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Cost and benefit estimates of partially-automated vehicle collision avoidance technologies

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ABSTRACT

Many light-duty vehicle crashes occur due to human error and distracted driving. Partially-automated crash avoidance features offer the potential to reduce the frequency and severity of vehicle crashes that occur due to distracted driving and/or human error by assisting in maintaining control of the vehicle or issuing alerts if a potentially dangerous situation is detected. This paper evaluates the benefits and costs of fleet-wide deployment of blind spot monitoring, lane departure warning, and forward collision warning crash avoidance systems within the US light-duty vehicle fleet. The three crash avoidance technologies could collectively prevent or reduce the severity of as many as 1.3 million U.S. crashes a year including 133,000 injury crashes and 10,100 fatal crashes. For this paper we made two estimates of potential benefits in the United States: (1) the upper bound fleet-wide technology diffusion benefits by assuming all relevant crashes are avoided and (2) the lower bound fleet-wide benefits of the three technologies based on observed insurance data. The latter represents a lower bound as technology is improved over time and cost reduced with scale economies and technology improvement. All three technologies could collectively provide a lower bound annual benefit of about $18 billion if equipped on all light-duty vehicles. With 2015 pricing of safety options, the total annual costs to equip all light-duty vehicles with the three technologies would be about $13 billion, resulting in an annual net benefit of about $4 billion or a $20 per vehicle net benefit. By assuming all relevant crashes are avoided, the total upper bound annual net benefit from all three technologies combined is about $202 billion or an $861 per vehicle net benefit, at current technology costs. The technologies we are exploring in this paper represent an early form of vehicle automation and a positive net benefit suggests the fleet-wide adoption of these technologies would be beneficial from an economic and social perspective.

1. Introduction

Many light-duty vehicle crashes occur due to human error and distracted driving. The National Highway Traffic Safety Administration (NHTSA) reports that ten percent of all fatal crashes and seventeen percent of injury crashes in 2011 were a result of distracted driving, while close to ninety percent of all crashes occur in part due to human error (NHTSA, 2013a; Olarte, 2011). Recent naturalistic driving data has confirmed the large prevalence of distracted driving and other driver-related factors in crashes (Dingus et al., 2016). Crash avoidance features offer the potential to substantially reduce the frequency and severity of vehicle crashes and deaths that occur due to distracted driving and/or human error by assisting in maintaining control of the vehicle or issuing alerts if a potentially dangerous situation is detected.

As the automobile industry transitions to partial vehicle automation, newer crash avoidance technologies are beginning to appear more frequently in non-luxury vehicles such as the Honda Accord and Mazda CX-9. The availability of Forward Collision Warning (FCW), Lane Departure Warning (LDW), and Blind Spot Monitoring (BSM) technologies could reach 95% of the registered vehicle fleet anywhere between the years 2032 and 2048 (HLDI, 2014a). The market penetration rate of these technologies depends on government mandates that could speed up implementation by up to 15 years (HLDI, 2014a). Automated vehicle technologies could have significant economic net benefits due to crash reduction (including direct cost savings and associated roadway congestion), enabling greater mobility for the disabled and

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elderly, and improved fuel economy due to more efficient driving (Anderson et al., 2014).

This paper estimates the costs and benefits of fleet-wide deployment of BSM, LDW, and FCW crash avoidance systems within the U.S. light-duty vehicle fleet. Two estimates are made to provide insight on current trends and technology potential. First, an upper bound of relevant U.S. crashes that potentially could be avoided or made less severe by the three technologies is estimated, assuming 100% technology effectiveness. Next, a lower bound in U.S. crash reduction is estimated using current changes in observed insurance collision claim frequency and severity (average loss payment per claim) in motor vehicles with these technologies. After these estimates are made, an annualized cost to equip each vehicle with the technologies enables a cost benefit analysis for the lower bound and upper bound estimates of net benefits in the U.S. The technologies we are exploring in this paper represent an early form of vehicle automation as defined by NHTSA (NHTSA, 2013b) and the estimates in this paper can help inform near-term decisions during the transition to automation.

2. Existing literature

Several researchers have analyzed the effectiveness of crash avoidance technologies in reducing crashes and severity. For example, Jermakian (2011) estimates that side-view assist and FCW systems could potentially prevent or reduce the severity of as many as 395,000 and 1.2 million crashes involving passenger vehicles annually, respectively, using crash records from the 2004–2008 National Automotive Sampling System (NASS) General Estimate System (GES) and Fatality Analysis Reporting System (FARS) databases (Jermakian, 2011). Kuehn et al. (2009) used insurance collision claims data along with human factors research and determined that equipping all cars with a forward collision warning and lateral guidance system that was 100% effective, could prevent up to 25% of all crashes (Kuehn et al., 2009). Sugimoto and Sauer (2005) estimated that a FCW system with autonomous braking could reduce the probability of a fatality in a rear end collision by as much 44% (Sugimoto and Sauer, 2005). A 2012 study concluded that Blind Spot Monitoring (BSM) systems could potentially prevent or reduce the severity of 22,000 combination tractor-trailer crashes annually (Jermakian, 2012). Kusano et al. (2014) developed a crash and injury simulation model in which each crash was simulated twice- once as it occurred and once as if the driver had a LDW system-and determined that a LDW system could potentially prevent up to 29.4 percent of all road departure crashes (Kusano et al., 2014). Blower (2013) used simulations and operational field tests to develop a range of estimates on the effectiveness of ESC, LDW, and FCW systems in reducing target crash types (Blower, 2013). The American Automobile Association (AAA) along with the MIT AgeLab conducted a study in which they assessed and provided ratings for both the potential and real world benefits of LDW, FCW, ESC, and other crash avoidance technologies based on data gathered from published literature (Mehler et al., 2014). Blanco et al. (2016) estimated and compared crash risks for self-driving and national crash rates using data from Google's Self-Driving Car program and the Second Strategic Highway Research Program (SHRP 2) Naturalistic Driving Study. This study suggests that less-severe crashes may happen a much lower crash rate for self-driving cars (5.6 per million miles driven) when compared to the national crash rate (14.4 per million miles driven) (Blanco et al., 2016). The Insurance Institute for Highway Safety (IIHS) estimates that forward collision systems with automatic braking could reduce rear-end crashes by about 40% while standalone FCW could reduce these crashes by about 23% (IIHS, 2016).

Researchers have also attempted to estimate the economic benefit of crash avoidance technology systems. For a consistent comparison, we used the consumer price index (CPI) to convert all benefits in previous literature to $2012 (Bureau of Labor Statistics, 2015). One prediction comes from Murray et al. (2009) who found that a FCW system in large trucks could provide a benefit ranging from $1.42 to $7.73 for every dollar spent on the system (Murray et al., 2009). This estimate is based on different vehicle miles traveled (VMTs), system efficacies, and technology purchase prices. Batelle (2007) reports that equipping all large trucks with a FCW system could have a negative net benefit approximately anywhere between −$66 and −27$ billion, depending on the cost of system and driver reaction time (Batelle, 2007). In that study, crash reduction frequencies for a FCW system were derived from statistical modeling. Another study found that at a 90 percent market penetration rate FCW along with adaptive cruise control could provide considerable safety benefits- $52 billion in economic costs (lost productivity, travel delay, etc.) and 497,100 functional person-years (Li and Kockelman, 2016). This paper makes a contribution to the literature by estimating the economic net benefits of three crash avoidance technologies in light-duty vehicles based on changes in observed insurance collision claim frequency and severity for vehicles with BSM, LDW, and FCW crash avoidance systems. We extrapolate the observed insurance data to estimate a lower bound of fleet-wide deployment benefits. It represents a lower bound because technology cost and performance are likely to improve, and additional benefits are likely as deployment increases. To estimate an upper bound, we assume the three crash avoidance technologies examined are 100% effective in preventing relevant crashes.

3. Data

To compute the upper bound annual net benefit of equipping all light-duty vehicles with BSM, LDW, and FCW systems, we first need to identify which types of crashes could potentially be prevented or made less severe by each technology. The primary sources of data used are the 2012 GES which provides information on crashes of all severities, the 2012 FARS which provides information on fatal crashes, and insurance data from various reports written by the Highway Loss Data Institute (HLDI). Table 1 (shown below) provides an overview of the primary data sources for this analysis and their use.

3.1. Overview of crash avoidance systems

As mentioned earlier, the crash avoidance systems we focus on for this paper are FCW, LDW, and BSM. FCW systems are intended to detect objects ahead that are stationary or moving at a slower speed and issue a warning to the driver if his or her closing speed represents risk of an impending collision. Many automakers pair FCW with crash imminent braking systems, and both BSM and LDW could be paired with active lane keeping assist technology. LDW systems monitor the lane markings in the roadway and alert the driver if they are drifting out of their own lane. BSM systems monitor the blind spots to the rear and sides of the car and issue a warning if a car enters the driver's blind spot. While these sensors serve the same purpose from vehicle to vehicle, their location on the vehicle could differ by manufacturer. For example, Honda's FCW system is located behind the windshield while Mercedes' and Acura's are located in the front bumper. Similarly, Mazda's BSM system is located in the rear bumpers, while Buick's system is located behind each rear quarter panel. Fig. 1 illustrates how the three crash avoidance systems interact with the roadway.

Table 1
Overview of Primary Data Sources and Their Use.

Data Source	Use	Source
2012 National Automotive Sampling System (NASS) General Estimate System (GES)	Estimate Relevant Non-Fatal Crashes	NHTSA
2012 Fatality Analysis Reporting System (FARS)	Estimate Relevant Fatal Crashes	NHTSA
The 2010 Economic and Societal Impact of Motor Vehicle Crashes Report	Estimate Crash Cost	NHTSA
Basav et al. (2003) Analysis of Lane Change Crashes Report	Identify Lane Change Crashes in FARS and GES	NHTSA
Gordon et al. (2010) Safety Impact Methodology for Lane Departure Warning Report	Identify Lane Departure Crashes in FARS and GES	NHTSA
A Collection of Collision Avoidance Reports	Estimate Changes in Crash Frequency and Severity	Highway Loss Data Institute (HLDI)

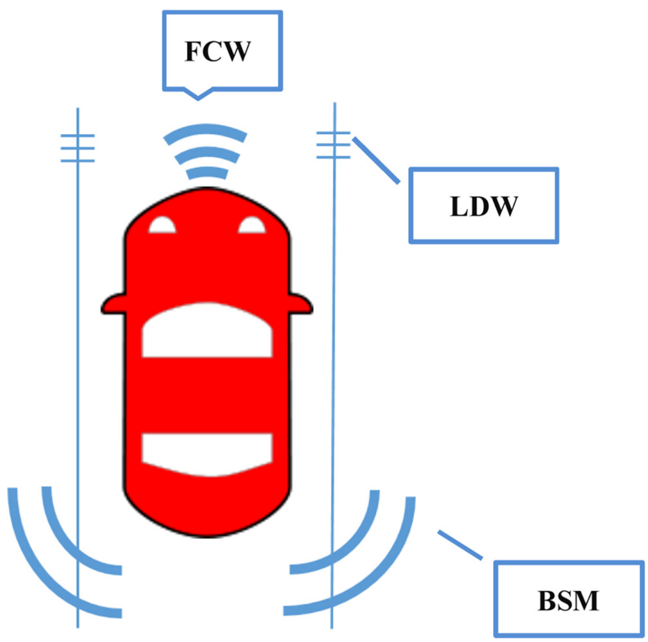

Fig. 1. Lane Departure Warning (LDW), Forward Collision Warning (FCW), and Blind Spot Monitoring Roadway (BSM) Interaction.

3.2. *Background on the general estimate system (GES) and fatality analysis reporting system (FARS)*

NHTSA annually collects information on both fatal and non-fatal motor vehicle crashes in the United States in order to aid researchers and other transportation professionals in evaluating the number of different crashes involving all types of vehicles and any relevant information regarding the crash that could be used to find and diagnose problems within traffic safety. Along with accident data, the 2012 GES and FARS datasets also include person and vehicle level data.

The 2012 GES attempts to represent the crash characteristics of the United States population on a national level and includes accidents of all severities. A weighting factor is provided for each person, vehicle, and accident included in the datasets. This weighting factor is the computed inference factor, which is intended to represent the total population from which the sample was drawn. The system has a population sample of about 62 thousand accidents that is representative of about 5.6 million crashes nationwide. All of the results presented in this report for non-fatal accidents were found using the full sample weights for the 2012 GES.

The 2012 FARS data contains information on every fatal crash occurring on a public roadway in the year 2012. In order for a crash to be included in the FARS dataset, the crash must result in the death of an occupant of a vehicle or a pedestrian within thirty days of the crash due to injuries suffered from the accident. Unlike the GES database, the FARS dataset does not include any weighted estimates since each fatal accident that meets the criteria outlined above is included in the dataset. All of the results presented in this reported related to fatal accidents were found using the 2012 FARS.

3.3. *Data selection methodology*

The 2012 NASS GES and FARS vehicle dataset contains information on in-transport vehicles and passengers. For all crash types, collisions that involved at least one light-duty passenger vehicle in the 2012 NASS GES and FARS files were used while all other crashes were truncated from the dataset. One and two vehicle crashes make up close to 94% of all vehicle crashes; evaluating three or more vehicle crashes adds complexity to the analysis for a small percentage of accidents, and as a result these were not considered. Crashes in the GES that were coded as fatal were excluded from the analysis since we were only interested in examining injury-related crashes from this dataset. In order to account for any missing data in the vehicle files, imputed data were used where available.

Target crash populations for each technology were established in order to sort crashes into identifiable categories, making it easier to estimate the relevant number crashes for each technology. For this analysis the three target populations are: lane-change crashes, lane-departure crashes, and rear-end collisions, which are most closely related to BSM, LDW, and FCW, respectively. These crash technologies are functional at certain speeds depending on the automaker. In order to identify vehicles that were traveling at a speed greater than or equal to the functional speed of the technologies in the vehicle file, the vehicle speed was taken into account. In cases where the vehicle speed was unknown, the roadway speed limit was considered due to the large percentage of unreported travel speeds. If the vehicle speed was unreported it is assumed that when the crash occurred, the vehicles involved were traveling at a speed greater than or equal to the reported speed limit. The functional speeds established for this analysis are 20, 40, and 20 miles per hour (MPH) for BSM, LDW, and FCW, respectively (HLDI, 2012b, 2011a).

3.3.1. *Blind spot monitoring*

BSM systems are designed to alert the driver when a vehicle encroaches into their blind spot by using cameras or sensors to monitor areas to the side of a vehicle. BSM would be most useful in preventing or reducing the severity of lane change crashes.

Table 2
Methods Used to Identify Lane Change Crashes in GES.

Filter #	SAS Code to Identify	Description
1	Identify which crashes involve at least one passenger car	Analysis concerned with crashes involving at least one passenger car.
2	if 44 < = acc_typ < = 49 or 70 < = acc_typ < = 75 and veh_invl = 2	Selects accident types that a lane change crash could fall under and crashes that involved two vehicles
3	if not 1 < = p_crash2 < = 09	Eliminates Crashes involving loss of control.
4	if not 80 < = p_crash2 < = 92	Eliminates crashes involving pedestrians and pedal cyclists, animals, or other objects.
5	if not p_crash2 = 54 62, 63, 67, 71, or 72	Eliminates crashes involving vehicles initially traveling or turning in the opposite direction.
6	if not p_crash2 = 59, 68, 73, or 78	Eliminates crashes where it is not clear if vehicles were initially traveling in same or opposite direction.
7	if not (acc_typ = 75 or 76 and p_crash2 = 15 or 16) or (p_crash1 = 10 or 11)	Eliminates crashes that do not conform to the definition of lane change crashes.
8	if not p_crash2 = 50, 51, or 52 for one vehicle, and p_crash2 = 18 or 53 for the other vehicle	Eliminates crashes in which it appears the vehicles were initially traveling in the same lane are eliminated.
9	if 20 < = speed < = 151 or (speed = 997) or (speed = 998 or 999 and 20 < = spdlim)	Functional speed of Blind Spot Information 20+ mph.
10	if not weather $\neq$ 2,3,or 4	Eliminates crashes that took place in inclement weather

Source: Adopted from Basav et al.'s Analysis of Lane Change Crashes report (Basav et al., 2003).

A lane-change crash was defined as where two vehicles were initially traveling along parallel paths in the same direction and the encroachment of one vehicle into the travel lane of another vehicle, was the primary reason for the crash occurring. The method used to identify lane-change crashes is outlined in Table 2.A similar method was used for lane departure and rear-end crashes. Crashes that occurred off-road and crashes involving loss of control were not included in the target crash population, since we are only concerned with crashes that occur on a roadway that are not a result of loss of traction due to wet surface, etc. Additionally, in cases where it was not clear whether or not two vehicles were traveling in the same or opposite direction, or if it appears two vehicles were initially traveling in the same lane, these entries were eliminated from the dataset. System limitations that could affect the operation of BSM were also taken into account. BSM systems use sensors and cameras to detect nearby vehicles and could become unreliable in inclement weather (rain, sleet, snow). As a result, crashes that occurred in inclement weather were not considered. The filtering of the lane-change crashes was done by using the pre-crash movement, critical event, accident type, and vehicle speed variables. This target crash population includes only two-vehicle crashes. BSM may have avoided some of these omitted crashes, hence as a result the BSM savings estimate provided here is more conservative. More information regarding lane-change crashes can be found in NHTSA's analysis conducted by Basav et al. Analysis of Lane Change Crashes report (Basav et al., 2003).

3.3.2. *Lane-departure warning*

The crashes included in the lane-departure crash target population are assumed to be situations where a LDW system would be active. As a result, lane-departure crashes are defined as one where the vehicle inadvertently departs its travel lane and the driver of the vehicle is not actively maneuvering the vehicle other than the general intent of lane keeping. This target crash population includes both single and two-vehicle crashes. The crash scenarios examined for this analysis in which LDW would issue a warning are: prior lane keeping, lane departure and single-vehicle lane departure. The critical events that would correspond to a lane or road departure are: "vehicle traveling over left of lane", "vehicle traveling over the right lane line", "vehicle off the edge of the road on the left side" and "vehicle off the edge of the road on the right side". "Going straight" and "negotiating a curve" were the pre-crash movements chosen for the lane departure scenario: prior lane-keeping, lane departure, where the vehicle was going straight or negotiating a curve (pre-crash movement) and at some point departed its lane (critical event). In addition to the pre-crash maneuvers of the vehicle, target crashes were also identified by looking at other factors such as whether the vehicle was involved in the first harmful event and its accident type, and the speed at which the vehicle was traveling. Because LDW uses cameras to monitor the vehicle's position within the lane markers, crashes that occurred while there was snow on the roadway were filtered from the dataset. While LDW (similarly to BSM) warn of sideswipe crashes, the FARS and GES datasets do not indicate the driver's intention (drift out of lane or active lane change), and as a result crashes with the pre-crash movement: "changing lanes" were not considered for the lane departure crash population. More information regarding LDW system crashes can be found in Gordon et al.'s Safety Impact Methodology for Lane Departure Warning report (Gordon et al., 2010).

3.3.3. *Forward collision warning*

FCW systems are designed to prevent or reduce the severity of rear-end collisions by using a camera or radar to detect whether a vehicle is approaching another object-vehicle, bicycle, or pedestrian- at an unsafe speed and issues alerts to the driver. In addition to FCW systems, some vehicles also include crash imminent braking systems that apply autonomous braking to the vehicle after a warning has been issued. Rear-end collisions were identified in both the FARS and GES data sets by referring to the accident type variable. Accident type variable codes in GES 20–29 correspond to a rear-end collision and were used to filter out accidents in which FCW systems would be active. Once the crashes that met the desired accident types listed above were identified, vehicle speed, pre-crash movement, and critical event were then taken into account. In cases where a lane change or merge occurred directly before the crash, these entries were eliminated since it is not clear whether or not a FCW system would have been effective in these scenarios. Crashes that occurred during inclement weather were filtered from the target crash population, since rain, snow, etc. could hinder the performance of the system. The pre-crash scenarios examined in this paper that could lead to a rear-end crash are: the lead vehicle stopped, lead vehicle decelerating, and lead vehicle moving at lower constant speed. The rear-end collision target crash population only includes two-vehicle crashes.

3.4. Estimation of crash frequency and crash cost reduction

To estimate the existing effectiveness of each technology, insurance data on changes in collision claim frequencies and severity (average loss payment per claim) were gathered from the HLDI (HLDI, 2014b, 2012a,b, 2011a,b,c). The HLDI derives its data by comparing the insurance records of vehicles with crash avoidance features against vehicles of the same model year and series assumed not to have any features.

First, it is assumed that a change (positive or negative) in collision claim frequency is the equivalent change in crash frequency for single and multiple-vehicle accidents. While not all accidents are reported to insurance companies and collision claim frequency does not mirror crash frequency, there is a relationship between the two statistics. Second, it is assumed that a change in collision claim severity is the equivalent change in crash cost for related accidents that are not prevented. Crash avoidance technologies could reduce crash severity, which should in turn reduce crash costs, as supported by the observed data.

The HLDI reports the number of insured years for each technology (blind spot monitoring, etc.) by vehicle make. To convert all reported values into a single value for each technology, a weighted average was calculated based on the total vehicle exposure. Specifically, the collision claim frequency of a technology by make with a higher exposure was weighted greater than those with a lower exposure. For example, if Hondas with FCW have a total exposure of 28,000 insured vehicle years and Volvos with FCW have a total exposure of 15,000 insured vehicle years, the change in collision insurance claim frequency for Hondas FCW system would contribute more to the final weighted average claim frequency for FCW than would that of Volvo. It should be noted that some of the insurance data reported by the HLDI for some vehicles are not statistically significant. Most crash avoidance technologies are fairly new and it is expected that they will improve with time.

4. Benefit cost analysis

The annual net benefit of crash avoidance systems is the difference between the total annual benefits and total annual costs and is expressed in Eq. (1):

$$NB = TB - TC \tag{1}$$

where NB is the annual net benefit, TB the total annual benefits, and TC is the total annual costs.

The total annual benefits are the savings that result from a reduction in crash frequency and crash costs due to the deployment of BSM, LDW, and FCW crash avoidance systems throughout the light-duty vehicle fleet. The total annual benefits of crash avoidance technologies for single and multiple-vehicle accidents are expressed in Eq. (2):

$$TB = CS_{CP} + CS_{LS} \tag{2}$$

where TB is the total annual benefit of equipping all light-duty vehicles with crash avoidance technologies, CS_{CP} the cost savings from crash prevention, CS_{LS} the cost savings from less severe crashes.

The total annual costs are the incremental annualized costs associated with equipping all light-duty vehicles in the vehicle fleet with the technologies. So the total costs can be expressed in Eq. (3):

$$TC = TP_C \tag{3}$$

where TC is the total annual costs of equipping all light-duty vehicles in vehicle fleet with BSM, LDW, and FCW crash avoidance systems, TP_C is the technology purchasing cost. Fig. 2 (shown below) shows the processes and steps taken to estimate the technology purchasing costs, and upper and lower bound benefits and net benefits.

4.1. Total annual benefits

The annual benefits of equipping all light-duty vehicles with the technologies come from a reduction in crash frequency and severity. Upper bound annual fleet-wide technology diffusion benefits are estimated by assuming all relevant crashes are avoided. Lower bound annual fleet-wide benefits are projected using crash frequency and severity reduction from current insurance data and estimated by applying observed changes in crash frequency to the total number of crashes that occurred in 2012 and changes in crash severity to relevant crashes not avoided.

Using the 2012 GES and FARS, we can generate estimates of relevant crashes for the technologies under consideration, and descriptive statistics about the sample sizes. We estimated that approximately 24 percent of the 5.6 million police reported crashes are relevant to at least one of the following three crash avoidance technologies: BSM, LDW, and FCW. With 100% effectiveness and deployment, the combination of all three technologies could prevent or reduce the severity of as many as 1.3 million crashes annually, including 133,000 injury crashes and 10,100 fatal crashes (See Table 3). Of the three technologies examined in this paper, FCW has the greatest potential to prevent or reduce the severity of the largest number of crashes overall. This technology could prevent or reduce the severity of close to 800,000 crashes or 14% of all crashes. The technology that could affect the largest number of fatal crashes is a LDW system, which has the potential to prevent or reduce the severity of up to 9020 fatal crashes or 29% of all fatal crashes. BSM addresses the second most crashes of any severity out of all three technologies. There are about 267,000 crashes including 17,000 injury crashes and 280 fatal crashes, relevant to this technology. The standard errors of the estimates for non-fatal crashes are listed in Table 3. The dataset used to estimate fatal crashes for this analysis, FARS, contains data on each police reported fatal crash, and as a result has no standard error associated with its estimate. Standard errors for non-fatal crashes were estimated using NHTSA's 2013 Traffic Safety Facts Report (NHTSA, 2014).

To estimate a lower bound fleet-wide reduction in crashes and severity, we use current insurance data for vehicles with these technologies and project the savings across assumed fleet-wide technology diffusion. Table 4 summarizes the change in crash frequency and severity for each crash avoidance technology from current insurance data. Vehicles with a FCW system show the greatest reductions in both collision claim frequency and severity. Collision claim frequency and severity for vehicles with this technology were reduced by about 4 percent and $225, respectively. BSM lowers collision claim frequency and severity by about 0.5 percent and $80, respectively. Vehicles with a BSM system have the lowest reduction in both collision claim frequency and severity. LDW has second highest reduction in both categories out of all three crash avoidance systems. This technology reduces both collision claim frequency and severity by about 1.2% and $155, respectively. Table 4 lists the exposure, measured in terms of insured years by technology for collision coverage. This statistic is intended to give the reader an idea of the total length of time the vehicles with the crash avoidance features examined in this study were insured under a given coverage type. The exposure for the control group, vehicles without any features, is not easily discernable from the data available online, and as a result is not reported in this paper.

In 2010 there were approximately 5.4 million crashes that resulted in about 1.5 million injuries and 30,196 fatalities. The economic toll and societal harm of motor vehicle crashes that year

Table 3
Relevant Crashes from the 2012 GES and FARS Data, Which Represent the Upper Bound that Potentially could be Prevented or Made Less Severe Annually by Crash Avoidance Technologies Given System Limitations.

Technology	All Crashes	Injury Crashes (A or B)	Fatal Crashes	Non-Fatal Crash Standard Error
Blind Spot Monitoring	267,000	17,200	280	19,927
Lane Departure Warning	262,000	58,100	9000	18,944
Forward Collision Warning	795,000	58,000	750	58,706
Total	1,320,000	133,000	10,100	99,678
Percent of Total Crashes	23.58%	8.16%	32.63%	N/A

Source: The 2012 National Automotive Sampling Survey General Estimate System and Fatality Analysis Reporting System Accident & Vehicle File, U.S. Department of Transportation.
Note: A or B refers to incapacitating and non-incapacitating injuries, respectively, as defined by the KABCO injury scale.

totaled about $836 billion, which includes $242 billion in economic costs and $594 billion due to loss of life and decreased quality of life from injuries (Blincoe et al., 2015). This would result in each crash costing close to $154,000 in $2010. Because the crash data used for this paper is from the year 2012, the Consumer Price Index (CPI) was used to find the total cost of a crash in 2012 dollars, which is approximately $162,400 or $47,021 in economic costs and $115,414 in quality-adjusted life years (QALYs) cost. Private Insur-

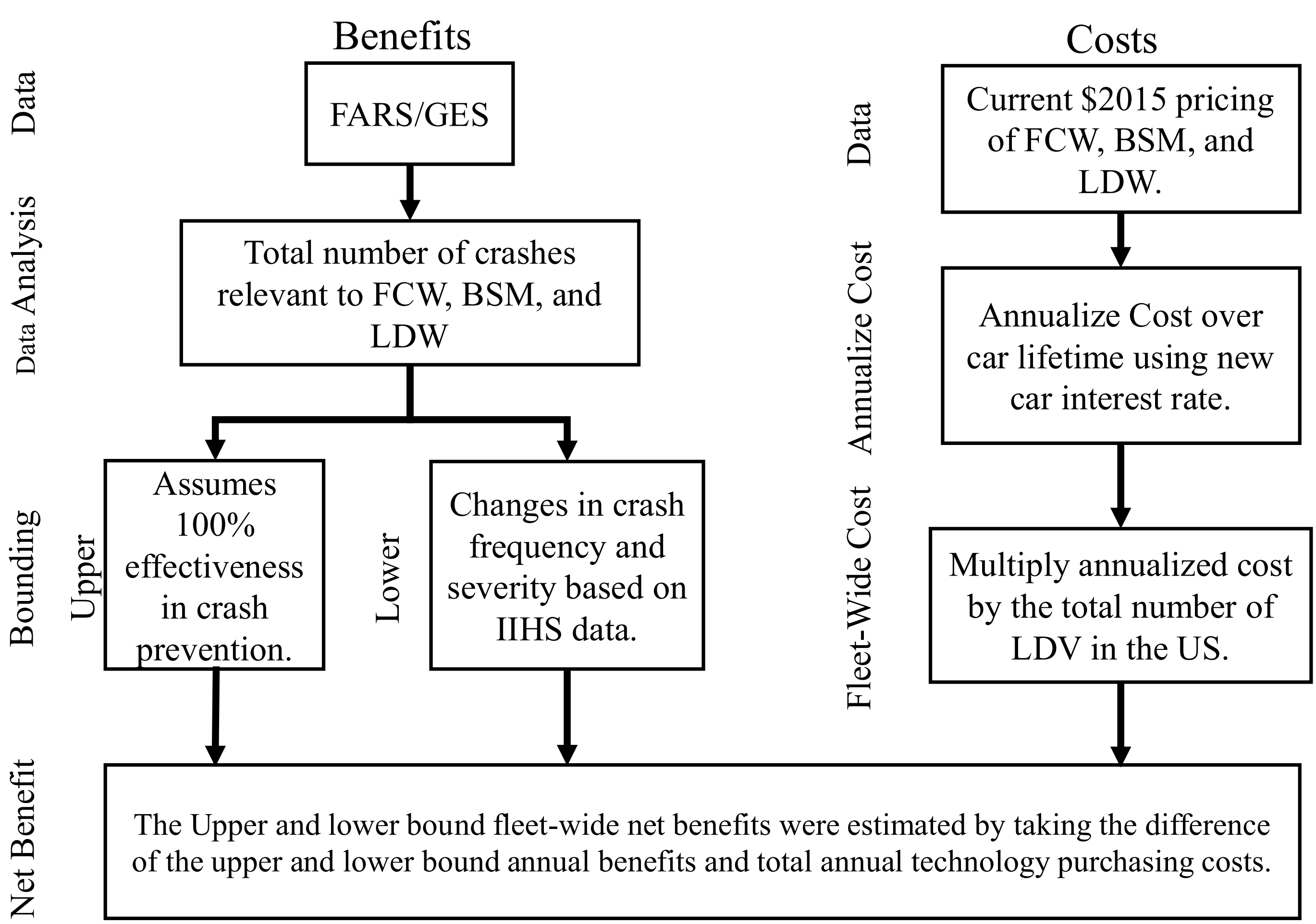

Fig. 2. Flow Chart of Cost and Benefit Estimates Process for Costs and Benefits.

Table 4
Observed Changes in Crash Frequency and Cost and Collision Exposure By Crash Avoidance Technology ($2012).

Crash Avoidance Technology	Change in Collision Claim Frequency[a]	Change in Collision Claim Severity[a]	Collision Exposure[c]
Blind Spot Monitoring	−0.53%	−$80	439,600
Forward Collision Warning[b]	−3.97%	−$221	272,900
Lane Departure Warning	−1.21%	−$147	229,900
Average	−1.90%	−$149	N/A

Source: A collection of Collision Avoidance Reports written by the Highway Loss Data Institute (HLDI, 2014b, 2012a, 2012b, 2011a, 2011b, 2011c).
[a] Weighted Average Based on Vehicle Exposure.
[b] Some of the vehicles included in this estimate had a forward collision warning system that includes autonomous emergency braking.
[c] This column represents total exposure for each technology, measured in terms of insured vehicle years.

Table 5
Estimation of Lower and Upper Bound Annual Benefits from Fleet-wide Deployment of Crash Avoidance Technologies in Light-Duty Vehicles.

Item of Benefits	Monetary value of the benefits (Billion $2012)	
Crash Prevention Cost Savings	Lower Bound Benefits	Upper Bound Benefits
Private Insurers	$2.90	$35
Households	$1.40	$17
Third-Parties	$0.78	$10
Public Revenue	$0.50	$6.2
QALYs	$12	$147
Total cost savings from Crash Prevention (CS_{CP})	$17	$215
Cost savings from Less Severe Crashes (CS_{LS})	$0.18	$0
Total annual benefits of fleet-wide deployment of crash avoidance technologies in light-duty vehicles (TB)	$18	$215

Note: Figures may not sum exactly due to rounding.

ers cover $25,391 or about 16 percent of the total cost of a crash, while about 7 percent or $10,815 is paid by households. Third parties (uninvolved motorists in congestion, charities, etc.) pay about 5 percent or $7523 of the total cost and public revenues pay about 2 percent or $3291. The remaining 71% comes from costs associated with lost QALYs from injuries or fatalities.

The direct benefits of equipping all light-duty vehicles with crash avoidance technologies consist of the cost savings from crash prevention and less severe crashes. Indirect benefits include savings from increased QALYs from more people living healthier lives from avoided crashes. The economic savings from crash prevention explain that private insurers, households, third-parties, and public-revenue sources saved money since each crash avoidance technology prevents a number of crashes. If these accidents had occurred each entity would need to pay a percentage of the cost of each crash. The lower bound fleet-wide annual accident prevention cost savings is shown in Table 5. The values in this table were estimated by using the using the average change in collision claim frequency and severity from Table 3 along with the total number of crashes that occurred in the year 2012. Total crash prevention cost savings are the sum of the economic cost savings and the cost savings from increased QALYs. The calculation of the total lower bound annual crash prevention cost savings is based on the following formula:

$$\text{total current crash prevention cost savings}$$
$$= NC \times CF \times SC$$
$$= 5.6\text{million crashes} \times 1.90\% \times \$162,400\text{per crash}$$
$$= 106,872\text{crashes} \times \$162,400\text{per crash}$$
$$= \$17.4\text{billion}$$

where,

$NC =$ total number of crashes which occured in 2012,

$CF =$ the average change in collision claim frequency for all three technologies (listed in column 2 of Table 4),

$SC =$ social cost of a crash

Less severe crash cost savings describe the savings to private insurers due to lower collision claim loss amounts. Because this paper uses a bounding assumption on 100% effectiveness and deployment of crash avoidance technologies it is assumed that all relevant crashes not prevented will have a reduction in average severity. The calculation of the total lower bound annual cost savings from less severe crashes is based on the following formula:

$$\text{total current cost savings from less severe crashes}$$
$$= \text{NO} \times \text{CP}$$
$$= (1.3\text{million crashes} — 106,478\text{crashes}) \times \$149\text{per crash}$$
$$= 1.2\text{million crashes} \times \$149\text{per crash}$$
$$= \$181\text{million}$$

where,

NO = number of crashes expected to still occur from upper bound estimate,

CP = average change change in collision claim severity for all three technologies (listed in column 3 of Table 4)

The total annual benefits (TB) from cost savings due to less severe and prevented crashes were estimated using Eq. (2). As presented in Table 5, the total lower bound annual benefits are approximately $18 billion. The most important sources of benefits are cost savings from crash prevention ($17 billion), and less severe crashes ($180 million). In this estimation, cost savings from people living healthier lives are only based on crashes that were prevented by the crash avoidance technologies, since we are not aware of how each technology impacts injury severity if a crash does occur. Although, more crashes are assumed to have a reduction in average severity than prevented, crash prevention provides a far greater benefit since the cost savings from less severe crashes is very small compared to the cost savings from avoiding a crash.

In order to estimate an upper bound fleet-wide benefit from the three technologies we will assume that each technology is 100% effective in preventing crashes from their respective target crash population. The calculation of the total upper bound annual crash prevention cost savings is based on the following formula:

$$\text{upper bound crash prevention cost savings}$$
$$= \text{M} \times \text{SC}$$
$$= 1.3\text{million crashes} \times \$162,400\text{per crash}$$
$$= \$215\text{billion}$$

where,

$M =$ upper bound estimate of crashes that could be prevented or made less severe by technologies (listed in column 2 of Table 3),

$SC =$ Social Cost of a Crash

Table 5 shows the upper bound benefit from equipping all light duty vehicles with FCW, LDW, and BSM. If each technology could prevent all crashes from their respective target crash populations, they would collectively provide an annual benefit of $215 billion. The most significant cost saving technology is FCW, which could provide an annual benefit of up to $129 billion or 60% of the total upper bound benefit. The large potential economic benefit from this technology can be attributed to the high number of rear-end collisions that occur annually. BSM and LDW systems could provide an upper bound annual benefit of about $43 and $42 billion, respectively. The upper bound benefit is representative of what may be achievable from an economic perspective as these technologies become more effective and widespread. It should be noted that the upper bound annual benefit does not consider less severe crashes since all relevant crashes are assumed to be prevented.

By using Bureau of Transportation Statistics (BTS) data of the number of light-duty vehicles in the US in 2012, the annual upper and lower bound per vehicle benefits of fleet-wide deployment can be estimated. BTS estimates that there were approximately 234 million registered highway vehicles in the US in 2012 (Bureau of Transportation Statistics, 2015). By dividing the number of light-duty vehicles by the total annual lower and upper bound benefits, we estimate a lower and upper bound per vehicle benefit of roughly $76 and $918, respectively.

4.2. Total annual costs

The total direct costs (TC) of fleet-wide crash avoidance technology deployment are the technology purchasing costs associated with purchasing a BSM, LDW, and FCW system for a bounded estimation where the entire light-duty vehicle fleet was equipped with these technologies, as shown in Eq. (3). This cost is annualized over the average lifetime of a vehicle in order to compare annual fleet-wide costs and benefits. Changes in car sales and travel lengths over time were not taken into account for this analysis. Most manufacturers offer the customer the option of adding a safety package onto higher model vehicles. When the three technologies were not a standard option, it is assumed for this analysis that the cost to add BSM, LDW, and FCW technologies to a vehicle is about $600, which is reflective of the current price drop in vehicle safety packages from Toyota (Lienert, 2015). If the same technology was available in 2012 the price would have been about $582. While most other manufacturers offer the same safety package for around $2100 we assume that they too will eventually decrease the price of their safety features in order to remain competitive. Since this paper evaluates the annual net benefit, the total unit technology cost was converted to an equivalent uniform annual cost (EUAC) by assuming a vehicle lifetime of 14 years and an average car loan interest rate of 4.46% (Andriotis, 2013; Ford, 2012; Tuttle, 2012). The total annual cost assumes that this equipment is placed on new vehicles and the cost to purchase the technologies is annualized over the lifetime of the vehicle. This would be the total annual cost to purchase the technologies if all of today's light-duty vehicles were replaced with new cars equipped with these three technologies. This resulted in an annualized cost of approximately $57 for each light-duty vehicle. The calculation of the total annual technology purchasing costs is based on the following formula:

total annual technology purchasing cost

$$= \mathrm{LDV} \times \mathrm{VT} \times [\mathrm{r}/1-(1+\mathrm{r})^{-\mathrm{n}}]$$

$$= 234\ \text{million vehicles} \times \$582\ \text{per vehicle} \times (4.46\%/1-(1+4.46\%)^{-14}$$

$$= 234\ \text{million vehicles} \times \$582\ \text{per vehicle} \times 0.098$$

$$= 234\ \text{million vehicles} \times \$57\ \text{per vehicle}$$

$$= \$13\ \text{billion in total costs to equip LDV fleet with these technologies} (\mathrm{TP_c})$$

where,

$LDV =$ total number of short base and long base light duty vehicles,

$VT =$ per vehicle technology purchasing cost,

$r =$ rate of return period,

$n =$ number of periods

According to the Bureau of Transportation Statistics, in 2012 there were approximately 234 million registered highway light-duty vehicles in the United States, which excludes motorcycles, buses, truck combinations, and single-unit trucks (Bureau of Transportation Statistics, 2015). The results above show that the total annual technology purchasing costs are about $13 billion.

4.3. Comparison of benefits and costs

In order to analyze the current economic feasibility, the annual net benefit (NB) was estimated from Eq. (1). The total annual benefits (TB) are the benefits that we would expect to accrue each year the vehicle is in operation from prevented and less severe crashes. The equivalent uniform annual costs (TC) are the total fleet-wide technology purchasing costs annualized over the lifetime of a vehicle. The annual net benefit is the difference between these two annual values.

It is shown in Fig. 3 that the current lower bound annual net benefit of fleet-wide deployment of crash avoidance technologies in light-duty vehicles is positive, which means that the benefits currently exceed the costs. In monetary value, the lower bound annual expected net benefit of equipping all light-duty vehicles with a BSM, LDW, and FCW system is about $4 billion. When we compare annualized per vehicle cost and lower bound per vehicle benefits, the annual lower bound per vehicle net benefit is approximately $20. The positive net benefit can be largely attributed to the low cost of the technologies. The lower bound annual net benefit is assumed to be the lowest net benefit achievable by these technologies since technology cost and performance are likely to improve, and additional benefits are likely as deployment increases.

Similarly to the lower bound annual net benefit, the upper bound annual net benefit is positive since the upper bound annual benefits far exceed current annualized technology costs. As shown in Fig. 4, the upper bound annual net benefit from all three technologies collectively at current technology prices, is about $202 billion or an $861 per vehicle net benefit. The upper bound annual net benefit is assumed to be the highest net benefit achievable, depending on the current price of the crash avoidance technologies.

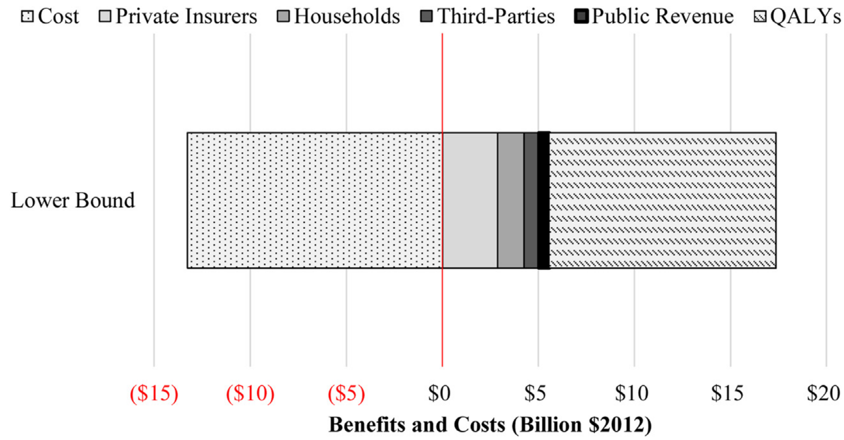

Fig. 3. Approximately $4 Billion Annual Lower Bound Net Benefit of Fleet-wide Deployment of Crash Avoidance Technologies in Light-Duty Vehicle Fleet.

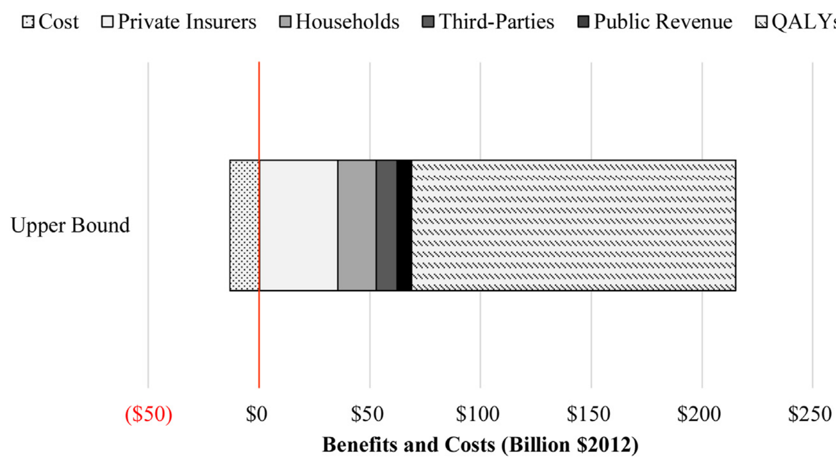

Fig. 4. Approximately $202 Billion Annual Upper Bound Net Benefit of Fleet-wide Deployment of Crash Avoidance Technologies in Light-Duty Vehicle Fleet.
Note: Upper bound annual net benefit represents an upper bound that is dependent on the current price of crash avoidance technologies.

4.4. Sensitivity analysis

The current annual net benefit shown above are based on a variety of assumptions, the most significant being the annualized technology purchasing cost and the effectiveness of each technology in reducing crash frequency and severity. Improvements in all three categories could result in a higher annual net benefit. As shown, it is economically feasible to equip the entire light-duty vehicle fleet with the three crash avoidance technologies examined in this paper. Higher annual net benefits can still be achieved either by lowering the cost of purchasing the technologies and/or making the technologies more effective in preventing and reducing the severity of crashes. In order to evaluate the impact other scenarios would have on the annual net benefit, two-way sensitivity analyses were conducted to examine how changes in the number of crashes prevented or a change in crash cost from less severe crashes along with the annualized technology cost per vehicle, would impact the annual net benefit.

Table 6 displays the sensitivity of the current annual net benefit to the annualized technology cost and the percentage of crashes prevented. A first prospective technology scenario, with conservative changes to the base case assumptions—annualized technology cost per vehicle of $40 and 10% reduction in crash frequency-would result in an annual net benefit of about $82 billion. A second prospective technology scenario with more aggressive changes to the base case assumptions-annualized technology cost per vehicle of $20 and 20% reduction in crash frequency-would result in an annual net benefit of about $178 billion.

At low cost savings from less severe crashes, the annual net benefit is positive at most technology costs. At much higher technology costs than those assumed for the base case analysis, the net benefit remains positive at high crash prevention cost savings, but is negative at lower cost savings. While there are a much larger number of crashes assumed to be less severe than prevented, less severe crashes have a smaller impact on the net benefit. The sensitivity of the annual net benefit to the annualized technology cost and cost savings from less severe crashes is shown in Table 7.

5. Discussion

In this paper a cost-benefit analysis of equipping the entire U.S. light-duty vehicle fleet with crash avoidance technologies is carried out based on the best available information about changes in collision insurance claim frequency and severity for vehicles with crash avoidance technologies. Insurance data was obtained from the HLDI and relevant crash data were from the 2012 FARS and GES datasets.

Approximately 24 percent of all crashes are relevant to one of the three crash avoidance technologies: blind spot monitoring, lane departure warning, and forward collision warning. All three technologies could collectively prevent or reduce the severity of as

Table 6
Annual Fleet-Wide Net Benefit from Changes in Crash Frequency and Technology Purchasing Costs (Billion $2012).

		Annualized Technology Cost per Vehicle ($2012)						
		$0	$20	$40	$60	$80	$100	$120
Percentage of Total 2012 Crashes Prevented	2%	$18	$13	$8	$3	-$1	-$6	-$11
	5%	$46	$41	$36	$32	$27	$22	$18
	10%	$91	$87	$82	$77	$73	$68	$63
	15%	$137	$132	$128	$123	$118	$114	$109
	20%	$182	$178	$173	$168	$164	$159	$154
	24%[a]	$215	$210	$206	$201	$196	$192	$187

Note: Areas shaded green indicate a positive annual net benefit whereas areas shaded yellow indicate a negative annual net benefit.
[a]Upper bound percentage of crashes that can be prevented, collectively by Lane Departure Warning, Forward Collision Warning, and Blind Spot Monitoring.

Table 7
Annual Fleet-Wide Net Benefit from Changes in Crash and Technology Purchasing Costs (Billion $2012).

		Annualized Technology Cost per Vehicle ($2012)						
		$0	$20	$40	$60	$80	$100	$120
Cost Savings from Less Severe Crashes for Each Technology (Thousand $2012)	$0	$18	$13	$8	$4	-$1	-$6	-$11
	$2	$20	$15	$10	$6	$1	-$4	-$8
	$4	$22	$18	$13	$8	$4	-$1	-$6
	$6	$25	$20	$15	$11	$6	$1	-$3
	$8	$27	$22	$18	$13	$8	$4	-$1
	$10	$29	$25	$20	$16	$11	$6	$1
	$12	$32	$27	$23	$18	$13	$9	$4
	$14	$34	$30	$25	$20	$16	$11	$6

Note: Areas shaded green indicate a positive annual net benefit whereas areas shaded yellow indicate a negative annual net benefit.

many as 1.3 million crashes a year including 133,000 injury crashes and 10,100 fatal crashes. FCW systems would address the greatest number of crashes overall and injury crashes, while a LDW could affect the largest number of fatal crashes.

In order to conduct a net benefit analysis to evaluate the economic feasibility of crash avoidance systems in light-duty vehicles, it was assumed crash frequency and crash cost mirrored changes in collision claim frequency and severity, respectively. If all three crash avoidance technologies were equipped on all light-duty vehicles, this would provide a lower bound annual benefit of about $18 billion with private insurers, households, and third-parties receiving annual benefits of about $2.9, $1.4, and $0.78 billion, respectively, from prevented and less severe crashes. Most of the benefit can be attributed to prevented crashes that accounts for almost 98% of the total benefit although a very small percentage of crashes are assumed to be prevented as opposed to less severe. With 2015 pricing for safety options, the total annual cost to purchase all three technologies for the entire light-duty vehicle fleet would be about $13 billion-resulting in an annual lower bound net benefit of approximately $4 billion or a $20 per vehicle net benefit. The technologies we explore in this paper represent an early form of vehicle automation and a positive net benefit suggests the fleet-wide adoption of these technologies would be beneficial from an economic and social perspective. Since the annual cost to purchase the crash avoidance technologies would come from household expenditures, all benefits to private insurers, third-parties, and public revenue sources should be realized when only considering technology purchasing costs.

If all three technologies could prevent all crashes in their respective target crash populations this would provide an upper bound annual benefit of about $215 billion. Of the three crash avoidance technologies examined in this paper, FCW could provide the greatest annual benefit. This technology could provide an upper bound annual benefit of up to $129 billion or a per vehicle benefit of up to $551, due to the relatively large number of crashes this technology addresses. At 2015 technology costs, the upper bound annual net benefit is approximately $202 billion or an $816 per vehicle net benefit. According to the GES and FARS datasets, in 2012 collectively there were about 5000 and 125,000 pedestrian and pedalcyclist fatalities and injuries, respectively, from crashes involving motor vehicles. While these crashes were not considered for this analysis, FCW could have considerable additional benefits by potentially reducing the frequency and severity of these crashes, resulting in higher economic benefits, which further supports the case that these technologies would provide a benefit if equipped on all vehicles.

The crash avoidance technologies examined in this paper are fairly new and have only recently begun to appear in non-luxury cars. The HLDI estimates that in 2013 the three crash avoidance technologies examined in this paper each came standard on about 2% of new car models. As a result, this is only a preliminary cost analysis as we expect the technologies to improve, costs decline, and diffusion increase—resulting in potentially higher changes in collision claim frequency and severity. In addition, some of the system limitations assumed for the current technologies in this analysis may not exist in the future and as result these technologies could become more effective in circumstances such as inclement weather, which would increase the number of relevant accidents, ultimately providing a larger benefit. As autonomous technology diffuses and starts to improve safety, there is the potential risk of an enhanced immunity fallacy (Will, 2005; Will and Geller, 2004), where occupants perceive a false sense of immunity from risk for injury in crashes. This could result in reduced use of seat belts or child restraints, which is not commensurate with the reduced risks. In the transition to partial vehicle automation, regulators should take best practices from the risk perception literature and should build upon previous efforts (Will, 2005) to enhance risk communication.

While the results from this net benefit analysis offer a new understanding of the economic benefits and costs of equipping the entire light-duty vehicle fleet with three crash avoidance technologies, there are several opportunities for improvement. Rather than calculating benefits for crash prevention solely on a per crash basis, future cost analyses should take crash severity in account. Changes to market penetration rates and VMT could also be incorporated, to reflect the influence that consumer demand and VMT could have on the net benefit. Different system efficacies could be taken into account in order to better model a real transportation system where crash avoidance technologies do not work perfectly and could be potentially disabled by the user of the vehicle.

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