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# **ASSESSMENT OF THE EFFECTIVENESS OF ADVANCED COLLISION AVOIDANCE TECHNOLOGIES**

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ASSESSMENT OF THE EFFECTIVENESS OF ADVANCED COLLISION  
AVOIDANCE TECHNOLOGIES

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16. Abstract <p>This report describes the current state of knowledge regarding the effectiveness of several advanced collision-avoidance technologies (ACATs) and presents an assessment of the effect of each technology on traffic safety. The report covers only ACATs for light-duty vehicles. The literature reviewed is primarily restricted to English language publications from the last ten years (2003 to 2013). The technologies included in the assessment address vehicle instability (electronic stability control); forward impact collisions (forward collision warning, autonomous emergency braking); and crashes related to lane/road departure (lane departure warning and prevention, blind spot detection). The methodologies and data used to evaluate ACAT effectiveness are also discussed. Data on the penetration of the technologies into the light-duty fleet are also presented.</p> <p>Overall, the systems reviewed here were estimated to be substantially effective in reducing their target crash types. The studies reviewed had a range of estimated reductions, and in some cases the differences were fairly substantial. However, even the lower-bound estimates are significant in most cases. Most studies relied on simulation or limited field operational tests to evaluate effectiveness. Other than electronic stability control, available crash data cannot yet support evaluation of the actual crash experience of the technologies, because penetration rates are low and vehicles with the technologies are not directly identified in the data.</p>					
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## List of Acronyms

ACAS	Advanced collision avoidance system
ACAT	Advanced Collision Avoidance Technology
ACC	Adaptive cruise control
A-CMB	Advanced collision mitigation braking
ADAS	Advanced driver assistance system
AEB	Automatic emergency braking or autonomous emergency braking
AEB-Ped	Automatic emergency braking and pedestrian detection
AEBS	Advanced emergency brake system
AIS	Abbreviated injury scale
BA	Brake assist
BSD	Blind spot detection
CDS	Crashworthiness Data System (part of National Automotive Sample System)
CMB	Collision mitigation braking
CSW	Curve speed warning
CW	Collision warning
DAS	Driver assistance system
EBA	Emergency brake assist
ESC	Electronic stability control
ESP	Electronic stability program
FARS	Fatality Analysis Reporting System
FCAT	Forward collision avoidance technology
FCW	Forward collision warning
FOT	Field operational test
GES	General Estimates System (part of NASS)
GIDAS	German In-Depth Accident Study
HLDI	Highway Data Loss Institute
IVBSS	Integrated Vehicle-Based Safety Systems
LCM	Lane change/merge
LDP	Lane departure prevention
LDW	Lane departure warning
LTV	Light truck and van
NASS	National Automotive Sample System
NHTSA	National Highway Traffic Safety Administration

PB	Pre-crash braking
PBA	Pre-crash brake assist
PCS	Pre-crash or pre-collision systems
PCW	Pre-collision warning or predictive collision warning
RDCW	Road departure crash warning
SIM	Safety impact methodology
SUV	Sport utility vehicle
TTC	Time to collision
TTLC	Time to lane crossing
UMTRI	University of Michigan Transportation Research Institute
VIN	Vehicle identification number
VMT	Vehicle miles traveled
VSC	Vehicle stability control

## 1. Introduction

This report describes the current state of knowledge regarding the effectiveness of several advanced collision-avoidance technologies (ACATs) and presents an assessment of the effect of each technology on traffic safety. The literature reviewed is primarily restricted to English language publications from the last ten years (2003 to 2013). Most of the literature covers the U.S. experience, but other literature is included when it sheds useful light on the effectiveness of technologies on improving traffic safety. In addition, publications prior to 2003 are included when they clearly aid understanding.

The technologies included in the assessment are as follows:

- Electronic stability control (ESC). This technology is also referred to as electronic stability program (ESP) and vehicle stability control (VSC).
- Forward-collision warning/collision-mitigation braking (FCW/CMB). This set of technologies includes autonomous emergency braking (AEB), including variants that brake for pedestrians and other nonmotorists (Ped-AEB).
- Lane-departure warning (LDW). This set of technologies includes lane-departure prevention (LDP), road-departure warning (RDW), and blind-spot detection (BSD). Lane-keeping assist also falls into this category.

The goal of the assessment is to provide estimates of the effect of each technology on traffic safety. The most valuable assessments are those that measure the safety effect of the technologies deployed in actual operations. Such assessments compare the crash risk of vehicles that have the technology compared with vehicles that do not have the technology, with appropriate controls for other factors. Another primary set of methodologies relies on simulation to estimate safety effects. These methodologies generally proceed by identifying target crash types that would be affected by specific ACAT systems, developing an understanding of the circumstances and events in such crash types from crash data, and then running simulations at varying levels of detail to estimate how the systems may perform against the crash types.

This report presents estimates of the effectiveness of the technologies, and in addition, discusses the assumptions, strengths, and limitations of the data and methodologies used. In addition, available data and estimates on the penetration of each technology into the fleet are presented. Finally, this report concludes with a discussion of data resources available that could support further research.

## **2. Assessment of Collision Avoidance Technologies**

### **2.1. Electronic stability control**

#### **2.1.1. How ESC works**

Electronic stability control (ESC), also called electronic stability program (ESP) or vehicle stability control (VSC), is a technology designed to prevent loss of control in steering maneuvers. The system compares the vehicle's direction of travel with the driver's intended direction based on steering wheel position. Sensors record lateral acceleration and yaw, and when the vehicle is yawing compared with the intended direction of travel from the position of the steering wheel, the system applies differential brake pressure to the wheels to bring the direction of motion back in alignment with steering. Some systems may also reduce engine torque.

ESC was first introduced in some passenger car and sport utility vehicle (SUV) models offered for sale in Europe in 1995 and subsequently in the United States. ESC was initially offered as an option, typically on luxury vehicles, but rapidly became standard equipment for some makes. By U.S. regulations, all cars and SUVs manufactured after September 1, 2011, must be equipped with ESC.

ESC evaluations are the strongest of all the crash-avoidance technology evaluations because they can be done from the actual crash experience. Vehicles with ESC as standard equipment can be identified in crash data. ESC was fairly readily rolled out and adopted as standard equipment, so there were enough vehicles in the system to allow statistically valid conclusions to be drawn.



ESC is not identified directly from the VIN but inferred based on make/model. The usual process is to identify light-duty vehicle make/models in which ESC was standard equipment and compare their crash experience with similar make/models for which ESC was not offered even as an option. For some passenger car models, ESC was not offered at all, but then in subsequent years it was made standard equipment. This permits comparison for the same make/model with and without ESC, though it is still necessary to control for the fact that the non-ESC equipped models are older than those equipped with ESC. Other make/model combinations transitioned from no ESC offered to ESC-optional. In these cases, comparisons are made between ESC-optional and no ESC, though they are weaker comparisons because the actual penetration of ESC within the ESC-optional population is not known.

### **2.1.2. Assessment methodologies**

In the literature reviewed, the effectiveness of the ESC technology was assessed by comparing crash risk in crash types where it would be expected to have an effect with crash risk in crash types where ESC should have no effect. As explained above, ESC operates by monitoring vehicle stability and intervening to restore or maintain stability when it is being lost. The crash types typically identified as relevant to ESC include rollovers (especially first-event rollover), single-vehicle crashes, crashes with fixed objects, crashes on low-friction (e.g., wet or icy) roads, as well as other specific crash types. Each of these crash types may be initiated by a yaw event. Note that single-vehicle crashes or crashes with fixed objects do not necessarily involve loss of control of the sort that is addressed by ESC. For example, a vehicle with a fatigued driver may drift off the road and collide with a fixed object. But many single-vehicle crashes do involve loss of control that results in road departure and collision. By intervening to stop the loss of control, ESC can reduce such crashes.

Two general methodologies were used to assess ESC effectiveness. The first set of methodologies relied only on crash data and compared involvement in crash types that are relevant to the system to those that are not relevant to the system. This technique is sometimes referred to as “induced exposure,” because the comparison crashes are in some sense representative of the general population of vehicles. The second method

computed crash rates using a measure of exposure to crashes. Both will be discussed here in some detail, using ESC as an example, because they are common evaluation techniques.

Comparison or control crash types are defined as crashes on which ESC should not have any effect. For example, ESC should not affect crashes in which a vehicle is struck in the rear or is stopped prior to a crash. The evaluation of system effectiveness then proceeds by comparing the ratio of ESC-relevant crashes to control crashes for ESC-equipped vehicles and for vehicles without ESC. ESC effectiveness is measured by the amount that ESC-relevant crashes are reduced for ESC-equipped vehicles compared with vehicles that do not have ESC.

An example:

$$\left(\frac{ER_{esc}}{Ctrl_{esc}}\right) / \left(\frac{ER_{no\ esc}}{Ctrl_{no\ esc}}\right)$$

where  $ER$  = ESC-relevant crash involvement

$Ctrl$  = Control crash involvement

$esc$  = ESC-equipped

$no\ esc$  = not ESC-equipped

$$= \left(\frac{10}{100}\right) / \left(\frac{30}{60}\right)$$

risk ratio = 0.2

percent effectiveness =  $(1 - 0.2) * 100 = 80\%$ .

Basically, vehicles with ESC should have fewer ESC-relevant crashes than vehicles without it, in comparison with crashes that should not be affected by the system.

In the second general methodology used in the literature, crash rates were computed for ESC-equipped vehicles and for vehicles not equipped with ESC. Vehicle registrations were used as the measure of exposure to compute the crash rates. Vehicles with ESC as standard or optional equipment are identified in the crash data and in vehicle registration data, and then rates of crashes per registered vehicle are computed. The crash rates are computed for ESC-equipped and non-ESC equipped vehicles. Crash rates can be

computed for different types of crashes, to test the effect on ESC-relevant crashes, or for different crash severities.

A limitation of this approach is the use of registration data, rather than vehicle miles traveled (VMT). Registration data indicates only that a vehicle is registered, not how frequently or even whether it is used. A more meaningful rate would use VMT for exposure, because VMT captures how much vehicles are in use on roadways and therefore exposed to the possibility of crashes. However, there is no source of VMT that distinguishes whether a vehicle has ESC or not. Registration data is used because it is the best available measure of exposure.

### **2.1.3. Evaluations of ESC effectiveness**

In one study of ESC effectiveness, Farmer (2004) used state crash files and vehicle registration data. He identified make/model series that changed from not offering ESC to making ESC standard equipment. The comparison was limited to make/model series that did not have any other significant changes between years, so that, arguably, the only significant difference was that one model year did not have ESC and the next model year did. Make/models with standard ESC in the 2000-2001 model years were compared with earlier model years with identical design and safety equipment, except for ESC (Farmer 2004).

Crash data from seven states were used, which had vehicle identification number (VIN) available. In addition, crash data from NHTSA's Fatality Analysis Reporting System (FARS) file were used. FARS is a census file of all motor vehicles involved in a fatal crash in the U.S. Decoding VINs identified make/models with ESC and the appropriate comparison make/models. Registration data from R.L. Polk and Company were used to identify make/models with ESC and the comparison make/models. Crash rates were computed with and without ESC. Rates were adjusted to account for vehicle age, because older vehicles tend to have higher crash rates, and the non-ESC vehicles were necessarily older than those with ESC.

ESC was found to be substantially effective in reducing crashes overall. In addition, ESC was found to be more effective in ESC-relevant crash types, such as

single-vehicle and rollover crashes, and resulted in greater crash reductions of more severe crashes. ESC reduced overall crash involvement by 7% and injury crashes by 9%. ESC reduced single-vehicle involvements of all severities by 41%, single-vehicle injury crashes by 41%, and single-vehicle fatal crashes by 56%. In terms of single-vehicle rollover, ESC was found to reduce all single-vehicle rollovers by 74%, single-vehicle injury rollovers by 78%, and fatal single-vehicle rollovers by 87%. Each of these reductions are statistically significant (Farmer 2004).

A 2010 study by Farmer followed essentially the same methodology but used FARS data for 1999 to 2008 on fatal crashes only. Part of the motivation for the later study was to determine if effectiveness of ESC held up after it had been in use for more than 10 years. Involvement rates in fatal crashes were computed per registered vehicle, and comparisons were drawn across model years, where crashes of a particular make/model series were compared before and after ESC was made standard. The crash types studied were all fatal crashes, multiple-vehicle crashes, single-vehicle crashes, rollovers, and crashes on low-friction (wet, snowy, or icy) roads. This study also distinguished the effect of ESC in passenger cars and in sport utility vehicles (SUVs). ESC effectiveness was expected to be higher in SUVs because they tend to be less stable than passenger cars.

In this study, ESC was estimated to reduce all fatal crash involvements by 33%, by 20% for multiple-vehicle crashes, and by 49% for single-vehicle crashes. Effectiveness was estimated to be higher for SUVs than for cars (35% to 30%), but the difference was not statistically significant. No significant difference was observed in passenger car rollover in multivehicle crashes, but single-vehicle rollover was reduced by 72%. In addition, crashes on low-friction roads were significantly reduced by ESC. There was a 73% reduction in passenger car multiple-vehicle crashes on wet roads, and a 55% reduction of single-vehicle crashes on wet roads. For SUVs, the reduction was 38% and 63%, respectively (Farmer 2010).

Effectiveness rates in the later study were somewhat lower than in the earlier study. In the earlier study, many vehicle types with ESC were more likely to be driven aggressively, such as sports cars, or in slippery situations, such as four-wheel drive

vehicles. The later estimates of ESC effectiveness were somewhat lower because ESC had penetrated further into the general fleet population.

Green and Woodrooffe (2006) used a case-control methodology to study the effects of ESC, using internal controls in the crash data rather than computing crash rates. This is the method described above that compares the incidence of crash involvements in ESC-relevant crash types for vehicles equipped and not equipped with ESC, compared with involvement in crashes where ESC would have no effect. As in all the ESC studies reviewed here, vehicles equipped with ESC were identified by make/model, and vehicles not equipped with ESC were the same make/models but consisted of model years when ESC was not available. The analysis was performed using FARS data (described above) from 1995-2003 and the General Estimates System (GES) crash files from 1995-2003. GES is based on a nationally-representative sample of police-reported crashes compiled by NHTSA. This study also distinguished passenger cars from SUVs.

In this study, ESC-relevant crashes included single-vehicle crashes, run-off-road crashes, and rollovers. Each of these crashes may have included an initial loss of control that could have been addressed by ESC. Using the FARS (fatal crashes only) data, the study reported a 30.5% reduction in single-vehicle crashes for passenger cars and 49.5% for SUVs; a 39.7% decrease in rollovers for passenger cars and a 72.9% decrease for SUVs. ESC was found to reduce run-off-road crashes by 34.8% for passenger cars and 56.1% for SUVs. Crashes on low-friction roads were reduced by 25.2% for passenger cars and 30.4% for SUVs, but these results were not statistically significant because of small sample sizes (Green and Woodrooffe 2006).

The study used GES to examine more directly the effect of ESC on loss-of-control crashes, using a crash type that identifies vehicles that lost control and ran off the road. The study reported a 54.5% reduction in run-off-road crashes for passenger vehicles and 70.3% for SUVs. A statistical model was used to control for the effects of driver age and gender. No significant effect was found for gender. However, driver age effects were significant. Older drivers tended to have greater crash reductions from ESC than younger drivers, and the effects were greater for drivers of SUVs than passenger cars. ESC also

was found to significantly reduce crashes on low-friction roads (Green and Woodrooffe 2006).

Two reports from NHTSA also used induced-exposure techniques to evaluate the effect of ESC on crash risk. Dang (2007) used FARS data from 1997 to 2004, as well as crash data from seven states. The state data was used to extend the analysis to all crash severities, not just fatal crashes. The basic approach was to compare the incidence of crashes relevant to ESC with crashes not relevant to ESC, for vehicles with and without ESC. The non-relevant crash conditions include vehicles that were stopped, parked, backing up, or entering/leaving a parking place, in addition to vehicles with a travel speed under 10 mph, rear-end struck vehicles, and vehicles not at fault in multi-vehicle crashes on dry roads. Relevant crash types included run-off-road into fixed object; at-fault multivehicle crash; and first-event rollovers. The study calculated crash reductions for passenger cars and LTVs, defined as light trucks and vans, which include most SUVs.

ESC was found to reduce single-vehicle crashes by 26% for passenger cars and 48% for LTVs; first-event rollovers by 64% for passenger cars and 85% for LTVs; run-off-road crashes by 45% for passenger cars and 72% for LTVs; and at-fault multivehicle crashes by 13% for passenger cars and 16% for LTVs. In each case, the crash reduction effect is higher for LTVs than for passenger cars (Dang 2007).

ESC was found to be more effective in fatal crashes, with higher rates of crash reduction in most crash types. ESC reduced fatal single-vehicle crashes by 36% for passenger cars and 63% for LTVs. In addition, ESC was estimated to reduce fatal first-event rollovers by 70% for passenger cars and 88% for LTVs. The effectiveness of ESC in fatal run-off-road crashes was actually a bit lower than in run-off-road crashes that included nonfatal crashes, but still substantial and with greater effectiveness for LTVs (70%) than for passenger cars (36%). Each of these effectiveness estimates was statistically significant.

Dang also fitted a logistic regression model, which controlled for driver age, sex, roadway type, area of operation (urban/rural) and car make. The model showed that ESC reduced fatal single-vehicle run-off-road crashes by 54%, controlling for those factors.

This reduction is greater than the decrease estimated accounting for no other factors (Dang 2007).

A subsequent NHTSA report used similar data and methods to the Dang (2007) study, but updated the work by adding additional years of data. Sivinski (2011) used FARS and GES from 1997 to 2009 to estimate effectiveness of ESC in passenger cars and LTVs. The same induced-exposure method was used, by comparing crash frequencies of make/models before ESC was offered with the same make/models when ESC was made standard.

The study estimated that ESC reduced all fatal crashes by 23% for passenger cars and 20% for LTVs. Among crash types expected to be sensitive to the presence of ESC, it was estimated that ESC reduced single-vehicle crashes by 32% for passenger cars and 57% for LTVs; first-event rollovers by 72% for passenger cars and 64% for LTVs; and fixed-object crashes by 30% for passenger cars and 67% for LTVs. All reductions were statistically significant except the single-vehicle and fixed-object crashes for passenger cars (Sivinski 2011).

Effectiveness of ESC was generally higher in fatal crashes, though not always. ESC was estimated to reduce fatal single-vehicle crashes by 55% for passenger cars and 50% for LTVs; first-event rollover by 56% for passenger cars and 74% for LTVs; and fixed-object crashes by 47% for passenger cars and 45% for LTVs. Each one of the fatal crash reductions was statistically significant (Sivinski 2011).

The study cautioned, however, that the effectiveness of ESC may be over-estimated if newer models also have other safety improvements. For example, side-curtain airbags were installed, in some cases, in the year prior to making ESC standard. The protective effect of the side-curtain airbags may exaggerate the apparent effect of ESC.

Studies in other countries used similar methodologies and reported similar results. An early study used Japanese vehicle registration and crash data to calculate crash rates for vehicle stability control (VSC), which is Toyota's system (Aga and Okada 2003). The report estimated that single-vehicle crashes were reduced by 35% and head-on collisions

by 30%. This study was the only one to use head-on crashes as an ESC-relevant crash type; the logic of this choice was not explained but it may be to capture situations in which a vehicle loses control and moves into the opposing lane of traffic. Like U.S. studies, VSC effectiveness was higher for more severe crashes. The authors speculated that VSC may be more applicable in high-speed crash events, where vehicle dynamics play a larger role.

Studies of ESC effectiveness from the United Kingdom reported that ESC reduced crashes of all severity by 7%, serious injury crashes by 11%, and fatal crashes by 25% (Weekes, Avery et al. 2009). These estimates are similar to those in the United States reported by Farmer (2004), Farmer (2010), and Sivinski (2011). Note that the estimates are for all crash types, not just ESC-relevant crash types.

A study of ESC effectiveness in Canada also used an induced-exposure method. Make/model information was used to identify passenger vehicles as ESC not available, ESC optional, or ESC standard. Only 1.8% of vehicles in the crash data were make/models in which ESC was standard equipment. A broad group of ESC-relevant crash types was defined. These crash types included all single-vehicle crashes, crashes coded as too-fast-for-conditions, police-identified loss of control, rollover, ran off road, and swerved to avoid collision. Crashes involving drivers coded as fatigued or asleep, lost consciousness, or under the influence of alcohol or drugs were excluded (Chouinard and Lecuyer 2011).

A statistical model was used to estimate ESC effectiveness in reducing involvement in the ESC-relevant crashes, controlling for driver age and sex. ESC was found to reduce involvement in the relevant crash types by 41.1%. ESC was found to be even more effective in reducing more serious crashes, reducing injury crashes by 54.8%. Estimated effectiveness was also higher for ESC-sensitive crashes on ice, snow, or slush-covered roads (low-friction circumstances) than on dry roads. These results are generally consistent with reported results in the U.S., United Kingdom, and Japan.



#### **2.1.4. Summary of ESC effectiveness estimates**

Hoye (2011) reported the results of a meta-analysis of 12 studies of the effects of ESC on traffic safety, with several of them discussed above. Overall, she found that ESC reduced loss-of-control crashes by about 40%. ESC also reduced about 50% of rollovers, 40% of run-off-road crashes, and 25% of single-vehicle crashes. ESC was reported to be more effective against more serious crashes. For example, some studies reported that 40% of fatal crashes were reduced with ESC. Fatal rollovers were reported to be reduced by as much as 70%. Also ESC was found to be more effective in crashes of LTVs than in passenger cars, meaning it was more effective in vehicles that have lower inherent stability (Hoye 2011).

The results of the literature reviewed here were very similar. All studies agreed that ESC significantly reduced crashes, and the studies reported fairly consistent results, even when there was some variation in the time period covered or the specific methodological approach. Overall, ESC reduced all crashes from 7% to 9%. Estimates of the reduction of fatal crashes ranged from 25% to 33%. In terms of crash types expected to be especially relevant to ESC, single-vehicle crashes were reduced from 35% to 41% and rollovers from 72% to 74%. Generally speaking, higher rates of reduction were achieved for more serious crashes and for SUVs than for passenger cars. One estimate had ESC reducing fatal rollovers by 87%.

ESC tends to reduce the crash types that one would expect it to, and in circumstances (e.g., low-friction) where one would expect it to be effective. In other words, the crash mechanism is clear and the technology directly addresses it. The strength of these findings is that they are from analysis of crash data of the technology in actual operation on the road. Most of the studies used pair comparisons of vehicles equipped and not equipped with ESC. Some studies were based on crash rates using registration data. These studies would be stronger if they were based on crash rates using VMT, but VMT data by ESC use are not available. However, the degree of agreement of results of the two methodologies is remarkable.

## **2.2. Forward collision avoidance technologies**

### **2.2.1. How forward collision avoidance technologies work**

This section describes the effectiveness of a set of technologies designed to mitigate or prevent forward collisions, sometimes referred to as Forward Collision Avoidance Technologies (FCAT). The technologies include forward collision warning (FCW), Brake Assist (BA), and Automatic Emergency Braking (AEB). These technologies are often deployed together and provide a layered approach to addressing forward collisions. In the initial stage, FCW issues a warning of an impending crash. The seat belts may be pre-tensioned. Brake Assist prepares the brake system to fire and sometimes increases braking. Finally, if the driver does not take sufficient action to avoid a crash, AEB engages the braking system. FCW can be deployed alone, but often it is part of a suite of systems that work together to prevent crashes.

Forward collision warning detects objects in the forward field of view using radar or lidar (using laser light). Early FCW systems could detect and warn on passenger cars and larger vehicles that were moving or had been seen to move. The FCW system computes the time to collision (TTC) and issues a warning, audible and/or visible. Subsequent generations added the ability to detect and warn on stopped objects, and objects smaller than a motor vehicle such as bicyclists or pedestrians.

BA and AEB work in combination with FCW to prevent or mitigate forward collisions. BA prepares the brake system so that it will activate quicker and ramp up full braking faster. In addition, BA amplifies brake force since drivers often fail to brake as hard as they should to avoid crashes. AEB applies the brakes if the driver fails to apply them. AEB systems usually are designed not to activate until a collision is unavoidable, in part to reduce the number of false activations.

FCATs are designed primarily to address rear-end crashes, where the crash opponent vehicle is traveling in the same lane and in front of the FCAT-equipped vehicle. Some FCATs also protect against conflicts with pedestrians or bicyclists. The most advanced systems include almost all forward collisions, including head-on, intersection,

and other crash geometries in which the opponent vehicle comes across the path of the subject vehicle.

Most FCWs are designed to work at speeds of 30-40 mph and higher. A version of forward collision avoidance technologies (FCAT) is designed to work in urban areas and activates at lower speeds and over shorter ranges, such as in stop-and-go traffic situations.

### **2.2.2. Assessment methodologies**

FCATs are not widely deployed enough currently to support retrospective studies in crash data. Moreover, publicly-available crash data systems do not yet include information on whether vehicles are equipped with one or more of the FCATs discussed above. To evaluate the safety impact of FCATs, the primary methodologies have been either FOTs (field operational tests) or simulation.

FOTs are used to evaluate technologies through limited and experimental deployments. Drivers are recruited and supplied with vehicles equipped with the technology. The vehicles are instrumented to record driver actions as well as the response and activity of the FCAT technologies. The drivers are instructed to use the vehicles as they would their own. There is usually a baseline period followed by a test period. In the baseline period, the FCAT technology is turned on to detect the target conflicts, but no warnings or other actions are taken. The baseline period gives the researchers information about normal driving, without the warnings, etc., from the FCATs. In the treatment period, the warning function and other interventions (such as BA and AEB) are turned on. Baseline driving patterns are compared with treatment patterns to determine the effect of the technologies.

Safety effects can be estimated from FOT data. However, FOTs seldom have enough crashes to estimate crash reduction directly. Instead, crash reduction is estimated from the difference in the number of forward conflicts with and without the technology. In addition, changes in normal driving behavior are noted, such as changes in following distance and hard brake applications.

The other primary method of estimating safety effects is through simulation. There are two broad categories of simulation studies. In one of them, target crashes are selected from an in-depth crash investigation database and reconstructed to estimate the primary parameters of the pre-crash situation, such as travel speeds, relative location of the vehicle, time-to-collision, and driver reaction. This information is then used to create a computer model of each crash. The action of the technology is then overlaid on simulations of each crash, to determine whether it would have avoided or mitigated the crash.

The second broad category of simulation also relies on crash data, but instead of simulating specific, well-described crashes, the crash data provide distributions of certain variables, such as travel speeds and driver avoidance maneuvers. Populations of simulated crashes are then created computationally to match the population of real crashes. The simulated crashes are then re-run with technology to determine how many crashes are prevented or mitigated.

Finally, one study was based entirely on results from a driving simulator. In this study, crash scenarios were identified from crash data. The crash scenarios were reproduced in the driving simulators. Subject drivers then drove the driving simulators with and without the FCAT technology engaged to determine the number of crashes avoided.

### **2.2.3. Evaluations of effectiveness of systems to address forward collisions.**

An FOT tested an early system that included FCW and Adaptive Cruise Control (ACC). The system was in development, and the FOT was designed to test effectiveness and driver acceptance. The FOT was conducted by UMTRI, with the Volpe National Transportation Systems Center of the US DOT evaluating the results.

The FCW component was active at speeds over 40 km/h, and was a warning-only system, with no braking component. The ACC system maintained headway using automatic braking and throttle control. The FOT had 66 subjects, 10 vehicles, and lasted for eight months. There was one week of baseline (system not operational) data for each driver, followed by three weeks with the system active (Najm, Stearns et al. 2006).

On average, drivers received 0.62 FCW alerts per 100 km of travel. Only 3% of the alerts were judged by an independent evaluation to be true alerts of an impending collision. In terms of safety, the combination of ACC and FCW was judged to reduce exposure to conflicts by 8% to 23% in good conditions (dry road, daylight, freeway-type road) at speeds over 35 mph. Forward conflicts were reduced by 11% to 26% where the lead vehicle was slowing, and by 19% to 46% where the lead vehicle was stopped in low-speed traffic. It was estimated that the system (FCW+ACC) could prevent 10% of rear-end crashes. However, it was also estimated that only about a quarter of drivers would actually buy the system. Moreover, about 41% of subjects said they would have turned the system off if they could (Najm, Stearns et al. 2006).

Kusano and Gabler (2010) used a methodology based on simulation of reconstructed crashes to test an AEB system. The purpose of this was primarily to determine the effect on injury severity of varying the timing of braking initiation and the amount of deceleration. Vehicle manufacturers do not offer automatic braking without also including FCW. The study was based on 1,406 rear-end crashes involving seat-belted drivers; data was extracted from the National Automotive Sampling System Crashworthiness Data System (NASS CDS) files for 1993 through 2008. Brake initiation varied from TTC of 0.3 to 0.6 seconds, and deceleration rates varied from 0.5 g to 0.8 g. The researchers measured the effect on the change in velocity ( $\Delta v$ ) in the collisions.

Depending on parameters (TTC and deceleration rate), the AEB system reduced  $\Delta v$  by 12% to 50%, and avoided 0% to 14% of the collisions. The researchers estimated that the AEB potentially could reduce the number of injured drivers by 19% to 57% (Kusano and Gabler 2010).

In a subsequent study, Kusano and Gabler (2012) developed an estimate of the safety benefits of a system that included FCW, BA, and AEB. They developed estimates of crash reductions as the layers of the interventions were added: FCW; FCW plus brake assist; FCW plus BA plus AEB.

The methodology was similar to the prior study. Target crash types, in this case rear-end crashes, were extracted from NASS CDS and reconstructed to determine certain

variables. Driver brake reaction times from driving simulator studies were used in the simulation, though only braking was simulated. Steering to avoid the crash was not incorporated in the model. As in the prior study, time of initiation of the AEB was varied, as was the deceleration rate. The resulting  $\Delta v$  was used to estimate the number of injuries avoided or mitigated.

The results of the simulations showed that FCW prevented 3.2% of rear-end crashes; the combination of FCW+PBA prevented 3.6%; and FCW+PBA+PB prevented 7.7%. The systems were more successful in reducing the severity of injuries. In this study, injury severity was classified using the Abbreviated Injury Severity scale, or AIS. The scale ranges from AIS 1 for minor injuries to AIS 7 for the most severe. The simulations predicted that FCW alone would prevent 29% of AIS 2+ injuries; FCW+PBA would prevent 39%; and FCW+PBA+PB would prevent 50%. These are all moderately severe to fatal injuries (Kusano and Gabler 2012).

Another U.S. study of FCATs was a project to develop a safety impact methodology (SIM) for NHTSA to use in estimating benefits for pre-crash systems. The team evaluated an Advanced Collision Mitigation Brake System (A-CMBS), which was the next generation of a system already deployed. The prior version (CMBS) responded to impending rear-end collisions with warning and intervention. The A-CMBS expanded the scope of target crash types to impending head-on, intersecting path, and pedestrian collisions in addition to rear-end collisions. The ACAT SIM program had the objective of developing a method for predicting safety benefits without waiting for deployment and actual experience or a full-scale FOT (Van Auken, Zellner et al. 2011).

The method employed was based on analysis of NASS CDS crashes and included identifying technology-relevant crash types, reconstructing the CDS crashes, validating the simulation model by reproducing the reconstructed crashes in simulation, and then predicting the outcome for each crash based on simulating the crash with the ACAT technology. Track testing and driving simulator testing was used to supply parameters not available from crash data and to calibrate the operation of the system. A driving simulator was used to obtain distributions of crash-avoidance behaviors.

This study estimated that if the system was used throughout the light-vehicle fleet, the number of crashes would decrease by 8.3%, vehicle crash involvements by 9.3%, and fatalities by 3.7%. Rear-end crashes would decline by 28.1% and fatalities in rear-end crashes would be reduced by 35.1%. It was also estimated that the system would prevent 4.2% of intersecting paths crashes, 1.8% of opposite-direction crashes, pedestrian crashes by 4.0%, and pedestrian fatalities by 12.0%.

There have been several relevant European studies, primarily from Sweden and Germany, as well as studies from Japan and Australia. These studies used the same general methodologies as the U.S. studies discussed above.

Coelingh et al. (2007) examined the safety benefits of Volvo systems that had different combinations of FCW (called just Collision Warning (CW) here); BA (called Brake Support); and AEB (termed Autobrake by Volvo). The first generation of the system protected against situations in which the lead vehicle was moving or had been detected as moving. This version included FCW and BA, but not AEB. The second generation activated for stationary vehicles and also included AEB.

The study methodology used crash data from the German In-Depth Accident Study (GIDAS) to identify crash scenarios and circumstances of rear-end crashes. GIDAS covers crashes in Hanover and Dresden areas. The study also used data from Volvo's own crash database and from NASS CDS to characterize speeds and driver responses in rear-end crashes. Crash analysis showed that rear-end crashes account for 6% to 9% of all impacts in the GIDAS data and about 5% of AIS 2+ injuries. Using simulation, the study estimated that the system would prevent 50% of rear-end crashes if all conditions were optimal, e.g., 100% penetration, dry road surface, and so on. Injury severity reduction was not quantified, but it was stated that neck injuries would be "considerably reduced" (Coelingh, Jakobsson et al. 2007).

A subsequent report estimated the benefit of a system that added pedestrian detection to the FCW with full AEB. This AEB would brake up to the friction limit of the tires and road surface, i.e., to brake lock-up. The system was designed to prevent crashes up to 35 km/h and to mitigate other unavoidable crashes by reducing impact speeds by up

to 35 km/h. The system uses radar and wide-angle camera to detect other vehicles and obstacles such as pedestrians. It will automatically apply brake force after warning if there is no response from the driver. When TTC is about 1 second, the system applies the brakes. The system works in parallel with Volvo's City Safety (Coelingh, Eidehall et al. 2010); see below.

This system was tested in a variety of scenarios, drawn from real crashes. From the tests, and based on the speed reduction achieved, it was estimated that the system could reduce fatalities in rear-end crashes by 30%. No specific estimate was given for injury reduction in pedestrian crashes, and it was noted that lowering speed in pedestrian collisions from 50 km/h to 25 km/h reduces fatality risk by 85%. Given that the system tested can reduce impact speeds by up to 35 km/h, the effect of this system would be substantial (Coelingh, Eidehall et al. 2010).

Another version of FCATs is designed to operate in low-speed environments such as in urban areas. One example is Volvo's City Safety system. This technology is aimed at preventing collisions at less than 30 km/h. It uses laser to monitor forward scene, and continuously computes deceleration needed to avoid collision. It can brake up to 0.5g. In addition, it activates brake lights, and has BA to boost driver-initiated braking if driver is braking less than necessary to avoid a collision. The system activates at 3.6 km/h and is started automatically on start up, though the driver can deactivate. Use of laser sensors means that the system is limited in fog, snow, and heavy rain. It is intended to protect against crashes that occur in stop-and-go traffic, parking, intersections, and roundabouts (Isaksson-Hellman and Lindman 2012).

This Swedish study is somewhat unusual because the safety benefits of the system were estimated using insurance claims data. Sweden requires collision insurance, and Volvo offers it free for the first three years of ownership. The data include crash type, parts damaged, car model, ownership, insured vehicle years, and estimated mileage per year. The researchers computed rear-end crashes per insured vehicle year for models with City Safety standard and for comparable models that did not have the system. Rear-end crashes were reduced by 23% for Volvos equipped with City Safety compared with other Volvo models without the system (Isaksson-Hellman and Lindman 2012).



Georgi et al. (2009) reported an evaluation of a Bosch FCAT system. The system combined FCW (called Predictive Crash Warning or PCW in the study) and AEB to protect against rear-end collisions. The Bosch system calibrates warning time based on the activity of the driver. Active drivers are assumed to be more alert and to react faster, so warning time is delayed. Less active drivers are given an earlier warning. The study examined rear-end crashes in the GIDAS database and computed effectiveness estimates based on the reaction of the Bosch system. As with most FCATs, the system works through increasingly vigorous interventions. Initially, it warns using audible and visual alerts. In the next phase, the brakes are briefly engaged. If there is no response or braking is inadequate, the brakes are automatically applied to achieve deceleration of about 0.3 g. If a collision is unavoidable, full braking is applied (Georgi, Zimmermann et al. 2009).

Using GIDAS data, a set of rear-end crashes applicable to the technology were identified and modeled. The models included a classification of the driver as active or not active. The effect of each layer of the FCAT was then computed. The results showed that the FCW alone would reduce rear-end crashes by 38%. The combination of FCW and EBA would reduce rear-end crashes by 55%, and the addition of AEB (for drivers who do not respond at all) reduces crashes by 72% (Georgi, Zimmermann et al. 2009).

Another study evaluated a FCAT that included pedestrian detection to estimate its effect on pedestrian fatalities and injuries. Part of the study was to determine the effect of the field of view of the pedestrian-detection system. As in the prior study, GIDAS crash investigations were used to derive the position of pedestrians in the pre-crash phase. The data include travel and impact speeds, braking and steering information, as well as sketches of the scene. It was determined that a 40° field of view was necessary to detect pedestrians 1 second prior to impact. The researchers assumed braking up to friction limits of the road, but not more than 0.6g. Using this information, they calculated the resulting impact speeds for pedestrians that would have been detected by the sensor. Risk curves were used to estimate the change in injury severity. The risk curves were derived from logistic regression estimates of the relationship between impact speed and pedestrian injury. The authors concluded that 40% of fatalities and 27% of serious injuries could be reduced with a field of view of 40°. They also found that 75% to 80% of

lives and 65% to 70% of injuries that are estimated to be prevented by the system came in crashes where the driver did not brake (Rosen, Kallhammer et al. 2009; Rosen, Kallhammer et al. 2010).

Yasuda et al. (2011) proposed a pure simulation method to estimate the effects of FCATs on effects of rear-end collisions. The simulation included road/traffic movements, driver behavior, and vehicle movements. The traffic environment simulation was based on traffic measurements. Rear-end collisions were created by introducing braking delays, reaction times, and decelerations in the traffic flow. Driver reaction times and decelerations were measured from drivers in simulators. By running simulations of the modeled traffic flow, sets of rear-end crashes were created. The distributions of travel speed and impact speed in the simulated rear-end crashes matched the distributions in actual crashes, so the simulated crashes were regarded as valid representations of actual rear-end crashes (Yasuda, Kozato et al. 2011).

The simulation was then run with a set of FCATs, including FCW, FCW+BA, and FCW+BA+AEB. At a relative velocity of 20 km/h, the simulation results showed that FCW prevented 30% of rear-end crashes, FCW+BA prevented 48%, and FCW+BA+AEB prevented 90% of crashes (Yasuda, Kozato et al. 2011)

In another Japanese study, forward-collision avoidance system that steered as well as braked was evaluated. At this point, the system only exists in software, but it adds the novel feature of steering toward an avoidance path if previous interventions have failed. Like other FCATs, this system includes multiple interventions that are activated in sequence. In the initial stage, a FCW issues a warning if the TTC is less than 2.0 seconds. If the driver initiates an avoidance maneuver, the system will apply full brake pressure regardless of the type of avoidance maneuver and will steer if the system detects an optimal avoidance path. After the FCW, the system only intervenes if it detects that the driver was acting to avoid a collision and then only if the intervention was necessary to prevent the crash. In this instance, steering is electronic and may be initiated without rotating the steering wheel. Thus, there could be a mismatch between steering wheel and steering angle. The driver may override the system maneuver if desired (Itoh, Horikome et al. 2013).

A driving simulator study was used to test this concept. The study used 20 subjects between 20 and 39 years of age, with six months to 19 years of driving experience. The simulator study showed that at a TTC of about 1 second, the steering avoided about 40% of collisions. The researchers noted several limitations to the study. Drivers could take avoidance maneuvers without worrying about other traffic, and were allowed to become familiar with how the system worked prior to the experiment (and thus were not surprised by the conflict scenarios tested). The study also assumed that the system worked perfectly in determining obstacle position and trajectory, as well as in being able to identify safe avoidance routes. Driver responses to the system were positive (Itoh, Horikome et al. 2013).

Finally, a recent Australian study used a more conventional crash-reconstruction technique to estimate the benefit of an FCAT. The system included FCW, BA, and AEB. The study considered the effect of varying radar range (long or short), the field of view of the radar, braking authority, and the timing of activation. Crash types addressed included rear-end, pedestrian, head-on, intersection and some fixed object crashes (Anderson, Doecke et al. 2012).

Crashes considered as relevant to the FCAT were identified in the crash data. Next, representative crashes were selected to represent the relevant crash types. These were simulated to estimate closing speeds. The FCAT technology was overlaid and resulting collision speed estimated. Risk curves were used to estimate reduction in injury associated with the lower estimated collision speed. Then, the results were applied to the whole population.

A total of 104 crashes were selected and analyzed. The results were a predicted reduction, assuming 100% penetration in the fleet, of 20% to 40% of fatal crashes and 30 to 50% of all injury crashes. The long-range radar condition operates primarily on higher speed roads. The short-range radar system is intended for urban areas with congested traffic and more pedestrians and bicyclists. For long-range radar conditions, higher braking force resulted in a slightly higher percentage of fatal crashes avoided; a shorter TTC slightly lowered the estimate of fatal crashes avoided; and a wider field of view made no difference. For the short-range radar condition, higher braking force resulted in

a significant increase in fatal crashes avoided; shorter TTC slightly reduced the percentage avoided; and a wider detection area substantially increased the percentage of fatal crashes avoided (Anderson, Doecke et al. 2012).

#### **2.2.4. Summary of forward collision technologies**

This section encompassed a diverse set of technologies that are designed to work together and in sequence to reduce forward collisions. In the initial stage of a forward-collision threat, a forward-crash warning system alerts drivers to impending conflicts. Most FCWs are designed to warn drivers of passenger cars, SUVs, or larger motor vehicles in the lane ahead, but some are designed to detect pedestrians and other non-motorists that may be nearing but not in the immediate line of travel. Next are various types of brake assist. These will pre-charge the brake system, so it can fire more quickly. Some will also increase brake pressure if the driver is not braking hard enough. The final system is automatic or autonomous emergency braking. These systems usually are designed to engage when the driver has not taken any avoidance maneuvers and a collision is unavoidable. Some systems are designed to operate in urban congestion, so they are active at slower speeds and monitor shorter ranges. Systems vary by the timing at which they issue warnings and fire the brakes, by how hard they brake, and by the area they monitor.

Most of the evaluations of effectiveness rely on simulations, more or less tied to crash data. Simulation methods are used because FCATs cannot be identified as such in publicly-available crash data. Furthermore, FCATs have not been deployed long enough or in sufficient numbers to produce statistically reliable results. Simulation is used as the next best alternative. However, it is important to recognize the limitations of the simulation technique. Simulations assume that the FCAT technology works as designed. Often only a limited number of crash scenarios are simulated. Most assume only braking without steering. Moreover, however sophisticated the driver model, driver reactions derived from driving simulators may not accurately reflect how real drivers react in a real crash situations.

However, virtually all the studies examined indicate that FCATs are highly effective. FCATs are usually designed for progressively greater interventions. Some studies estimated the cumulative effectiveness of the accumulating interventions. Studies estimated the effectiveness of FCW alone as ranging from preventing 29% of severe injuries to preventing 38% of rear-end crashes. One study estimated that FCW+BA would reduce the incidence of severe injuries by 39%, while two other studies estimated the reduction in the number of rear-end crashes to be 50% to 55%. The combination of FCW, BA, and AEB was estimated to reduce the number of severe injuries by 27% to 50%; reduce the number of rear-end crashes by 9.3% to 72%; and reduce the number of fatalities by 30% to 40%.

There is obviously a large range of variation in these estimates. The studies varied by the systems tested, by the methodologies used in the evaluation, and in the sources of data used. Nevertheless, all found significant reductions in crashes, fatalities, and injuries.

### **2.3. Lane/road departure and lane-change technologies**

This section reviews estimates of the effectiveness of a set of technologies that monitor a vehicle's position in the lane of travel, warn the driver in the event of imminent or actual lane departure, warn the driver in case the movement is into a lane that is already occupied, and in some cases attempt to move the vehicle back into lane. The technologies include lane- or road-departure warning, collectively referred to as LDW in this report, lane-departure prevention (LDP), which actively assists the driver in returning to the lane, and blind-spot detection (BSD).

#### **2.3.1. How lane/road departure warning systems work**

Lane-departure warning systems work by monitoring lane edge markings, usually through optical (camera) systems. If a vehicle approaches or crosses the lane lines, the system warns the driver, usually through a warning tone. Some systems use haptic warning systems; for example, the driver's seat may vibrate on the side of the departure. Some systems also include active "prevention" of lane/road departure. In these systems, the car is actively moved back into lane, either by applying the brakes on the wheels

opposite the side of departure, or by applying torque to the steering system to steer the car back (Yang 2013). Lane-change/merge systems use radars to monitor the lane adjacent and to the rear of a vehicle, alerting the driver to the presence of a vehicle in the blind-zone, or to a vehicle rapidly overtaking.

### **2.3.2. Assessment methodologies**

LDW/LDP systems are not yet in sufficient deployment to allow retrospective crash studies, as has been done with ESC. Accordingly, the primary assessment tools for this set of ACATs are simulations based on crash data analysis, and field operation tests (FOTs) in controlled experimental tests.

The primary method used to estimate the safety effect of LDW uses simulation. In this method, crash data are used to characterize the nature of crashes that are initiated by departing from lanes. Important factors include speeds, road geometry (degree of curvature or straight), angle of departure, and driver actions. Data is collected, often from driving simulators, on driver response (steering and braking) and reaction times to lane-departure warnings. Simulations are run to reproduce the distribution of crashes observed in the crash data. Then the simulations are repeated, with simulated active LDW systems and simulated driver responses to observe crash outcomes. The difference between the simulated crash distribution with and without LDW provides an estimate of the effect of the system. The effect of LDP is determined by the same means.

There have been some studies of field operational tests (FOTs) of vehicles with LDW systems. In FOTs, drivers are recruited from the population and supplied with vehicles that have the LDW technology. The drivers are instructed to use the vehicles just as they usually would. The vehicles are equipped with a suite of sensors that record how the vehicle is driven, including lane/road departures, travel speed, and other parameters of interest. Typically, baseline driving patterns are recorded to characterize normal driving before the LDW system is turned on. Data on the incidence and characteristics of lane/road departures in normal driving is collected, prior to activating the warning system. Then the LDW system is activated and the same data is collected on lane/road

departures in normal driving. The effect of the LDW on lane/road departures is then examined to see whether and how driving is changed.

### **2.3.3. Evaluations of crash avoidance technologies related to lane/road departure**

An early evaluation of lane-departure technologies was of an integrated set of technologies that included LDW as part of a set of ACATs. The project was structured as an FOT of Road Departure Crash Warning systems, or RDCW. The RDCW included several technologies related to different types of lane/road departure. An LDW component used video cameras to monitor lane position and time-to-lane crossing (TTLC). If the vehicle was about to depart the lane or road and no turn signal was activated, the system warned the driver. In addition, radars were used to monitor adjacent lanes for objects (vehicles) and issued an additional warning if the vehicle was drifting into a lane that was already occupied (blind-spot detection or BSD). Finally, a curve speed warning (CSW) system used global positioning satellites (GPS), digital maps, and vehicle sensors measuring lateral acceleration to determine if a vehicle was entering a curve at a speed too fast to negotiate safely. The FOT included 11 vehicles and 78 drivers who accumulated 83,000 miles of driving (LeBlanc, Sayer et al. 2006).

Data from the RDCW FOT was independently evaluated by a team within the US DOT. The effect of the systems was evaluated in two ways: researchers measured changes in the frequency of “conflicts” and estimated the effect on crashes. With only 83,000 miles of travel, there were not enough crashes to support analysis. Conflicts were defined, for the purpose of the lane/road departure technologies, as lane or road excursions. Such events are plausible conflicts because they could potentially lead to a crash. Analysis of results showed a decrease of 31% in lane boundary conflicts (road departure conflicts) in the treatment period compared with the baseline period. During the day, road departure conflicts were reduced by 40%. At speeds over 55, road departure conflicts were reduced by 44% (Wilson, Stearns et al. 2007).

There were also significant changes to driver behavior. There was an increase in the proportion of signaled lane changes from 61.5% to 69% in the treatment period. There was a small improvement in lane-keeping. Drivers averaged 2 cm closer to the

center line. However, the CSW system had no significant or substantial effect on lateral acceleration in curves (Wilson, Stearns et al. 2007).

Because there was an insufficient number of crashes to analyze, the effect on crashes was estimated based on the change in conflicts. The crash types relevant to the RDCW technologies included crashes initiated by going straight and drifting off the road, and negotiating a curve and running off road. It was estimated that at speeds over 55 mph, the systems would reduce road departure crashes by 7% to 57% (Wilson, Stearns et al. 2007).

The Integrated Vehicle-Based Safety System (IVBSS) FOT was another test of a fairly comprehensive set of ACATs, included FCW, curve-speed warning (CSW), lane-change/merge (LCM), and LDW. LDW operated in two modes: a cautionary mode, which issued a warning when a vehicle drifted out of lane into an unoccupied lane or shoulder, and an imminent mode, which warned when a vehicle drifted into an occupied lane or roadside hazard. Warnings were visual, auditory, and haptic. Like the RDCW FOT, this study measured not crash reduction but changes in driving behavior and conflict reduction. Crash reduction was estimated based on the reduction in conflicts (Sayer, Bogard et al. 2011).

Data from the IVBSS FOT was evaluated by an independent team within the US DOT. Like the RDCW, there were significant changes in driver behavior. Drivers using the suite of systems increased the proportion of signaled lane changes, reduced the number of lane excursions per 100 miles of travel, and reduced the duration of lane excursions (Nodine, Lam et al. 2011).

For the crash-reduction analysis, the target crash types include rear-ends, lane/road departure, lane change/merge, and loss of control in a curve. Analysis of the conflict data showed that the systems reduced lane-change near-crashes (conflicts) by 33% and road-departure near-crashes by 19%. Relating these changes in conflicts to crashes, it was estimated that the set of ACATs would reduce target crash types between 6% and 29% (Nodine, Lam et al. 2011).



A project in 2009-2010 evaluated a pre-production LDW system from Volvo. As with other LDW systems, it used cameras to detect lane lines and determine the vehicle's position in the lane. The system also included Driver Alert Control to detect degraded driver control in lane keeping, and Emergency Lane Assist to detect vehicles in the adjacent lane, both on-coming and same-direction, and steer the vehicle back into lane in the event of a conflict. However, the DAC and ELA systems were not included in the crash-reduction estimates because of the methodological complexity of doing so. Crash reduction effectiveness was only estimated for the LDW system itself (Gordon, Sardar et al. 2010).

This project used simulation that incorporated information from crash data, driver simulator studies, and naturalistic driving data. The basic methodology was an analysis of crash data to identify crashes that would be addressed by the LDW technology. The target crash types were those initiated by inadvertent (unsignaled) lane departure not produced by loss-of-control. Consequently, the target crashes were primarily those in which a vehicle drifts out of lane into another vehicle or off the road. These crashes were then described to identify road characteristics and driver responses for the simulation model. Other data, such as distributions of driver reactions in steering and braking, were collected from driving simulator studies. A simulation model was developed, with sub-models for driver actions and responses; vehicle dynamics; the roadway environment; and the activity of the LDW technology. Crash distributions were generated in simulation and weighted to match the real-world distribution of lane-departure crashes. The simulations were run again with the LDW technology to determine the number of crashes avoided.

The effectiveness of the LDW was estimated at 47% in reducing lane-departure crashes as a whole. This estimate assumed full system effectiveness, meaning that the system was operational at all times and working perfectly. However, system performance was reduced on wet roads, at night time, and when lane lines were worn, because the camera system's ability to identify lane boundaries was degraded in those conditions. With realistic allowance for reduced effectiveness because of degraded conditions, it was estimated that the system would reduce the target crash types by 33%. The estimate was

further refined by accounting for underreporting of fatigue in the crash data (which is also associated with drift-out-of-lane crashes), driver compliance rates, and driver adaptation to the system. Taking these factors into account, the final estimate of target crash reduction was 13% to 31% (Gordon, Sardar et al. 2010).

Kusano and Gabler (2012) presented results from a simulation model based on analysis of a database of 890 serious road-departure crashes. Unlike the Gordon, et al., (2010) project, this project used only crash data. The crash investigations had enough information about the movements of the vehicles to permit computer simulation of the crashes. The crash type simulated was lane/road departure with little or no steering by the driver, resulting in collisions with fixed objects located near the road. This crash type accounted for about 26% of the serious-injury lane departures in their data. In the simulation, the driver model included reaction time to the warning and the process of steering back into lane at a constant rate. Driver reaction times and steering angles were taken from published simulator studies. The simulation was run with different combinations of reaction times, steer angles, and braking. The percentage of crashes avoided depended on the timing of the warning. Warnings delivered at lane-crossing avoided 3-5% of crashes. Warnings delivered 1 second prior to lane-crossing averted 19-34% of crashes (Kusano and Gabler 2012).

Another study used a driving simulator to test driver response to adaptive and non-adaptive LDW systems. One challenge for LDW systems is driver annoyance with false alarms, such as warning on lane excursions that the driver was already aware of. In this test of an adaptive system, driver state was monitored, and if the driver state indicated that the driver was looking away from the road ahead for 2 seconds or more, an alert was given if the vehicle crossed a lane line. The purpose of an adaptive LDW is to reduce such false alerts. In this study, 40 volunteer drivers tested adaptive and non-adaptive systems in an advanced, moving-base, driving simulator. There were two primary results. In the adaptive mode, about one-third of subjects did not receive an alert when they should have. In addition, lane excursions tended to be greater in the adaptive mode than non-adaptive. This is consistent with the findings elsewhere that early alerts

result in less lane excursion, since the adaptive mode tended to delay or suppress driver alerts (Tijerina, Blommer et al. 2010).

Studies of lane/road departure technologies in other countries used similar methodologies and obtained similar results.

Tanaka, Mochida, et al. (2012) examined an LDW system using Japanese crash data. The authors state that their method could be used in other countries but caution that their results may not be applicable directly, since the results depend on the traffic environment and crash statistics, which vary across countries (Tanaka, Mochida et al. 2012).

The system tested was a pure LDW system, with no LDP component. The methodology used was similar to several U.S. studies discussed above. Tanaka, et al. used simulation based on driving and crash characteristics derived from crash analysis. Driver responses and reaction times were derived from experiments in driving simulators. The authors observed that an advantage of using simulation is that it allows comparison of the effect of variations in critical parameters of the LDW system, such as the timing of the warning. Such analysis of specific parameters is generally not feasible in an FOT, which typically tests single systems in a controlled deployment (Tanaka, Mochida et al. 2012).

The study found that system effectiveness in reducing lane-departure crashes varied by the activation time of the warning. Activation time was defined as Time to Lane Crossing, or TTLC. At -1.0 second TTLC (that is, warning given 1 second after lane crossing), there was a reduction of about 5% of crashes. The maximum benefit of LDW was achieved at 1 second TTLC (a 25% reduction). Warnings given before 1 second did not result in significant additional benefit. The simulation results also showed that crash severity was not affected by TTLC. It was concluded that LDW helps avoid crashes but was not effective at mitigating their severity (Tanaka, Mochida et al. 2012).

A study in the United Kingdom examined the effectiveness of LDW, along with certain other technologies. The system evaluated was a pure LDW system, with no LDP functionality. It also did not have a BSD functionality. Target crash types included head-

on and sideswipe (same and opposite-direction), and run-off-road crashes. The analytical method was to identify target crash types in U.K. crash data and then apply published effectiveness estimates to determine the crash-reduction potential. Overall, the report estimated that the LDW could prevent 7%-29% of fatalities, 13%-34% of serious injuries, and 13%-35% of minor injuries (Robinson, Hulshof et al. 2011).

An Australian study examined the potential benefits of several active safety systems, including LDW. The study used crash data from the Australian state of New South Wales to identify relevant crash types and characteristics. As in other areas, deployment of lane/road departure technologies is too low to support a retrospective crash study. The potential effectiveness of the technologies was estimated by a combination of published estimates and expert judgment (Anderson, Hutchinson et al. 2011).

The report estimated that LDW would reduce fatal crashes relevant to the technology by 11%-13% and injury crashes relevant to the technology by 2% to 9%. The lower bound estimates are for target crash types with no alcohol or speeding and on roads with good lane markings. For LCM target crash types, the report estimates that the technology would reduce fatal crashes by 1% and injury crashes by 3%. LCM crash reductions are lower than for LDW because the LCM target crash type is a same-direction sideswipe, in which closing speeds are low and the probability of injury is also low. Lane/road departure crashes can involve collisions with fixed objects off road and rollovers, which can be very severe (Anderson, Hutchinson et al. 2011).

#### **2.3.4. Summary of lane/road departure crash warning effectiveness**

Findings for the effectiveness of lane/road departure technologies are based primarily on simulation, rather than on a direct study of the crash experience of vehicles with the technologies. Two primary methods were used. The first used estimates of reductions in the number of lane excursions and conflicts derived from FOTs, between the baseline period with no LDW and the treatment period when the LDW was engaged.

The other primary method is based to a greater or lesser extent on computer simulation. Crash data are analyzed to determine how many crashes the technology might

address. The crash data are also used to generate simulated crashes, and then the simulated crashes are run with the technology overlaid to see how crash outcomes are affected. Some studies also used data on driver response and reaction times to different situations and warnings collected from driving simulators.

Estimates of the effectiveness of lane/road departure technologies are reasonably consistent. Results from a small early FOT estimated that the road-departure system would reduce road departure crashes by 7% to 57%. Later crash-reduction estimates were derived from different types of simulations. Estimates from four different simulations put the reduction of lane/road departure crashes at 6% to 34%. Another study estimated a 7% to 29% reduction in fatal injuries; 13% to 34% reduction in serious injuries; and 19% to 35% reduction in minor injuries.

Timing of the warning was generally found to be a critical feature whether it is given before, at, or after lane crossing. Earlier warnings were found to be associated with higher reductions in crashes and injuries, but warnings more than 1 second before lane crossing did not result in significant additional savings. However, it is important to note that these results are primarily from simulation studies, which assume that drivers will leave the systems activated and comply. Many studies cautioned that setting systems to issue early warning can result in frequent false alarms, which may annoy drivers and cause them to turn off the systems.

### **3. Summary of the effectiveness of Collision Avoidance Technologies**

Overall, the systems reviewed here were estimated to be substantially effective in reducing their target crash types. Table 1 brings together some of the estimated reductions by different measures. The studies reviewed had a range of estimated reductions, and in some cases the differences were fairly substantial. However, even the lower-bound estimates are significant in most cases.

It is important to recall that, for the most part, the estimates are based on simulation studies. Only ESC could be evaluated in retrospective studies using the actual crash experience of systems because of widespread deployment. The other technologies

were evaluated primarily through FOTs and simulation studies. Therefore, the results need to be validated by actual highway experience.

Table 1  
ACAT Effectiveness Summary.

Measure	ESC	FCAT (FCW+BA+AEB)	LDW/LDP
All crashes	7-9%		
All fatal crashes	25-33%		
Fatal injuries in relevant crash types		30-40%	7-29%
Serious injuries in relevant crash types		27-50%	13-34%
Single vehicle crashes	34-41%		
Rollover crashes	72-74%		
“Target crashes”	See above	9.3-72%	6-34%

In general, appropriate crash data are not yet available. Whether vehicles are equipped with ACATs cannot be directly determined in crash data, because no state data system and none of the major national crash data systems capture that information. Many crash data systems capture the VIN, but the presence of an ACAT is not coded into the VIN either. The only way vehicles with ACATs can be identified in crash data is if the system is standard equipment for a particular make/model. The crash experience of ESC-equipped cars and SUVs could be assessed because there have been enough specific models for which ESC is standard. But that is not yet the case for the other technologies.

It is possible that in the future, VINs will incorporate information on ACATs installed. NHTSA may be considering changes to the format of VINs. Another possibility is that manufactures supply information about specific equipment installed on vehicles by VIN to crash data systems. The information could then be joined to crash records, using the VIN. But this would raise important privacy and proprietary-data issues.

One of the studies reviewed here used a novel proprietary crash database, based on the OnStar system (Geisler and Micheline 2011). The OnStar system includes crash-

notification so that emergency responders are alerted to a crash. It also captures information about the nature of the crash and the vehicle's mileage. This information was used in the study to calculate crash rates for vehicles equipped with an ACAT (in this case, LDW/LCM technologies) and comparable vehicles without.

This study suggests that it suggests other future possible crash and exposure data resources that can be used to study the effectiveness of these technologies. In the wired world, the types of data that are captured and communicated for navigation and crash notification purposes may provide rich resources for safety studies.

#### **4. Penetration of collision avoidance technologies in the U.S. fleet**

There is no comprehensive data on the actual penetration in the U.S. fleet of the various collision avoidance technologies discussed in this report. This information is not contained in the vehicle identification number (VIN), so it cannot be “decoded” from the VIN using registration data. Some ACATs are standard equipment on certain models for certain years, so the presence of an ACAT can be known with certainty in those cases. However, some ACATs are only offered as optional equipment on many vehicles, or not at all on others. Thus, there is no comprehensive source.

The best estimate of penetrations of different ACATs was recently prepared by the Highway Loss Data Institute. This study provided an analysis and projection of penetration rates for six technologies, including three crash avoidance technologies: ABS, ESC, and FCW. The other technologies were driver front airbags, driver side airbags, and driver side head-protecting airbags. The analysis was based on vehicle registration data from R.L. Polk, which covers 95% of the light-vehicle fleet every year from 1985 to 2010. Each vehicle in the data was classified by model year, make, and series. Each of the technologies was classified as either standard, optional, or not available for the combination of model year, make, and series. Then, the proportion of the fleet for which the technologies were standard or optional was computed. The sum of standard and optional gives an estimate of the proportion of the fleet for which the technology is “available.” Future availability is predicted assuming a value for the annual number of

new vehicles that enter the fleet each year and an estimated attrition rate, based on vehicle age. A logistic regression model of the availability rate was fitted to the data to predict the year when availability would reach 100% (Highway Loss Data Institute 2012).

It is important to note that availability is not the actual take-rate, just the proportion of the fleet for which a given technology was standard or optional. As such, the data provide both a floor and a ceiling for the actual penetration, that is, the proportion of vehicles that have a given technology installed. Table 2 collects some of the estimates from the HLDI bulletin. The left-most two columns show the percentage of 2010 model year light-vehicle series for which the technology was either standard or available. ABS was standard equipment on 99% of vehicle models in 2010, and available as optional equipment on the remaining 1%. In terms of the fleet, 55% of registered vehicles were equipped with ABS, while it was optional equipment on an additional 33%, for a total availability of 88%. Thus, in 2010, at least 55% of the fleet was equipped with ABS, and up to 88% may have had ABS installed. Results of the logistic model imply that ABS will be available (though not necessarily installed) on the entire fleet by 2030 (Highway Loss Data Institute 2012).



Table 2  
Estimated Availability of Selected Technologies in 2010 Based on HLDI 2012.

Technology	New vehicle series in 2010		Fleet penetration			Predicted year available in 100% of the fleet
	Standard	Available	Standard	Optional	Available	
ABS	99%	1%	55%	33%	88%	2030
ESC	91%	4%	15%	12%	27%	2040
FCW	1%	11%	<0.5%	<0.5%	<1%	95% by 2050
Driver front airbags	100%	0%	88%	0%	88%	2030
Driver side airbags	92%	4%	26%	23%	49%	2040
Driver side head-protecting airbags	88%	3%	21%	20%	41%	2040

Overall, the study shows that penetration of new technologies can be slow, regardless of whether the technology is mandated by law. ABS is not required, yet was standard on 99% of vehicle series in the 2010 model year. It was first offered in 1985, yet is not predicted to become 100% available for the entire fleet until 2030. The document notes that if FCW was standard on all new vehicles starting in 2013, it would take until 2034 for it to be available on 95% of the fleet. As of 2010, less than 0.5% of the fleet was equipped with FCW, and if all the vehicles for which FCW was optional actually had it installed, fleet penetration would be less than 1% in that year (Highway Loss Data Institute 2012).

Data on penetration rates outside of the U.S. are also rare. It appears that, as in the U.S., there is no comprehensive source for this information. A few estimates were located, however. Schram, et al., reported that in 2012 AEB was offered on 21% of car models in Europe, mostly as optional equipment (Schram, Williams et al. 2013). Weeks, et al. (2009) developed a model of ESC penetration in the U.K. market. EC regulation requires ESC on new cars beginning in 2014. The model predicted “full car stock”

penetration by 2021. However, manufacturers report the take-up rate for optional ESC is only 1% (Weekes, Avery et al. 2009).

In contrast, in Sweden by the end of 2008, almost all new cars sold were equipped with ESC. A study by Krafft et al. (2009) undertook to explain why. The authors observed that virtually all studies, even the early ones, showed ESC to be highly effective. But without legislation, penetration into the fleet was slow in most countries (Krafft, Kullgren et al. 2009).

ESC was first introduced in the Swedish automotive market in 1998 as an option. Based on the scientific evidence of high effectiveness, the Swedish Road Administration (SRA) and Folksam insurance company recommended that buyers all select cars with ESC and also decreed that their employees would lease only ESC-equipped passenger vehicles. By 2003, up to 15% of new light vehicles sold were equipped with ESC. Various government agencies also attempted to influence individuals and businesses to buy and rent passenger vehicles with ESC. By 2005, almost 70% of new car sales in the country had ESC. Insurance companies reduced premiums for cars with ESC by as much as 15%. By December 2008, penetration in new car sales was close to 100% (97.9%). The major factors identified as producing high rates of penetration were the scientific evidence for the efficacy of ESC and pressure from important stakeholders, including decisions on the cars that government agencies and major stakeholders purchase and lease (Krafft, Kullgren et al. 2009).

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