TITLE: EVALUATION OF AUTOMATIC EMERGENCY BRAKING IN HELPING PREVENT FRONT-TO-REAR CRASHES AMONG TOYOTA MODELS

Rebecca Spicer
Amin Vahabaghaie
George Bahouth
Impact Research, LLC
United States

Paper Number 19-0146

ABSTRACT

This study estimated the effectiveness of Toyota Safety Sense (TSS) in helping prevent front-to-rear collisions among three Toyota models (Avalon, Prius, RAV4). TSS, offered as an option in model year 2016 vehicles, includes a pre-collision warning system with automatic emergency braking (AEB), in addition to lane departure alert and automatic high beam. This study addresses the hypothesis that TSS-equipped vehicles will be less likely to experience a front-to-rear crash (as the striking vehicle) compared to those not equipped with TSS.

Using Toyota-supplied production data linked to police reported crash data from 5 US states (Florida, Louisiana, Michigan, Pennsylvania, Texas) for crash years 2014-2016, the study compared crash rates (crashes per 10,000 vehicle months) of TSS equipped (n= 23,394) versus non-equipped (n= 294,931) vehicles. TSS equipment present per vehicle was identified based on VIN. This study evaluated the impact on front-to-rear crashes where the Toyota was the striking vehicle.

Exposure, using vehicle-months, was computed based on aggregate vehicle sales in the five study states for TSS equipped and non-equipped model year 2014 to 2016 vehicles. The crude rate ratio (CRR) of front-to-rear crash rates where the Toyota was the striking vehicle was calculated as the front-to-rear crash rate for TSS-equipped vehicles divided by the crash rate for non-equipped vehicles.

Given that TSS is optional, it is possible that customers who choose to purchase these safety systems also exhibit different driving and risk-taking behaviors compared to those who do not purchase the safety systems. To address a possible selection bias, sensitivity analysis examined the control outcome of front-end damage in a multi-vehicle crash, excluding the types of crashes targeted by AEB (front-to-rear).

Of the TSS-equipped vehicles, 2.46 per 10,000 vehicle-months (95%CI:1.75-3.17 per 10,000 vehicle-months) experienced a front-to-rear crash as the striking vehicle, compared to 4.55 per 10,000 vehicle-months (95%CI:4.37-4.73 per 10,000 vehicle-months) of the non-equipped vehicles. Therefore, study Toyotas equipped with TSS were 46% less likely to experience a front-to-rear crash as the striking vehicle compared to non-equipped (CRR=0.54; 95%CI:0.40-0.67).

The study found that when the outcome was broadened to include all vehicles with front-end damage in multi-vehicle crashes, TSS-equipped vehicles experienced 17% fewer crashes than non-equipped vehicles (CRR=0.83; 95%CI:0.71-0.94) . However, no significant difference was observed if front-to-rear crashes were excluded (CRR=1.02; 95%CI:0.86-1.16) suggesting that selection bias did not play a significant role in this study.

The TSS option was only available in model year 2016 vehicles, limiting the sample size and follow-up time of TSS-equipped vehicles. Future research that includes additional state data, models and model years, will increase sample sizes and may allow for estimates by model and other crash types.

In conclusion, vehicles equipped with TSS, were nearly half as likely to be the striking vehicle in a front-to-rear crash compared to non-equipped vehicles. This study contributes to the growing evidence of the effectiveness of AEB in helping prevent a significant number of front-to-rear crashes.

INTRODUCTION

The National Motor Vehicle Crash Causation Survey, administered by the National Highway Traffic Safety Administration found that driver error was the critical reason for 94% of crashes [1]. These errors included recognition error (e.g. driver inattention and inadequate surveillance), decision error (e.g. driving too fast for conditions, misjudgment of gap or other's speed), and performance (e.g. overcompensation, poor directional control) and non-performance (e.g. falling asleep) errors.

Advanced Driver Assistance Systems (ADAS) are in-vehicle technologies developed to counteract these driver errors and help prevent crashes or mitigate the severity if a crash occurs. These systems provide drivers timely warnings and some will actively and automatically intervene to help avoid hazardous situations. Examples of ADAS technologies include lane departure warning and active lane keep assistance, blind spot detection, forward collision warning and automatic emergency braking (AEB). In vehicles with pre-collision warning and AEB, the driver is alerted if the speed of the equipped vehicle and the vehicle ahead and the distance from the vehicle or object ahead indicate that a collision is possible. AEB will finally apply the brakes if the system predicts a high probability of a crash to help prevent the collision regardless of driver response.

Many manufacturers offer these technologies as options or standard on some their vehicles. ADAS technologies are the precursor to autonomous vehicles and, depending on the combination of ADAS equipment installed in a vehicle, can allow level 1 through level 3 autonomous driving at the present time [2].

While controlled track and simulated testing of ADAS technologies suggest that they will greatly impact crash involvement rates, real world evidence that characterizes their effectiveness is still limited. Previous evaluations of AEB and other ADAS have found reductions in both injury-involved and, to a lesser extent, all-severity (injury and non-injury) crashes. An evaluation of police-reported crashes in the United States found that vehicles equipped with AEB experienced a 42% reduction in injury front-to-rear crashes and a 39% reduction in all-severity front-to-rear crashes compared to non-equipped vehicles [3]. A meta-analysis of pooled data from multiple countries determined that AEB was associated with a 38% reduction in real-world rear-end crashes [4].

In Toyota vehicles the Toyota Safety Sense (TSS) package includes a pre-collision warning system with AEB, in addition to lane departure alert and automatic high beam. TSS was first offered as an option in some model year 2016 vehicles and standard in most model year 2017 Toyota and Lexus passenger vehicles. Toyota is the frontrunner among manufacturers in the number of model year 2017 vehicles equipped with AEB: 1.4 million vehicles, 56% of its model year 2017 fleet [5].

This study evaluates the effectiveness of TSS among three Toyota models (Avalon, Prius, RAV4) in helping prevent the types of collisions AEB is designed to address: striking another vehicle in a front-to-rear collision. This study hypothesizes that vehicles equipped with AEB will be less likely to be involved in a front-to-rear crash as the striking vehicle compared to non-equipped vehicles.

METHODS

This retrospective cohort study of three Toyota models (Avalon, Prius, RAV4), model years 2014-2016, compares rates in vehicles with TSS versus without TSS in order to estimate the effectiveness of TSS in helping prevent front-to-rear crashes.

Toyota production data was used to compute the aggregate number of vehicles sold in the five study states by model, model year and TSS equipped/non-equipped. Some model year 2014 and 2015 vehicles are equipped with a previous version of the Pre-Collision System. These are not included in the comparison between TSS-equipped vehicles and non-equipped vehicles. Exposure was computed in vehicle-months: the number of vehicles sold multiplied by the estimated number of months on the road. We assumed an average seven months of exposure for the first year of a model year platform; e.g. Model year 2014 vehicles had an average seven months exposure during calendar year 2014.

The study used state police crash reports from five states (Florida, Louisiana, Michigan, Pennsylvania, Texas) for crash years 2014-2016. Vehicles in these five states make up an estimated 23% of U.S. vehicle miles travelled.

The TSS options data were linked at the individual VIN level to the five state police crash report data files, identifying which crashed vehicles were TSS-equipped and which were not. The state police reported crash data included information on the crash type (e.g. front-to-rear, side swipe, angle, etc.) and the location of vehicle damage per vehicle involved.

The outcome evaluated in this study was the subset of crashes targeted by AEB: front-to-rear crashes where the Toyota was the striking vehicle. Using the state police reported crash files, a striking vehicle in a front to rear crash was identified as a vehicle involved in a front-to-rear collision where the Toyota was coded with front-end damage (the striking vehicle) and at least one other vehicle was coded with rear-end damage (the struck vehicle). Figure 1 describes the process. Of all Toyota vehicles involved in a crash ([1] in Figure 1), those involved in multi-vehicle crashes ([2] in Figure 1) were identified. Of the vehicles involved in multi-vehicle crashes, those that experienced front-end damage where identified ([3] in Figure 1). Of these, those involved in a front-to-rear crash ([4] in Figure 1) were defined as the striking vehicle in a front-to-rear crash. Crashes where the Toyota was first involved in a front-to-rear crash as the struck vehicle (rear damage) and subsequently struck a second vehicle from the rear as the striking vehicle were excluded from the evaluation.

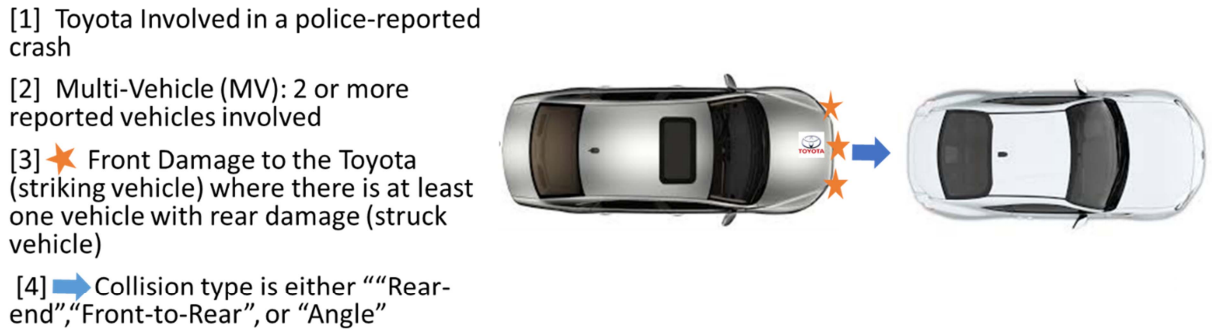

Figure 1. Process for Identifying Crash-Involved Toyotas where Toyota is the Striking Vehicle in a Front-to-Rear Crash

The rate of vehicle involvement in a front-to-rear crash as the striking vehicle was computed as the total number of crashes divided by the total number of vehicle months. Crash rates were computed separately for TSS-equipped and non-equipped vehicles. The state data are a census of police-reported crashes and therefore not subjected to sampling variability. However, to account for random variation, confidence intervals were computed based on the method described by Arias and Smith, 2003 [6].

The crude rate ratio (CRR) for TSS-equipped versus non-equipped vehicles was calculated as the front-to-rear striking vehicle crash rate for TSS-equipped vehicles divided by the crash rate for non-equipped vehicles. Crude rate ratios are interpreted to describe the percent reduction in front-to-rear crashes associated with TSS.

Given that TSS was optional, it is possible that customers who choose to purchase these safety systems also exhibit different driving and risk-taking behaviors compared to those who don't purchase the safety systems. To address a possible selection bias, sensitivity analysis examined two additional outcomes: the broad outcome of front-end damage in a multi-vehicle crash and the subset of these crashes excluding the types of crashes targeted by AEB (front-to-rear where Toyota is the striking vehicle). This control analysis tests the hypothesis that differences in crash rates for TSS (thus, AEB)-equipped vehicles are only observed in front-to-rear crashes.

RESULTS

A combined total 318,325 Toyota Avalon, Prius and RAV4 vehicles, model year 2014-2016, were sold in the five study states. Of these, 23,394 (29%) of the model year 2016 vehicles (the first year TSS was offered as an option) were equipped with TSS (Table 1). Take-rates in model year 2016 vehicles varied; 24% for the Avalon, 28% for the RAV4 and 38% for the Prius.

Table 1
Number of Toyotas Sold in the Study States, by Model Year and TSS Option

Model Year	Without TSS	With TSS	Total
2014	86,401	-	86,401
2015	127,310	-	127,310
2016	81,220	23,394	104,614
Three Model Total	294,931	23,394	318,325

The five state police reported crash files from years 2014-2016 captured 18,454 vehicles involved in crashes among the study cohort of 318,325 vehicles ([1] in Table 2). Of these, 17,402 were vehicles involved in multi-vehicle crashes ([2] in Table 2). Of the vehicles involved in multi-vehicle crashes, 6,076 experienced front-end damage ([3] in Table 2). Of these, 2,749 were involved in a front-to-rear crash ([4] in Table 2), i.e. the striking vehicle in a front-to-rear crash. This outcome was evaluated in this study. Table 2 further presents the number of crashes by state.

Table 2
Number of Crash-Involved Toyotas among the Vehicles Sold in the Study States, by Crash Population and Crash State

Crash Population	Total 5 States	FL	LA	MI	PA	TX
[1] All Crash-Involved Toyotas	18,454	9,534	1,296	1,355	1,116	5,153
[2] Toyotas involved in a Multi-Vehicle (MV) crash	17,402	9,168	1,255	1,130	937	4,912
[3] Toyotas involved in a MV crash with Front-end damage	6,076	3,069	442	472	417	1,676
[4] Outcome Evaluated: Toyota involved in a MV front-to-rear crash with front-end damage (striking vehicle)	**2,749**	**1,282**	**164**	**199**	**155**	**949**

Among the study cohort of 318,325 vehicles, 2,617 (0.82%) were involved in a front-to-rear crash as the striking vehicle. Of the TSS-equipped vehicles, 46 (0.20%) experienced a front-to-rear crash as the striking vehicle, compared to 2,571 (0.87%) of the non-equipped vehicles (Table 3).

To compare crash risk among TSS equipped versus non-equipped, crash rates were computed to account for the overall greater exposure (vehicle-months) of the non-equipped vehicles. Of the TSS-equipped vehicles, 2.46 crashed per 10,000 vehicle-months (95%CI:1.75-3.17), compared to 4.55 crashes per 10,000 vehicle-months (95%CI:4.37-4.73) among the non-equipped vehicles (Table 3).

Therefore, study Toyotas equipped with TSS were 46% less likely to be a striking vehicle in a front-to-rear crash compared to non-equipped (CRR=0.54; 95%CI:0.40-0.67) (Table 3).

Table 3
Number and Rate of Vehicles involved in a Front-to-Rear Crash as the Striking Vehicle, by TSS equipment; Crude Rate Ratio of Vehicles With versus Without TSS

	Number of Striking Vehicle in a Front-to-Rear Crash (A)	Vehicle-Months (B)	Rate Per 10,000 Vehicle-Months C=(A/B)*10,000	Crude Rate-Ratio ($C_{withTSS}$):($C_{withoutTSS}$)
Equipped with TSS	46	187,215	2.46	0.54
Not equipped with TSS	2,571	5,650,834	4.55	

The study found that when the outcome was broadened to include all front-end damaged vehicles in multi-vehicle crashes, TSS-equipped vehicles experienced 17% fewer crashes than non-equipped vehicles (CRR=0.83; 95%CI:0.71-0.94) (Table 4). However, no significant difference was observed for the control crash population where the subset of crashes targeted by AEB (front-to-rear) was excluded (CRR=1.02; 95%CI:0.86-1.16). Table 4 also presents CRR for all crashes and multi-vehicle crashes.

Table 4
Crude Rate Ratio for Crashing Among Vehicles With Versus Without TSS, by Crash Population

Crash Population	Crude Rate Ratio	95% Confidence Interval
[1] All Crash-Involved Toyotas	1.01	(0.94 to 1.08)
[2] Toyotas involved in a Multi-Vehicle (MV) crash	1.00	(0.93 to 1.08)
[3] Toyotas involved in a MV crash with Front-end damage	0.83	(0.71 to 0.94)
[4] Outcome Evaluated: Toyota involved in a MV front-to-rear crash with front-end damage (striking vehicle)	**0.54**	**(0.40 to 0.67)**
Control crash population: MV crash with front-end damage [3] excluding front-to-rear crashes	1.01	(0.86 to 1.16)

CONCLUSIONS

Vehicles equipped with TSS, were 46% less likely to be a striking vehicle in a front-to-rear crash compared to non-equipped vehicles. This study contributes to the growing evidence of the effectiveness of AEB in helping prevent a significant number of crashes.

The control analysis found that differences in crash rates for TSS-equipped vehicles were only observed in front-to-rear crashes. Therefore, selection bias (customers who opt for TSS are safer drivers) did not likely play a significant role in this study. Further research is warranted to explore if the crash reductions in AEB-equipped vehicles found by this and other studies persist once these technologies are offered standard.

This study uses real-world data of a cohort of Toyota vehicles linked to crash events. The strengths of this study include the large sample size of a well-defined vehicle cohort, the ability to identify the individual options for each vehicle, and a well-defined outcome measure.

A limitation of the study is the short (less than one year) follow up of model year 2016 vehicles, limiting the sample size of TSS-equipped vehicles and crashes. In addition, this study uses estimated vehicle-months based on aggregate counts of vehicles by model year.

The current study served as the pilot for a more rigorous Phase 2 study, currently ongoing. Phase 2 uses retail dates of each vehicle to accurately estimate vehicle-months. In addition, Phase 2 expands the field study by incorporating

additional Toyota and Lexus models (Highlander, Corolla, Lexus ES and Lexus RX), more recent model years (model years 2015 to 2017; TSS was standard on model year 2017 vehicles), more recent crash data (years 2015 to 2017) and an additional three states' police reported data. Using the increased sample sizes and accurate computation of exposure at the vehicle level, phase 2 incorporates regression modeling techniques that control for exposure and time and compute adjusted risk ratios to quantify effectiveness. These findings will be reported in the near future.

ACKNOWLEDGEMENT

Toyota Motor Corporation supported this research.

REFERENCES

[1] Singh S. Critical reasons for crashes investigated in the National Motor Vehicle Crash Causation Survey. (Traffic Safety Facts Crash Stats. Report No. DOT HS 812 115). Washington, DC: National Highway Traffic Safety Administration. 2015.

[2] SAE International. Standard J3016 titled Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems. Society of Automotive Engineers. 2014.

[3] Cicchino JB. Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates. Accident Analysis and Prevention. 2017;99(Pt A):14-152.

[4] Fildes B, Keall M, Bos N, Lie A, Page Y, Pastor C, Pennisi L, Rizzi M, Thomas P, Tinvall C. Effectiveness of low speed autonomous emergency braking in real-world rear-end crashes. Accident Analysis and Prevention. 2015;81:24-29.

[5] NHTSA, National Highway Traffic Safety Administration (2017). NHTSA-IIHS Announcement on AEB: Manufacturers make progress on voluntary commitment to include automatic emergency braking on all new vehicles (accesed online, February 1, 2019 at https://www.nhtsa.gov/press-releases/nhtsa-iihs-announcement-aeb)

[6] Arias, E., & Smith, B. L. (2003). Deaths: Preliminary data for 2001. National vital statistics reports (vol. 51, No. 5). Hyattsville, MD: National Center for Health Statistics