury}_{i,j}|\text{crash}_{i,j}]$ is the probability that the driver sustained a serious injury given that a crash occurred.

$$P\left[\text{injury}_{i,j}\right] = P\left[\text{injury}_{i,j}\middle|\text{crash}_{i,j}\right] P\left[\text{crash}_{i,j}\right] \tag{2}$$

To calculate the potential crash and safety benefits of LDW and LDP for each roadway infrastructure scenario, the number of crashes

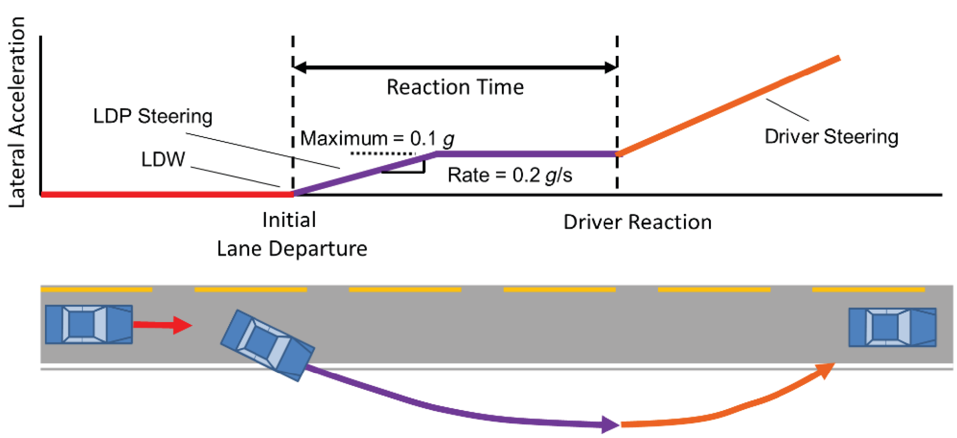

FIGURE 3 Depiction of LDP vehicle trajectory modulation used in this study.

TABLE 2 Cross Tabulation of Presence of Lane Markings Versus Roadway Shoulder Width at Location of Vehicle Departure

	Number and Percentage of Crashes by Shoulder Width				
Measure	<0.3 m	0.3–1.0 m	1.0–3.6 m	> 3.6 m	Total
Lane markings present					
No	12,090 (8.2%)	3,414 (2.3%)	1,947 (1.3%)	11 (0.0%)	17,463 (11.8%)
Yes	73,640 (49.9%)	31,523 (21.3%)	19,248 (13.0%)	5,789 (3.9%)	130,199 (88.2%)
Total	85,730 (58.1%)	34,937 (23.7%)	21,195 (14.4%)	5,800 (3.9%)	147,662 (100.0%)

NOTE: All values are weighted with NASS weightings.

(N_{crashes}) and seriously injured drivers ($N_{\text{MAIS3+}}$) had to be determined for vehicles equipped with LDW or LDP systems. Because nationally representative weightings and injury information were provided for each of the cases, the numbers of crashes and seriously injured drivers were known from the simulation case set. The numbers of crashes and injured drivers with LDW or LDP could then be calculated through Equation 3 or 4, respectively, in which $w_{i,j}$ is the ratio of the case weight to the number of representative simulations.

$$N_{\text{crash with LDW/LDP}} = \sum_{i=1}^{\text{\# cases}} \sum_{j=1}^{\text{\# simulations}} \frac{P\left[\text{crash}_{i,j}\right]_{\text{LDW/LDP}}}{P\left[\text{crash}_{i,j}\right]_{\text{no LDW/LDP}}} w_{i,j} \tag{3}$$

$$N_{\text{injured with LDW/LDP}} = \sum_{i=1}^{\text{\# cases}} \sum_{j=1}^{\text{\# simulations}} \frac{P\left[\text{injury}_{i,j}\right]_{\text{LDW/LDP}}}{P\left[\text{injury}_{i,j}\right]_{\text{no LDW/LDP}}} w_{i,j} \tag{4}$$

The effectiveness ($\in$) of these systems was then calculated, through Equation 5, as the potential reduction in the number of crashes and seriously injured drivers.

$$\in = \frac{N_{\text{without LDW/LDP}} - N_{\text{with LDW/LDP}}}{N_{\text{without LDW/LDP}}} \tag{5}$$

RESULTS

In total, 478 crashes from the 2012 NASS-CDS database were used in this study and were representative of 147,662 crashes nationally. Over 20% of these crashes resulted in serious injuries to the driver. The simulation case sets with no roadway infrastructure improvements and added lane markings were both composed of 20,118 unique simulations. The simulation case sets with only expanded shoulders or with added lane markings plus expanded shoulders were each composed of 13,290 simulations. In total, 66,816 unique simulations were performed in this study.

As shown in Figure 1, more than half the drivers departed roadways without crossing a shoulder (<0.3 m). Approximately one-third of the drivers departed roads that did not have the lane markings that could have potentially activated an LDW-LDP system. A very low percentage of crashes (3.9%) took place on roadways on which the driver crossed a shoulder width greater than 3.6 m, which is the maximum highway lane width in the United States. A cross tabulation of lane markings by shoulder width is shown in Table 2.

Table 3 gives a complete summary of the calculated crash and safety benefits for each simulation case set. With no roadway infrastructure improvements, LDW was found to potentially prevent 28.4% of road departure crashes and 20.7% of cases of serious driver injury; LDP was found to potentially prevent 32.1% of crashes and 27.8% of cases of serious driver injury. The results indicate that if all of the vehicles in the data set had departed roadways with lane markings, LDW could have prevented an additional 3.8% of crashes (32.2%) and 6.4% of cases of serious driver injury (27.1%) and LDP could have prevented an additional 4.3% of crashes (36.4%) and 3.4% of cases of serious driver injury (31.2%). If these roadways had had expanded shoulder widths (3.6 m), LDW could have prevented an additional 21.8% of crashes (50.2%) and 23.4% of cases of serious driver injury (44.1%) and LDP could have prevented an additional 21.9% of crashes (54.0%) and 20.1% of cases of serious driver injury (47.9%). If all of the roadways had had lane markings and expanded shoulder widths (3.6 m), LDW could have prevented an additional 43.2% of crashes (71.6%) and 39.0% of cases

TABLE 3 Potential Crash and Safety Benefits of LDW and LDP for Each Roadway Infrastructure Scenario

	Baseline Infrastructure		Added Lane Markings		Expanded Shoulder Width		Added Lane Markings Plus Expanded Shoulder Width	
Measure	Values	Effectiveness (%)	Values	Effectiveness (%)	Values	Effectiveness (%)	Values	Effectiveness (%)
Crashes								
No LDW or LDP	147,662	—	147,662	—	147,662	—	147,662	—
With LDW	105,657	28.4	100,080	32.2	73,540	50.2	41,963	71.6
With LDP	100,261	32.1	93,920	36.4	67,909	54.0	32,946	77.7
Injuries (MAIS3+)								
No LDW or LDP	30,167	—	30,167	—	30,167	—	30,167	—
With LDW	23,871	20.7	22,121	27.1	16,948	44.1	12,232	59.7
With LDP	21,722	27.8	20,862	31.2	15,800	47.9	10,488	65.4

NOTE: — = not applicable. Effectiveness measure represents percentage of crashes or cases of injury prevented.

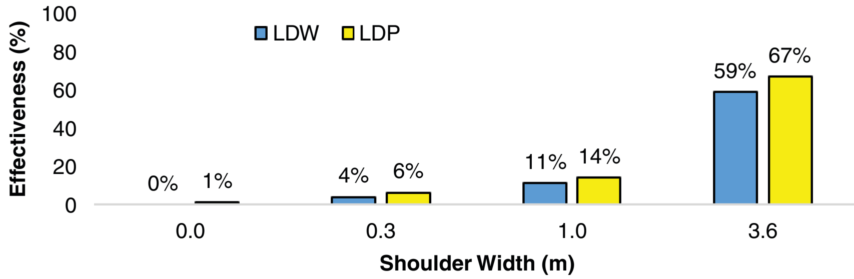

FIGURE 4 Potential effectiveness of LDW and LDP for simulated shoulder widths on basis of baseline infrastructure data set [data set restricted to crashes in which no adjacent lanes were crossed (e.g., a right-side departure while traveling in leftmost lane) and consisted of 16,920 simulations].

of serious driver injury (59.7%) and LDP could have prevented an additional 45.6% of crashes (77.7%) and 37.6% of cases of serious driver injury (65.4%).

To examine the influence of shoulder width, the potential effectiveness of LDW and LDP by simulated shoulder width was plotted for the baseline infrastructure data set. For shoulder widths of 1.0 m, an estimated 11% to 14% of crashes could have been prevented with LDW-LDP systems. However, the results indicate that 59% to 67% of the crashes with shoulder widths of 3.6 m could have been prevented by LDW-LDP systems (Figure 4).

DISCUSSION AND LIMITATIONS

The results provide compelling evidence of the importance of roadway infrastructure on the potential effectiveness of LDW and LDP. With the existing roadway infrastructure, the simulations indicated that LDW-LDP systems could prevent 28% to 32% of single-vehicle, drift-out-of-lane road departure crashes and 21% to 28% of cases of serious driver injury. If lane markings were present on all roadways, these systems were estimated to prevent 32% to 36% of crashes and 27% to 31% of cases of serious driver injury. If the shoulders were expanded to 3.6 m, LDW-LDP systems were estimated to prevent 50% to 54% of crashes and 44% to 48% of cases of serious driver injury. If lane markings were present and the shoulders were expanded to 3.6 m, LDW-LDP systems were estimated to prevent 72% to 78% of crashes and 60% to 65% of cases of serious driver injury.

The results suggest that modifying all roadway infrastructure to include lane markings would have a more modest impact than expanding roadway shoulder width on LDW-LDP effectiveness. This finding is attributed to many of the road departure crashes taking place on roadways with narrow shoulders (over half of the crashes took place on roadways with negligible shoulder widths of less than 0.3 m). Additionally, roadways without lane markings tended to have narrower shoulders. For example, 57% of roadways had a shoulder width narrower than 0.3 m when lane markings were present, and 69% of roadways had a shoulder width narrower than 0.3 m when no lane markings were present.

The infrastructure improvements proposed in this study would be very costly. However, the results from these simulations highlight how dependent LDW and LDP effectiveness is on these roadway infrastructure features. The performance of these active safety systems currently relies heavily on the ability to not only detect an imminent lane departure but also steer the vehicle back onto the roadway. Although the provision of wider shoulders that yield additional time and space to steer the vehicle back onto the roadway is a less easily solvable task, the development of road edge detection technologies may help improve the performance of these systems. Additionally, modifications to the LDW-LDP timing algorithm and LDP vehicle trajectory manipulation may help to reduce the likelihood of the vehicle departing the roadway.

There are some important limitations to the findings of this study. First, LDW and LDP were assumed to become activated at the instant the leading wheel touched the lane markings. However, past work has shown that current production vehicles equipped with LDW deliver warnings both before and after the initial lane departure, depending on the vehicle make and model (*14, 26*). Additionally, these systems can be deactivated by drivers or may not become activated if some speed threshold is not reached. Second, the LDP system implemented is a simplified representation of how the actual systems work in the fleet. The potential benefits of an LDP system are expected to be dependent on the magnitude of the system's input and the mechanism used to alter vehicle trajectory (e.g., steering angle control or selective braking of the vehicle's wheels). Third, these systems were assumed to become activated on all roadways with lane markings. However, poor visibility and marking clarity will vary with weather and road conditions. Fourth, traffic in adjacent lanes and objects on the roadway were not considered in this study. Information about traffic density was not provided in the NASS-CDS database, so the approach used provided a best case scenario. Fifth, this study's benefits estimation method assumed that the improved roadway infrastructure features would not affect driver recovery in the no–LDW or LDP scenario. This assumption may lead to an overestimation of the effectiveness of the performance of LDW-LDP systems in these scenarios.

CONCLUSIONS

This study investigated the influence of roadway infrastructure on LDW and LDP effectiveness. On current roadways, LDW and LDP were estimated to prevent up to 32% of drift-out-of-lane road departure U.S. crashes and up to 28% of cases of serious driver injury. The results suggest that LDW-LDP systems could prevent up 36% of crashes and 31% of cases of serious driver injury if all roadways had lane markings. If roadways were to have expanded shoulders, the results indicate that LDW-LDP systems could prevent up to 54% of all crashes and 48% of cases of serious driver injury. If these roadways had lane markings and expanded shoulders, these systems could prevent up to 78% of crashes and 65% of cases of serious driver injury. Although the proposed infrastructure modifications would be costly, the results highlight the importance of lane markings and adequate shoulder width on LDW-LDP system effectiveness. Although providing vehicles with adequate shoulder width is the less practical countermeasure, the issue of absent lane markings may be addressed with a road edge detection algorithm for LDW-LDP systems.

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