Comparison of Expected Crash and Injury Reduction from Production Forward Collision and Lane Departure Warning Systems

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Objectives: The U.S. New Car Assessment Program (NCAP) now tests for forward collision warning (FCW) and lane departure warning (LDW). The design of these warnings differs greatly between vehicles and can result in different real-world field performance in preventing or mitigating the effects of collisions. The objective of this study was to compare the expected number of crashes and injured drivers that could be prevented if all vehicles in the fleet were equipped with the FCW and LDW systems tested under the U.S. NCAP.

Methods: To predict the potential crashes and serious injury that could be prevented, our approach was to computationally model the U.S. crash population. The models simulated all rear-end and single-vehicle road departure collisions that occurred in a nationally representative crash database (NASS-CDS). A sample of 478 single-vehicle crashes from NASS-CDS 2012 was the basis for 24,822 simulations for LDW. A sample of 1,042 rear-end collisions from NASS-CDS years 1997–2013 was the basis for 7,616 simulations for FCW. For each crash, 2 simulations were performed: (1) without the system present and (2) with the system present. Models of each production safety system were based on 54 model year 2010–2014 vehicles that were evaluated under the NCAP confirmation procedure for LDW and/or FCW. NCAP performed 40 LDW and 45 FCW tests of these vehicles.

Results: The design of the FCW systems had a dramatic impact on their potential to prevent crashes and injuries. Between 0 and 67% of crashes and 2 and 69% of moderately to fatally injured drivers in rear-end impacts could have been prevented if all vehicles were equipped with the FCW systems. Earlier warning times resulted in increased benefits. The largest effect on benefits, however, was the lower operating speed threshold of the systems. Systems that only operated at speeds above 20 mph were less than half as effective as those that operated above 5 mph with similar warning times. The production LDW systems could have prevented between 11 and 23% of drift-out-of-lane crashes and 13 and 22% of seriously to fatally injured drivers. A majority of the tested LDW systems delivered warnings near the point when the vehicle first touched the lane line, leading to similar benefits. Minimum operating speed also greatly affected LDW effectiveness.

Conclusions: The results of this study show that the expected field performance of FCW and LDW systems are highly dependent on the design and system limitations. Systems that delivered warnings earlier and operated at lower speeds may prevent far more crashes and injuries than systems that warn late and operate only at high speeds. These results suggest that future FCW and LDW evaluation should prioritize early warnings and full-speed range operation. A limitation of this study is that additional crash avoidance features that may also mitigate collisions—for example, brake assist, automated braking, or lane-keeping assistance—were not evaluated during the NCAP tests or in our benefits models. The potential additional mitigating effects of these systems were not quantified in this study.

Keywords: safety benefits, active safety, forward collision warning, lane departure warning

Introduction

Active safety systems such as forward collision warning (FCW) and lane departure warning (LDW) aim to help the driver avoid collisions by warning of potentially dangerous driving conditions. These 2 systems are becoming available on production vehicles to prevent or mitigate frequent and harmful crash modes. FCW systems use sensors—for example, radar and/or cameras—to determine whether a forward collision is likely. If the FCW system determines that there is a risk of a collision, the system can warn the driver by a combination of visual, audible, and/or tactile alerts. The main crash scenario that FCW is likely to mitigate is rear-end collisions, where the front of one vehicle contacts the rear of another. LDW systems use primarily cameras to track vehicle’s location with respect to the lane boundaries. If an unintended departure is likely to occur, the system can warn the driver. The main crash scenario that LDW is likely to mitigate is road departure crashes where the vehicle unintentionally drifts out...
of its lane. Rear-end collisions account for 32% of all collisions and 7% of fatal crashes, and lane departure crashes account for 12% of all crashes and 32% of fatal crashes (Kusano and Gabler 2014).

Early studies that used insurance claims data have found that FCW systems can reduce insurance claims but that the LDW systems evaluated did not produce a significant change in insurance claim amounts (Moore and Zuby 2013). Similar results for FCW have been found using Swedish insurance claim data, finding a 23% reduction in claim frequency for vehicles equipped with low-speed warning and automated braking (Isaksson-Hellman and Lindman 2012). The same low-speed warning and automated braking system is estimated to save €2 billion in repair costs and whiplash compensation in the United Kingdom (Avery and Weekes 2009). Because these systems are not widely deployed in the vehicle fleet, it is difficult to perform retrospective crash data analysis to determine their effectiveness. As a result, there have been numerous simulation studies that aim to predict the effect of FCW (Aoki et al. 2009, 2010; Bálint et al. 2013; Kusano and Gabler 2012; van Auken et al. 2011) and LDW (Gordon et al. 2010; Kusano, Gorman, Sherony, and Gabler 2014; Morales Teraoka et al. 2014; Tanaka et al. 2012) systems as if they were widely deployed. All of these past simulation studies have found that FCW and LDW can prevent crashes and injuries. Most past studies, however, have focused on a single or narrow range of system designs that may not be representative of production systems. The current study will compare multiple production active safety systems using data collected as part of consumer ratings tests from the United States.

FCW and LDW have shown promise as crash avoidance systems and as a result are starting to be incorporated in the consumer ratings programs. In the United States, the New Car Assessment Program (NCAP) began to test for the presence of FCW and LDW starting with model year 2010 vehicles. In order to claim a vehicle has FCW or LDW, a test track confirmation test must be passed. This U.S. NCAP evaluation is a pass/fail test only and does not include a ratings system that evaluates the performance of the systems. In addition to the U.S. NCAP, the EuroNCAP for the European region evaluates forward crash avoidance systems, including the presence of FCW. The results of U.S. NCAP confirmation tests performed on model year 2010 to 2014 vehicles will be used to develop models of production FCW and LDW system function for this study. These models will be used to determine the number of crashes and injuries that could be prevented if each production system was widely deployed using existing benefit estimates models for FCW (Kusano and Gabler 2012) and LDW (Kusano, Gorman, Sherony, and Gabler 2014).

The objective of this study is to compare the potential safety benefits of production FCW and LDW to determine how the design and limitations of these systems affect expected field performance.

Methods

Fleetwide Safety Benefits Estimates

The goal of a safety benefits estimate analysis is to predict the number of crashes and injuries that could be prevented if a safety system was deployed in the fleet. Such an approach is especially useful when a safety system such as emerging crash avoidance technologies have not yet penetrated the vehicle fleet in large numbers. The process for such a benefits estimate framework was proposed in the Advanced Crash Avoidance Technologies (ACAT) program by the NHTSA (Carter et al. 2009; Funke et al. 2011). The methodology to determine safety benefits is based upon crash data and modeling of the crash, driver response, and countermeasure performance. First, scenarios that could be mitigated by the crash avoidance system are identified using representative crash data. These scenarios along with a description of the system inform the design of a computational model of the systems and of the crash. Next, the crash data and scenarios are used to generate data to describe the initial conditions and outcomes in a representative crashes. Finally, the models are used to compare the crash outcome with and without the system to derive the benefits of a proposed system.

To estimate the safety benefits of FCW and LDW in the vehicle fleet, this study will use 2 previously published benefits estimates methodologies. The general organization of the benefits estimate models was modeled after the ACAT benefits framework. Additional details of these past studies are provided in Kusano and Gabler (2012) for the FCW model and Kusano, Gorman, et al. (2014) and Gabler et al. (2013) for the LDW model. A summary of these past benefits models are included in the Appendix (see online supplement). In short, the benefits estimates models predict the number of crashes and injured drivers that could be prevented if all vehicles were equipped with a proposed crash avoidance feature. The models simulate real-world crashes as if the safety system were present.

Modeling of System Parameters from NCAP Data

The results of the NCAP confirmation tests were used to determine system function for input to the benefit estimate models. The Appendix contains a full description of the test procedures for the FCW and LDW confirmation test. In summary, the FCW test is run in lead vehicle stopped, lead vehicle decelerating, and lead vehicle moving a lower speed configurations with a host vehicle speed of 45 mph (72.4 kph). The LDW confirmation test is run on a straight road segment at a speed of 45 mph (72.4 kph).

The 2 parameters that represented each system were a warning activation time (FCW) or distance (LDW) and the lower operating speed threshold of the system. In the test reports for each NCAP confirmation test, there is a summary of each trial that lists the test condition and when the warning activated. If multiple warning modalities were present—for example, audible, visual, and tactile modes—each warning mode has a separate activation time or distance listed. To characterize the FCW systems in this study, the average of the earliest audible or visual warning was taken. Many systems delivered warnings in multiple modalities—for example, audible, and visual warnings—at consistently different times before an event. In this study, we only examined the earliest delivered warning during the tests because the earliest warning is the warning that would first alert the driver. Visual warnings were only considered if they were delivered through a heads-up display and not as a telltale symbol on the instrument panel. An SAE
International standard being developed for human factors in FCW warning alert design suggests that visual displays be within 10° of the driver’s line of sight (SAE 2003). This standard indicates that visual warnings delivered on the instrument panel may not be effective in alerting drivers of an impending collision but may still be useful to help the driver determine the cause of a warning. To characterize LDW warnings, the earliest audible or tactile warning was taken. Similar to FCW, a standard for LDW warning design dictates that visual warnings are most useful to help a driver determine the cause of a warning and were not considered for this study (SAE 2007).

The model for FCW simulates benefits for lead vehicle stopped scenarios only (Kusano and Gabler 2012). Lead vehicle stopped accounts for 63% of all rear-end crashes in NASS-CDS. This limitation is due to the crash reconstructions performed to estimate change in velocity during the crash (delta-V) done in NASS-CDS. The impact speed of the striking vehicle can be estimated from the impacting vehicles delta-V if the speed of the struck vehicle is known; that is, assumed to be zero. Therefore, only results from the lead vehicle stopped NCAP confirmation tests were used for this study.

The LDW confirmation data contains trials for combinations of 3 different lane line and 2 departure sides that were used in the benefits estimate models. A manual inspection of scene photographs and diagrams from every road departure crash in the 2012 NASS-CDS case year was performed to construct the LDW benefit estimates model (Kusano, Gorman, Sherony, and Gabler 2014). Part of this examination of scene photographs was determining the initial departure side and lane marking style. Crashes that occurred on roads with solid, double solid, or dashed-solid lines were simulated with the average departure distance at warning from the solid lane line NCAP test results. Crashes that occurred on roads with dashed lane lines were simulated with the dashed NCAP test results. There were no crashes in NASS-CDS that occurred on roads with “Botts dots” raised markings. This is likely due to the fact that NASS-CDS data are not collected in states—for example, California—where these raised markings have been widely adopted.

Lower operating speed thresholds for FCW and LDW systems were indicated in user manual excerpts provided in the NCAP confirmation test reports. The lower operating speed thresholds were often indicated in the “system limitation” or “system operation” sections of the user manual. The threshold indicates the speed under which the warnings from the system will be suppressed or inactive. Upper operating speed thresholds were not often listed in the users’ manuals. Sensitivity analysis of the benefits estimate models indicated that upper operating speed thresholds did not have a large effect on the results (Kusano, Gorman, and Gabler 2014c). As a result, no upper operating speed thresholds were assumed for FCW and LDW in this study.

### Results

**Production FCW and LDW System Performance**

A total of 45 FCW and 40 LDW test series were performed on model year 2010 to 2014 vehicles as part of the NCAP confirmation tests. In total 54 vehicle makes and models were tested. The following 2 sections describe the TTC at FCW delivery and the distance to lane marking at LDW delivery. A complete list of vehicles tested, the lower operating speed of the systems, and the warning delivery time or distance is included in the Appendix.

#### Potential Fleetwide Benefits of FCW and LDW Systems

Table 1 lists the number of rear-end and departure crashes that were simulated to generate FCW and LDW benefits. Cases included in the FCW benefits model were required to have data from a detailed crash reconstruction and vehicle information for both the striking and struck vehicle. These data are not available in every NASS-CDS case. To increase the number of cases considered, cases were extracted from NASS-CDS years 1997 to 2013. Vehicles were restricted to airbag-equipped model year 1998 or newer vehicles. The scene photos and diagram for each case included in the LDW benefits model were manually examined to determine road curvature, shoulder width, and lane marking presence and type. This time-consuming task limited our analysis to a single year of NASS-CDS.

Figure 1 shows the proportion of rear-end crashes that could be prevented by each FCW system. Both warning delivery time and lower operating speed threshold greatly affected predicted benefits. The percentage of crashes prevented ranged from 9 to 67%. The number of moderate to fatally injured drivers (MAIS 2+) followed the same trend as the crashes prevented with systems preventing between 19% and 69%. The appendix lists the results of injuries prevented.

Figure 2 shows the proportion of departure crashes that could be prevented for each tested LDW system. The benefits estimate model was not very sensitive to warning distance, but was greatly affected by lower operating speed threshold. The proportion of crashes that could be prevented ranged from 11 to 23%. Changing the operating speed threshold from 45 mph (72.4 kph) to 32 mph (51.4 kph) could approximately double

| Measure                | Rear-end (FCW) | Departure (LDW) |
|------------------------|---------------|-----------------|
| NASS-CDS years         | 1997–2013     | 2012            |
| Number of crashes      | 1,042         | 478             |
| Weighted crashes       | 888,376       | 147,662         |
| Simulations            | 7,616         | 24,822          |

Fig. 1. Reduction in the number of rear-end crashes due to FCW by warning timing and lower speed operating threshold.
the potential effectiveness of a LDW system. The number of seriously to fatally injured (Maximum Abbreviated Injury Score [MAIS] 3+) drivers followed the same trend as the crashes prevented with systems preventing between 13 and 22%. The Appendix lists the results of injuries prevented.

Figure 3 shows a cumulative distribution of departure speeds for the LDW benefits simulations (Kusano, Gorman, Sherony, and Gabler 2014). A large proportion of the departures are in the 30 and 50 mph (48.3 to 80.5 kph) range where the LDW systems have lower speed thresholds. These lower speed departures also stand to benefit the most from LDW because there is more time for drivers to react and steer back to the road than at higher speeds.

Discussion

The results of this study showed that the designs of production FCW and LDW systems vary greatly, which affects the expected field performance of these systems. For FCW, warnings were delivered over a wide range of time to collision (TTC) values that had a pronounced effect on benefits. For LDW, the systems all delivered warnings when the vehicles were very close to the lane lines, resulting in similar benefits estimates across the range of distance to warnings observed. For both LDW and FCW, the lower operating speed threshold of the system greatly influenced benefits. Systems that operated at lower speeds prevented more crashes than those that only operated at high speeds. Overall, FCW systems operated at lower speeds compared to LDW systems. This speed difference reflects that LDW systems are being designed to be used on collector to arterial roadways where speeds are higher than on residential streets. Roadway characteristics greatly influenced the effectiveness of LDW, regardless of LDW system design, which may help explain why the LDW systems evaluated had similar projected benefits. Our benefits model assumed LDW would have no effectiveness if there were no lane lines (30% of crashes) or if there was no shoulder present (29% of crashes). An LDW system that does not depend on the presence of visible lane markings may be able to prevent additional road departure crashes.

Previous benefits estimate studies have primarily focused on presenting the methodology and evaluating a single proposed system as an example of an application of the model. Few studies have compared multiple systems in order to determine the effect of system design choices on the potential field benefits of systems. Therefore, it is difficult to directly compare the results of this study to previous benefits estimates study. The results of the current study are potentially informative for system designers and those designing evaluations for FCW and LDW. The results show the importance of including lower operating speed threshold in the evaluation, because the lower speed threshold has a measurable effect on both FCW and LDW benefits.

Although there are industry standards (SAE standards J2400 and J2808; SAE 2003, 2007) to suggest that telltale icons on the instrument panel should not be used as a primary means of warning the driver, the NCAP test procedures allow such instrument panel warnings to satisfy the testing requirements. This fact could be exploited by delivering instrument panel warnings first while delaying the audible or tactile warnings to meet the test specification. There is no evidence from the NCAP data that this practice is being employed, because the visual warnings are generally delivered close to the other warnings. However, if visual warnings on the instrument panel were not allowed to fulfill the FCW warning requirements, 3 of the 46 vehicles tested for FCW would have failed the lead vehicle stopped scenario.

This study has several important limitations. First, the benefits models were only based on FCW and LDW performance. Some vehicles have other safety systems that work alongside FCW and LDW. For example, some vehicles with FCW were also equipped with autonomous emergency braking (AEB). Some vehicles with LDW were also equipped with LDP that could actively apply steering or steer the vehicle with differential braking. A concern for the designers of active safety systems is false system activations. For warnings, these false or nuisance alarms may cause the driver to distrust and eventually disable the systems (Bliss and Acton 2003). A system designer may choose to delay the warning delivery to reduce false alarms while relying on these accompanying safety systems to mitigate crashes. The FCW and LDW benefits estimate methods used in this study have capabilities to model these additional active safety systems. The NCAP test procedures do not, however, include evaluations of these other safety systems, which makes extracting model parameters impossible. Future work can include modeling these production systems as additional test data become available. This limitation suggests that future regulatory and consumer ratings tests should evaluate the warning systems alongside the assistance or autonomous
crash avoidance features. The results of this study, however, show that for FCW it does not appear that vehicles that also include AEB have greatly modified warning delivery times. For example, the 2013 Cadillac SRX and 2014 Cadillac ATS were equipped with AEB, whereas the 2013 Cadillac XTS was not. The XTS and ATS have almost identical warning delivery times, whereas the SRX warned the driver approximately 0.1 s later. The trend is less clear for LDW. Half of the 10 vehicles with LDP were among the 7 latest warning distances. There were fewer vehicles equipped with LDP than AEB, so it is possible that there are too few cases to determine the effect of the presence of LDP on LDW warning distances. If there was a design choice to warn later for vehicles with LDP, the effects on this study’s results are small because the benefits of LDW were not sensitive to the differences in warning distances measured for this study. The benefits of LDW were most sensitive to lower operating speed threshold.

A second limitation is that the system parameters extracted from the NCAP test data were collected at a single vehicle speed of 45 mph (72.4 kph). It is possible that warning delivery times for some systems have a speed dependency. Third, the estimates assume that all drivers would have the systems active while driving. Some drivers may disable the system as a personal preference. In addition, some systems are initially inactive when the vehicles are started and require the driver to press a button to turn them on. Drivers choosing to disable or forgetting to turn on the systems will reduce the effectiveness and may be dependent on the design of the systems. Fourth, driver reaction to the systems in these retrospectively investigated crashes was unknown, which necessitated estimating likely driver response using population distributions of reaction times. The accuracy of these distributions in representing the U.S. driving population will affect the accuracy of the benefits estimates made for this study.

This study extracted FCW and LDW parameters from NCAP confirmation tests and used these parameters to estimate the potential crashes and injuries that could be prevented if all vehicles were equipped with the systems. The production FCW systems could prevent between 9 and 67% of rear-end, lead vehicle stopped crashes and 19 and 69% of MAIS 2+ drivers involved in these crashes. The production LDW systems could prevent between 11 and 23% of drift-out-of-lane crashes and between 13 and 22% of MAIS3+ drivers involved in these crashes. The results showed that the minimum operating speed of the systems had an important effect on potential effectiveness of the systems. For FCW, the TTC at warning delivery also greatly impacted system effectiveness. The LDW effectiveness of the systems all delivered warnings that were close to when the vehicle traveled over the lane line and, as a result, benefits were not strongly correlated to warning delivery distance. The results of this study suggest that future evaluation and consumer ratings tests for FCW and LDW should consider minimum operating speed of the systems.

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### Supplemental Materials

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

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