Potential Occupant Injury Reduction in the U.S. Vehicle Fleet for Lane Departure Warning–Equipped Vehicles in Single-Vehicle Crashes

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Objective: Single-vehicle collisions involve only 10 percent of all occupants in crashes in the United States, yet these same crashes account for 31 percent of all fatalities. Along with other vehicle safety advancements, lane departure warning (LDW) systems are being introduced to mitigate the harmful effects of single-vehicle collisions. The objective of this study is to quantify the number of crashes and seriously injured drivers that could have been prevented in the United States in 2012 had all vehicles been equipped with LDW.

Methods: In order to estimate the potential injury reduction benefits of LDW in the vehicle fleet, a comprehensive crash and injury simulation model was developed. The model's basis was 481 single-vehicle collisions extracted from the NASS-CDS for year 2012. Each crash was simulated in 2 conditions: (1) as it occurred and (2) as if the driver had an LDW system. By comparing the simulated vehicle's off-road trajectory before and after LDW, the reduction in the probability of a crash was determined. The probability of a seriously injured occupant (Maximum Abbreviated Injury Score [MAIS] 3+) given a crash was computed using injury risk curves with departure velocity and seat belt use as predictors. Each crash was simulated between 18 and 216 times to account for variable driver reaction, road, and vehicle conditions. Finally, the probability of a crash and seriously injured driver was summed over all simulations to determine the benefit of LDW.

Results and Conclusions: A majority of roads where departure crashes occurred had 2 lanes and were undivided. As a result, 58 percent of crashes had no shoulder. LDW will not be as effective on roads with no shoulder as on roads with large shoulders. LDW could potentially prevent 28.9 percent of all road departure crashes caused by the driver drifting out of his or her lane, resulting in a 24.3 percent reduction in the number of seriously injured drivers.

The results of this study show that LDW, if widely adopted, could significantly mitigate a harmful crash type. Larger shoulder width and the presence of lane markings, determined by manual examination of scene photographs, increased the effectiveness of LDW. This result suggests that highway systems should be modified to maximize LDW effectiveness by expanding shoulders and regularly painting lane lines.

Keywords: active safety, lane departure warning, safety benefits, simulation

Introduction

Lane departure crashes are an especially harmful crash mode on U.S. roads. Single-vehicle crashes account for only 10 percent of occupants involved in crashes yet account for 31 percent of all fatalities (Kusano and Gabler 2014). Lane departure warning (LDW) is an active safety system that delivers a warning to the driver when the vehicle is drifting out of its lane. The aim of LDW is to alert drivers to unintentional lane departures—for example, those caused by distraction—in order to prevent or mitigate the consequences of lane departure crashes.

LDW and other active safety systems are in the early stages of adoption. First available on luxury brand vehicles only, active safety features are starting to be offered on a wider range of nonluxury vehicles. Still, in almost all cases, the active safety systems are optional equipment that must be purchased by the consumer, which may decrease its market penetration. The number of active safety systems on vehicles in the U.S. vehicle fleet is difficult to estimate. An analysis by the Highway Loss Data Institute (HLDI 2012) using vehicle registration data through 2010 found that approximately 1 percent of
registered vehicles had forward collision warning, another active safety system, as either standard or optional equipment. According to HLDI projections, it will be 2017 when 10 percent of vehicles have these systems. No estimate of LDW market penetration was made by the HLDI study, presumably because there were even fewer vehicles equipped with LDW than forward collision warning by year 2010.

Because of the relatively low market penetration of LDW, there is a crucial need for predictions of LDW benefits in the U.S. vehicle fleet. Adoption of LDW in the vehicle fleet is still at its early stages, which makes it difficult to retrospectively determine its effectiveness using crash data such as for more mature safety systems; for example, electronic stability control (Erke 2008; Ferguson 2007; Hoye 2011). Early studies have used insurance claims data (Moore and Zuby 2013) and automated crash notification (Geisler and Michelini 2011) to evaluate performance on select systems. Market penetration is still too low to perform fleet-wide benefits estimates for LDW as has been done with electronic stability control, for example.

One promising approach is to develop a national model of LDW in the vehicle fleet to predict the system’s effectiveness. Such a model of LDW benefits could be used by policymakers to assess the importance of LDW in future regulatory and consumer rating programs. System designers could use such a model to weight design decisions; for example, warning delivery timing or target operating conditions. Such a model was developed under the Advanced Crash Avoidance Technologies research program, sponsored by the NHTSA (Gordon et al. 2010). The safety impact methodology is a framework to predict safety benefits of a proposed system in future vehicle fleets and is the basis for the methodology used in this study (Burgett et al. 2008).

The objective of this study was to estimate the number of crashes and seriously injured drivers that could have been prevented if all vehicles in the U.S. vehicle fleet were equipped with LDW in the year 2012.

### Methods

#### Overview of Model of LDW Benefits

Figure 1 summarizes the approach developed to estimate benefits of LDW in the U.S. vehicle fleet. The basis for the model was a large set of lane departure crashes extracted from the NASS-CDS. The coded data were supplemented by estimation of conditions at departure and an examination of the scene photographs and diagrams to create a case set for simulations. The simulations took each initial vehicle and road condition and simulated 2 driver steering reactions derived from driving simulator experiments from the literature. The outcome of each simulation was the probability of a crash and the probability of a seriously injured driver given the vehicle’s simulated trajectory. For each initial condition and driver reaction, the lane departure was simulated with and without LDW. Finally, all simulations were assigned a weight based upon how likely they were to occur. The total number of crashes and seriously injured drivers was summed over all simulations to determine the effectiveness of LDW.

#### NASS-CDS Lane Departure Crashes

NASS-CDS is a nationally representative sample of crashes that is collected and released annually by the NHTSA. Crashes included in the database must have involved a passenger vehicle that had to be towed from the scene due to damage. Field investigation teams throughout the country investigate approximately 5000 crashes each year. The data collected include information on the road, vehicle, and environment in the crash. Detailed injury information derived from medical records is also collected.

NASS-CDS year 2012 was the basis for the LDW benefits simulation. A single year of data was used instead of a combination of multiple years to facilitate the manual review of scene photographs. Single-vehicle road departure crashes were identified using the coded precrash variables in NASS-CDS. The goal was to identify single-vehicle crashes where the driver drifted out of his or her lane and exclude other single-vehicle crashes, such as loss of control and contact with animals in the roadway. Comprehensive precrash scenarios were used as developed by Kusano and Gabler (2014).
Next, candidate models were built to maximize the adjusted R² to determine which predictors were correlated with the outcome. That is, velocity, angle, or receiver operating characteristic, to be performed between predictors and the desired outcome; to fit the regression models to preserve normality of the variables.

To account for variability in the estimates of the missing variables, 3 values of departure velocity, departure angle, and radius of curvature were predicted for each NASS-CDS case. For a given NASS-CDS case, the regression models were used to generate a value for each missing variable. The resulting value was used as the mean and the root mean squared error of the regression model was used as the standard deviation to form a normal probability distribution function for the missing variable in the case. For the simulation case set, 3 values were chosen that represented the 17th, 50th, and 83rd percentiles of the distribution. These percentiles were chosen as characteristic points of 3 equal area portions under the normal probability density function, as shown in the Appendix (see online supplement).

In order to form these multiple linear regression models, a data source with both the NASS-CDS variables and velocity, angle, and radius of curvature was required. The National Cooperative Highway Research Program (NCHRP) Project 17–22 performed supplemental crash reconstructions on a set of 890 NASS-CDS cases (Mak and Sicking 2010). Cases were selected from NASS-CDS years 1997–2004 that involved a single vehicle in a road departure crash. The NCHRP 17–22 project investigators made supplemental measurements at the crash scene and performed energy-based crash reconstructions for each crash. The resulting data set thus contained both full NASS-CDS data as well as these supplemental reconstructions.

Model formulation was performed manually by examination; that is, not by a proscribed model formulation algorithm such as stepwise addition. First, univariate analysis of variance was performed between predictors and the desired outcome; that is, velocity, angle, or receiver operating characteristic, to determine which predictors were correlated with the outcome. Next, candidate models were built to maximize the adjusted R² or goodness of fit measure to the data. This methodology for estimating the missing initial departure parameters was previously developed (Gorman et al. 2013). For the current study, the models were refined to better fit the data. Details of the model development are included as an Appendix.

### Simulation Case Set

#### Estimation of Conditions at Departure

Although the data coded in NASS-CDS have detailed information on the roads and occupants involved in a collision, key parameters needed to simulate lane departures are not collected as part of a standard NASS-CDS investigation. Specifically, the vehicle speed, angle relative to the road, and radius of curvature at departure are not included in the data. To estimate these missing parameters, multiple linear regression models were used to predict the most likely values given the observed coded variables in NASS-CDS. The log transform of the departure angle and radius of curvature were used to fit the regression models to preserve normality of the variables.

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### Review of Scene Photographs

In order to effectively model benefits of LDW, information about the shoulder width of the road, the travel lane of the vehicle, and lane markings are important parameters. These measures are not included in the NASS-CDS data but in almost all cases can be readily identified by examining the scene diagram, scene photographs, and event narratives prepared by the investigators. Analysts performed a supplemental analysis to manually examine all road departure crashes from NASS-CDS year 2012.

First the analysts examined the scene diagram with the event narrative to determine whether the departure was a valid drift-out-of-lane road departure crash. Road departure crashes were identified using precrash variables coded in NASS-CDS that corresponded to drift-out-of-lane precrash scenarios. It became apparent from the event narratives, however, that the codes are not always consistently applied by the investigators. Crashes that mentioned control loss prior to the first lane departure, the driver having a medical condition (e.g., heart attack) prior to the departure, or other conditions where LDW would not be effective were marked as invalid and excluded from further analysis.

Shoulder width is a critical parameter that affects LDW benefits estimates. In the model without LDW active, the driver starts to steer back toward the road when the leading wheel of the vehicle first leaves the shoulder. In the model with LDW, a warning is delivered when the vehicle’s leading wheel touches the lane marking and driver steering begins after a reaction time to LDW. Therefore, LDW is most effective in simulations with large shoulders because the driver can often avoid leaving the road surface altogether, resulting in zero risk of a collision. Conversely, LDW had no effectiveness in simulations with zero shoulder width.

The shoulder width was estimated from the scene photographs showing the roadside where the vehicle departed. Shoulders could be categorized by the analysts as (a) being zero width, (b) between 0.3 and 1 m wide, (c) between 1 to 3.6 m wide, or (d) over 3.6 m wide. If the shoulder was less than 0.3 m (1 ft), the shoulder was considered to be of negligible width; that is, zero shoulder width. A width of 3.6 m was chosen as a reference distance for the analysts because a typical highway lane in the United States is no wider than 3.6 m. Thus, the lanes shown in the scene photographs could be used as a reference. For the simulation case set, cases with labeled shoulder widths of 0.3 to 1 m and 1 to 3.6 m were simulated twice, once with each width to account for uncertainty in the identification of shoulder width. For example, a crash that had a 0.3 to 1 m shoulder width as determined by the analyst was simulated once with a 0.3 m shoulder and once with a 1 m shoulder, both with equal probability of occurring.

The analysts also collected data about the number of travel lanes and position of the vehicle in the travel lanes before the first departure. Because most crashes occurred on 2-lane undivided roads, determining travel lane was trivial in most cases. On multilane roads, however, there was some uncertainty in the initial travel lane of the vehicle. In some cases the initial travel lane is explicitly named in the written narrative prepared by the investigator. If not included in the narrative, the analysts used the scene diagram to determine the initial travel lane. The number of travel lanes the vehicle traveled across before departing the paved roadway was incorporated into the simulation model. In the simulation model, risk of a collision only occurred when the vehicle left the paved
roadway. Risk of colliding with vehicles traveling in adjacent lanes—that is, in the opposite or same direction—was not modeled.

The lane marking was identified at the approximate point of the first lane departure that led to the crash. The presence of a painted lane line was noted. No evaluation of lane marking clarity or quality was made.

Creation of Simulation Case Set

Each NASS-CDS case was represented in the simulation case set multiple times. The number of representations in the case set was dependent on the conditions in the crash. A crash that occurred on a curved road and with a shoulder width coded had the greatest number of simulations (3 departure velocities × 3 departure angles × 3 radius of curvatures × 2 shoulder widths = 54 simulations). A crash that occurred on a straight road with either no shoulder or a shoulder greater than 3.6 m had the lowest number of simulations (3 departure velocity × 3 departure angle = 9 simulations). Each of the simulations was assigned an equal proportion of the NASS-CDS sample weight for the given case because all conditions were equally likely to occur. This simulation will be denoted as \( w_{i,j} \) in the following discussion.

Simulations of Lane Departure Crashes

Driver Reaction Model

Driver reaction to an LDW is not instantaneous. There is a reaction time delay between the warning and driver reaction in response to the warning. In the simulation model there was a reaction time after the warning followed by driver steering, which was modeled as a step function. Real-world driver steering is rarely a perfect step function. A step response was selected for this study to simplify the mathematical trajectory model.

Several studies have characterized driver reaction times and steering to an LDW. Suzuki and Jansson (2003) performed a study in a driving simulator with 24 drivers and 54 departure events. Depending on the warning modality and whether the driver was informed of the LDW system, the reaction times varied between 0.38 and 1.36 s. Drivers were distracted by a secondary task to cause departures. Kozak et al. (2006) conducted a similar simulator study involving 32 subjects who had been awake for 23 h prior to the test. Each driver had at least 8 departure events that were related to fatigue. In these experiments, the average reaction time of all drivers was 0.62 s.

For the current study, drivers were simulated as having reaction time of either 0.38 or 1.36 s. These values were chosen as upper and lower bounds from the simulator studies. The LDW was delivered when the leading wheel of the vehicle first touched the lane line. Driver steering would start after the warning was delivered by the specified reaction times. In the scenarios in which the vehicle was not equipped with an LDW system, the driver was modeled as starting to steer 0.38 or 1.36 s after the vehicle’s leading wheel first left the road’s shoulder. Each reaction time was given equal probability of occurring.

In addition to reaction time, the magnitude of the steering response was specified in the model. Mazzae et al. performed both simulator (1999b) and test track (1999a) studies of an intersection incursion scenario. The drivers were not informed of the critical scenario in either study. Approximately 15 min into the test drive, a vehicle or surrogate vehicle pulled into the test vehicle’s lane as the test vehicle approached an intersection, forcing the driver to take an evasive maneuver to avoid a collision. In the test track study, the average of the maximum steer angle during the evasive maneuver was reported as 53°.

Steering was characterized in the model by a turning radius, \( R \), that resulted from the driver steering. Turning radius was estimated as

\[
R_{\text{min}} = \frac{v^2}{\mu g},
\]

where \( v \) was the vehicle speed at departure, \( g \) is the acceleration of gravity, and \( \mu \) is the coefficient of friction of the roadside surface. In this study, we assumed a coefficient of friction of 0.5, which resulted in steering angles similar to those reported by Mazzae et al. (2009a).

Vehicle Trajectory Model and Probability of a Crash

Simulations were performed using all initial conditions in the simulation case set, indexed by \( i \), and the 2 driver reaction times, indexed by \( j \), in order to estimate the corresponding probability of a crash and seriously injured driver. In these simulations, the vehicle was assumed to be a point mass that departed the road in a straight line as a driver who was distracted would do. The driver would start to steer back toward the road after a prescribed reaction time. The event that would bring the driver’s attention back to the road was either the vehicle departing the paved roadway or an LDW that was delivered.

The roadside terrain was discretized into zones, index by \( k \), that were parallel to the road boundary. To predict the probability of a crash occurring off the road, the model considered the distance the vehicle traveled in each one of the zones. The probability of a crash occurring would thus increase with the distance the vehicle traveled laterally from the road as well as the total distance traveled off road.

In order to create such a crash probability model, an estimate of the risk of a collision in each on the roadside zones was created using the NCHRP 17–22 data discussed previously. In addition to the departure conditions, the 17–22 data also included the position of objects impacted. From these data, the number of crashes in each of the roadside zones, \( C_k \), and the distance traveled in each roadside zone, \( \gamma_k \), could be determined. Consider if the vehicle’s off-road path was split into equal size lengths of size \( s \). The probability of a crash occurring, \( P[\text{Crash}_{i,j,k}] \), given that one has not occurred in a previous segment of the simulated trajectory path \((i, j)\) traveled in zone \( k \) can be defined as

\[
P[\text{Crash}_{i,j,k}] = 1 - \left(1 - \frac{s C_k}{\gamma_k} \right)^{\frac{\ell_{i,j,k}}{s}},
\]

where \( \ell_{i,j,k} \) is the length of the previous segment. The probability of a crash occurring in zone \( k \) given that a crash has occurred in an adjacent zone \( k' \) can be defined as

\[
P[\text{Crash}_{i,j,k} | \text{Crash}_{i,j,k'}] = 1 - \left(1 - \frac{s C_{k'}}{\gamma_{k'}} \right)^{\frac{\ell_{i,j,k}}{s}},
\]

where \( \ell_{i,j,k} \) is the length of the previous segment. The probability of a crash occurring in zone \( k \) given that no crash has occurred in any adjacent zone can be defined as

\[
P[\text{Crash}_{i,j,k} | \text{No Crash}_{i,j,k'}] = 1 - \left(1 - \frac{s C_{k'}}{\gamma_{k'}} \right)^{\frac{\ell_{i,j,k}}{s}},
\]

where \( \ell_{i,j,k} \) is the length of the previous segment. The probability of a crash occurring in zone \( k \) given that a crash has occurred in an adjacent zone \( k' \) and no crash has occurred in any adjacent zone \( k'' \) can be defined as

\[
P[\text{Crash}_{i,j,k} | \text{Crash}_{i,j,k'} | \text{No Crash}_{i,j,k''}] = 1 - \left(1 - \frac{s C_{k'}}{\gamma_{k'}} \right)^{\frac{\ell_{i,j,k}}{s}} - \left(1 - \frac{s C_{k''}}{\gamma_{k''}} \right)^{\frac{\ell_{i,j,k}}{s}},
\]

where \( \ell_{i,j,k} \) is the length of the previous segment. The probability of a crash occurring in zone \( k \) given that a crash has occurred in an adjacent zone \( k' \) and no crash has occurred in any adjacent zone \( k'' \) and \( k''' \) can be defined as

\[
P[\text{Crash}_{i,j,k} | \text{Crash}_{i,j,k'} | \text{No Crash}_{i,j,k''} | \text{No Crash}_{i,j,k'''}] = 1 - \left(1 - \frac{s C_{k'}}{\gamma_{k'}} \right)^{\frac{\ell_{i,j,k}}{s}} - \left(1 - \frac{s C_{k''}}{\gamma_{k''}} \right)^{\frac{\ell_{i,j,k}}{s}} - \left(1 - \frac{s C_{k'''}}{\gamma_{k''}} \right)^{\frac{\ell_{i,j,k}}{s}},
\]

where \( \ell_{i,j,k} \) is the length of the previous segment.
where \( L_{i,j,k} \) is the total simulated trajectory length in zone \( k \). Consider, for example, that zone number 2 had a total of 3 trajectory lengths in the crash data and one crash occurred. If a simulated trajectory had 3 trajectory lengths, the probability of a crash occurring would be \( 1 - \left( 1 - \frac{s}{\gamma} \right)^{3} \). Equation (2) is a generalization of this example.

Taking the limit of Eq. (2) as \( s \) approaches zero produces the solution to the probability of a crash occurring in a given zone:

\[
P[\text{Crash}_{i,j,k}] = \lim_{s \to 0} \left[ 1 - \left( 1 - \frac{s C_k}{\gamma_k} \right)^{L_{i,j,k}} \right]
\]

\[
P[\text{Crash}_{i,j,k}] = 1 - \exp \left( - \frac{C_k L_{i,j,k}}{\gamma_k} \right).
\] (3)

Multiplying over all zones yields the probability of a crash occurring on the simulated trajectory

\[
P[\text{Crash}_{i,j}] = 1 - \prod_{k=1}^{K} \exp \left( - \frac{C_k L_{i,j,k}}{\gamma_k} \right).
\] (4)

**LDW Model**

An LDW system was modeled that delivered a warning when the leading wheel of the vehicle touched the lane marking on the road. Driver steering back toward the road started after the prescribed reaction time.

**Probability of Seriously Injured Driver**

A seriously injured driver was defined as a driver with a Maximum Abbreviated Injury Score of 3 or greater (MAIS 3+). The MAIS 3+ determination for drivers was made using the AIS version 98 injury coding available in the NCHRP 17–22 database. The probability of an injury for a given simulated trajectory, \( P[\text{Injury}] \), was a function of the probability of an injury given a crash, \( P[\text{Injury}|\text{Crash}] \), and the probability of a crash, \( P[\text{Crash}] \):

\[
P[\text{Injury}_{i,j}] = P[\text{Injury}_{i,j}|\text{Crash}_{i,j}] P[\text{Crash}_{i,j}].
\] (5)

The probability of an injured driver given a crash was modeled using logistic regression and the NCHRP 17–22 data. The outcome was whether the driver was seriously injured or not (MAIS 3+) and the predictors for the model were driver seat belt use and departure velocity. Seat belt use is closely tied to injury outcome. Change in velocity during the crash, or delta \( V \), is commonly used in injury risk curves as a measure of crash severity. Because of the reconstruction methods used in NASS-CDS, delta \( V \) is missing in more fixed object and rollover crashes than vehicle-to-vehicle collisions. As a result, departure velocity was used as a metric of crash severity instead of delta \( V \).

**Benefits of LDW**

Finally, simulations using all of the initial conditions in the simulation case set and driver reactions were summed to determine the total number of crashes,

\[
N_{\text{crashes}} = \sum_{i=1}^{m} \sum_{j=1}^{2} P[\text{Crash}_{i,j}] w_{i,j}^*.
\] (6)

Similarly, the number of seriously injured drivers were summed for all simulations:

\[
N_{\text{injured}} = \sum_{i=1}^{m} \sum_{j=1}^{2} P[\text{Injury}_{i,j}] w_{i,j}^*.
\] (7)

The effectiveness of LDW, \( \epsilon \), for either number of crashes or injured drivers was found by

\[
\epsilon = \frac{N_{\text{without LDW}} - N_{\text{with LDW}}}{N_{\text{without LDW}}}.
\] (8)

In order to adjust the simulation weights for the probability of a crash not occurring, the weights were normalized relative to the probability of crash occurring during the without LDW simulations:

\[
w_{i,j}^* = \frac{w_{i,j}}{P[\text{Crash}_{i,j}]}.
\] (9)

**Results**

**Selected Cases and Simulation Case Set**

Table 1 summarizes the number of single-vehicle drift-out-of-lane departure crashes in NASS-CDS. In total, 14.7 percent of all crashes from NASS-CDS 2012 were drift-out-of-lane departure crashes. Of crashes from NASS-CDS 2012 that were coded as LDW applicable, the manual inspection of the cases showed that 92 percent were valid drift-out-of-lane departures. NASS-CDS is a probability sample of crashes and each crash has a case weight. Crashes with serious injury are oversampled and crashes with minor outcomes are undersampled. These minor collisions, therefore, have much higher weights than serious injury crashes in order to make the entire sample nationally representative. When examining subsets of NASS-CDS, these high-weight cases can dominate the analysis. In NASS-CDS 2012 departure cases, for instance, 4 cases out of 556 made up 34 percent of the case weights. If these cases were left in the LDW benefits analysis, the outcome of simulations for these 4 cases would skew the results. For this study, any NASS-CDS cases with weight greater than 5000 were excluded, as others have done in the existing literature (Kononen et al. 2011). We also excluded 8 end departures, where the vehicle departed the road “T” intersections of a perpendicular road. Finally, we excluded crashes with multiple departure sides, discussed in more detail below. The resulting 478 lane departure crashes formed the simulation set for LDW benefits estimates.
Table 1. Number of Drift-Out-of-Lane, Single-Vehicle Crashes in NASS-CDS 2012

| Group                              | n     | Frequency  |
|------------------------------------|-------|------------|
| All crashes in CDS 2012            | 3581  | 1,996,016  |
| Drift-out-of-lane departures       | 629   | 293,937    |
| Valid departure after manual       | 556   | 271,810    |
| inspection                         |       |            |
| Exclusions for valid departures    |       |            |
| Weight > 5000                      | 5     | 91,577     |
| End departures                     | 8     | 1767       |
| Multiside departures              | 65    | 30,804     |
| Total excluded                     | 78    |            |
| Final data set for LDW modeling    | 478   | 147,662    |

The sequence of lateral departures that occurred prior to the first harmful event was examined using the scene diagrams and event narratives. For example, some drivers depart on one side of the road, apply too much corrective steering, and depart the opposite side of the road. The sequence of lateral departures that could be used to determine whether the departure was a multiple departure is not included in the NASS-CDS data. The examination of NASS-CDS 2012 scene diagrams showed that 11 percent of departures had multiple lane departures prior to the first harmful event. The model of LDW benefits developed in this study only simulates the return to the lane after the first departure. Therefore, we only simulated LDW benefits for the crashes with a single lane departure before a crash.

Figure 2 summarizes the road alignment, side of first lane departure, and presence of a lane marking at the side of the first lane departure. All measures in Figure 2 were found from the visual inspection of the NASS-CDS case material, not the coded NASS-CDS variables. The NASS-CDS variables were found to be inconsistent with respect to the site of the first lane departure as opposed to the site of the first road departure. For example, in 46 percent of cases coded as “curve right” and 45 percent of cases coded as “curve left” road alignments in NASS-CDS, the examination of scene photographs found that the first lane departure occurred on a straight road segment. Often these mismatches between NASS departure side and scene photograph occurred near the transition to or from a curved section. In contrast, road segments coded in NASS as occurring on straight sections matched the review of the scene photographs in 96 percent of cases.

The presence and width of a shoulder were also determined from the visual inspection of scene photographs, as shown in Figure 3. Half (51%) of all lane departure crashes occurred on 2-lane undivided roads, which explains why the majority of crashes had little or no shoulder (58%). The next most frequent road configurations were 2-lane divided roads—that is, highways (15%)—and 3-lane divided roads (10%). These divided highways are more likely to have shoulders than undivided 2-lane roads. Shoulder width is crucial to the LDW benefits model because LDW will have little or no benefit in simulations where the driver departs from the travel lane directly onto the roadside.

Figure 4 shows the number of adjacent travel lanes the vehicle crossed prior to crossing a shoulder and the width of the shoulder if there was one. In 63 percent of crashes the vehicle crossed directly onto the shoulder or roadside, 32 percent crossed one lane, and 5 percent crossed more than one lane. In the model of LDW benefits, the risk of colliding with adjacent vehicles was not explicitly modeled.

Multiple linear regression models were used to predict the most likely departure velocity, departure angle, and radius of curvature (if a curved road section) because these measures were not included in the NASS-CDS data. The details of the formulation of these models are included in the Appendix. In total, the 478 NASS-CDS cases resulted in a simulation case set of 10,941 simulation initial conditions. Two simulations were performed for the 2 driver reaction times, resulting in a total simulation case set of 21,882 simulations performed.
The distributions of departure velocity, departure angle, and radius of curvature used in the simulation case set are shown in the Appendix.

**Injury Risk Curves**

The probability of an injured driver given a crash was estimated using a logistic regression model. The model was developed using 849 cases corresponding to 273,001 weighted collisions from the NCHRP 17–22 database. In order to be selected, driver injury outcome (MAIS 3+), seat belt use, and vehicle departure speed must have been available. In the sample, 67 percent of drivers were belted and 13.3 percent of drivers were seriously injured (MAI 3+). The intercept was $-3.0257$, the coefficient for departure speed (km/h) was 0.0277, and the coefficient for seat belt use (belted = 1, unbelted = 0) was $-1.910$. Increases in departure speed increase injury risk (positive coefficient) and a driver who is wearing a seat belt decreases injury risk (negative coefficient).

**Benefits of LDW**

Table 2 lists the number of crashes and injuries without and with LDW along with the predicted effectiveness of LDW. Overall, LDW would cause a 28.9 percent reduction in the number of all drift out of lane road departure crashes, which would result in a 24.3 percent reduction in the number of seriously injured drivers. In the simulations, in 36,027 departures (or 24%) the driver would have enough time to steer back toward the road without the vehicle leaving the paved surface; that is, shoulder and/or adjacent lanes. Simulations where the vehicle never left the road accounted for 85 percent of the overall effectiveness of LDW.

In the model we assumed that there were no objects or vehicles in adjacent lanes that the simulated vehicle could collide with. Therefore, after LDW was activated, additional lanes crossed would provide more time and space for steering to begin and the vehicle to return to its lane prior to departing the road. Figure 5. shows the effectiveness of LDW in simulations by the number of lanes crossed prior to exiting the road. Additional lanes greatly increased the effectiveness of LDW.

Like additional travel lanes crossed, shoulder width increased the effectiveness of LDW by providing additional time for the vehicle to return to the road. The effect of shoulder width on LDW effectiveness is tabulated in the Appendix.

**Discussion**

This study introduced a comprehensive simulation framework for estimating the fleet-wide benefits of an LDW system. The methodology uses NASS-CDS as the basis for simulation to create a nationally representative sample of lane departure crashes. To supplement vehicle, road, and occupant information included in the NASS-CDS data, supplemental data collection and predictive models were developed. These supplemental data sources were necessary to create simulations of LDW benefits. The results of the simulations show that LDW can prevent a large number of crashes and seriously injured drivers. These benefits are despite the fact that 30 percent of crashes occurred on roads with no lane markings and 29 percent of crashes occurred on roads with no shoulder. In the model of LDW benefits developed in this study, LDW had no benefit in crashes that occurred on roads with no lane marking and with no shoulder.

The results of this study show that the benefits of LDW can be maximized by improving roadway design features. Namely, LDW is most effective when there are lane markings, so that the system can deliver a warning effectively, and large shoulders, so the driver has more distance to recover. The implications of these results are that governmental highway agencies should prioritize widening shoulders and maintaining lane markings when they consider design of future roads or upgrades to current roads.

The model developed in this study makes use of available driver characteristics and behavior data that are in the literature, mostly from driving simulator studies. It is an open research question, however, what constitutes a truly representative driver response during emergency lane departure events. An emerging data source that might shed light on population distributions of driver behavior is the Strategic Highway Research Program 2 (SHRP-2) Naturalistic Driving Study (NDS). The SHRP-2 data will provide 1 to 2 years of fully instrumented everyday driving for over 3000 drivers throughout the United States (Antin et al. 2011). The SHRP-2 NDS data could be used to develop better estimates of steering and braking parameters used in the current model by observing behavior during lane departure events.

The simulations conducted for this study assume that LDW could effectively return the driver’s attention to the road and help mitigate the time the vehicle spends out of its lane and
thus reduce the risk of a crash. Not considered in this model, however, are the driver-related factors that lead to the road departures. LDW will likely be most effective at mitigating departures caused by driver distraction, either internal or external to the vehicle. A previous study on crash causation factors in drift-out-of-lane road departure crashes found that only 24 percent of crashes were caused by distraction (Kusano and Gabler 2014). Almost as frequent at 22 percent of lane departure crashes, however, were crashes caused by actually falling asleep—that is, not drowsiness—or medical emergencies; for example, a heart attack or loss of consciousness. LDW may not be as effective at mitigating all types of lane departure critical reasons. Lane keeping assistance systems, which can actively apply steering torque to the vehicle, may be more effective at mitigating departures where a warning may be less effective.

The model in this study also assumes that LDW systems will be active during all driving. Some drivers may choose to deactivate the system if they do not find it useful. One early survey of owners of Volvo vehicles with advanced crash avoidance features found that only 59 percent of owners reported always driving with the LDW system enabled, compared to over 80 percent who reported always driving with the forward collision warning system active (Insurance Institute for Highway Safety 2012). As more consumer acceptance data become available, the proportion of drivers who would disable the system can be incorporated into the model developed for this study.

The assumption that the simulated vehicle crosses adjacent lanes without contacting other objects or vehicles provides an optimistic or best-case scenario. The traffic density or presence of other vehicles prior to the crash was not recorded in NASS-CDS. Therefore, it is difficult to develop a model of the crash risk of traveling over adjacent lanes. Further, injury risk of colliding with a vehicle traveling in the opposite direction may be more severe than colliding with a vehicle in an adjacent lane because of higher relative impact speeds. More data are needed in order to estimate both the crash and injury risk for collisions with adjacent vehicles.

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Supplemental Material

Supplemental data for this article can be accessed on the publisher’s website.

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