POTENTIAL SAFETY BENEFITS OF LANE DEPARTURE WARNING AND PREVENTION SYSTEMS IN THE U.S. VEHICLE FLEET

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ABSTRACT

Road departures account for nearly one-third of all fatal crashes. Lane departure warning (LDW) and lane departure prevention (LDP) have the potential to mitigate the number of crashes and fatalities that result from road departure crashes. The objective of this study was to predict the effectiveness of LDW and LDP in preventing road departure crashes if all vehicles in departure crashes in the U.S. fleet were equipped with either system. A set of 478 road departure crashes extracted from NASS/CDS 2012 were used to formulate a simulation case set. Each of these crashes were than simulated with and without LDW and LDP systems. The LDW system was assumed to alert the driver at the instance the leading wheel touched the lane marking. A steering-based LDP system was assumed to operate in conjunction with LDW (i.e. by alerting the driver of a lane departure) and directly modulate steering wheel angle at the instance the leading wheel touched the lane marking. Four hypothetical LDP designs were evaluated, using typical evasive maneuvering behavior from a lane departure, to be representative of "light", "moderate", "aggressive", and "autonomous" steering. The LDW system was estimated to reduce the number of crashes by 26.1% and the number of seriously injured drivers by 20.7%. In contrast, the light steering to aggressive steering LDP systems were estimated to reduce the number of crashes by 32.7% to 37.3% and the number of seriously injured drivers by 26.1% to 31.2%. The LDP system with autonomous driving characteristics were estimated to reduce the number of crashes by 51.0% and the number of serious injuries by 45.9%. This study shows that LDW and LDP could mitigate a large proportion of crashes and injuries in lane departure crashes. This paper is directly relevant to the design and evaluation of LDW and LDP systems.

INTRODUCTION

Road departure crashes are one of the most harmful crash modes in the United States. A review of crashes in the National Automotive Sampling System (NASS) General Estimates System (GES) and Fatality Analysis Reporting System (FARS) databases from years 2010 to 2011 indicate that departure crashes accounted for only 10% of all crashes yet comprised 31% of all fatal crashes [1]. Lane departure warning (LDW) and lane departure prevention (LDP) are emerging active safety systems that have the potential to prevent departure crashes and injuries.

LDW works by alerting the driver, via an auditory, visual, or haptic warning [2], of a lane departure. However, the effectiveness of this system is limited by the driver's ability to respond to the departure event. In contrast, LDP can directly modulate vehicle trajectory using various modalities, including steering or selective braking of the vehicle's wheels.

There is a need to distinguish between the expected benefits of LDW and LDP, specifically for the implementation and design of these systems. In the U.S., the New Car Assessment Program (NCAP) tests for the presence of LDW only [3]. In the European NCAP (EuroNCAP), the presence of LDW or LDP is awarded equal points because of a lack of evidence that one system is more beneficial than the other [4].

The objective of this study was to compare the predicted safety benefits of LDW and LDP as if all vehicles in departure crashes in the U.S. fleet were equipped with either system. Two measures of safety benefits were evaluated: (1) the number of crashes that could have been avoided were investigated, and (2) the number of seriously injured drivers that could have been prevented.

METHODOLOGY

Figure 1 summarizes the approach for estimating LDW and LDP benefits in the U.S. vehicle fleet. Each process in the model is discussed in detail in the following sections.

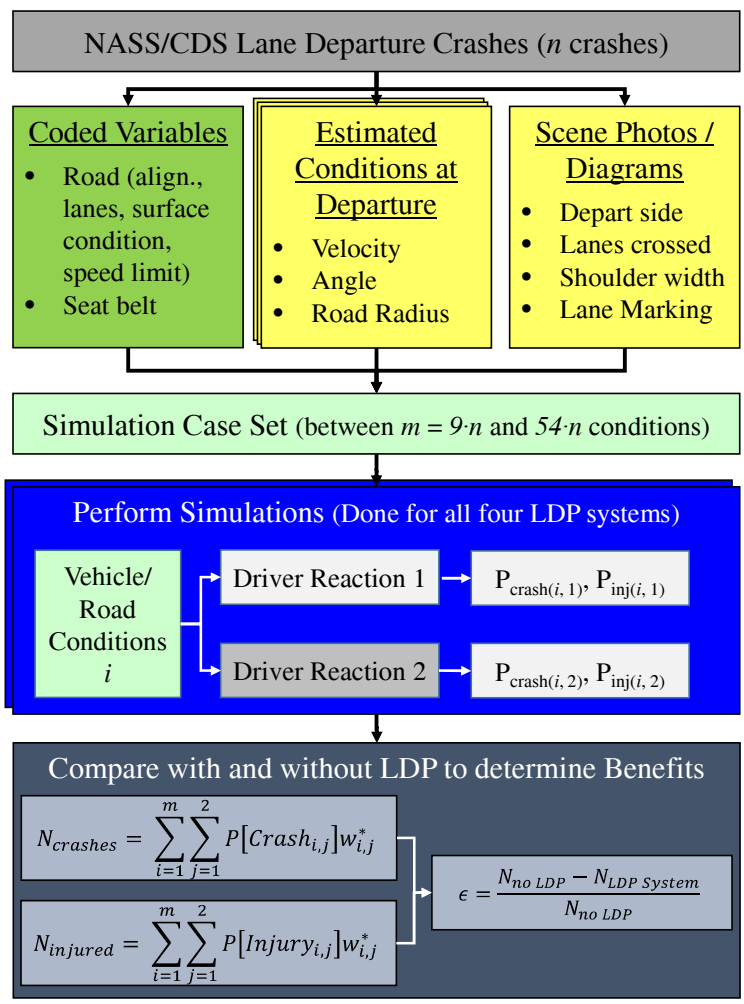

Figure 1. Simulation of NASS/CDS Road Departure Crashes to Estimate Benefits of a Steering-Based LDP System.

Formulation of a Simulation Case Set

Data Source

Crashes in the 2012 National Automotive Sampling System Crashworthiness Data System (NASS/CDS) were used to formulate the simulation case set. NASS/CDS is a nationally representative sample of crashes that occurred in the U.S. Approximately 5,000 crashes are investigated annually by the National Highway Traffic Safety Administration (NHTSA), and data collected by these investigators are compiled into the NASS/CDS database. To be included in the database, at least one vehicle had to have been towed from the scene due to damage. The database includes detailed medical records and information from the crash environment, such as road characteristics and vehicle information, which make it ideal for this study. Each case is assigned a national weight factor. The weight indicates the number of similar crashes that occurred annually in the United States. The results presented in this paper use these case weightings, in order to make them nationally representative. The simulation case set in this study included only single vehicle crashes where the driver drifted out of their lane, and excluded other single vehicle crashes, such as control loss or contact with animals in the roadway.

Estimating Departure Conditions

Although a very detailed database, NASS/CDS lacks many of the lane departure conditions needed for this study, including departure speed, angle, and road radius of curvature. In order to estimate these missing parameters, the National Cooperative Highway Research Program (NCHRP) Project 17-22 was used to predict these missing parameters. The NCHRP 17-22 dataset consists of 890 NASS/CDS road departure crashes from 1997-2004 for which supplemental data collection was conducted on road departure conditions [5].

Statistical multivariate models for estimating departure conditions were formulated using the following process. First, one-way ANOVAs were used to determine which predictors significantly correlated with the departure conditions of interest. Second, models were developed to maximize the adjusted-R^2, or goodness of fit measure to the data. Three values were selected for each variable that represented the 17th, 50th, and 83rd percentiles of three equally portioned areas under a normal probability distribution. This model development strategy was previously implemented by Kusano et al. [6].

Review of Event Records

The shoulder width of the road, the travel lane of the vehicle, and lane markings were required for the simulations. However, these parameters are not coded in the NASS/CDS database. Accordingly, these measures were determined through manual review of scene evidence. Shoulder width was estimated from scene photographs. Our approach was to categorize shoulder width as (a) 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, it was coded as zero-width. A width of 3.6 m was chosen because a typical highway lane in the U.S. is no wider than 3.6 m. Initial travel lane was determined through reading the written event narrative and review of the scene diagrams. Manual reviewers identified the presence of lane markings on scene photographs at the approximate point of the first lane departure that led to the crash.

Driver Reaction Time

Drivers were simulated as having reaction times of either 0.38 s or 1.36 s. These values were chosen as upper and lower bounds on reaction times based on a past driving simulator study by Suzuki and Jansson [7]. They performed a study in a driving simulator with 24 drivers and 54 departure events. Depending on the warning

modality and if the driver was informed or not informed of the LDW system's function, the reaction times varied between 0.38 s to 1.36 s.

Simulation Case Set Replications

Each case was represented in the simulation case set multiple times. Each replication was given an equal probability of occurring. The number of replications were determined using the possible crash conditions previously described. For example, a crash that occurred on a curved road and with a shoulder width between 0.3 and 3.6 m had the most number of simulations (2 reaction times x 3 departure velocities x 3 departure angles x 3 radius of curvatures x 2 shoulder widths = 108 simulations).

Simulation of Lane Departure Crashes

Kinematics simulations were performed using CarSim® vehicle simulation software [8]. The CarSim vehicle model was of a model year 2000 Ford Taurus assumed to be a representative car in the fleet. This specific vehicle was selected to be consistent with the VFU driver model [9]. Trajectories were simulated using initial conditions from the simulation case set, the VFU ACAT driver model [9], the LDW model, and the LDP model. All numerical integration was performed using 4th order Runge-Kutta method, and the simulation time step was set to 0.01s. The travel lane in the simulations was 3.48 m wide for divided highways and 3.64 m wide for undivided highways, as found from cases in the NCHRP 17-22 database.

Driver Model

To model driver control we used a driver recovery model developed by Volvo, Ford, and UMRTI (VFU) through the Advanced Crash Avoidance Technologies (ACAT) Program, with sponsorship from NHTSA [9]. This model was developed to study driver steering and speed response to lane departure warning systems. Steering is adjusted through a proportional control feedback loop based on the yaw rate of the vehicle. 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 [10]. The parameters for the driver model were based on driving simulator experiments performed in Ford's VIRTTEX driving simulator, which matches the 2000 Ford Taurus CarSim model that was developed for the VFU ACAT project and that was used in this study. Driver steering control was only implemented after vehicle departure occurred and the driver had become attentive.

LDW and Steering-Based LDP modeling

In our simulations, the LDW system alerted the driver at the instance the leading wheel touched the lane markings. The modeled LDP system works by directly modulating steering wheel angle. Additionally, the LDP system was assumed to work in conjunction with an LDW system, i.e. the driver will still react after a lane departure occurs. When the driver became attentive, LDP was assumed to no longer contribute modulating steering.

Four potential LDP system designs were evaluated. Each LDP systems has unique steering wheel angular rates and maximum steering angles that were intended to replicate "light", "moderate", "aggressive", and "autonomous" LDP systems. As shown in Figure 2, when LDP became activated, steering wheel angle would change linearly at the prescribed angular rate, and would become saturated at the LDP maximum value. The "moderate" LDP system (rate = 20 degrees/second, maximum = 4 degrees) was designed using data from low severity departures. An analysis was performed on low angle departures that occurred during the IVBSS naturalistic driving [11]. The "light" (rate = 10 degrees/second, maximum = 2 degrees) and "aggressive" (rate = 40 degrees/second, maximum = 8 degrees) steering parameters were scaled to be one-half and two-times the "moderate" values, respectively. The "autonomous" LDP (rate = 100 degrees/second, maximum = 50 degrees)

steering parameters were determined using emergency driver steering data following severe lane departures. These values were taken from a previous study by Kusano and Gabler [12] that investigated severe lane departures during the Virginia Tech Transportation Institute (VTTI) 100-car study [13, 14].

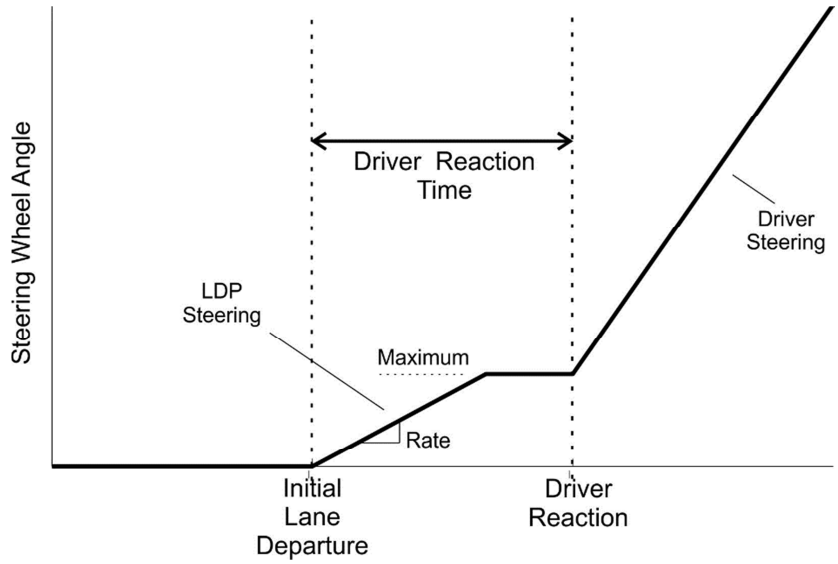

Figure 2. ***Steering control with LDP system.***

Benefits Estimation

This study was interested in the number of crashes and seriously injured drivers that could have been prevented with LDW and LDP. The benefits estimation methodology used have been previously implemented and described by Kusano et al. [6].

Probability of a Crash

For a given simulation, indexed by i, the roadside terrain was discretized into zones, indexed by k, that were parallel to the road boundary. The road boundary was defined as the edge of the paved road, i.e. crashes were only assumed to occur off the paved road. We assume that the probability of a crash was dictated by two factors: 1) the distance travelled laterally from the road, and 2) the total distance travelled off-road.

The NCHRP 17-22 data was used to estimate collision risk in these zones. The 17-22 dataset was ideal for this, because the number of crashes in each of the roadside zones, C_k, and the distance traveled in each roadside zone, γ_k, could be determined. Given 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.

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

Probability of Seriously Injury Driver

The NCHRP 17-22 dataset was used to calculate probability of an injury given a simulated trajectory. For this study, a seriously injured driver was defined to be a driver with a Maximum Abbreviated Injury Score of 3 or greater using AIS98 [15]. In summary, the probability of a seriously injured driver was statistically modeled using logistic regression functions. Departure velocity and seat belt usage were used as independent variables, and injury outcome

was the dependent variable. After determining the probability of an injury given the departure conditions P[injury$_{IC}$], the probability of an injury given the simulated trajectory, P[injury$_i$], could be calculated using Equation 2.

$$P[Injury_i] = P[\boldsymbol{Injury_{IC}}]\, P[Crash_i] \quad (2)$$

Effectiveness Calculation

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 or LDP. As shown in Equation 3, this can be represented by an effectiveness measure, ϵ, that is computed as the proportion of crashes reduced with LDW/LDP. Because the number of nationally representative crashes and seriously injured drivers without LDW are known, the simulated cases without LDW or LDP were additionally weighted to reflect these counts.

$$\epsilon = \frac{N_{without\ LDW/LDP} - N_{with\ LDW/LDP}}{N_{without\ LDW/LDP}} \quad (3)$$

RESULTS

Table 1 summarizes the number of single vehicle drift out of lane road departure crashes in NASS/CDS 2012. Approximately 15% of all NASS/CDS 2012 crashes were drift out of lane departures. A manual review of cases was then performed to eliminate incorrectly coded cases within the database. Additional, cases were excluded for having disproportionally high case weight, for the departure being at a T-intersection, and for having multiple departure sides. Cases with weightings greater than 5,000, as others have done in the existing literature [16], were eliminated, because their simulated effectiveness greatly skew the data. The resulting 478 lane departure crashes formed the 20,118-simulation case set for making LDW/LDP benefits estimates, and are represented of 147,662 crashes nationally.

Table 1. Case count summary. Cases were eliminated in the sequence described.

Group		n	Freq.
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
	Multi-side Departures	65	30,804
Final Dataset for LDW Modeling		478	147,662

Table 2 lists the number of crashes and injuries without LDW/LDP systems along with the predicted effectiveness of LDW and LDP systems. The LDW system was estimated to reduce the number of these drift out of lane road departure crashes by 26.1% and the number of seriously injured drivers by 20.7%. In contrast, the light steering to aggressive steering LDP systems were estimated to reduce the number of crashes by 32.7% to 37.3% and the number of seriously injured drivers by 26.1% to 31.2%. The LDP system with autonomous driving characteristics were estimated to reduce the number of crashes by 51.0% and the number of serious injuries by 45.9%.

Table 2. Effectiveness of LDP in U.S. Vehicle Fleet.

Measure		Values	Effectiveness (% Improvement)
Crashes			
No LDW or LDP		147,662	---
with LDW		109,404	26.1%
with LDP	Light	99,412	32.7%
	Moderate	96,939	34.4%
	Aggressiveness	92,613	37.3%
	Autonomous	72,403	51.0%
Injuries (MAIS3+)			
No LDW or LDP		30,098	---
with LDW		23,871	20.7%
with LDP	Light	22,233	26.1%
	Moderate	21,722	27.8%
	Aggressiveness	20,694	31.2%
	Autonomous	16,274	45.9%

The effectiveness of LDW and LDP depended on the number of lanes crossed before departure. Figures 3 and 4 show the effectiveness of LDW and LDP by the number of lanes crossed before departure. Because this model assumes no objects or vehicles on the paved road, the effectiveness of LDW and LDP were expected to be dependent on the system's ability to prevent a departure from the paved road.

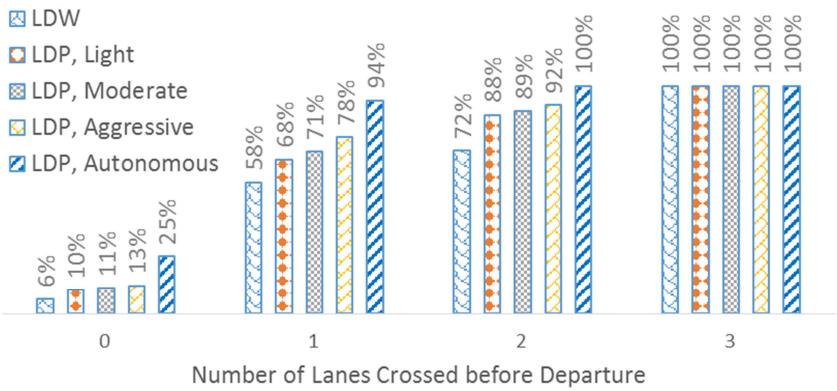

Figure 2. Effectiveness of LDW and LDP in reducing the number of crashes given the number of lanes which needed to be crossed prior to leaving the road (n=20,118 simulations).

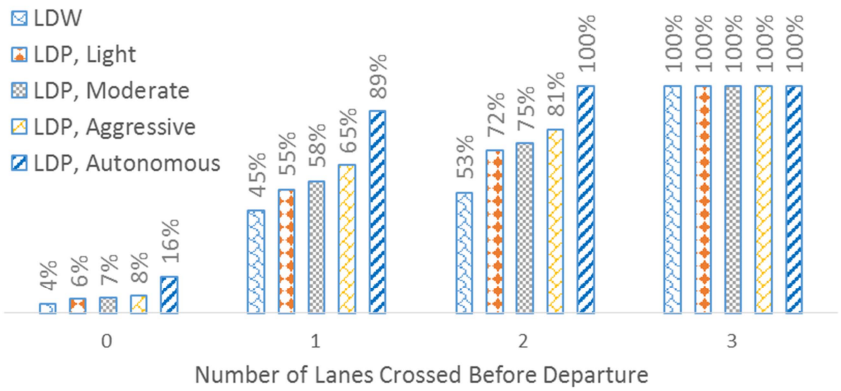

Figure 3. Effectiveness of LDW and LDP in reducing the seriously injured drivers (MAIS 3+) as a function of shoulder width (n=16,920 simulations).

Figures 3 and 4 show the effectiveness of LDW and LDP by shoulder width. Like number of lanes crossed before departures, wider shoulders provided additional time and space for returning the vehicle to the road. 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 before departure.

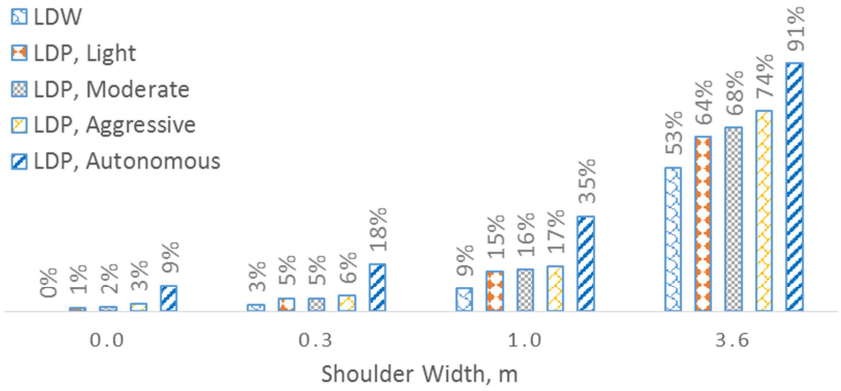

Figure 3. Effectiveness of LDW and LDP in reducing the number of crashes as a function of shoulder width (n=16,920 simulations).

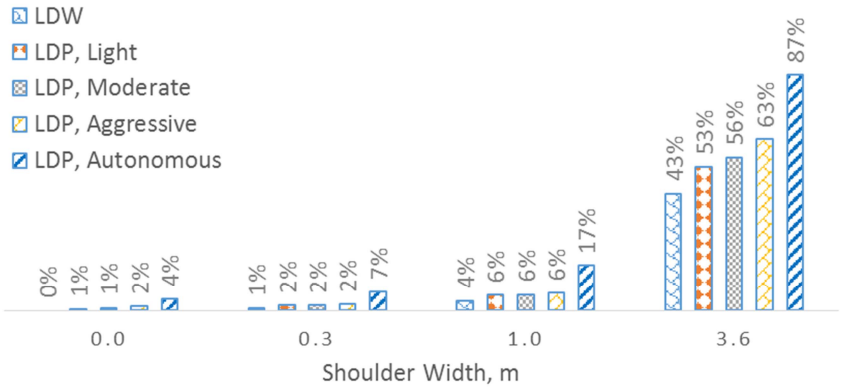

Figure 4. Effectiveness of LDW and LDP in reducing the seriously injured drivers (MAIS 3+) as a function of shoulder width (n=16,920 simulations).

DISUSSION

These results indicate that LDP systems can prevent a larger number of crashes and seriously injured drivers than vehicles instrumented with only LDW. The potential benefits of LDP are dramatically influenced by the number of lanes crossed before departure and shoulder width. The influence of these factors on benefits is especially important when considering that 30% of crashes occurred on roads with no lane markings, and 29% of crashes occurred on roads with no shoulder.

Steering-based LDP systems are attractive for a number of reasons. First, by modulating vehicle trajectory, LDP not only warns the driver of a lane departure, but also gives the driver directional information about the required recovery maneuver. By its nature, this warning with directional information may serve to further improve driver reaction time and response. Second, steering-based LDP systems have the ability to begin returning the vehicle to the departed lanes prior to driver reaction. Even steering-based LDP system with relatively light steering input still yielded a substantially greater effectiveness than a simple LDW system.

There are several limitations to the current study. First, the mechanism which led to the lane departure was not considered. The reason for initial lane departure, such as distractive driving or drowsiness, may be important to consider when predicting driver response. Second, this model assumes that when the vehicle crosses adjacent lanes there is no contact with other objects or vehicles. This approach provides a best case scenario, and may lead to an overestimation of the systems effectiveness. Third, the LDP systems used in this study are simplistic representations of actual LDP systems. For instance, the current model applies an angular rate to the steering wheel that becomes saturated at some nominal value. Actual steering-based LDP systems may have more complex steering inputs that are dependent on a variety of factors, such as vehicle speed and trajectory. Also, LDP systems can provide other modes of lane departure prevention, such as through selective braking of wheels to direct the car back into the lane. Fourth, LDW and LDP were assumed to become activated when the leading wheel crosses the line. In reality, systems can become activated before or after lane departure occurs.

CONCLUSIONS

This study shows that LDW and LDP could mitigate a large proportion of crashes and injuries in lane departure crashes. The results indicate that LDP systems are more effective than LDW systems at preventing the number or crashes and seriously injured drivers in the U.S. fleet. This data also demonstrates the sensitivity of these measures to LDP steering prior to driver reaction, and the dependency of effectiveness on number of lanes to road departure and road width. This paper is directly relevant to the design and evaluation of LDW and LDP systems. The results of this study could inform policy on regulatory and consumer rating tests.

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REFERENCES

1. Kusano, K.D. & Gabler, H.C., 2014. Comprehensive Target Populations for Current Active Safety Systems using National Crash Databases. *Traffic Injury Prevention*, 15(7), pp.753–761. doi:10.1080/15389588.2013.871003.
2. Beruscha, F., Augsburg, K. & Manstetten, D., 2011. Haptic warning signals at the steering wheel: a literature survey regarding lane departure warning systems. *Haptics-e*, 4, pp.1–6.
3. NHTSA, 2013. Lane Departure Warning System Confirmation Test, Washington, D.C.: U.S. Department of Transportation, National Highway Traffic Safety Administration.
4. Euro NCAP, *Euro NCAP Rating Review 2015*, in *Ratings Group Report*. 2015, European New Car Assessment Programme.
5. Mak, K.K. & Sicking, D.L., 2010. Identification of Vehicular Impact Conditions Associated with Serious Ran-off-Road Crashes, Transportation Research Board, National Cooperative Highway Research Program, NCHRP Report 665.
6. Kusano, K.D., Gorman, T.I., Sherony, R., Gabler, H.C.., 2014. Potential occupant injury reduction in the U.S. Vehicle fleet for lane departure warning-equipped vehicles in single-vehicle crashes. *Traffic injury prevention*, 15 Suppl 1(sup1), pp.S157–64. doi:10.1080/15389588.2014.922684
7. Suzuki, K. & Jansson, H., 2003. An analysis of driver's steering behaviour during auditory or haptic warnings for the designing of lane departure warning system. *JSAE Review*, 24(1), pp.65–70.
8. Mechanical Simulation, *CarSim*. 2012.
9. Gordon, T, Sardar, H., Blower, D., Ljung Aust, M., Bareket, Z., Barnes, M., Blankespoor, A., Isaksson-Hellman, I., Ivarsson, J., Juhas, B., Nobukawa, K., Theander, H., 2010. Advanced Crash Avoidance Technologies (ACAT) Program - Final Report of the Volvo-Ford-UMTRI Project: Safety Impact Methodology for Lane Departure Warning - Method Development and Estimation of Benefits, Department of Transportation.
10. Gordon, T., Blankespoor, A., Barnes, M., Blower, D., Green, P., Kostyniuk, L., 2009. Yaw rate error - a dynamic measure of lane keeping control performance for the retrospective analysis of naturalistic driving data. In Proceedings of the 20th International Enhanced Safety of Vehicles Conference. Stuttgart, Germany.
11. Sayer, J.R., Bogard, S.E., Buonarosa, M.L., LeBlanc, D.J., Funkhouser, D.S., Bao, S., Blankespoor, A.D., Winkler, C.B., 2011. Integrated Vehicle-Based Safety Systems Light-Vehicle Field Operational Test Key Findings Report, U.S. Department of Transportation, Research and Innovative Technology Administration.
12. Kusano, K.D. & Gabler, H.C., 2013. Driver Response to Road Departures in the 100-Car Naturalistic Study. In Proceedings of the 4th Road Safety and Simulation International Conference. Rome, Italy.
13. Dingus, T.A., Klauer, S.G., Neale, V.L., Petersen, A., Lee, S.E., Sudweeks, J., Perez, M.A., Hankey, J.M., Ramsey, D., Gupta, S., Bucher, C., Doerzaph, Z.R., Jermeland, J., Knipling, R.R., 2006. The 100-Car Naturalistic Driving Study - Phase II Results of the 100-Car Field Experiment, Washington, D.C.: National Highway Traffic Safety Administration.
14. McLaughlin, S.B., Hankey, J.M., Klauer, S.G., Dingus, T.A., 2009. Contributing Factors to Run-Off-Road Crashes and Near-Crashes, National Highway Traffic Safety Administration, Report DOT HS 811 079.
15. AAAM, *The Abbreviated Injury Scale-1990, Update 1998*. 1998: Des Plaines, IL.
16. Kononen, D.W., Flannagan, C.A. & Wang, S.C., 2011. Identification and validation of a logistic regression model for predicting serious injuries associated with motor vehicle crashes. Accid Anal Prev, 43(1), pp.112–122. doi: 10.1016/j.aap.2010.07.018