Estimating the Effects of Vehicle Automation and Vehicle Weight and Size on Crash Frequency and Severity: Phase 1

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16. Abstract

Most light-duty vehicle (LDV) crashes occur due to human error. The National Highway Safety Administration (NHTSA) reports that eight percent of fatal crashes in 2018 were distraction-affected crashes, while close to ninety-four percent of all crashes occur in part due to human error. Crash avoidance features could reduce both the frequency and severity of light and heavy-duty vehicle crashes, primarily caused by distracted driving behaviors and/or human error by assisting in maintaining control 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. Additionally, the market penetration of electric vehicles (EVs) is increasing, in turn increasing the weight and size of vehicles on the road. This project develops a replicable, open, deployable model that can: 1) estimate the upper-bound crash avoidance potential that could be achieved as the effectiveness of warning and partial automation systems improve and adoption increases, 2) estimate the societal costs and benefits of fleet-wide deployment of crash avoidance technologies considering technology costs and benefits from avoided and less severe crashes, 3) estimate the number of lives that have been saved by forward collision warning, lane departure warning, and blind spot monitoring, and 4) estimate the effects of vehicle weight and size on crash frequency and severity.

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Problem Statement

Most light-duty vehicle (LDV) crashes occur due to human error. The National Highway Safety Administration (NHTSA) reports that 8.7 percent of fatal crashes in 2019 were distraction-affected crashes, while close to ninety-four percent of all crashes occur in part due to human error [1], [2]. Crash avoidance technologies could reduce both the frequency and severity of light and heavy-duty vehicle crashes, primarily caused by distracted driving and/or human errors by assisting in maintaining control or issuing timely alerts when a potentially dangerous situation is detected.

This study estimates annual net-societal and net-private benefits of fleet-wide deployment of BSM, LDW, FCW, and AEB within the U.S. light-duty vehicle fleet. Societal benefits are estimated from observed reductions in crash frequency and severity for vehicles equipped with warning devices coupled with NHTSA estimates of crash costs. Private benefits are the fraction of these societal benefits received by vehicle owners. Costs are the annualized costs of equipping vehicles with these devices. The number of lives saved are estimated using observed changes in crash frequency, along with an estimate of the number of average fatalities per vehicle involved in crash.

Data

The primary sources of data used in this paper are: 1) reports from Highway Loss Data Institute (HLDI), which estimate the changes in crash frequency and severity for crash avoidance features by make and model; 2) 2019 Crash Report Sampling System (CRSS), which provides information on crashes of all severities, and 3) 2019 Fatality Analysis Reporting System (FARS), which provides information on police-report fatal crashes. In order to estimate the total societal benefits of fleet-wide deployment of warning systems only (i.e., FCW, LDW, and BSM) and AEB in addition to the warning systems, the estimates of frequency/severity changes from HLDI insurance data were used as the effectiveness of these features. CRSS and FARS crash databases were used to identify populations of relevant types of crashes that could potentially be prevented by each crash avoidance feature to estimate an upper bound of cost savings from fleet-wide deployment of these features.

BSM systems incorporate camera or sensor-based technology to notify drivers of vehicles entering their blind spot, an area outside the driver's direct line of sight. A lane-change crash is defined as an incident where two vehicles initially travel parallelly in the same direction, and the encroachment of one vehicle into the travel lane of another is the primary cause. It's essential to note that crashes involving loss of control, cases where it is unclear whether vehicles are traveling in the same or opposite direction, or instances where two vehicles initially share the same lane, are excluded from the analysis for clarity and precision. The method used to identify lane-change crashes is adopted from Sen et al., [3].

Lane Departure Warning (LDW) systems actively monitor a vehicle's alignment within its travel lane and issue warnings to the driver in the presence of imminent or actual lane departure. A lane departure crash is defined as one where a vehicle unintentionally veers out of its designated travel lane, with the driver not actively maneuvering the vehicle beyond the general intent of lane-keeping. The criteria for identifying lane departure crashes is adopted from Gordon et al., [4].

FCW provides visual, audible, and/or tactile alerts to warn a driver of an impending collision with a car or an object directly in its forward path. The target crash population includes single vehicle front-end collisions with pedestrians, animals, and/or bicyclists, as well as rear-end collisions involving two vehicles. The criteria for identifying front-end collision is adopted from Khan et al., [5].

AEB is an advanced driver-assistance system that employs sensors, cameras, or radar to detect impending collisions with obstacles, vehicles, or pedestrians and, if necessary, autonomously intervene to apply the brakes. Since AEB is meant to address front-end collision crashes, we assume the target crash population for AEB and FCW are the same.

Methodology

Effectiveness of Crash Avoidance Systems in Reducing Crash Frequency and Crash Cost

The authors gathered changes in collision claim frequencies and collision claim severity from insurance data published by HLDI for major automakers between 2017 and 2019 [6], [7], [8], [9], [10], [11], [12], [13], [14], [15].

Two major assumptions are made to estimate the costs and benefits of fleet-wide deployment. First, we assumed that a change (positive or negative) in collision claim frequency is the equivalent change in crash frequency for single and multiple-vehicle crashes. While not all crashes are reported to insurance companies and collision claim frequency does not perfectly reflect crash frequency, there is a relationship between the two statistics. Second, we assume that a change in collision claim severity is the equivalent change in crash cost, whether positive or negative, for crashes that are not prevented.

For each type of technology HLDI provides the exposure, measured in insured vehicle years for each make and model. To estimate changes in collision frequency and severity, the authors estimated a weighted average based on the total vehicle exposure. Table 1 summarizes the change in collision frequency and severity, and the total exposure from the insurance data collected. Table 5 shows the weighted average results of collision frequency and severity changes for each crash avoidance feature based on the vehicle exposure.

TABLE 1 Details of Collision Claim Frequency, Severity, and Exposure by Car Make and Model

Technology	Manufacturer/ Series	Additional technologies [a]	Change in Collision Frequency	Change in Collision Severity	Collision Exposure (thousands of insured vehicle years)
Blind Spot Monitoring	Acura (TLX)	FCW, LDW	-0.23%	$376	81.4
	Acura (MLX, RL, ZDX)		1%	$636	100
	Audi		-3%	$111	1,502
	Mercedes-Benz		-1.4%	-$138	74.6

	BMW		-0.9%	-$203	832
	General Motor		0.5%	-$68	926
	Subaru		2.4%	$0	305
	Mazda		-3.5%	$118	2,975
Forward Collision Warning	Acura (TLX)	BSM, LDW	-0.23%	$376	81.4
	Audi		-3%	$315	38.5
	Mercedes-Benz		-2.6%	$779	110
	BMW	LDW	1.05%	$439	594
	General Motor	LDW	-2.05%	-$114	814
	Honda (Odyssey)	LDW	-0.8%	-$76	294
Lane Departure Warning	Acura (TLX)	BSM, FCW	-0.23%	$376	81.4
	Mercedes-Benz		6.4%	$197	43.4
	BMW	FCW	1.05%	$439	594
	General Motor	FCW	-2.05%	-$114	814
	Honda (Odyssey)	FCW	-0.8%	-$76	294
	Mazda		-5.6%	$33	181
AEB + FCW	Audi		-5.30%	-$131	154
	Acura		-4.60%	$92	121
	Mercedes-Benz		-7.20%	$629	124

[a] Additional technologies refer to technologies that are coupled together and estimates in collision claim frequency and severity cannot be separately distinguished.
Source: Collection of Collision Avoidance Features Reports published for Mercedes-Benz, BMW, Acura, Audi, General Motor, Honda, Mazda, and Subaru. [6], [7], [8], [9], [10], [11], [12], [13], [14], [15].

Cost-benefit Analysis

The total costs of equipping all light-duty vehicles with crash avoidance systems () consider the purchasing costs of each technology annualized over the average lifespan of a vehicle to enable the assessment of yearly fleet-wide costs and benefits.

(1)

where is the total number of registered light duty vehicles, is the average technology purchasing costs for each vehicle. is the average vehicle loan interest rate and is the average vehicle lifespan.

Total annual societal benefits (SB) are the sum of the cost savings from changes in crash frequency and costs from the fleet-wide deployment of crash avoidance systems and is expressed as follows,

(2)

where is the cost savings from avoided crashes, and is the cost savings from changes in crash cost.

Societal benefits can also be divided into public and private benefits:

(3)

where is the share of societal benefits to private individuals (i.e., vehicle owners), and is the share of societal benefits reaped by the public.

Cost savings from crash prevention () is estimated as follows,

(4)

where is the total number of crashes, is the aggregated change in collision claim frequency, is the societal cost of a single crash.

Cost savings from crashes severity change () is the sum of severity change of crashes not prevented, which is estimated as follows:

(5)

where is the average change in collision claim severity.

The authors estimate an upper bound of cost savings () assuming a full deployment of crash avoidance features with 100% crash reduction rates. Therefore, the upper bound is the total costs savings from the preventions of all the relevant crashes, which can be estimated as follows:

(6)

where M is the upper bound estimate of the number of crashes that could be prevented by the three crash avoidance technologies, and is the average societal cost of each crash. Note that M is estimated from the total number of relevant crashes instead of the observed data from HLDI.

The annual net-societal benefit , which is the difference between the societal benefits () and total costs () can be derived as follows:

(7)

The annual net-private benefits can be estimated by the difference between the private benefits () and the total costs () as follows:

(8)

Number of Lives Saved

The total number of lives saved is based on the existence of crash avoidance features in all the vehicles involved in crashes in 2019. The formula used to estimate the number of lives saved annually (LS) from different combinations of crash avoidance technologies is as follows:

(9)

where is the total number of vehicles involved in crashes in 2019 with at least one standard crash avoidance features, is the change in collision claim frequency summarized from Table 5, and is the expected number of fatalities per vehicle per crash.

Here, estimates the number of crashes that were prevented due to the reduction in collision claim frequency.

Results and Recommendations

Total Annual Costs of Crash Avoidance Systems

For the cost benefit analysis, we considered two scenarios. One scenario is fleet-wide deployment of warning features only (i.e., FCW, LDW, and BSM), another scenario is fleet-wide deployment of all warning features plus AEB. NHTSA [16] estimated the consumer costs that the purchaser of a new vehicle will pay to have various sensors equipped on a light-duty vehicle. This estimate is how much the retail price of a car will increase to cover the cost to the manufacturer, plus a manufacturer profit and a dealer profit for selling the vehicle. The authors used the median estimate cost of installing various sensors into vehicles (i.e., radar backup sensors and camera system) and converted this value to 2019 dollars, which results in a total of $503 on a per vehicle basis. This value is consistent with numerous reports regarding the crash avoidance systems costs (27). For the additional cost in technology package that includes AEB in addition to the warning systems, we add the incremental cost of $82.15 per vehicle on top of the costs of the warning systems [18]. We converted this value to 2019 dollars for the annual cost estimation.

We assumed the average vehicle lifespan is 11.8 years [19] and the average vehicle loan interest rate is 4.69% [20]. As of 2019, the total number of registered light-duty vehicles in the national fleet was 254 million (253,814,184) [21]. The costs to purchase these technologies will be distributed over the lifetime of the vehicle. The total cost can be derived as follows,

where and are the total technology purchasing costs for the packages of features, is the total number of registered light duty vehicles, and are the average technology purchasing costs for each vehicle. is the average vehicle loan interest rate and is the average vehicle lifespan.

Total Annual Societal Benefits

As shown in Table 2, BSM has the greatest collision frequency reduction of the warning systems. BSM reduces collision claim frequency by 2.13% but increases collision severity by about $54. LDW would reduce collision frequency by 1.01% and is associated with a $95 increase in claim severity. FCW has the lowest reduction in crash frequency and the largest increase in crash costs of the warning systems. Specifically, FCW could reduce collision claim frequency by 0.88% and increase collision claim severity cost by $142. The combination of these warning features would lower collision claim frequency by 4.03% but increase average crash costs by $292. Compared to the results of Khan et al., [5] the aggregate effectiveness of the warning systems in preventing crashes has improved but the overall change in crash costs is higher. When AEB is coupled with FCW, collision claim frequency improves to 5.68% but this package is also associated with a higher collision severity change of $172, which makes sense as the automation system equips additional sensors and components to the vehicles that may need to be replaced when a crash occurs. The systems with automatic features have a collision frequency change of -8.82%, with $321 increase claim severity.

TABLE 2 Observed Changes in Crash Frequency, Cost Severity ($2019), and Collision Exposure by Crash Avoidance Technology from Actual Insurance Reports (2017 – 2019)

Crash Avoidance Technology	Change in Collision Frequency [a]	Change in Collision Severity [a]	Collision Exposure (millions of insured vehicle years)
Blind Spot Monitoring	-2.13%	$54	6.80
Forward Collision Warning	-0.88%	$142	1.93
Lane Departure Warning	-1.01%	$95	2.01
FCW+AEB	-5.68%	$172	0.40
Sum (Warning Features Only)	**-4.03%**	**$292**	**N/A**
Sum (Warning and Automatic Features)	**-8.82%**	**$321**	**N/A**

[a] Weighted average based on vehicle exposure.
Source: Collection of Collision Avoidance Features Reports published for Mercedes-Benz, BMW, Acura, Audi, General Motor, Honda, Mazda, and Subaru. [6], [7], [8], [9], [10], [11], [12], [13], [14], [15].

In a detailed study of societal and economic costs of motor vehicle crashes in 2019, the aggregate amount equates to $1,370 billion, out of which $1,030 billion is attributed to the loss of life and decreased quality of living while the remaining $340 billion are economic costs [22]. From the total number of crashes in 2019, the authors estimate each crash costing approximately $164,000, with $123,000 for quality-adjusted life-years (QALYs) and $41,000 in economic costs. The direct measure of benefits from crash avoidance technologies is the cost saved from crash prevention and changes in severity of crashes. The estimation of cost savings from crash prevention is based on the following formula:

where and are the cost savings from crash prevention due to the fleet-wide deployment of warning systems only and AEB in addition to the warning systems, respectively, is the total number of crashes in 2019, and are the change in collision claim frequency for vehicles equipped with warning systems only and AEB in addition to the warning systems, respectively, is the societal cost of a single crash.

With fleet-wide deployment of crash avoidance technologies, it is assumed that all crashes not prevented will have a change in average severity. Our results in Table 5 show that the average claim amount per vehicle has increased by $292. The cost savings arising from changes in crash severity are estimated as follows:

where and are the cost savings from less severe crashes due to the fleet-wide deployment of warning systems only and AEB in addition to the warning systems, respectively, and are the change in collision claim frequency for vehicles equipped with warning systems only and AEB in addition to the warning systems, respectively. and are the average severity changes for vehicles equipped with warning systems only and AEB in addition to the warning systems, respectively.

Subsequently, the estimation of the total annual societal benefits is:

where and are the societal benefits of fleet-wide deployment of warning systems and AEB in addition to the warning systems, respectively.

Due to the difference in collision frequency change, automatic systems with AEB have a much higher total societal benefits compared to warning systems only. In both cases although the increase in the amount of claim severity added additional costs, the primary contributor to the societal benefits are the cost savings from crash preventions.

Number of Lives Saved Estimation

A major benefit of crash avoidance systems is saved lives. Based on the effectiveness estimation of these crash avoidance systems, the authors estimated how many people would have died if the vehicles had not been equipped with any of the safety technologies. The Vehicle Identification Number (VIN) for each vehicle recorded in CRSS/FARS, was used to identify whether the vehicle involved in crashes was equipped with crash avoidance technology. Only vehicles that had these technologies described as "standard" were assumed to have the technology. Vehicles where the feature was listed as "optional" were assumed not to have the feature. Therefore, this value of lives saved is a lower bound estimation. In Table 3, we have 12 different combinations of features possible in vehicles and the number of crashes avoided and lives saved from crash avoidance technologies. Only less than 5% of the vehicles involved in a crash have one or more crash avoidance technology. Note that in Table 7 we count the number of vehicles involved in crashes instead of the number of crashes. If the crash recorded in CRSS or FARS involves two vehicles, it will be counted as two separate data, each represents a vehicle with the corresponding technology combination.

In 2019, the average number of fatalities per vehicle involved in crash is 0.0030. Using equation (9) it is estimated that a total of 111 lives were saved by the presence of crash avoidance technology in a vehicle, out of which 90% of lives saved are saved by vehicles equipped with automatic braking systems. The effectiveness of packages including AEB is 6%-10% which is substantially higher than warning-only systems. Among all the vehicles involved in crashes, FCW+LDW+AEB is the most popular crash avoidance package, accounting for 35% of the cases. Overall, this estimate of live saved from crash avoidance systems is based on current market penetration of these technologies, which is relatively low. As market penetration increases and technology efficacy improves, the number of lives saved should be greater in the future.

TABLE 3 Life Saved Estimation of Each Category of Vehicles

Technology Combinations	Number of vehicles involved in non-fatal	Number of vehicles involve	Total number of vehicles involved	Percentage of vehicles involved in crashes for	Crash prevention effectiveness of each	Estimate of Crashes Avoided	Estimate of Lives Saved

	crashes	d in fatal crashes	in crashes	each technology combination	technology combination		
BSM	102,454	326	102,780	0.86%	2.18%	2,291	7
FCW	13,879	83	13,962	0.12%	0.89%	125	0
LDW	1,903	3	1,906	0.02%	1.02%	20	0
BSM+ FCW	7,264	31	7,295	0.06%	3.10%	233	1
BSM+ LDW	10,494	41	10,535	0.09%	3.24%	353	1
FCW+ LDW	11,342	125	11,467	0.10%	1.93%	226	1
BSM+FCW+ LDW	5,172	99	5,271	0.04%	4.20%	231	1
FCW+ AEB	34,868	90	34,958	0.29%	6.02%	2,239	7
FCW+ AEB+BSM	19,759	45	19,804	0.16%	8.47%	1,833	6
FCW+ AEB+LDW	188,515	410	188,925	1.57%	7.17%	14,592	44
BSM+FCW+ LDW+AEB	138,827	324	139,151	1.16%	9.67%	14,896	45
Total	534,477	1,577	536,054	4.46%	N/A	37,039	111

Discussion

This study evaluates both the net-societal and net-private benefits associated with equipping all light-duty vehicles with advanced crash avoidance technologies, drawing on the most reliable insurance information available. In 2019, around 29% of crashes were associated with one of the three technologies: BSM, LDW, or FCW. With fleet-wide deployment, it is projected that nearly 2 million police-reported crashes annually could be either prevented or mitigated, including 4,711 fatal crashes. Among the three technologies, LDW could address the largest number of fatal crashes, while the FCW system could address the greatest number of crashes overall.

To estimate net-societal benefits, it is assumed that changes in collision claim frequency and severity reflect corresponding changes in real-world crash frequency and costs. If FCW, BSM and LDW were universally equipped on all light-duty vehicles, this would provide an annual benefit of approximately $42.8 billion dollars. With AEB plus the three warning systems, the annual benefit could increase to $95.8 billion dollars. Despite observing increases in the average crash costs for vehicles equipped with these technologies, the marginal rise does not offset the annual benefits derived from prevented crashes. Using an annualized costing method, the total cost of equipping all vehicles with FCW, BSM and LDW is $14.3 billion dollars. With AEB in addition to the warning systems, this number would increase to $16.6 billion dollars. These purchasing costs are low compared to the cost savings from collision frequency reductions.

The authors estimated the lives saved from crash avoidance systems in 2019 based on the crash frequency change and average number of fatalities. A total of 111 lives were estimated to be saved due to crash avoidance technologies preventing crashes. According to the crash frequency changes from the HLDI reports, FCW itself would provide subtle effects in preventing crashes, however, the effectiveness of AEB+FCW is more double that of FCW alone. It is estimated that about 37,000 vehicles could have been involved in crashes that were prevented, with AEB presence in more than 90% of the cases. While the findings indicate that crash avoidance systems are effective in reducing crash frequency, less than 5% of vehicles involved in crashes were equipped with at least one of these technologies examined in this study. Among all the vehicles involved in crashes that were equipped with at least one crash avoidance technology, the combination of FCW+ LDW+ AEB and FCW+ LDW+ BSM+AEB are the most prevalent, accounting for 35% and 26% of the total, respectively. The third most prevalent technology in vehicles involved in crashes is BSM only, representing 19% of the total. Given the higher effectiveness of BSM (2.18%) compared to the other two warning technologies LDW (1.02%) and FCW (0.89%) and higher market penetration rate, BSM alone is estimated to have saved 12 lives and prevented more than 2,000 crashes in 2019.

The results of this paper offer an understanding of the net-benefits of and number of lives saved by crash avoidance technologies, and shows the substantial opportunities for both private and public benefits as well as lives saved from a fleet wide deployment of crash avoidance technologies.

Future Work

Remaining tasks from this project include estimating the effects of vehicle weight and size on crash frequency and severity, which will be completed with our Year 2 project.

Project Outputs

- In August 2023, project PI Corey Harper presented a paper at the Bridging Transportation Researchers Conference titled “What Stay-at-home Orders Reveal about Dependence on Transportation Network Companies.”
- In October 2023, project PI Corey Harper published a paper in *Transportation* titled “What Stay-at-home Orders Reveal about Dependence on Transportation Network Companies.”
- In October 2023, project PI Corey Harper presented a seminar titled “Advancing Towards a Smarter and More Sustainable Transportation System” at UT Austin.
- In November 2023, project PI Corey Harper presented a Safety21 Smart Safety Connection seminar titled “Advancing Towards a Smarter and More Sustainable Transportation System.”
- In November 2023, project PI Corey Harper participated in the Safety21 Deployment Partner Consortium Symposium.
- In January 2024, project PI Corey Harper presented a paper at the Transportation Research Board 103rd Annual Meeting titled “Congestion and Environmental Impacts of Short Car Trip Replacement with Micromobility Modes.”
- In January 2024, project PI Corey Harper presented a paper at the Transportation Research Board 103rd Annual Meeting titled “Exploring How Fleet Size and Pricing Policy in Shared Autonomous Vehicle Systems Affect Travel Efficiency, Equity, and Profitability.”
- In January 2024, project PI Corey Harper participated in Intersection of Energy and Transportation Panel: Scott Energy Institute panel.

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